Reuse of steel and aluminium without melting

Daniel Cooper

Darwin College

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Carbon dioxide emissions must be dramatically reduced to avoid the potentially dangerous effects of climate change. The steel and aluminium industries produce large amounts of carbon dioxide, accounting for 6% of anthropogenic emissions. Previous studies have shown that in these industries there is limited scope for further improvements in energy efficiency. Material efficiency strategies can, however, further reduce emissions. This thesis focuses on materially efficient reuse without melting. A scoping study of current reuse found three opportunities, an examination of which forms the basis of this thesis: reusing components at end of product life; extending the lifespan of products; and reusing manufacturing scrap.

The opportunity to reuse components has received little attention to date and there is no clearly defined set of strategies or barriers to enable assessment of appropriate component reuse; neither is it possible to predict future levels of reuse. This thesis presents a global assessment of the potential for reusing steel and aluminium components. A combination of top-down and bottom-up analyses is used to allocate the final destinations of current global steel and aluminium production to final products. A substantial catalogue has been compiled for these products characterizing key features of steel and aluminium components including design specifications, requirements in use, and current reuse patterns. To estimate the fraction of end-of-life metal components that could be reused for each product, the catalogue formed the basis of a set of semi-structured interviews with industrial experts. The results suggest that approximately 30% of steel and aluminium used in current products could be reused. Barriers against reuse are examined, prompting recommendations for redesign that would facilitate future reuse.

In order to understand how product lifespans can be extended it must first be understood why products are replaced. A simple framework with which to analyse failure is applied to the products that dominate steel use, finding that they are often replaced because a component/sub-assembly becomes *degraded*, *inferior*, *unsuitable* or *worthless*. In light of this, four products, which are representative of high steel content products in general, are analysed at the component level, determining profiles of cumulative steel mass over the lifespan of each product. The results show that the majority of the steel components are underexploited – still functioning when the product is discarded. In particular, the potential lifespan of the steel-rich structure is typically much greater than its actual lifespan. Evidence from twelve case studies, in which product or component life has been increased, is used to tailor life-extension strategies to each reason for product failure, providing practical guidelines for designers.

There is currently no commercial method of reusing small manufacturing scrap; however, previous research has demonstrated that extruded profiles can be created from small clean aluminium scrap, the scrap fragments solid-state welding together when extruded. In order to evaluate potential applications for these profiles four case studies are conducted in collaboration with aluminium producers and product manufacturers. It was found that strong and formable profiles could be produced from scrap. However, contaminated scrap sources, unreliable bonding and poor surface quality limited their potential for commercial use. No model exists for solid-state weld strength that is applicable to scrap extrusion. This prevents optimisation of the existing extrusion process and the development of new, potentially better, processes. Subsequently, this thesis presents a new model of weld strength as a function of relevant deformation parameters. The model is evaluated using a new experiment in which the deformation conditions can be varied independently. The experiments establish the basic relationships between deformation parameters and weld strength. The model correctly predicts these trends with predicted weld strengths typically lying within the experimental error range.

The technical assessment of reuse presented in this thesis demonstrates the scope of potential change. If implemented, the opportunities presented would greatly increase the reuse of steel and aluminium, reducing the emissions emitted from liquid metal production in conventional recycling.

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Declaration: This dissertation is the result of my own work and includes nothing that is the outcome of work done in collaboration except where specifically indicated in the text. The dissertation contains approximately 50,000 words and 80 figures and tables, within the word and figure limits set by the Degree Committee.

Publications

Journal papers (in print)

Cooper, D.R. & Allwood, J.M., 2012. Reusing Steel and Aluminium Components at End of Product Life. Environmental Science & Technology, 46(18), 10334–10340.

Journal papers (submitted)

Cooper, D.R., Skelton, A.C.H., Moynihan, M.C. & Allwood, J.M. 2013. Component level strategies for exploiting the lifespan of steel in products. Submitted to Resources Conservation & Recycling

Cooper, D.R. & Allwood, J.M., 2013. The influence of deformation conditions in solid-state aluminium welding processes on the resulting weld strength. Submitted to the Journal of Materials Processing Technology

Books

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Monographs

Allwood J.M., Cullen J.M., **Cooper D.R.**, Milford R.L., Patel A.C.H., Carruth M.A., McBrien M., 2010. Conserving our metal energy: avoiding

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Nomenclature

	Solid-state processes and welding equations (Chapter 2.3 and 5)
ARB	*Accumulative roll bonding*
JLR	*Jaguar Land Rover*
PDE	*Porthole die extrusion*
TUD	*Technische Universität Dortmund*
WQI	*Welding quality index*
	Bond properties
σ_b	*Tensile bond strength*
τ_b	*Shear bond strength*
	Deformation parameters
σ_n	*Normal contact stress*
τ_{app}	*Interfacial shear stress*
ε ($\dot{\varepsilon}$)	*Engineering strain (strain rate)*
η	*Threshold strain required for bonding*
ν	*Fraction of final interface area consisting of exposed aluminium substrate*
R_f (R')	*Rolling reduction (Limiting rolling reduction required for bonding)*
T	*Process temperature*
τ_{crit}	*Critical shear stress for welding initiation in Güley (2013) model*
	Aluminium properties
σ_o (k_0)	*Aluminium strength at room temperature (shear strength)*
Y (k)	*Flow stress of aluminium (in shear)*
r (ψ)	*Surface roughness mean asperity height (mean asperity inclination)*
	Oxide properties
σ_{oxide}	*Tensile strength of aluminium oxide*
t_c	*Oxide thickness*
λ	*Oxide fragment length*
	Contact region parameters
A_n	*Nominal area*
A_c	*Area of contact between asperity tips*
A_{ex}	*Area of exposed aluminium substrate*
A_s	*Area of contact between the substrate aluminium*
e	*Micro-extrusion channel width*
p_{ex}	*Pressure required to micro-extrude aluminium through oxide layer cracks*
	Diffusion parameters
X (t)	*Diffusion distance (process time)*
D	*Diffusion coefficient*

1 Introduction

The high standard of living enjoyed in the developed world depends on the use of engineered materials to provide shelter, sanitation, medical equipment, consumer appliances, and communications and transport systems. Steel and aluminium, possessing many properties relevant to such uses and being relatively cheap, are widely used to provide these services. Useful properties of steel include high strength and stiffness and a high melting point. Aluminium is tough, conductive, corrosion resistant and has a low density. Both metals are ductile, making them ideal for structural applications and allowing forming operations to create a range of products. Alloying and post-solidification thermo-mechanical processes can vary the strength and ductility of both metals. Their relative cheapness is due to the abundance and concentration of iron oxide and aluminium oxide (alumina) in naturally occurring iron ore and bauxite deposits, as well as our ability to reduce efficiently these oxides to the base metals.

Since the development of the Bessemer steel-making process in the 1850s and the Hall–Héroult aluminium-making process in the 1880s annual steel and aluminium production has rapidly increased, reaching 1330Mt of steel (WSA, 2009) and 73Mt of aluminium (IAI, 2008) in 2008, equivalent to 200kg of steel and 10kg of aluminium for each person on Earth. Steel and aluminium are likely to remain widely used as the relatively high cost and embodied carbon of alternatives limits the potential for material substitution. International Energy Agency projections are that steel production will roughly double (IEA, 2008a) and aluminium production triple (IEA, 2008b) between 2006 and 2050, driven largely by demand from developing countries.

1.1 Climate change and the steel and aluminium industries

Over recent centuries the average global temperature has increased concurrently with atmospheric concentrations of greenhouse gases. The fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC) concludes that increases in global temperature since the mid-twentieth century are 'very likely' to be due to man-made greenhouse gas emissions (IPCC, 2007), the most significant of which is carbon dioxide. To avoid the potentially dangerous effects of climate change the IPCC has recommended a minimum 50% cut in global carbon dioxide emissions from 2000 levels by 2050, which is predicted by the IPCC to limit the increase in global temperatures to 2-2.4°C.

The process of converting natural resources into engineered materials requires multiple steps, each of which requires energy and has associated emissions. For example, metal production requires mining, crushing, washing, separation of the ore from the gangue (the remainder of the mined material) and a reduction process that separates the metal from its oxide. The immense demand for engineered materials means that industry (tasked with their production) accounts for over a fifth of all anthropogenic emissions. Allwood et al. (2010a) have shown that if industry fails to match the 50% emissions cut reaching the overall target is likely to become unfeasible. Figure 1.1 shows that the steel industry is the single greatest emitter of industrial emissions. The aluminium industry, although a much smaller carbon dioxide emitter at present, is growing rapidly. As the dominant metal-polluters it is sensible to consider steel and aluminium together when analysing credible mitigation options.

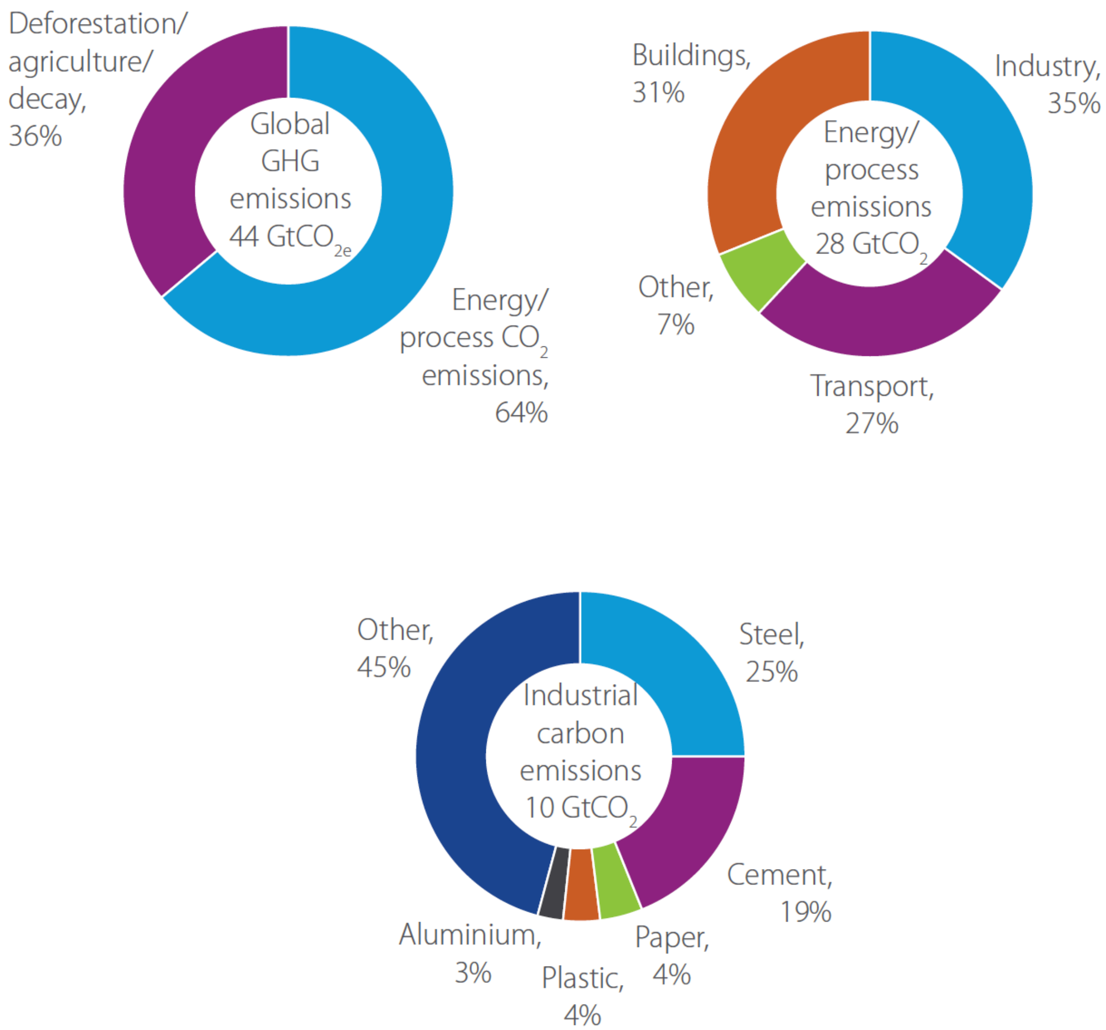


Figure 1.1: Global CO2 emissions for (a) all anthropogenic activity, (b) related to energy and industrial processes and (c) for industry. From Allwood et al. (2012) based on International Energy Agency data

1.2 Energy and emissions in steel and aluminium making

Industrial data reported by Worrell et al. (2007) and BCS (2007) shows that most of the energy needed for steel and aluminium production is used in the creation of the liquid metal, not in post-solidification forming and fabrication. The liquid metal is produced by one of two routes: the reduction of the metal oxide found in naturally occurring ores (primary production) or by melting scrap (secondary production).

In primary steel production, blast furnaces are used to reduce iron oxide with carbon monoxide derived from coke, producing liquid iron. The iron is then converted to steel using a basic oxygen furnace, where oxygen is blown through the liquid iron to oxidise the majority of the remaining carbon. In secondary steel production, electric arc furnaces are used to remelt the scrap. It is less energy-intensive than primary steel making, requiring 5.5GJ/te compared to 18GJ/te for primary steel making (Milford et al., 2011).

In primary aluminium production, alumina (separated from the rest of the bauxite) is dissolved in molten cryolite and reduced to aluminium via electrolysis. Aluminium atoms are strongly attracted to oxygen, so the reduction process is very energy intensive, requiring 168GJ/te (Milford et al., 2011). In secondary aluminium production, remelters and refiners are used to remelt scrap destined for wrought and casting alloys respectively. As reduction is not necessary, the energy intensity of secondary production is only 7.6GJ/te (Milford et al., 2011).

Carbon emissions are released in these production processes both directly and indirectly. Direct emissions are produced from fuel combustion, burning of carbon anodes and the reduction of iron oxide with carbon monoxide. Indirect emissions are related to electricity usage (accounting for over 80% of emissions in aluminium production).

Assigning a single figure for emission intensity to steel or aluminium production is complex, as it depends on the relative scale of primary and secondary production and the carbon intensity of the electricity supply. However, Milford et al. (2011) provide approximate ranges of carbon dioxide intensities (from 100% primary to 100% secondary) equal to 1.6-0.4tCO_2/t for steel and 8.6-0.43tCO_2/t for aluminium.

1.3 Options to meet the 50% emissions target

The energy efficiency of metal production could be improved by upgrading major steel and aluminium production facilities to best available technologies and practices. Attainable improvements, as described by Worrell et al. (2007), include some coke substitution in steel making, more efficient electrolysis in aluminium production, better use of by-products and more energy efficient furnaces and motor driven systems. In addition, many recent technological innovations could be implemented at scale over the next forty years. These innovations, as described by Allwood et al. (2012), include smelt reduction and electrolysis for steel and inert anodes in aluminium production. Allwood et al. (2010a) study the potential impact on emissions of such developments, calculating maximum emission cuts of 34% in steel and 23% in aluminium. The limitations of available improvements in energy efficiency are due to the existing efficiency of metal production. Energy purchases account for a third of the costs of both basic steel (Bettinger, 2011) and aluminium (CRU, 2005) production. The pursuit of profit alone, therefore, has motivated metals producers to research improvements in energy efficiency. After one hundred years the result is that the practical limit of energy efficiency in steel and aluminium production is being reached (Gutowski et al., 2013).

The impossibility of reaching the 50% target by focusing solely on energy efficiency improvements prompted Allwood et al. (2010a) to conclude that radical process improvements or a reduction in the demand for steel and aluminium production is needed. Radical process innovations may occur, but are difficult to implement into a carbon abatement strategy. Allwood et al. (2010b) therefore identify strategies to increase material efficiency (delivering services with less material production). Non-destructive reuse could be highly effective; by preserving the microstructure and geometry of existing components, it avoids the high-energy costs of recycling by melting.

1.4 Reducing demand for liquid metal through reuse

Reusing metal prevents the majority of emissions associated with recycling, which at 0.4tCO_2/t for steel and 0.43tCO_2/t for aluminium, although less than in primary production, are still considerable. Any reconditioning emissions associated with reuse are likely to be small in comparison. However, we are still far from recycling all of our scrap; Allwood et al. (2010a) estimate current recycling rates at 65% for steel and 39% for aluminium. The remaining material is destined for land-fill and this short-fall in scrap being returned for recycling is accounted for with energy intensive primary production. If reuse can encourage more steel and aluminium to be diverted away from landfill it will save primary as well as secondary emissions. Allwood et al. (2010a) calculate that, given scrap recovery rates increase to 90% by 2050, a diversion of 92% of steel away from recycling and into reuse would allow steel emissions to be halved.

The research presented in this thesis was undertaken to elucidate the practical options for reuse. Only a technical understanding of reuse is considered here, recognizing that subsequent work is required to evaluate its economic and policy consequences. A survey of steel and aluminium reuse activity was conducted at the beginning of this research through site visits to UK companies throughout the metal supply chain. Figure 1.2 summarises characteristic opportunities found at different length scales. The x and y axes designate product and reuse definitions used in preliminary research.

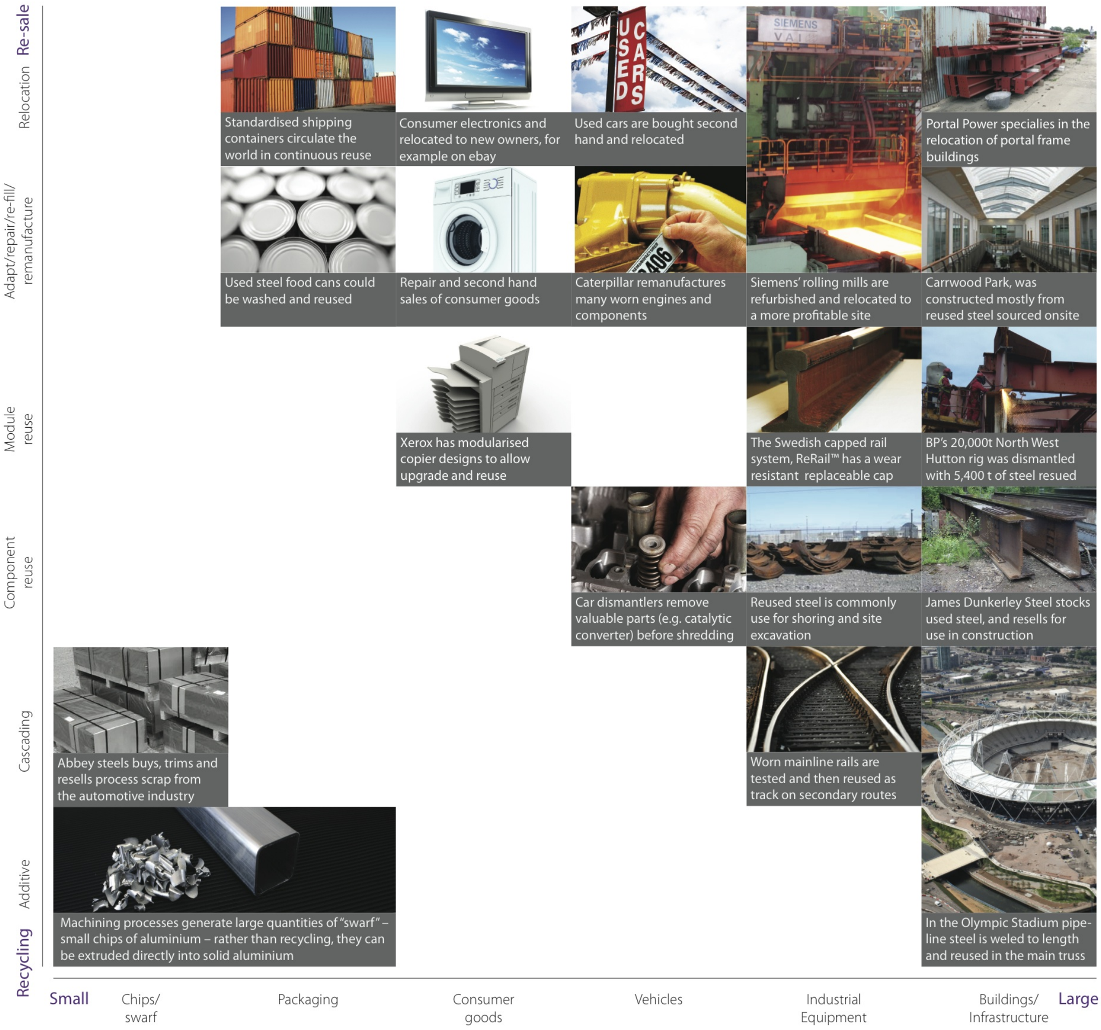


Figure 1.2: Examples of reuse (including emerging technologies)

Examples of product life extension (such as building refurbishment and second hand cars) and component reuse (such as remanufactured engines and photocopier modules) were found in small volumes among several product categories. The survey found no examples of post-consumer reuse at small length scales (the white band running from top left to bottom right on Figure 1.2). Small length scale reuse is instead dominated by the reuse of manufacturing scrap where the metal is of known quality and can be processed in bulk. The reuse activities presented in Figure 1.2 can, therefore, be grouped into three distinct categories:

- Component reuse
- Product life extension
- Reuse of manufacturing scrap

1.4.1 Reuse of manufacturing scrap

There are two different opportunities to reuse manufacturing scrap presented in Figure 1.2: reusing large sheet metal scrap in the manufacture of small components, and the solid-state welding of machining chips to produce extruded profiles.

The opportunity to reuse sheet metal scrap exists because manufacturers often require sheet metal in shapes (known as blanks) that do not tessellate. When manufacturers cut these shapes from sheet, large pieces of scrap known as 'blanking skeletons' are produced, an example of which is shown in Figure 1.3.

Figure 1.3: Blanking skeleton scrap from the production of circular blanks

Abbey Steel is a company which for 30 years has bought, trimmed, and re-sold around 10,000te per year of blanking skeleton scrap from the automotive industry as blanks to manufacturers of smaller components, such as filing cabinets, electrical connectors and shelving.

There is currently no commercial method of reusing aluminium chips. However, solid-state welding of scrap fragments through an extrusion process has been demonstrated at universities. If applications can be found for the extruded profiles the scrap will have been successfully reused, saving most of the energy associated with melting; Allwood et al. (2005) and Güley et al. (2010) calculate energy savings of over 90% compared with conventional recycling. This process is also attractive because of the high volumes of chip scrap available and the low material yield, as well as high energy intensity, of conventional chip recycling.

Aluminium chips are produced during the scalping of aluminium ingots and during machining processes. For example, in high performance applications a final part (such as an aerospace wing skin panel) is often machined from a large rectangular block of aluminium with a material yield less than 20% (Milford et al., 2011). A global figure is not available, but Kirchener (1994) reports that 25% of German aluminium manufacturing scrap is in the form of chips. There would, therefore, be no shortage of chips available to use in an extrusion welding process.

Conventional recycling of aluminium chips is not only energy intensive but also difficult due to the chips' large surface area (covered in oxide) to volume ratio. There are losses of metal at every stage of the chip recycling process: metal being oxidised during melting, some lost through mixing with the slag from the surface of the melt, and scrap resulting from casting and further processing of the aluminium ingots. All these losses contribute to an aluminium yield that can be as low as 54% (Gronostajski et al., 1997). An extrusion process to weld the chips together presents an opportunity not only to reuse the metal but also to increase the material yield of reprocessing; Pantke et al. (2011) report a potential chip extrusion yield of 95%.

1.5 Thesis structure

This thesis presents research conducted on the three reuse categories identified in section 1.4: component reuse, product life extension, reuse of manufacturing scrap. Research on the reuse of manufacturing scrap focuses on the solid-state welding of aluminium chips. Chapter 2 presents a review of previous work in these areas.

Chapter 3 presents research on the global potential to reuse steel and aluminium components at the end of product life. Strategies to reuse components and barriers against their implementation are also presented.

In Chapter 4, research on increasing the average lifespan of steel in products is presented. Life-extension strategies are identified and tailored to reasons for product failure. A product template is identified that encourages product life extension.

Chapter 5 presents case studies on potential applications for extruded scrap profiles. A new model of weld strength is then presented and evaluated using an experiment designed to independently test the influence of separate deformation conditions on the resulting weld strength.

A summary of the main findings is presented in Chapter 6, along with potential further research that could be conducted in these three research areas.

2 Literature review

This chapter includes reviews of the existing literature on component reuse, product life extension, and the solid bonding of aluminium, and provides supporting material for Chapters 3-5 of this thesis.

Section 2.1 focuses on the practical lessons for the reuse of components from the literature, examining current and future reuse, key barriers and design recommendations that encourage reuse.

Section 2.2 reviews the literature on product life extension, examining the environmental benefits of extending product life, current reasons for product replacement, and design strategies for long-life products.

Section 2.3 focuses on using solid-state welding of aluminium as a method to reuse aluminium chips. A review is conducted on the theories of weld formation and the development of the chip extrusion process, which finds that no models of weld strength applicable to chip extrusion have been developed. In order to help develop such a model a review is conducted on modeling of other solid-state welding processes. The review in section 2.3 informs the development of a new model of solid-state weld strength introduced in Chapter 5.

2.1 Component reuse

The majority of literature on reusing metal focuses on the refurbishment of high value sub-assemblies, such as engines, starter motors and compressors (Parker and Butler, 2007). This activity, called 'remanufacture', was first defined in a published article by Lund (1984) who described it as an industrial process in which "worn-out [sub-assemblies] are restored to like-new condition" by deconstructing the sub-assembly, cleaning and refurbishing usable components, and then reassembling with any new parts if required. These labour intensive processes mean that remanufacturing is typically restricted to high value items where significant monetary value can be added to the scrap metal, making it profitable. There is a poor correlation between the metal content and monetary value of a product. For example, Allwood et al. (2012) report that the steel structure of an office building accounts for 75% of the building's mass, but less than 10% of its cost. As a result the volume of metal that can be remanufactured relative to the total volume of metal is likely to be small. This is consistent with Parker and Butler's (2007) assessment of UK remanufacturing, finding that most remanufactured products are "very small items [so] the most important environmental benefit lies elsewhere". Therefore, despite the dominance of remanufacturing in the reuse literature, this review cites a disproportionate number of other studies that consider reuse of more metal intensive components.

2.1.1 Current and future reuse

Component reuse occurs in many sectors, but the amount of metal reused is typically small. The only extensive industry wide example is ship dismantling in Asia, where the majority of the world's discarded ships are broken. Tilwankar et al. (2008), in a life cycle assessment of the Indian steel industry, and Asolekar (2006), in an assessment of the waste produced by ship-breaking, both claim that up to 95% of the steel recovered from the vessels in India is in the form of re-rollable ferrous sheets. Tilwankar et al. (2008) describe the process: oxy-fuel cutting is used to slit the steel into plates that are then re-rolled (without melting) into flattened plates, bars and rods for use in the construction sector.

In construction, Gorgolewski et al. (2006) assess reuse of structural sections in Canada, finding that despite having good mechanical properties, uncertainty about the steel's origin and a lack of available stock leads to relatively limited reuse (approximately 10%), generally only for less demanding applications—such as shoring of construction works.

Kay and Essex (2009) report that 1.5% of end-of-life structural steel in the U.K. was deconstructed in 2007. The amount reused is not reported but will be only a fraction of this.

A range of industrial equipment is reused. Parker and Butler (2007) give several examples, including the remanufacture of worn pumps, compressors, excavation equipment engines, and tool bits. The worn surfaces are recovered by recoating and then grinding the surface back down to a 'like-new' condition. Butler (2009) describes the reuse of components from industrial food processing equipment (IFPE). The equipment is disassembled and the components used for ad hoc substitutions in other IFPE products. Butler (2009) report that 15% of the IFPE market (by monetary value) is devoted to the sale of second hand components.

Elsewhere, in consumer goods, the remanufacturing of Xerox photocopier modules is reported by Ayres et al. (1997). Xerox remanufactures approximately 500,000 photocopier modules every year. However, these modules contain little metal and the activity is insignificant to the steel and aluminium industries. Sundin and Bras (2005) describe domestic appliance remanufacture in Sweden. However, this reuse is mainly of newly manufactured products with non-structural failures covered by warranties, and does not constitute component reuse at end of product life.

In the transport sector, Ferrer (1997) describes tyre remanufacturing (retreading), reporting that this supplies 85% of the replacement demand for truck and bus tyres. Steinhilper (2011) reports the remanufacture of car starters and alternators (30-40million units per year), and Smith and Keoleian (2008) describe the process to remanufacture engines, but do not quantify reuse levels. Clearly many car components are being reused; however, the majority of metal in cars is in the structure and closures (doors, bonnet, boot). No literature on the current reuse of these components has been found, but future reuse of these components could be facilitated by technologies that reshape sheet metal components. This has been demonstrated by Tekkaya et al. (2008) in a process where hydro-forming is used to flatten contoured sheet parts and incremental forming is used to create new shapes. Examples of these ideas, as applied to a car bonnet and washing machine side panel, are presented in Figure 2.1.

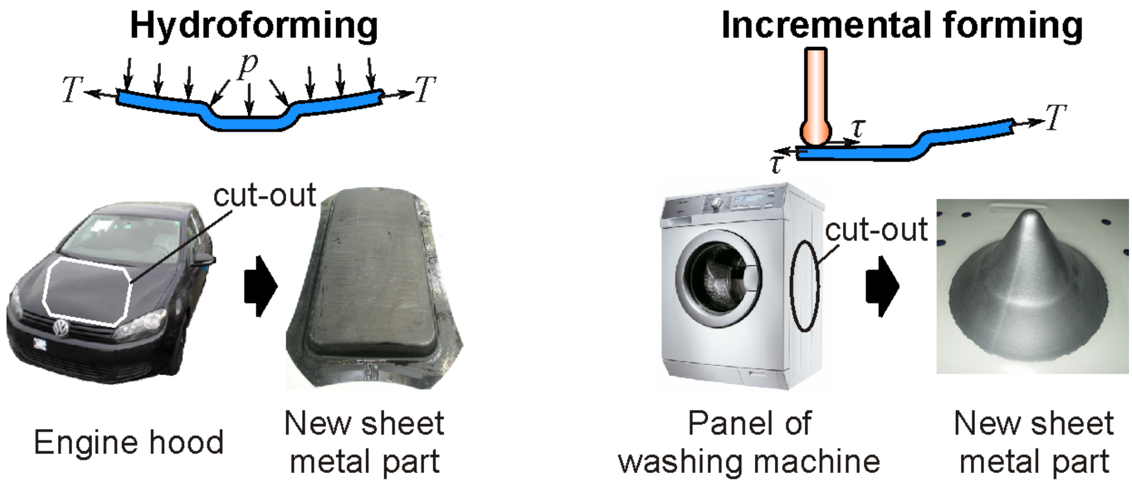


Figure 2.1: Reshaping of sheet metal scrap using hydroforming and incremental forming (Tekkaya et al., 2008)

Similar concepts on reshaping bent sheet metal parts are demonstrated by Takano et al. (2007, 2008), and presented in Figure 2.2. Takano et al. (2007) develop an incremental process to flatten bent sheet metal, resulting in a locally thickened area at the site of the former bend, which Takano et al. (2008) show does not significantly effect the formability of the sheet. The technologies demonstrated by Tekkaya et al. (2008) and Takano et al. (2007, 2008) could potentially be used to transform car closures, such as bonnets and doors, and appliance panels into other useful shapes for reuse.

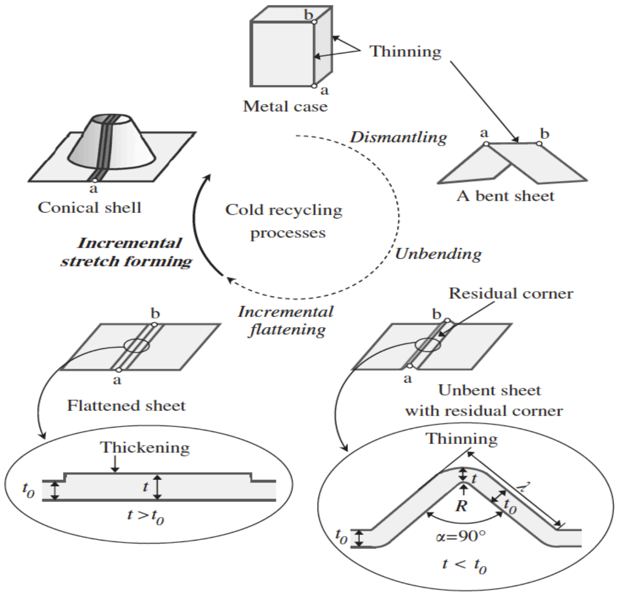


Figure 2.2: Incremental flattening and forming process to reuse bent sheet metal (Takano et al., 2008)

No analyses have been found on the global potential of component reuse across all products. Sherwood et al. (2000) analyze the waste streams of remanufacturing companies and report that most discarded parts are worn and unusable, suggesting that efficient reuse of components might be feasible. This analysis, however, focuses only on existing remanufacturers, ignoring, for example, metal reuse in buildings and infrastructure. An analysis of all steel and aluminium intensive products is needed to determine potential reuse volumes.

2.1.2 Barriers to reuse

For reuse to occur there needs to be both a supply of reclaimed components and a demand for these parts. Three related supply and demand side barriers have been found in the literature:

- **Disassembling** a product without damaging components
- Unknown **properties** of reclaimed parts
- **Obsolescence** of reclaimed parts

Several authors have reported the challenge of **disassembling** a product or building without damaging otherwise reusable components. For example, in a case study described by Gorgolewski (2008)—in which a typical one-storey steel framed building is reused—the open web steel joists are badly distorted during deconstruction and the steel roof deck, which was welded to the frame, is damaged beyond repair. Even reversible connections can be difficult to unfasten if corroded during use or situated high up in a structure. For example, Hammond et al. (1998), based on a survey of existing remanufacturers, find that corroded joints pose the greatest hindrance to car part disassembly. Gorgolewski et al. (2006) and Kay and Essex (2009), based on independent surveys of reuse in Canadian and British construction respectively, both attribute the dominance of demolition over deconstruction partly to the increase in health and safety regulation over the last 20 years; Gorgolewski et al. (2006) claim this regulation has reduced the likelihood of people working at height to unfasten bolted connections.

There is a lack of demand for reclaimed components because their **properties** are unknown. Gorgolewski et al. (2006) find that this leads to reclaimed structural steel being used not in a building but for less demanding applications; large sections are often used to support building work during construction (shoring), or as bracing members in temporary structures. Other uses for this material could be found if its properties were known. In the case of reclaimed structural steel from a building the original specification is sufficient to give designers confidence in its current properties. This is because it undergoes negligible degradation—corrosion or fatigue loadings—during use (Addis, 2006). For example, in the building reuse case study described by Gorgolewski (2008) the original specifications were available and used to label all the steel that was dismantled. Several authors recommend directly marking components during manufacture to aid identification at end of product life: Gorgolewski et al. (2006) recommend stamping structural steel with a permanent barcode; Gray and Charter (n.d.) recommend labeling all components in a product with Radio Frequency Identification (RFID). No authors have thoroughly assessed the feasibility of these suggestions. If the original specification of the metal is unknown, or the metal has corroded or been subject to fatigue loadings, testing is required to determine the properties. Mechanical tests on samples cut from the reclaimed metal can determine the strength and ductility, and chemical tests can determine the welding properties (Gorgolewski et al., 2006). However, these tests are currently prohibitively expensive, Gorgolewski et al. (2006) finding commercial testing companies charging $200 per test.

Products with a high rate of technological development are difficult to sell back to consumers due to falling demand for older, **obsolete**, products. Umeda et al. (2006) investigate the balance of supply and demand for components to determine maximum possible reuse rates: for rapidly developing products without any component standardization, any reclaimed components at end-of-life are incompatible with new product design and cannot be easily reused. This is also studied by Östlin et al. (2009). They split the length of time for which a company manufactures a rapidly developing product into five stages: introduction, growth, maturity, decline and cancellation. The shaded area in Figure 2.3 represents the potential volumes of remanufactured components over the product lifecycle. The time delay between the initial demand for reclaimed components and their availability from end-of-life products limits potential reuse volumes. In contrast, Butler (2009) finds that the evolution rate of technology in industrial food processing equipment is low, meaning that reclaimed components are still useful in new production lines. Reuse is therefore more likely for mature products or for where certain components can be standardized across product generations.

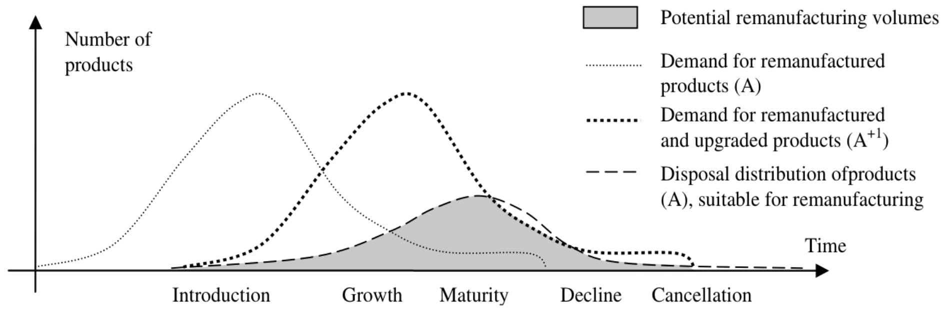


Figure 2.3: Potential remanufacturing volumes for a product with a high rate of technological development (Östlin et al., 2009)

2.1.3 Design recommendations for reuse

Reusing components in the future depends on the ability to extract and reuse components entering products now. Several authors suggest design guidelines to facilitate future reuse of components, and these are presented in Table 2.1. The design recommendations in Table 2.1 have been structured using a framework adapted from Sundin and Bras (2005) who define seven stages in the remanufacture of a product, the 'reuse steps' in Table 2.1. Remanufacture typically entails further disassembly, cleaning, and refurbishment of a component and is, therefore, the most complex form of reuse. It is therefore appropriate to use Sundin and Bras' framework to structure the design guidelines found in the literature.

Design recommendations that are most repeated in the literature include the standardising of parts and connections, clear labeling of components, and production of a deconstruction plan at the design stage. Implementing these guidelines should minimise the time needed to disassemble the product and maximise the reusability of reclaimed components. The studies that provide these design recommendations are nearly all focused on either the remanufacture of a small, high value item or the reuse of building elements. There is no way of evaluating how relevant these guidelines are to increasing the reuse of components in other products without a global assessment of reuse across all metal intensive products.

Product property	Design guidelines	Reuse step								
		Aquir-ing used compon-ents	Inspect-ion	Clean-ing	Disass-embly	Storage	Repair	Reass-embly	Testing	Selling reused comp-onents
Ease of identification	Clear labeling of reusable components (potentially RFID)[3,4,9]; produce well-documented report on original component specification and anticipated loadings[4]; clear (and certified) testing procedures with easy access to test points[9]	X	X			X		X	X	X
Ease of access	Smooth surfaces[2]. Avoid sharp edges and grooves[2]	X	X	X	X		X		X	
Ease of handling	Minimize number of parts[5,7]. Modular[5], standardized design[5] with durable parts[5]. Self-locating interfaces[2]		X	X				X		
Ease of separation	Prepare deconstruction plan[4,6,9]; modular design[5]; minimum number of reversible joints[7] or connectors with fracture points ("breakable snap-fits"[2]). Avoid use of mixed materials[5,7]. Corrosion resistant joints[3]. Self-locating interfaces[2]. Localise wear / sources of failure[8]	X		X	X		X			
Ease of securing	Standardised joints[1,9]. Reduced complexity (modular, standardized parts)[1]. Corrosion resistant joints[3]. Self-locating interfaces[2]. Ensure screw threads are sufficiently robust[9].				X			X		
Ease of upgrade	Modular design[5] with the minimal use of specialised parts[5]						X			X

Table 2.1: Design recommendations for reuse within a similar framework to that used by Sundin and Bras (2005). "Acquiring used components" and "Selling reused components" have been added to Sundin and Bras' seven reuse stages. These additions reflect the supply and demand barriers identified in the section 2.1.2.

References. *Design for remanufacturing*: 1. Sundin and Bras (2005); 2. Ijomah et al. (2007); 3. Gray and Charter (n.d.) *Design for reusing structural steel:* 4. Gorgolewski et al. (2006) *Design for product disassembly:* 5. Bogue (2007) *Design for deconstruction in buildings:* 6. Morgan and Stevenson (2005); 7. Brewer and Mooney (2008); 8. Addis and Schouten (2004) *A review of all 'Design for X' literature (where X maybe 'environment', 'reuse', 'disassembly' or other related words):* 9. Watson et al. (1996)

2.2 Product life extension

Component reuse as described in section 2.1 involves separating the product into components or sub-assemblies and reusing these parts. However, a further reuse option is to extend the life of steel and aluminium within a product.

Interest in product lifespans first emerged in the aftermath of the consumer boom in 1950s America with Packard's *The Waste Makers,* a popular critique of consumerist culture (Packard, 1960). Following from this, Walter Stahel's paper *The Product-Life Factor* was one of the first to argue that extending the life of goods was a sensible starting point in the transition towards a sustainable society (Stahel, 1982). However, although there is no robust data on the overall change in product life expectancy, there is some indicative evidence that, if anything, the expected lifespans of products are reducing over time: Babbitt et al. (2009) report the lifespan of computers purchased by US universities has dropped from 10.7 to 5.5 years between 1985 and 2000, and between a study conducted by Cooper and Mayers (2000) and a more limited (focus groups only) study conducted by Defra (2011) the reported expected life of televisions in the UK reduced from 10 to 7 years and that of computers from 6 to 4 years.

Product replacement is often justified by claiming an environmental benefit from the use of new products, and often newer products are admittedly more efficient than older ones. There is, therefore, a trade-off to be made when extending the life of a product: that between saving the embodied emissions associated with new production and failing to take advantage of the latest efficiency improvements. This trade-off is considered in Van nes and Cramer's (2006) study on optimal product lifespans; Figure 2.4 presents their depiction of the total environmental impact of two products with different lifespans. Manufacturing new products causes emissions, represented in Figure 2.4 as steps in the line graph. Once manufactured, however, the new products operate more efficiently than their predecessors, represented in Figure 2.4 as a decrease in the line gradients after each replacement step. The "E_{gain}" presented in Figure 2.4 suggests that early product replacement is wanted. The graph is, however, only a representation of the trade-off using arbitrary values for the relative scale of embodied and use phase emissions.

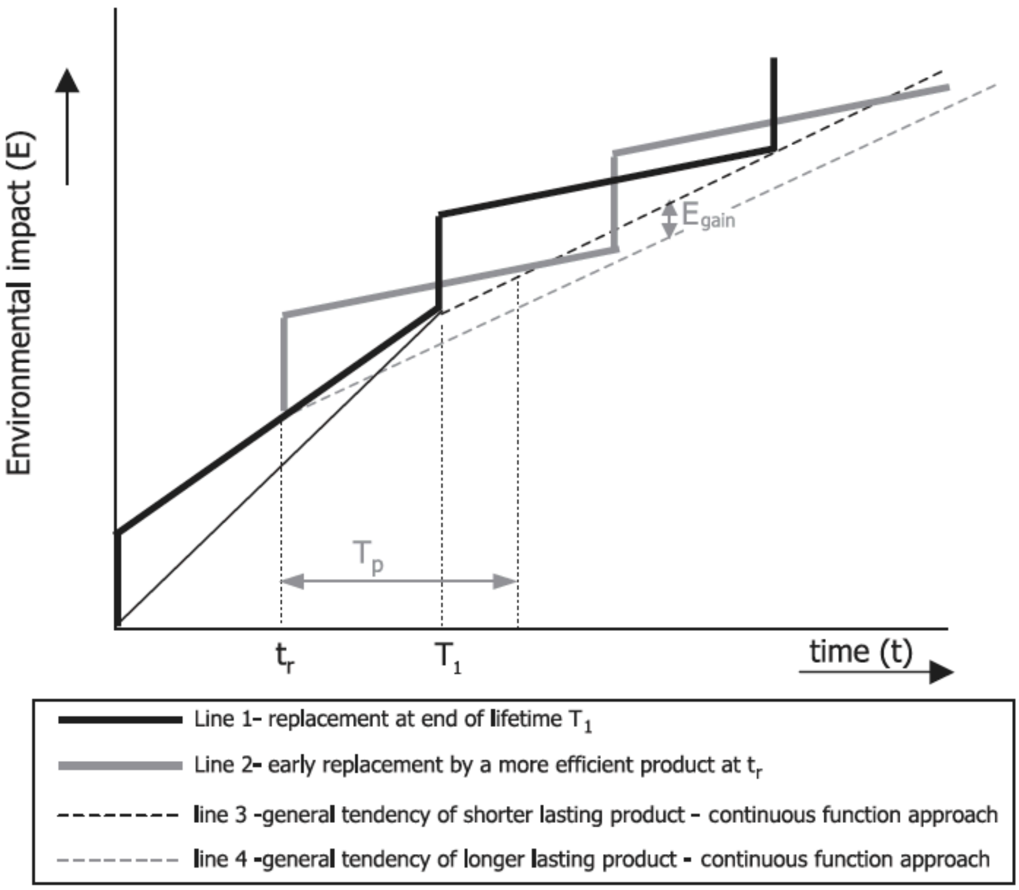


Figure 2.4: The environmental effect of product lifespan extension versus replacement by a more energy efficiency product (Van nes and Cramer, 2006)

Several authors have used product specific data to evaluate the trade-off. For example, with regard to domestic product remanufacture by Gutowski et al. (2011), for white goods by Boustani et al. (2010) and Truttmann and Rechberger (2006), and for personal computers by Sahni et al. (2010). In addition, the optimal product lifespan for reducing emissions has been calculated for cars by Kim et al. (2003), for specifically fridges by Kim et al. (2006), for air-conditioning units by de Kleine et al. (2011), and for cars, planes, office buildings and washing machines by Skelton and Allwood (2013).

The majority of these studies find that products should be frequently replaced and that extending the life of a product is a net-energy expanding activity. This is because, as observed by Gutowski et al. (2011), the emissions associated with "powered" products, which require an energy source, are dominated by the energy requirements in use. As a result, even small improvements in use phase energy means that frequent replacement causes the lowest emissions. In contrast, the total emissions associated with un-powered products, such as a building structure, is dominated by the production phase; Skelton and Allwood (2013) find the actual lifespan of a typical office building (50 years) is less than half the optimal lifespan (135 years).

The above studies assume that use phase emissions improvements can only be achieved through product replacement, whereas modular design could allow replacement of powered sub-assemblies. Therefore, extending the lifespan of products is not incompatible with taking advantage of improvements in use phase emissions.

2.2.1 Product failure

Extending the lifespan of a product depends upon postponing product failure. Therefore, in order to understand how to increase the lifespan of a product it is necessary to first assess why it is replaced.

The causes of product failure are multifaceted, ranging from inevitable physical degradation over time, to the deliberate curtailment of product life by producers seeking to force replacement purchases, to the voluntary premature replacement of products by consumers in the pursuit of psychological (as opposed to purely functional) benefits. Efforts to create a single set of reasons for product failure from these various influences include: Woodward (1997), who distinguishes between functional lifespan, physical lifespan, technical lifespan, economic lifespan, social and legal lifespan; Cooper (2005), who makes the distinction between absolute (forced) and relative (unforced) obsolescence; Thomsen and van der Flier (2011), who focus on buildings and identify four types of failure along two axes (endogenous-exogenous/physical–behavioural); and van Nes and Cramer (2006) who define four types of failure (wear-and-tear, improved utility, improved expression and new desires). Skelton (2013) constructs a set of failure modes that can specifically be applied to all the key end-uses of metal, being pertinent to both household and commercial product replacement decisions. Table 2.2 displays this failure framework.

The performance of the product has declined …	**DEGRADED** … relative to when it was bought	**INFERIOR** … relative to what is currently available
The desire for the product has changed …	**UNSUITABLE** … in the eyes of its current user	**WORTHLESS** … in the eyes of all users

Table 2.2: Product failure framework (Skelton, 2013)

The columns distinguish between changes that affect only the current individual product and user, and more systemic changes that come about through developments elsewhere in the market. This is illustrated by considering the declining performance of products over time: productivity falls, operating and maintenance costs rise, aesthetics degrade and safety becomes compromised. This decline in performance can cause failure in its own right (in which case the product is said to be "degraded") or can merely contribute to failure relative to the best available alternatives on the market (in which case the product is said to be "inferior").

The two rows of the framework distinguish between failure that arises from a change in the state of the product, and failure that arises from a change in the desires of the user. Changes to an individual's or business' circumstances can mean that products no longer meet the needs of their current users. When this is the case the product is said to become "unsuitable". More systemic changes, for example changes in legislation or changes in the context in which a product is used, can mean that a product is unsuitable for a larger group of people ultimately resulting in the product becoming "worthless".

There are no studies that analyse the causes of failure of steel and aluminium products; however, the framework introduced by Skelton (2013) could be used to structure replacement decisions if the data is collated.

2.2.2 Design for long life products

Durability

The simplest option to postpone the *degraded* failure of a product is to make the product more durable. Allwood et al. (2010b) summarise the major causes of physical failures and potential technical responses, shown in Table 2.3.

Failure mechanism	Options in response	Examples of leading edge practice
Fatigue	Material inspection for cracks prior to manufacturing, and in service; redesign for reduced stress cycling (for example, increase cross-sections)	Aeroplane wings experience significant cyclic loading throughout their life, but failure is now extremely rare
Wear	Surface hardening and polishing, design for reduced contact pressures, manufacture with sacrificial material	Automotive bearings are now sold guaranteed for life
Corrosion	Sacrificial anodes, other electro-chemical response, coatings	Oil rigs operate in salt water without significant repair throughout the lifetime of a particular oil field
Creep	Reduction of cracks and grain boundaries in vulnerable components	Blades in high performance gas turbine engines are made from single crystals to withstand high centrifugal loads for long periods of service at high temperatures

Table 2.3: Technical causes of end-of-life and options to overcome them (adapted from Allwood et al., 2010b)

Many of these technical strategies cause either increased emissions in manufacture (for example, in the manufacture of single crystal turbine blades) or in the use of additional material in the product (for example, the use of sacrificial wear parts or increased cross-sections to reduce stresses). The justification for adding extra emissions to make products more sturdy, increasing product lifespan, is examined by Skelton and Allwood (2013). They derive a model of the total emissions associated with a product that takes account of lifespan and use-phase and embodied energy improvements over time. The model is used to find the optimal product lifespan that minimises total emissions. Skelton and Allwood (2013) find that "built-in redundancy" that increases the embodied emissions in a product by 10% can only be justified if a product fails before two-thirds of its optimal life. For example, Skelton and Allwood (2013) calculate additional embodied emissions may be justified to increase the lifespan of a washing machine (actual life: 6 years, optimal life: 21 years) or office block (actual life: 50 years, optimal life: 135years), but not a car (actual life: 13years, optimal life: 10years) or an aeroplane (actual life: 25years, optimal life: 12years). Therefore, the environmental case for increasing the overall durability of a product is unclear. Also, the failure framework presented in Table 2.2 shows that products may fail not because they are *degraded* but because they are *inferior*, *unsuitable* or *worthless*.

Repair and upgrade

Strategies to repair or replace components have the potential to prevent failure, affecting only the product element that has become *degraded*, *inferior*, *unsuitable* or *worthless*. The literature on methods to repair and upgrade products focuses on three related strategies: standardisation, modularity and functional segregation.

Standardised components and reversible, uniform joints facilitate easy replacement and adjustment because the same tools and techniques can be used for each component. Webster et al. (2005) suggest establishing a standardised ‘kit of parts’ for steel framed buildings, determining a limited number of regular component sizes predrilled with boltholes at set intervals. Many building structures are already bolted, rather than welded, together. However, as discussed in the section 2.1.2, demolition is still a lot more prevalent than deconstruction.

Reversible joints with inherent stability and fewer bolts to unfasten may allow for quicker and safer deconstruction. Figure 2.5 presents a range of common and novel structural connections. The joints are grouped into two families: shear force resisting simple connections (as commonly used in low-rise buildings) and moment connections (as used in portal frame construction). Novel joints such as the *Quicon Slotted Tee* (Burgan, 2002; Heywood, 2004), *ATLSS* (Perreira et al., 1993), and *ConXtech* (Hamburger, 2010) simplify demounting the beams. Quicon Slotted Tee offers simple removal, and ATLSS and ConXtech provide stability with male-female interlocking secured with bolts. *Girder Clamps* (Lindapter, n.d.) use friction to secure the joint without having to either weld or drill into the beam. Specifying these more novel joints may allow greater reuse in the future.

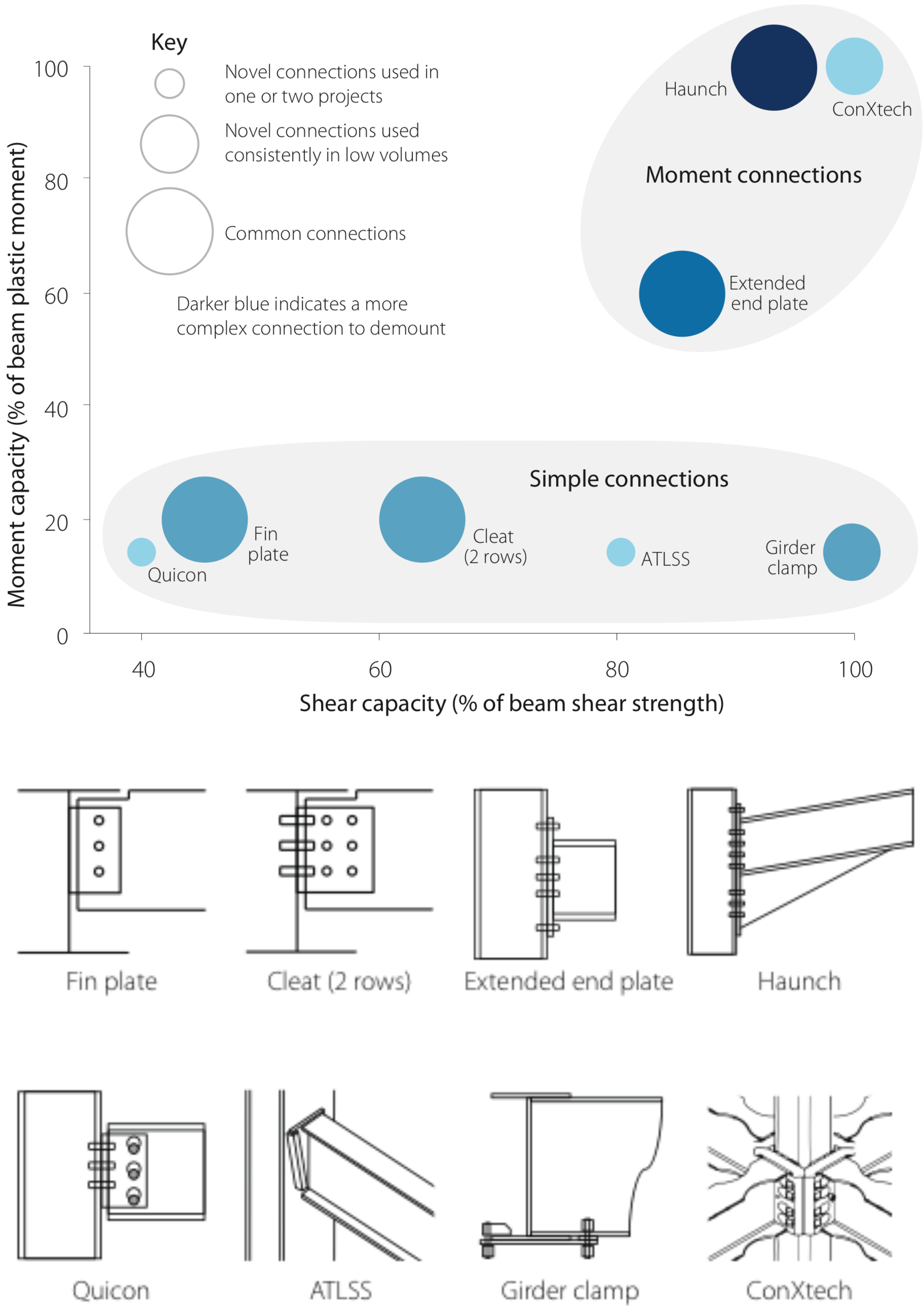


Figure 2.5: Novel structural joints (with fewer bolts to unfasten) compared to conventional joints

Modular design separates a product into distinct components/sub-assemblies with standardised interfaces, usually with reversible connections so that they can be easily replaced and upgraded. Palanirajan et al. (2005) attempt to assess the effect of modularity on products' lifespan using a "change modes and effects analysis" for seventeen consumer goods. They assess the likelihood of a product being discarded after potential changes to how it is used (e.g. a kitchen chair now used as a computer chair) and find that greater modularity increases the lifespan of the product because it is more adaptable (e.g. a multi-bit screwdriver is more adaptable than a fixed-bit equivalent).

The first step in **functional segregation** is to identify the function that each element of a product performs. Once isolated, the product or component can be redesigned so that only the elements most susceptible to failure need be replaced. Figure 2.6 presents an example of functional segregation applied in the design of a newly developed rail track, Rerail (2010). Identification of the prominent failure mechanism of the rails has inspired replacement of the contact surface with a wear-resistant boron steel push-fit replaceable cap, localising both function and a prominent mode of failure (wear). Only 15% of the rail need be replaced when changing the rail.

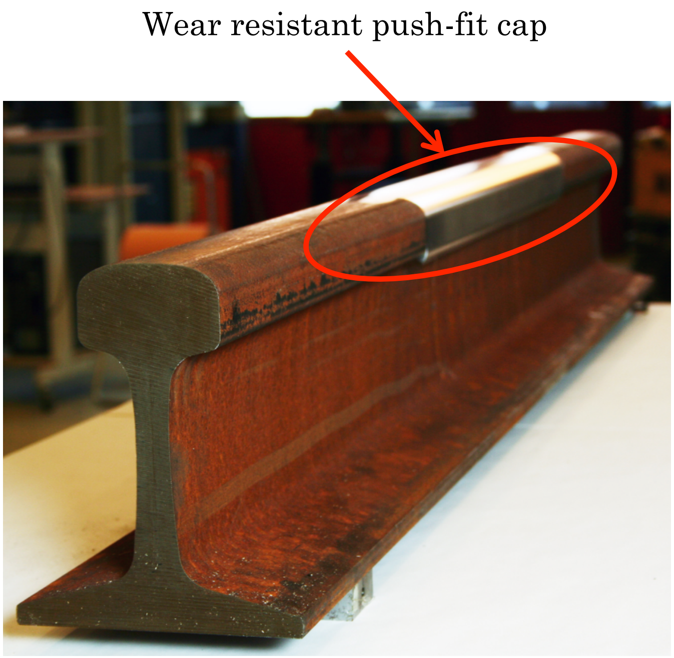


Figure 2.6: Functional segregation of rail head and web (Rerail, 2010)

Reversible connections, like push-fits, aid functional segregation by allowing easy, quick replacement; Morgan and Stevenson (2005) and Bogue (2007) both consider this a critical enabler of longer lifespan products. Durmisevic and Brouwer (2002) argue that traditional construction techniques encourage integration rather than segregation of components, causing demolition of buildings when actually only small alterations are required.

Brand (1994) introduces a useful tool to analyse functional segregation by examining the interaction between components within a product. He distinguishes six systems within a building that he depicts as layered upon each other. Each layer changes at a different rate and affects the adjacent layers. Brand notes that building alteration decisions are usually based on the slower-changing layers (e.g. structural capacity), but occasionally a faster-changing layer causes major alterations because it cannot be modified independently (e.g. installing heavy equipment requiring structural strengthening).

The literature reviewed in this section has provided a range of design strategies that may increase the lifespan of a product. However, the repair and upgrade strategies rely on replacing failed components; there are no studies that assess the extent to which failure occurs at the product rather than the component level. Only with a more comprehensive understanding of product failure can design strategies be targeted to reasons for product replacement.

2.3 Solid bonding of aluminium

Solid bonding is welding without the addition of a brazing filler at a temperature significantly below the base metals' melting points. Solid state welding includes some of the world's oldest welding processes, such as forge welding, which was used to produce the 1600-year-old 'Iron pillar of Delhi' (Wranglen, 1970) and the folded steel katana swords used by the samurai of ancient Japan (Smith, 1988). Forge welding of wrought iron was routine practice until the end of the nineteenth century. For example, it was the process used to make the propeller shaft and sternframe of Brunel's ship, the Great Eastern, launched in 1858 (Tylecote, 1968).

The first scientific study of solid bonding was by Desaguliers in 1724; he demonstrated to the Royal Society that two lead balls, when pressed together and twisted, could result in a weld with a strength up to that of the bulk metal (Desaguliers, 1724). The next significant study was not until 1878, when Spring investigated the adhesion of various non-ferrous metals by pressing together the bases of hot metal cylinders. It was found that aluminium in particular produced a strong weld at low deformations (Spring, 1894). At the beginning of the twentieth century, the growing use of steel (which is harder to forge weld than wrought iron) and the development of fusion welding for both steel and aluminium led to a lack of interest in solid bonding. However, the development of roll bonded clad metals in particular prompted a flurry of research in the mid-twentieth century, summarized in Tylecote's comprehensive 1968 review, *The Solid Phase Welding of Metals* (Tylecote, 1968). In recent decades, researchers have demonstrated that clean aluminium machining chips can be extruded into a solid product without any melting of the material. This process could potentially allow reuse of the chips if applications could be found for the extruded profiles.

In order to understand how aluminium chips can be directly extruded into solid metal the first sub-section in this review (section 2.3.1) presents a critique of the main solid-state welding theories. Section 2.3.2 then focuses on the development of aluminium chip extrusion, finding that two related technical barriers have prevented the process being widely used: imperfect bonding between the chips, and a porous extruded profile with a blistered surface finish. No predictive models of profile strength (as a function of the deformation conditions) have been found in the literature. This prevents the chip extrusion process from being optimised, which might minimise the above barriers. It also hinders the development of new processes that could help make solid-state reuse of aluminium chips widespread. In section 2.3.3, as a first step towards producing a predictive model, a literature review is presented on other prevalent aluminium solid-state welding processes—porthole die extrusion (extrusion to create hollow cross-sections) and accumulative roll bonding, where one strip of aluminium is stacked on top of another and then rolled.

2.3.1 Theories of bond formation

When aluminium atoms - electron configuration [Ne] 3s2 3p1 - combine to form aluminium metal the 3s and 3p valance electrons form an enormous number of delocalized electrons, resulting in a face-centered cubic lattice of positive ions in a ‘sea’ of electrons. The metallic body is held together by the attraction between the positive ions and the free electrons. Inter-atomic and van der Waals forces are the major sources of attraction between the atoms. When two atoms are widely separated, these forces are negligible; however, when intimate contact of less than 10 atomic spacings is achieved (the metallic radius of aluminium atoms being 0.143nm) the attractive inter-atomic force will form a joint, the crystal mismatch causing a non-cohesive grain boundary (Tylecote, 1968). For such close contact to occur, there must be no intervening film of oxides or other contaminants. This explains the findings of a 2009 European Space Agency report in which several spacecraft failures are attributed to unwanted 'cold welding' (Merstallinger et al., 2009); the lack of an atmosphere prevents the oxidation of metal substrate that has been exposed in space by the cracking of surfaces when struck by gear teeth.

Van der Waals forces of attraction act over greater distances than inter-atomic forces. They will, therefore, be present across an entire interface, whereas inter-atomic forces will be limited to areas of asperity tip contact. Despite this, Inglesfeld (1976) shows that the ratio of inter-atomic to van der Waals forces across an interface is typically very large, implying that bonding is the result of inter-atomic forces when contact is made between clean metal surfaces.

The film theory and energy barrier theory have been proposed to explain the characteristics of solid-state welding processes. The film theory is consistent with the above theory of forces, stating that intimate contact between metal surfaces causes a weld to form and that the presence of different surface oxides and contaminants explains the varying propensity of metals to weld in the solid state (Kazakov, 1985). The research of Conrad and Rice (1970) supports this theory, finding that the adhesion strength between clean metal surfaces previously fractured in a vacuum is almost equal to the load applied, implying that areas in close contact have bonded. In the presence of surface films, bonding requires that, (a), substrate metal must first be exposed by cracking the surface films and, (b), that a normal contact stress then establishes close contact between the substrate metal.

The energy barrier mechanism has yielded two theories: the 'mismatch of the crystal lattice' and 'recrystallisation' theories. The mismatch of the crystal lattice theory, proposed by Semenov (1960), dictates that some distortion of the crystal lattices of the two surfaces must be achieved to obtain bonding, representing an energy barrier that must be overcome. However, the Conrad and Rice (1970) experiments indicate that bonding is possible without deformation ('energy-free' bonding) if intimate contact is made between clean surfaces. In a review of the state of the art of cold welding, Zhang and Bay (1995) believe that any energy barriers are associated with the plastic deformation needed to establish intimate contact between the surfaces and to fracture the surface films, rather than with any distortion of the crystal lattice. The recrystallisation theory, proposed by Parks (1953), suggests that crystal growth during recrystallisation eliminates the films as a non-metallic barrier. In this theory, deforming the metal produces heat, decreasing the temperature necessary for recyrstallisation. Pendrous et al. (1984), however, find that no recrystallisation occurs during low temperature solid bonding.

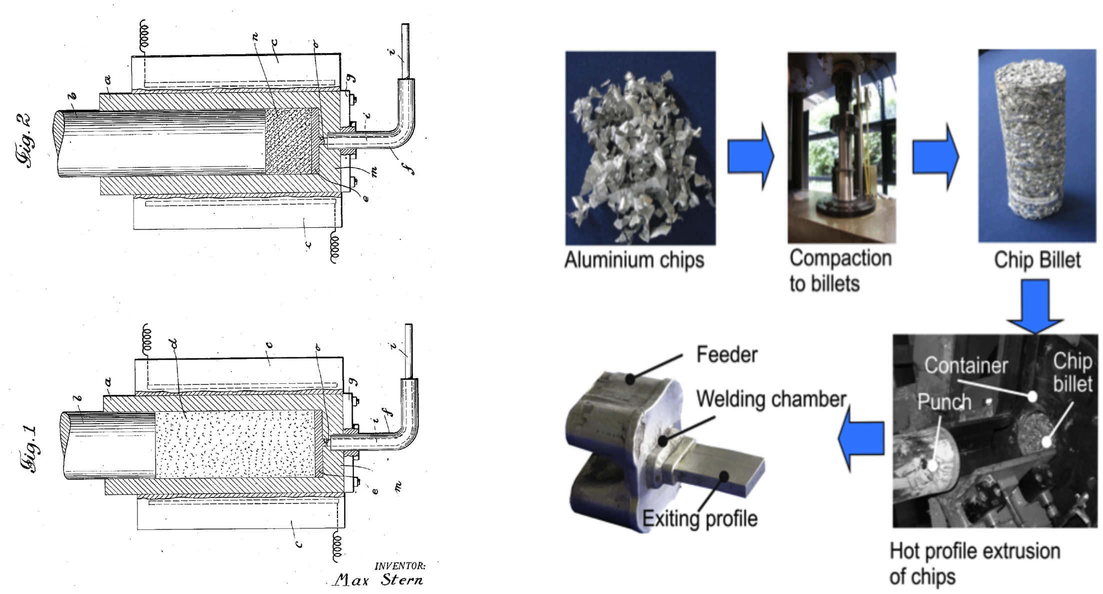
There is very little literature on the science of solid-state bond formation. Only two theories of the welding process have been found. The energy barrier theory states that bonding requires distortion or recrystallisation of the welding lattices; however, the results of several experiments contradict this idea. The film theory states that welding occurs when close contact is established between the substrate aluminium, requiring any surface films to be either removed or broken. No work has been published that contradicts this claim. In light of this, the film theory of bond formation is used in this work to explain solid-state welding characteristics.

2.3.2 Aluminium chip extrusion

Early development

In 1945 Stern patented an extrusion process, shown in Figure 2.7a, for directly producing finished profiles from aluminium scrap, the scrap fragments solid welding together in the extrusion die before deforming around a 90° bend (Stern, 1945). The process outlined by Stern is presented in Figure 2.7b and contained the following key steps:

- Cleaning of the scrap to remove lubricants and coolants from the manufacturing process
- Compaction of the scrap fragments into a 'green billet'
- Hot extrusion of this green billet at a temperature greater than 200°C



(a) (b)

Figure 2.7: (a) Schematics from Stern's U.S. patent application (Stern, 1945); (b) Clean chip extrusion process steps (Tekkaya et al., 2010)

The film theory of welding explains why the scrap must be cleaned prior to extrusion; an intervening film of lubricant/coolant would prevent close contact between the substrate aluminium.

Stern's patent generated little interest at the time, but three decades later Sharma et al. (1977) demonstrated the direct hot extrusion of aluminium chips into bars, reporting the presence of pores in the extruded product that undermined both the mechanical properties and the surface finish. In the same year, Takahashi (1977) performed a similar experiment but used a vacuum pump to remove the air in the extrusion press container. This resulted in an extruded profile with superior mechanical properties and a less blistered finish. Deaerating the extrusion press, however, made it both a high cost and energy intensive process. No other studies using this method have been found, and although the issue of porosity and blistering has been regularly observed in the literature no other attempts have been made to reduce it.

Etherington (1978) recommended recycling aluminium manufacturing scrap by using the conform process, a continuous version of extrusion (as shown in Figure 2.8). This was demonstrated by Pardoe (1984), and Lazzaro and Atzori (1992) describe an industrial application (the only example of industrial solid-state welding of aluminium scrap found in the literature): the conform process was used in an aluminium cast house to bond granulated saw trimmings to produce rod for steel deoxidant. Sharma et al.'s (1977) observation that extruded scrap profiles have a blistered surface finish and porous structure explains why the rod produced by the process described by Lazzaro and Atzori (1992) was only used for a destructive purpose (the deoxidation of liquid steel) rather than a structural, mechanical or aesthetic application.

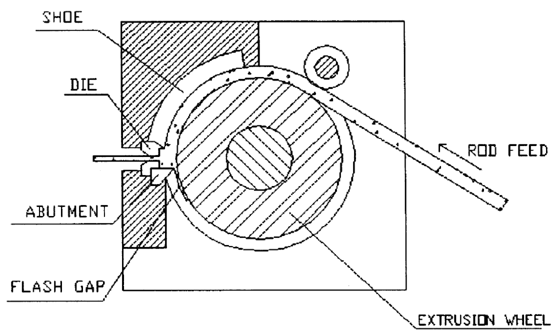


Figure 2.8: Conform continuous extrusion process (Kim et al., 1998)

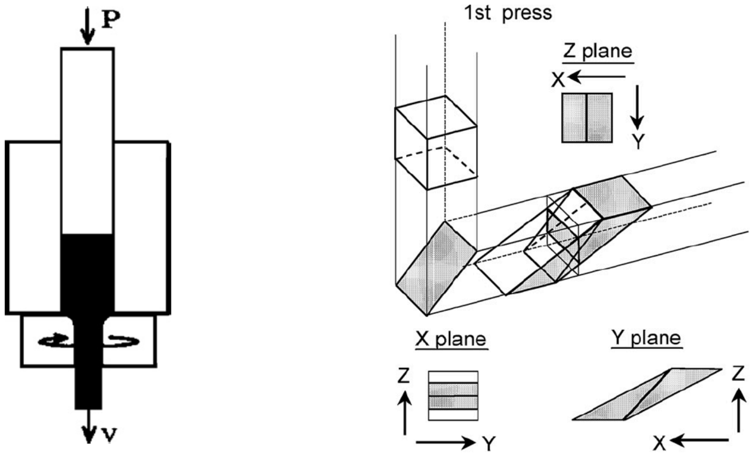
At the turn of the century several researchers attempted to improve the quality of extruded aluminium scrap by first reducing the chips into a powder, analogous to powder metallurgy processing routes. Zapata et al. (1997) convert chips into powder by ball milling, Gronostajski et al. (1997, 2000) granulate chips in a cutting device and Samuel (2003) uses a milling machine to reduce the size of the chips. These authors do not compare the properties of the resulting profiles to those created by directly extruding compacted chips; therefore, it is impossible to know if the powder production step improved profile quality. Creating powder is, however, expensive and energy intensive, prompting Fogagnolo et al. (2003) to investigate lower energy production routes that still result in welding of the chips. Fogagnolo et al. (2003) find the lowest energy and cost method to be compaction of machining chips (without milling) followed by extrusion. In subsequent research authors have similarly not converted the chips into powder.

Recent developments

In the last decade researchers have started to focus on two areas: alternative processes to extrusion, and quantifying the properties of chip extruded profiles.

Several authors have investigated using alternatives to extrusion to weld the chips together. For example, Allwood et al. (2005) experimented with rolling flattened rolls of domestic cooking foil as a proxy for compacted aluminium scrap. However, the flattened foil did not readily thread into the roll bite and the experiments resulted in unstable deformation with little bonding. Other investigated processes fall under the banner of *severe plastic deformation* (SPD) processes, in which very high pressures and strains are imposed on the metal. Experiments using SPD processes include Tang and Reynolds' (2010) friction extrusion (shown in Figure 2.9a) of one inch diameter compacted chip billets into wire; Cui et al. (2010) uses equal channel angular pressing, known as ECAP, to bond hot chips (shown in Figure 2.9b); and Haase et al. (2012) integrate extrusion and ECAP processing by extruding a compacted billet of AA6060 chips straight into a four turn 90° ECAP channel. Of these studies, only Haase et al. (2012) provides a comparison with direct extrusion, finding that their integrated extrusion and ECAP route results in significantly higher strength (≈10%) and ductility (≈50%) than normally extruded chip profiles.

However, the process also requires over twice the extrusion force of normal chip extrusion. Such high forces are typical of SPD processes, restricting their use to manufacture of small samples. It therefore seems likely that direct extrusion is still the most viable process to reuse aluminium chips.



(a) **(b)**

Figure 2.9: Schematics of (a) Friction (torsional) extrusion (b) Equal Channel Angular Pressing (ECAP) (Azushima et al., 2008)

Very few studies have investigated the properties of profiles extruded from chips. Studies that do investigate this focus on the profiles' strength and ductility parallel to the extrusion direction. The only studies that compare the strength of extruded chip profiles with conventional profiles extruded from cast billets are Tekkaya et al. (2009) and Güley et al. (2010). Tekkaya et al. (2009) conduct tensile tests on profiles resulting from the hot extrusion of AA6060 chips, finding similar properties to when extruding from a cast AA6060 billet; a tensile stress at least 90% of the cast billet extruded profile and generally similar ductility (though some samples had a reduced ductility of up to 20%). Similar findings on the mechanical properties of chip profiles are presented by Güley et al. (2010), also investigating hot extrusion of AA6060 chips. They find only "slight deviations in strength and ductility" between extruded chips and extruded cast billets.

A few authors have performed small parametric studies on the influence of material and process parameters on the strength of chip profiles. Their findings, along with references, are summarised in Table 2.4. In most of these studies only two values of each parameter are tested. Therefore, the trends described in Table 2.4 should be seen as indicative only; more nuanced relationships between the parameters and profile strength could exist that have so far not been revealed by the small number of tests.

Parameter	Effect on tensile strength of the extruded profile	Evidence	Reference
Material			
Alloy	No studies have examined the effect of the alloy on product quality or optimum processing conditions. A wider range of alloys needs to be examined and a parametric study on the effect of alloy choice performed. Extruding multiple alloys (composites) results in intermediate strength, but very poor surface quality.	Severe surface imperfections for extruded composite (AA6061 + AL_2O_3) Severe surface imperfections for extruded composite (AA6060+ SiC) Mechanical properties between the two alloys for extruded composite (AA1050 + AA6060)	Fogagnolo et al. (2003) Tekkaya et al. (2009) Güley et al. (2010)
Chip size and shape	Chip size and shape does not effect the properties of resulting profiles	Profiles produced from both large and small chips display a similar peak tensile strength. Variations in the shape (surface area to volume ratio) of chips does not have a significant effect on the strength of resulting profiles.	Suzuki et al. (2005) Tekkaya et al. (2009)
Extrusion process			
Temperat-ure	A strong positive correlation between tensile strength and extrusion temperature. Room temperature extrusion can still produce bonded profiles	Cold extrusion of AA1050 chopped sheets into a bonded profile Increase in tensile strength of 40% for temperature increase from 450 to 550°C (AA6061 chips)	Allwood et al. (2005) Suzuki et al. (2005)
Ratio	Increases in extrusion ratio increase the bond strength	Increasing extrusion ratio from 10 to 20 can facilitate a 3% increase in tensile strength and 5% increase in ductility for AA6061 chips	Suzuki et al. (2005)
Ram Speed	An increase in the ram speed reduces the strength and bonding of the extruded profile	Pure aluminium alloy extruded at different rates	Gronostajski et al. (1997)
Die design	Porthole dies increase bonding of the extrudant, but more than double the required ram force	Ductility of extruded AA6060 chip profiles increases by 80% when a porthole die is used instead of a flat die	Güley et al. (2013); Misiolek et al. (2012)
	Insufficient research has been conducted on the effect of die angle on the extent of bonding, with preliminary evidence indicating little effect.	Extrusion of chips at two different die angles (20º and 45º) has little impact on the extent of bonding	Allwood et al. (2005)

Table 2.4: Summary of parametric investigations on the effect of material and process parameters on the strength of chip extruded profiles

No predictive models of profile strength have been found in the literature. Güley et al. (2013) have, however, recently proposed a *Welding Quality Index* (WQI) for chip extrusion. The WQI does not attempt to predict the strength of chip profiles but can be used as a tool to compare between different die designs and process conditions. In the WQI model it is assumed that the onset of welding occurs when the shear stress in the extrusion die (τ) is greater than a critical shear stress (τ_{crit}), as shown in equation 2.1.

$$\tau > \tau_{crit} \tag{2.1}$$

The pressure-time-flow criterion (Donati et al., 2007), a model usually used to predict weld quality in the extrusion of hollow profiles, is then integrated between the location of bonding onset and the die exit, as shown in equation 2.2.

$$WQI = \int_{L_1 \;\; when \;\; \tau=\tau_{crit}}^{L_2 = die\ exit} \frac{\sigma_n}{k} \, dl \tag{2.2}$$

where σ_n is the normal contact stress between the chips, and k is the material yield stress in shear. Güley et al. (2013) determine the critical shear stress (τ_{crit}) by sectioning billet discards from successfully bonded chip extrusions and using microscopy to find the location where the chips first weld together. Finite element simulations of the extrusion then determine the shear stress at this location during the extrusion process.

The WQI is the first attempt to model any form of chip extrusion process. However, its accuracy is likely to be compromised by assuming that the onset of welding is independent of strain and normal contact stress, which the film theory suggests should contribute to close contact of the substrates.

Summary of chip extrusion developments

In the seventy years since Stern invented the concept of aluminium scrap extrusion there has been only one industrial application. No studies have been found that attempt to find applications for the extruded profiles and only recently have authors started to investigate their properties, most commonly their strength and ductility. It has been shown that tensile properties very similar to those of profiles extruded from cast billets are possible. However, nowhere in the literature reviewed has the anisotropy between longitudinal and transverse tensile strength been tested; alignment of the chips as they flow through the die may cause preferential welding perpendicular to the extrusion direction.

No predictive models of profile strength have been found in the literature, preventing optimization of the current extrusion process and development of new, superior, processes. In order to understand the important factors that affect solid-state welding of aluminium the literature on analogous processes must be reviewed.

2.3.3 Other solid-state welding processes: Parametric investigations and models of weld strength

Previous research on the influence of deformation conditions on the weld strength has focused on accumulative roll bonding (ARB) and the extrusion of cast billets into hollow sections, known as porthole die extrusion (PDE). Accumulative roll bonding is a process developed by Saito et al. (1999) where one strip of aluminium is stacked on top of another and then rolled, bonding the strips together as they go through the roll bite. Researchers in the aerospace industry have investigated the process as a means of introducing intense straining into a bulk material, reducing the grain size to less than 1μm. This results in a very high strength material because of the Hall-Petch relationship. Extrusion of cast billets into hollow sections is described by Xie et al. (1995). The process typically uses a porthole die, which has a central mandrel that the metal deforms around, forming the hollow section. A bridge to the die rim supports the base of the mandrel. The metal billet splits around this bridge before welding back together before the die exit. The strength of this weld determines the extrudate's mechanical properties.

The following deformation parameters have been identified in the literature review as important to the welding process: *normal contact stress* across the bonding interface, *temperature*, the *longitudinal strain* at the bonding interface, *strain rate*, and *shear*.

Studies on the effect of aluminium accumulative roll bonding (ARB) parameters on the weld strength, such as Jamaati and Toroghinejad (2010) on cold rolling and Eizadjou et al. (2009) on warm and cold roll bonding, find that higher temperatures, greater reductions and slower wheel speeds result in stronger welds. It is consistently found that a threshold reduction of approximately 35% is necessary for any welding to occur (equivalent to a 54% stretch of the bonding surface) and that this value slightly decreases as the process temperature increases (Eizadjou et al., 2009), but is independent of the normal contact stress (Bay, 1983).

Models for predicting the bond strength in ARB are based on the film theory of bonding. They do not consider the effect of shear on bonding, as the bonding interface usually passes through the centre of the roll bite, and therefore experiences limited shear. The most comprehensive model is presented by Bay (1983), who considers cold roll bonding between two scratch brushed surfaces. Bay assumes the surfaces consist of an oxide film covering a fraction, ψ, and a brittle cover-layer of work-hardened aluminium, created by the scratch brushing, covering the remaining area. Rolling of two samples creates three types of contact: cover-layer to cover-layer, oxide film to oxide film, cover-layer to oxide film. Bay's model for the resulting weld strength is given by equation 2.3.

$$\frac{\sigma_b}{\sigma_0} = \left(1-\psi^2\right) R_f \frac{\sigma_n - p_{ex}}{\sigma_0} + \psi^2 \frac{R_f - R'}{1-R'} \frac{\sigma_n}{\sigma_0} \qquad (2.3)$$

where σ_b is the resulting strength, σ_0 is the normal strength of aluminium, σ_n is the normal contact stress, p_{ex} is the micro-extrusion pressure needed to force substrate material through the cracks in the cover layer, R' is the threshold rolling reduction needed for initial welding and R_f is the actual rolling reduction:

$$R_f = 1 - \frac{initial\ thickness}{final\ thickness} \qquad (2.4)$$

Bay's model assumes that any stretching of the interface immediately cracks the brittle cover-layer, and that these brittle cover-layers crack together, creating channels through which the aluminium substrate is extruded. The oxide film, however, is assumed not to crack immediately, but only after a pre-determined rolling reduction (R'), after which any exposed substrate metal immediately welds. In reality, it is likely that some pressure will be required to extrude the aluminium through the cracks in the oxide. Bay (1983) performs plane strain compression tests on aluminium interfaces to evaluate the model. The results are very dispersed, but a general trend following the theoretical results can be observed. Bay's model does not attempt to quantify R' without experimentation, nor is there any consideration of the spacing of welded portions of the interface. The model does not consider hot rolling and assumes that the aluminium sheets can be modelled as perfectly flat surfaces; practically, however, the topography of the surfaces will cause local surface shear forces and air to be trapped between the two surfaces as they are rolled. Given that an oxide film of 2-4nm will form within milliseconds of exposure to the air (Vargel, 2004), this entrapped air may oxidise some of the exposed metal, decreasing weld strength.

Parametric studies by Jian et al. (2010) and Ceretti et al. (2009) on the effect of porthole die extrusion (PDE) parameters on the weld strength find that higher temperatures, greater extrusion ratios and slower ram speeds result in stronger welds. Several weld strength criteria have been proposed for PDE, based on the energy barrier theory. The earliest model was the maximum pressure criterion, first proposed by Akeret (1972), where bonding is considered to have occurred once the normal contact stress is greater than a certain limit. Donati and Tomesani (2004) state that there has never been an experimental validation of this model. More recently, the pressure-time criterion was introduced by Plata and Piwnik (2000), and presented in equation 2.5.

$$\int \left(\frac{\sigma_n}{k} \right) dt > C \tag{2.5}$$

where σ_n is the normal contact stress experienced on the bonding plane, and k is the material yield stress in shear. The ratio is integrated over the time for bonding. When the integral exceeds a critical value, C, bonding may be assumed to have occurred. Ceretti et al. (2009) determine 'C' from numerical models of successful ARB experiments and, using the pressure-time criterion, correctly predict superior weld quality with increasing extrusion ratio in PDE of AA6061. However, Donati and Tomesani (2004) compare the bonding predicted by the pressure-time criterion with experimental results from Valberg (2002), finding that the prediction of a decrease in bonding quality for a decrease in die leg angle is incorrect.

The pressure-time criterion ignores the effect of strain (altered by changing the extrusion ratio) and makes long time periods essential to bonding, suggesting that diffusion plays an active role in bonding even during high strain rate processes. Consistently, Gronostajski et al. (1997), in a study on extrusion of machining chips, explain the poor bonding produced with a higher ram speed with the hypothesis that the higher speed reduces the time for the diffusional transport of matter. However, Wu et al. (1998) claim that diffusion is likely to be irrelevant in extrusion processes because of the short time period in which material passes through the die.

The results of the pressure-time criterion are distorted by the long process times of material in the dead metal zone. Recognising this problem, Donati and Tomesani (2004) adjust the criterion, introducing velocity as a factor to reduce the influence of stationary metal in the dead zone. They propose the pressure-time-flow criterion, shown in equation 2.6.

$$\int\left(\frac{\sigma_n}{k}\right)dt.v > C' \quad \Rightarrow \quad \int\left(\frac{\sigma_n}{k}\right)dl > C' \qquad (2.6)$$

Where v is the velocity of the aluminium and l is the length of the welding plane from the point the converging metal streams first make contact to die exit. Donati and Tomesani (2004) compare the bonding predicted by the pressure-time-flow criterion with experimental results from Valberg (2002), finding that it correctly predicts an increase in bonding quality for a decrease in die leg angle.

Both the pressure-time and pressure-time-flow criteria do not take account of strain (altered by changing the extrusion ratio). It is assumed that the reason for this is a belief that there will be no surface oxides present on the welding planes. However, given that an oxide film will form on aluminium within milliseconds of exposure to air it is likely that oxides are present. High strains would help crack these oxide layers, revealing more of the substrate aluminium for welding.

A few studies have investigated the effect of shear on the weld strength. Bowden and Rowe (1956) find that two contacting specimens experiencing both a tangential and normal force have higher real contact area and bond strength than two specimens subject to a normal force. Cooke and Levy (1949) make welds by rotating one metal bar against another under a normal load, at 260°C. 'Satisfactory' welds were created with minimal lateral strain. Cui et al. (2009) investigate solid bonding of aluminium chips via cold compaction followed by equal channel angular pressing (ECAP) at 450-480°C. All the material experiences intense shearing because it deforms around a 90° bend. Despite the presence of voids in the centre and hot tearing on the surface of the resulting specimens, bonding has occurred. These studies have attempted to assess the influence of a shear stress between bonding surfaces. However, none of these experiments test for the influence of shear alone. For example, in ECAP processing very high pressures are required and, given Mohr's circle of strain, a plane of chips experience only normal strain.

Models of weld strength have been found for both PDE and ARB. Models of PDE are based on the energy barrier theory of welding and do not account for the effect of interfacial strain on the weld strength. Bay's model of ARB (equation 2.3) is derived from the film theory of bonding and considers both strain and normal contact stress. Bay's model is a good indicator of bond strength in roll bonding and could be extended to take account of temperature and strain rate by modeling the material strength as a function of these deformation conditions.

2.4 Conclusions and research plan

The literature on component reuse is largely focused on the reuse of structural steel and the remanufacture of high value, but typically small, sub-assemblies. This limitation prevents a clear set of principles being defined to establish when a product or its components can be reused; neither is it possible to predict future levels of reuse. An analysis of component reuse across all steel and aluminium intensive products would help define the physical strategies to reuse metal and the scope of potential change. That is the aim of Chapter 3 of this thesis.

In the literature on product life extension it is unclear why steel and aluminium intensive products are replaced and the extent to which failure occurs at the product rather than the component level. As a result, the aims of Chapter 4 are: to determine the prevalent causes of product replacement; to establish how many of a products' components are still functioning when it is replaced; and to target design strategies that help extend product lifespan to the causes of product replacement.

The literature on aluminium solid-state welding does not include a model of weld strength that accounts for all the important deformation parameters in chip extrusion. Therefore, the first aim of the work presented in Chapter 5 is to produce a welding model that addresses the limitations of previous attempts. The second aim is to evaluate the model using an experiment where aluminium can be solid-state welded whilst the relevant deformation conditions (*strain*, s*train rate, normal contact stress*, *temperature* and *shear*) are controlled independently.

3 Reusing steel and aluminium components at end of product life

Reuse has received little attention despite being one of the well-known "3Rs" – reduce, reuse and recycle – promoted by government organisations such as the Waste and Resources Action Programme (WRAP) in the UK. Policy makers must know the possible scale of reuse across all products and understand the technical, system and policy changes required to develop reuse at scale for it to contribute significantly to emissions abatement. This chapter addresses reuse's technical potential, recognising that subsequent work is required to evaluate its economic and policy consequences. The chapter targets component reuse in which old products are disassembled and components reused in a new product, rather than product life extension that occurs, for example, through second hand-sales.

An analysis of metal intensive products is required to estimate whether component reuse can make a significant difference to global demand for liquid metal. Existing global analyses of metal end-use include the World Steel Association (WSA, 2009) and International Aluminium Institute (IAI, 2008) for steel and aluminium respectively, but both present only the destinations of intermediate metal products at a sector level, such as 'transport' and 'construction', rather than attributing demand to final products. Assessing the potential scale of reuse requires knowledge of the actual products and components. This chapter therefore addresses three questions:

- In which final products is steel and aluminium used?
- What are the key design requirements for the steel and aluminium components in these products?

- What fraction of the end-of-life components in these products could technically be reused and how, and what physically prevents reuse of the remaining components?

3.1 Methodology

An extensive search of the academic and company literature, as well as structured interviews, are used to address these questions. A range of data sources and calculations is used, necessitating the summary of the methodology and examples described here. Full details are presented in the supporting information accompanying the journal article, Cooper and Allwood (2012). It is available for download at http://pubs.acs.org/doi/suppl/10.1021/es301093a, and also can be emailed on request. The extensive supporting information contains 168 pages in which a catalogue of 23 product descriptions is presented, derived from 200 literature sources and informed by 17 interviews with industry experts.

3.1.1 In which final products is steel and aluminium used?

Component reuse becomes possible when products reach end-of-life, so future reuse patterns depend on replacing the stock of products already in service. However, no global stock data is recorded and estimates must be inferred from historical production data using product life distributions. Historical production records are lacking, therefore such stock estimates can only be made in aggregated form. Instead, this section focuses on the final products of current steel and aluminium production. These products will be scrapped in the future; therefore, looking forward to 2050, current production data provides an estimate of future scrap streams. Current production data are not collected in any uniform manner, requiring inferences to be made from other sources. Three methods could achieve this: using input-output economic data, scaling national or local studies to global level, and combining top-down and bottom-up studies on end-use.

Input-output analysis could be used if metal tonnages were assigned to money flows traceable from production to end-use. However, metal tonnages do not necessarily relate directly to money flows; double counting due to trade when considering multiple regions is likely; data are sparse; the relevant data tables provide only end-use data at the sector level, making further analysis necessary to resolve metal use to specific products.

Various academic studies and large company reports provide data on local metal use in regions and states, which could be scaled to a world level. For example, Wang and Graedel (2010) and Recalde et al. (2008) present detailed aluminium stock data for China and Connecticut respectively, and Davis et al. (2007) provide scrap stream data for 9 different UK product categories. However, most of these studies target either stock or scrap flows, so production data must be inferred from estimates of product life distributions, and regional differences inhibit scaling. For instance, there are more steel framed buildings in the UK, Japan and USA than elsewhere. This method cannot therefore be used in isolation, but can help to estimate demand of specific products when cross-validated with global studies on aggregated end-use.

Integrated top-down and bottom-up analysis is therefore used to determine the end-use products. The analysis is based on a 2008 production mix, the most recent year for which sufficiently detailed data is available. Top-down data, recording the production of intermediate goods, are collected by large metal producers and collated by global and regional trade organisations (WSA, 2008; WSA, 2009; Eurofer, 2009; for steel, and IAI, 2008; AA, 2007; for aluminium). This has a low resolution, for example reporting tonnages for 'transport' and 'packaging' rather than products such as 'cars', 'ships', 'drinks cans' and 'packaging foil' etc. As these top-down sources do not typically report fabrication yield losses in converting intermediate goods to finished products, yield data from

Hatayama et al. (2010) for steel and IAI (2008) for aluminium are used to create top-down estimates of end-use requirements in major sectors.

Bottom-up data for particular products is derivable from sales figures for particular product types multiplied by academic or commercial data on product composition, in the form of 'bills of materials'. For example, the Organisation Internationale des Constructeurs d'Automobiles (OICA, 2007) presents global car sales, and Bertram et al. (2009) report the average aluminium content in cars. Such bottom-up studies give more detailed resolution for specific products, but insufficient studies exist to provide coverage of all products in all regions. Therefore, bottom-up data must be reconciled with top-down figures by scaling bottom-up figures from regions to global coverage, applying yield ratios between intermediate products and final goods, and organising the mix of products into the sectors used in top-down analyses. Such reconciliation is data and reference intensive, so a 13 page summary of the methodology (including references) is presented in Appendix A. The process is reported in detail in section 1 of the supporting information accompanying the journal article, Cooper and Allwood (2012).

Wherever possible, 2008 production data is used; when this is not feasible, figures from surrounding years are used and interpolated where possible. As metal use can vary with recessions and government spending, this introduces some uncertainty into the results.

For some products only regional data on composition is found. Care is taken to avoid scaling local distortions in relative metal use to a world level. For example, the relative use of aluminium in transport in China is much lower than the worldwide average. Typically, the largest aluminium components in a passenger car are the cast engine and, in a few cases, the body structure. The high cost of aluminium may reduce its prevalence in developing markets such as China, where a cast iron engine block and steel sheet body structure are more common, accounting for the reduced relative use. In this work, the “typical” car material composition is an average from North American, European, and Japanese manufacturers (Bertram et al., 2009), representing over 65% of the market. Despite this covering most car production, attempting to define the 'typical' product inevitably introduces errors.

When scaling regional production statistics, an appropriate scaling factor has been chosen depending on the product and country. For example, the only data found on the production of shipping containers was a national study on production in Japan (JISF, 2007). It is likely that Japan, as one of the world’s biggest exporters of manufactured goods, produces more shipping containers than the global average. Therefore, the Japanese share of world exports has been used to scale the national data to a global level.

Production statistics are not published with error bars. It is, therefore, impossible to perform sensitivity analyses on the results presented in this chapter. However, the global metal tonnages derived from bottom-up and regional studies, when aggregated into low resolution sectors (such as transport or construction), are within 2% agreement of estimates derived from global top-down data—WSA (2009) for steel and IAI (2008) for aluminium. The top-down global estimates are likely to be accurate because the World Steel Association’s members account for around 85% of the world’s steel production, whilst the International Aluminium Institute represents 100% of global primary production and, although aluminium recycling is more dispersed, the International Aluminium Institute still estimate aggregated recycling statistics.

3.1.2 Design requirements for major components in the main steel and aluminium using products

For each identified product, which accounts for more than 1% of the end-use mass of metal, a product design description has been created and is presented in section 2 of the supporting information accompanying the journal article, Cooper and Allwood (2012). Four examples of these product descriptions, one for each of the four major end-use sectors—transport, construction, industrial equipment, metal products—is presented with references in Appendix B. The descriptions were informed by an extensive product specific literature review. Each description details both current reuse activities and the major steel and aluminium components in the product, specifying at the component level the design constraints, materials (alloy and coating), construction process, life expectancy, reasons for failure, and historic and predicted future trends. Companies familiar with the manufacture, use, or disposal of the product validated the descriptions, and contacting multi-national companies encouraged a global perspective. Gathering such a breadth of information allows consideration of the opportunities and barriers in each activity required for reusing the component, from disassembly of the old product, to any reconditioning, and to assembly in the new, possibly updated, product.

Key findings from the product descriptions have been summarized in Table 3.1. Component specific design constraints and reasons for failure are widely discussed in the results (section 3.2.1-4) and are, therefore, omitted from Table 3.1 for the sake of concision. The production processes described in Table 3.1, however, often allude to the design constraints in use and hence the potential to reuse metal. For example, the micro-alloying required to produce steel plate for line pipe (to produce a strong and tough steel) means that it is unlikely other steel plate could be reused in the application.

Product description	Lifespan (years)	Major components (construction process)	Materials and material production
		Transport	
Cars (2 descriptions)	13-14	Drivetrain (machined castings), body structure and panels (deep drawn galvanized sheets), wheels (cast aluminium or pressed steel sheet)	Engine block: Aluminium (AA356) or cast iron Gears: Medium carbon steel Body structure: Hot dip galvanised (HDG) steel sheet Transmission casings: Aluminium (AA380) Wheels: Aluminium (AA356) / Carbon-manganese steel
Trucks	10 Tractors: 5-10 Trailers: 10-15	Drivetrain (machined castings), body structure and panels (flat, welded, galvanized sheets), wheels (pressed steel sheet)	Engines almost exclusively made from steel Cab structure can be made from HDG steel or aluminium Frame rails and cross members in trailers are typically high tensile steel Aluminium used in mass limited applications, otherwise steel Fuel tankers and silo semi-trailers are made entirely from aluminium
Ships	30	Steel ship plate (welded normally rectangular plates)	Mild steel. Production from primary steel using thermo-mechanically controlled rolling (TMRC) for high strength at low temperatures. Painted or has cathodic protection
Aeroplanes	25	Wing (torsional box of Al extrusions and machined plates); fuselage (riveted sheet skin on circumferential frame); tail (see wings)	Upper wing: AA7xxx; Lower Wing: AA2xxx Fuselage skin AA2xxx; Fuselage frame: AA7xxx. All typically anodized. Very high yield losses in machining wing spars (>80%)
		Construction	
Structural sections	Buildings:50 Infrastructure:60	Web and flanges (typically steel hot rolled with 5% welded from plates)	Structural steel. Coatings: (intumescent) paint, cementitious sprays, mineral wool boards. Hot-rolled sections of uniform cross-section cut to length by fabricator
Concrete reinforcement	″	Ribbed steel rod (steel hot rolling and notching); fabricated from steel wire rod; drawn steel wire	Unfinished tempered low carbon manganese steel. Marine environment coatings (galvanized or epoxy based). Otherwise, often left to rust for better bonding to concrete
Steel sheet	″	Purlins, decking, roofing cladding (cold rolling)	Cladding (stainless steels)
Window frames	40	Exterior and interior frames (aluminium extrusions)	Aluminium (AA6060 or 6063) Coatings: Anodized, sealed with baked-on fluoropolymer paint or powder coated
Curtain walls	40	Mullions (Al extrusion), transoms (Al extrusion), pressure plates (Al cut sheet)	Extrusions: Aluminium (AA6060 or 6063) Anodized, sealed with baked-on fluoropolymer paint or powder coated
Roofing and cladding	40	Profiled aluminium liners (cold formed) and sandwiched insulation	Sheet: AA3003/3103 or AA5005/5005A Polyvinylidene fluoride (PVDF) coating
Line pipe	30 (design life 20, but typically exceeded)	Welded steel sheet (typically longitudinally welded; very large diameters are spiral welded)	Micro-alloyed steel (typically niobium or vanadium or titanium). Production process: thermo-mechanically controlled rolling (TMRC). Accelerated cooling rate for high strength and toughness. Coatings: Polypropylene copolymers
Rail track	25	Rail head and section (hot rolled)	Plain carbon-manganese pearlitic steel. Production from primary or secondary steel. The liquid steel is not Al deoxidised (the aluminates can create crack propagation sites)

Product description	Lifespan (years)	Major components (construction process)	Materials and material production
		Industrial equipment	
Mechanical machinery	14	Rolling mills, ordinary mechanical workshop equipment (lathes, pillar dills etc.). Intermediate products in this sector are dominated by hot rolled bar, plate, and hot and cold rolled coil	Failure is typically physical. For example, wear of rolling mill work rolls. Subsequently, techniques are used to produce localized wear resistant surfaces. In the case of rolling mill work rolls the outer layer is made of a hard chrome steel, increasing their durability
Electrical cables	30	Concentrically stranded aluminium wire (drawn) around a coated steel wire core (drawn)	Aluminium wire: AA1350 Steel wire galvanized, aluminium coated, or aluminium clad
Other electrical equipment (2 descriptions)	40	Pylons (bolted cold-formed L-section steel) Transformers (wound coil of electrical steel sheet in a steel casing)	Transformer and motors: High silicon content electrical steel (hot rolling, cold rolling and then high temperature reheating-1400°C-necessary to produce fine precipitates as inhibitors)
		Metal products	
Drinks cans	≈0	Body and base (circular aluminium blanks are drawn and wall ironed-DWI-into the base and body of the can). Lid (circular blanks are punched from aluminium sheet and crimped to the rim at the top of the body)	Body and base: AA3104/3004/3204 Wide strip coil is hot and cold rolled from 30" thick ingots. Casting aluminium in thinner slabs has been investigated, but due to the faster cooling and reduced rolling reduction, the desired textures (for easy DWI and low earring) have been difficult to achieve. Suggestions from the literature include altering the cooling rate and the composition of the alloy. Lid: Coated AA5182. Tab: AA5182
Steel packaging	13	Food can (folded tin-plate steel strip) Aerosols (folded tin-plate steel strip) Shipping container (corrugated steel sheets welded to square section frame)	Food can: Double reduced tinplate steel. Coating: lined with polymer lacquer Aerosol: Double reduced tinplate steel Production of tinplate: steel coils are pickled in sulphuric acid to clean the surfaces before a thin layer of tin is applied by electrolysis
Aluminium foil packaging	≈0	Household foil, foil pouch, semi-rigid 'take-away' packaging	Household foil: AA8011 Foil pouch: laminated 1xxx and 8xxx Semi-rigid packaging: 3xxx predominate (1xxx and 8xxx also used)
Consumer durables (domestic appliances)	9	Paneling (cold rolled steel or aluminium sheet) Cooling system (al heat exchangers/Motors)	Cold rolled steel sheet Aluminium: AA3003 and AA3103 are common appliance panels and fridge linings Heat exchangers: Tubes (AA1050) Fins (AA1060 or 3004) Electrical steel in motors
Lithographic plate	≈0	Anodised aluminium sheet covered in emulsion and then ink	AA1050 and AA1100 usual. 3xxx used for mass printing (more durable) Production from primary or secondary aluminium (closed loop near 100% recycling). Hot & cold rolling, stretching, and electro-graining for good flatness and surface finish
Deox. of steel	35	Added as circa 1kg bars to liquid steel	Circa 98% aluminium purity often used

Table 3.1: Summary of product catalogue: metal-intensive products, major metal components, alloys, coatings, fabrication and material production processes

3.1.3 Determining the fraction of components that can be reused, and the barriers to reusing the remainder

The product catalogue created by the methodology of section 3.1.2 was used to seed a series of interviews with relevant industrial experts. For each of the twenty-three products in the catalogue, appropriate individuals were identified through a large multi-national company. The experts are familiar with the product in use, ensuring practical knowledge of the design requirements and end-of-life condition. Table 3.2 presents the product descriptions and corresponding interviews conducted.

Product description	Fraction of end-use		Interviews
	Steel	Aluminium	
Cars (2 descriptions)	7%	20%	Jaguar Land Rover
Trucks	1%	4%	Isuzu Truck Ltd. and Professor in heavy vehicle design
Ships	3%	4%	Professor specialising in Indian ship breaking
Aeroplanes	Negligible	Negligible	Boeing
Structural sections (hot rolled and fabricated)	9%		Tata Steel Europe, Portal Power and a leading demolition contractor
Concrete reinforcement (rebar, wire rod, drawn wire)	22%		Celsa Steel UK, Arup and a leading demolition contractor
Steel sheet in construction (purlins, cladding, metal decking, sheet piling)	16%		Portal Power and Arup
Window frames		8%	Innoval Technology
Curtain walls		5%	Innoval Technology
Roofing and cladding		5%	Innoval Technology and Portal Power
Line pipe	2%		Siemens VAI
Rail track (and rolling stock)	1%		Network Rail
Mechanical machinery	13%	7%	Siemens VAI
Electrical cables		9%	National Grid UK
Other electrical equipment (2 descriptions) (Transformers, steel towers, bus bars, conduits)	3%	5%	National Grid UK
Drinks cans		7%	Crown Cork and Seal
Steel packaging (food cans; aerosols; shipping containers)	3%		Crown Cork and Seal
Aluminium foil packaging (household foil; drinks and food pouches; semi-rigid 'take-away' containers)		6%	Novelis
Consumer durables (Washing machines, fridges, TVs)	3%	7%	ISE Appliances
Lithographic plate		1%	Alcoa
Deox of steel		3%	Tata Steel Europe, Celsa Steel UK

Table 3.2: Product descriptions and interviews conducted for metal intensive end-use products

For each of the resulting 17 interviews, the experts received in advance the catalogue product description to facilitate discussion of the key design features that enable or inhibit component re-use. Each interview lasted for at least thirty minutes and, following four trial interviews, a set of standard questions was used to direct the discussion:

- What is the average lifetime/design life of the main components?
- What is the prominent cause of failure of each of the main components?
- How does the performance of an equivalent new component compare?
- Can the components be retrieved from the product without destruction?
- Can any degraded components be restored?
- Can the components be standardised across brands and products?
- Does any reuse currently take place and what is the potential from any of these known reuse activities?

Detailed notes for each interview were recorded and analysed to identify common strategies and barriers.

The potential fraction of metal components that could be reused in each product was then estimated. All existing component reuse activities and constraints were examined and four common strategies emerged: relocation, remanufacture, re-shaping or cascading to an alternative use (see section 3.3.1 for definitions and discussion of these terms). The potential for reuse of each component by employing these strategies was then examined. Where possible the estimates are based on explicit information from the interviews or literature. For example, Tilwankar et al. (2008) state that over the life-span of a ship approximately 10% of the steel is lost by corrosion and that 95% of the steel at end-of-life is in the form of re-rollable sheet, implying approximately 85% of the ship's original steel mass could be reused.

Reforming of sheet metal components requires flattening, cutting and bending into new shapes. The reuse potential is based on the material loss in this process, estimated at 50% - the worst yield of the stamping process for some automotive parts (Corus Automotive, 2010). Life expectancies are used to estimate the potential reuse fraction of other components; for example, buildings typically last approximately ten years longer than the first set of aluminium window frames, allowing only the second set to be reused – approximately 50% of all window frames. When there is a limited but clear opportunity to reuse components, a conservative potential of 10% is assumed. For instance, some aluminium heat exchangers in cars could be reused, but designs vary according to brand and they are also subject to corrosion and damage from front-end vehicle collisions.

It is impossible to anticipate future technology and motivations accurately. However, the aim in deriving these percentages is to provide logical estimates based on sensible technical limitations. They account for both the fraction of products eligible for component reuse and the mass breakdown of reusable components within the steel or aluminium product.

3.2 Results

In 2008, 1025Mt of steel and 45Mt of aluminium end-use products were made globally. Liquid metal production in the same year was 1330Mt of steel (WSA, 2009) and 73Mt of aluminium (IAI, 2008), implying an average yield from liquid to final product of 77% and 62% respectively.

Figure 3.1 and Figure 3.2 show the end-use breakdown, the potential reuse of components and reuse strategy, and the barrier constraining reuse of the remaining components. These reuse strategies and constraints are defined and discussed in sections 3.3.1 and 3.3.2. The y-axes sum to the global consumption in 2008.

A detailed breakdown of steel and aluminium end-use products, and the potential to reuse their components, is shown in Table 3.3 and Table 3.4.

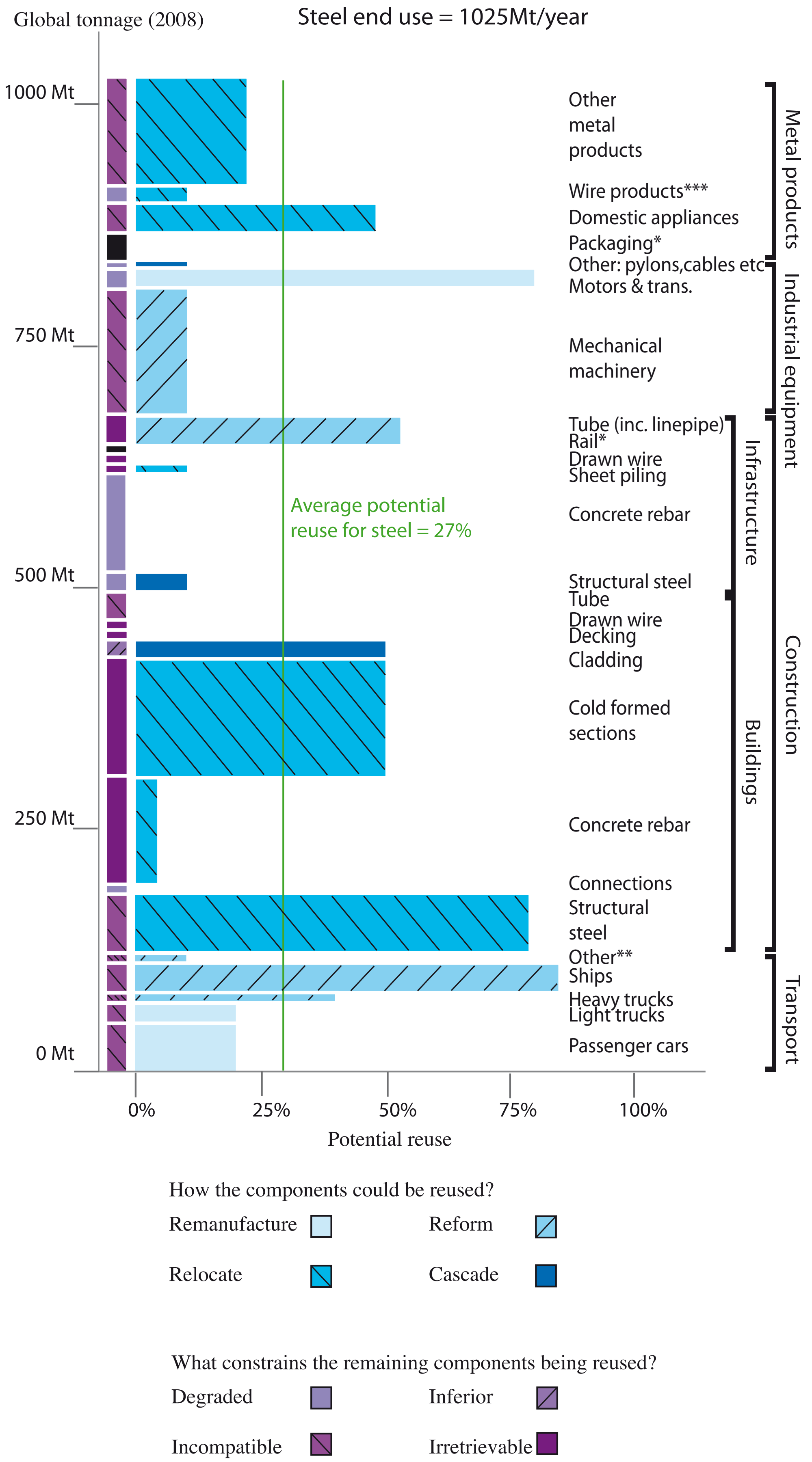


Figure 3.1: Potential reuse of steel components

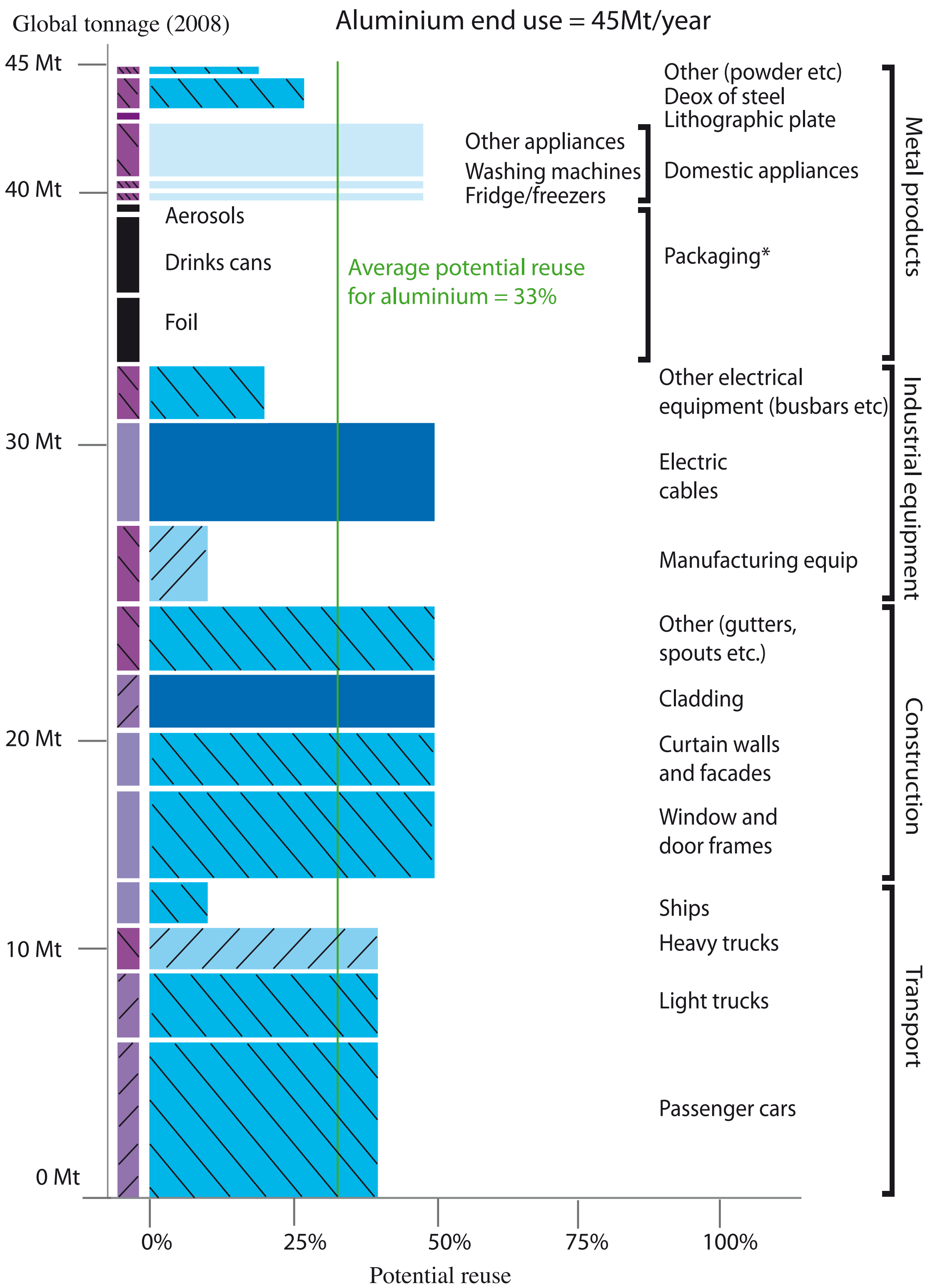


Figure 3.2: Potential reuse of aluminium components in metal intensive products

***As reuse is component based, returnable packaging/continued use of rail track is instead classed as life extension and has not been included in this analysis. **Military, rolling stock, aerospace etc. ***Barbed wire in agriculture, wire ropes in the mining sector, wire springs etc.**

Steel	End use per annum		Potential Reuse
	Mt	Fraction	
Transport	**131**	**13%**	**37%**
Cars and light trucks	70	7%	20%
Cars	51	5%	20%
Light trucks	19	2%	20%
Heavy trucks and buses	15	1%	40%
Ships	31	3%	85%
Other (rolling stock, aero, military)	15	1%	10%
Construction	**540**	**53%**	**29%**
Buildings	364	36%	38%
Structural Steel	61	6%	79%
Connections	6	1%	0%
Reinforcement steel	110	11%	4%
Cold formed sections	122	12%	50%
Cladding	21	2%	50%
Decking	10	1%	0%
Drawn wire	8	1%	0%
Tube	27	3%	46%
Infrastructure	176	17%	11%
Structural Steel	20	2%	10%
Connections	2	≈0%	0%
Reinforcement steel	98	10%	0%
Sheet – sheet piling	6	1%	10%
Rails	10	1%	0%
Drawn wire	7	1%	0%
Linepipe	18	2%	80%
Structural Tube	4	≈0%	20%
Non-structural Tube	10	1%	14%
Industrial Equipment	**166**	**16%**	**17%**
Mechanical Machinery (predominantly manufacturing equipment)	135	13%	10%
Electrical Machinery	31	3%	48%
Motors and Transformers	17	2%	80%
Other (pylons, cables, sheathing)	14	1%	10%
Metal products	**187**	**18%**	**22%**
Packaging	26	3%	0%
Shipping containers	16	2%	0%
Drinks cans	1	≈0%	0%
Aerosols	3	≈0%	0%
Food cans	6	1%	0%
Consumer durables	28	3%	50%
Fridge/freezers	12	1%	50%
Washing machines	8	1%	50%
TV	3	≈0%	50%
Other appliances	5	1%	50%
Wire products	20	2%	10%
Other goods (inc. other packaging)	113	11%	22%
Total	**1024**	**100%**	**27%**

Table 3.3: Potential reuse of steel components (ref: 2008 consumption)

Aluminium	End use per annum		Potential Reuse
	Mt	Fraction	
Transport	**13**	**28%**	**36%**
Cars and light trucks	9	20%	40%
Cars	6	14%	40%
Light trucks	3	6%	40%
Heavy trucks and buses	2	4%	40%
Heavy trucks	2	4%	40%
Heavy buses	≈0	≈0%	40%
Marine	2	4%	10%
Other (eg. Aerospace)	≈0	≈0%	36%
Construction	**11**	**24%**	**50%**
Window and door frames	4	8%	50%
Curtain walls and Facades	2	5%	50%
Cladding	2	5%	50%
Other (gutter, spouts etc,)	3	6%	50%
Industrial Equipment	**10**	**21%**	**29%**
Mechanical machinery (predominantly manufacturing equipment)	3	7%	10%
Manufacturing equip	3	7%	10%
Electrical	6	14%	39%
Cables	4	9%	50%
Other (busbars)	2	5%	20%
Metal products	**12**	**26%**	**17%**
Packaging	6	14%	0%
Foil	3	6%	0%
Drinks cans	3	7%	0%
Aerosols	≈0	1%	0%
Domestic Appliances	3	7%	50%
Fridge/freezers	1	1%	50%
Washing machine	1	1%	50%
TVs	≈0	1%	50%
Other Con. Durables	2	4%	50%
Litho plate	≈0	1%	0%
Deox of steel	1	3%	27%
Other – powder metallurgy etc.	1	1%	17%
Total	**45**	**100%**	**33%**

Table 3.4: Potential reuse of aluminium components (ref: 2008 consumption)

Aggregating across end-use, the global technical potential of component reuse is 27% for steel and 33% for aluminium. Little reuse of both metals occurs at present, excepting reforming of steel ship plate, which accounts for less than a tenth of the potential reuse of steel. The following sub-sections detail the logic behind the potential reuse estimates presented in Table 3.3 and Table 3.4.

3.2.1 Reuse in transport

Some remanufacture of car and truck drive-train components already takes place. This practice could be expanded, with more standardisation of both the engines and the interfaces between the engine and the rest of the vehicle. However, step-changes in drivetrain technology (the introduction of turbo-chargers, hybrids, automatic gearboxes etc.) limit potential reuse. Assuming a step-change in design every twenty years and a car life expectancy of 13-14years the potential reuse of drivetrain components is approximately 40%. Aluminium is mainly used in the drivetrain; therefore, the overall potential to reuse aluminium in cars is also close to 40%. The overall potential for reuse of steel in cars is much lower because steel is mainly used in the body structure (deep-drawn sheet metal). Reshaping deep-drawn sheet metal is possible, as discussed in section 2.1, but has yet to be demonstrated at scale. Just 10% of the body structure is therefore estimated to be reusable.

A typical heavy truck consists of a relatively short-lived tractor unit (5-8 years) and a long-lived trailer unit (12-15 years). The steel sheet used in trailer-units is flat and there is a greater potential to reshape it into other useful shapes than the sheet used in a car body structure. Up to 50% of the steel sheet used in trailer-units could be reused, with the potential reuse of tractor-unit components likely to be similar to that for a car.

The reuse of steel ship plate was discussed in section 3.1.3. Aluminium sheet used in the hulls of yachts could be re-rolled and aluminium components used in the structure of cruise ships could be standardized; however, corrosion in an aggressive marine environment prevents widespread reuse. Overall, a conservative 10% of aluminium used in marine applications is estimated to be reusable.

Aeroplanes, despite being an iconic application of aluminium, account for a negligible amount of the aluminium used in final products. The reuse of any aluminium plane components is also likely to negligible given the high fatigue loadings in service and the safety critical nature of the parts.

3.2.2 Reuse in construction

Structural steel used in buildings is typically undamaged at end of building life (only fire causing permanent damage) and the standards for steel sections have changed little over recent decades. Most structural steel is bolted together, with only the bases of a minority of columns embedded in concrete. Structural steel could, therefore, be dismantled without damage at building end-of-life. Hot rolled structural steel (95% of all structural steel) is manufactured to standardized cross-sectional dimensions. Most buildings have standardized beam spans, but some sections are cut to bespoke lengths during construction. This could limit their reusability at end of building life. Overall, it was estimated in the interviews that up to 80% of hot rolled structural steel used in buildings might be reused. Sections fabricated from plate (approximately 5% of structural steel) are likely to have bespoke dimensions and are therefore more difficult to reuse; 10% of these sections are estimated to be reusable.

Structural steel in infrastructure (for example, offshore structures) both corrodes and is subject to fatigue loadings. It is unlikely this steel will be reused in safety critical applications; however, it is estimated that up to 10% could be reused in less demanding applications such as shoring and temporary structures.

Connections consisting of bolts, cleats and fin plates are often damaged during assembly or disassembly, and are small and dispersed. It is estimated that only a negligible percentage of these components could be reused.

Reinforcement steel used in buildings is typically undamaged at end of building life; however, it cannot be retrieved from the concrete without damage. Pre-cast concrete modules are more likely to be reused; however, connections between modules often contain in-situ concrete, making their recovery difficult. Approximately 20% of global concrete production for use in buildings is in the form of pre-cast modules. Assuming 20% of these modules could be recovered results in an estimated 4% of the reinforcement bars in buildings potentially being reused. Reinforcement steel in infrastructure both corrodes and is subject to fatigue loadings; it is estimated that the potential to reuse reinforcement steel used in infrastructure is negligible.

Sheet is used in construction for cladding, cold-formed sections (purlins etc.), metal decking for composite floors, and sheet piling. Cladding is subject to changing standards for thermal insulation, so reuse is currently restricted to agricultural sheds. However, the opportunity to reuse cladding is likely to increase as new insulation standards become widespread. Purlins are often damaged during deconstruction, but can be reused if successfully retrieved from a building. It is estimated that 50% of sheet in cold-formed sections and cladding is reusable. The metal decking for composite floors is irretrievable without damage because in-situ concrete is poured on top of the metal decking; therefore, no reuse of metal decking is assumed possible. Sheet piling used in infrastructure is difficult to retrieve from the ground at end of life. However, 4% of sheet piling in infrastructure is currently extracted from the ground and reused. Given greater economic incentive and better workmanship to ensure easy extraction, it is estimated that this could rise to 10%.

Line pipe both corrodes and is subject to fatigue loadings. However, it is assumed that, in a similar method to the re-rolling of ship plate in Asia, large diameter line pipe could be re-rolled into construction products (rebar etc.); up to 80% of line pipe is estimated to be reusable.

Re-use of aluminium window frames and other building components is not yet practiced, and is prevented by the current use of many different designs, the difficulty of extracting used components without damage, and water staining of older frames. Re-design could enable easier disassembly and standardization could occur in the future. Water staining of older frames is a problem; however, the predominant failure mode is condensation between the panes, which could be rectified if the frame could be deconstructed, cleaned and reassembled. Reuse of window frames is possible and it is estimated that up to 50% could be reused (as explained in section 3.1.3). The same issues apply to aluminium curtain walls so a potential reuse of 50% is also estimated here.

The same issues apply to aluminium cladding as to steel cladding, so the same potential reuse value is used. Other aluminium-intensive products used in buildings include gutters and spouts. These can be removed and relocated in other buildings, without any safety concerns. However, bespoke geometries limit their potential reuse. Greater standardisation in the future could allow up to 50% of these products to be reused.

3.2.3 Reuse in industrial equipment

Mechanical equipment includes products used in manufacturing, construction and agricultural machinery. The analysis on mechanical equipment focused on rolling mills and small workshop equipment, such as lathes and pillar drills. These products are typically replaced when they break. Broken motors and gearboxes can be remanufactured but the interviews revealed that, instead, owners typically take the opportunity to upgrade their products. Reuse is further hindered by a lack of standardized components across products and brands.

Over half of the steel used in mechanical equipment is in the form of plates or sheets. There is some potential to reshape these components into other useful shapes for reuse. In addition, there is some potential to redesign mechanical components to isolate wear surfaces, allowing the rest of the component to be reused. For example, research is being conducted on making the worn surface of rolling mill work rolls restorable by using a replaceable, short-lived work roll 'sleeve' around the long-lived structural core (Hadjduk et al., 2010). In the absence of more robust data, a conservative reuse potential of 10% has been estimated for mechanical equipment. It should be noted that steel and aluminium in mechanical equipment is mainly used in manufacturing machinery, which will be used to produce all the products shown in Table 3.2 and Table 3.3; therefore, effective reuse of metal products will reduce demand for mechanical machinery.

Steel and aluminium are used to provide both the structural infrastructure for electrical grids, and as an active electrical component in distribution and use. Galvanised steel towers (made from cold-formed steel L-sections) create electrical corridors that criss-cross nations as they distribute electricity from centralised power stations. The failure of one of these towers would cause power-cuts and widespread disruption, so the towers are typically well maintained and only replaced when corrosion has undermined the integrity of the tower. It is unlikely that the corroded steel L-sections could then be reused. However, some electrical routes become obsolete with falling energy demand from dis-industrialisation. Power companies will, however, often keep the towers standing, as regaining building permission can be difficult. Therefore, there is a limited opportunity to reuse the steel in these towers, estimated at 10% in the interviews. Electrical steels, with high silicon content, are used in large transformers throughout the electrical network, for example to step down the voltage from power stations to household voltage. At transformer end-of-life, the steel tank surrounding the transformer could be reused, along with up to 60% of the transformer itself. Transformer design has been stable for the last 50 years and therefore reuse could be drastically expanded, estimated at 80% in the interviews.

Steel and aluminium are both used in electrical transmission and distribution cables. The aluminium conducts the electricity while the steel provides the strength to span the long distances between the towers. Overhead transmission cables' end-of-life is often caused by corrosion of the steel at the connection to a steel tower. This can be prevented with good workmanship during installation. The other predominant source of failure is annealing of the cable. Over time the cables are required to transmit more power than initially intended. This excess power causes the cable to heat up, causing annealing and thus a permanent reduction in tensile strength. This, in combination with the tension in the cable, causes structural sag, prompting replacement before or after contact with an obstacle such as a tree. Proactive overhead cable replacement in the future may allow reuse of cables on lower power routes, estimated at 50% in the interviews.

Aluminium strips (known as bus bars) are used to connect elements in switchboards, and aluminium conduits protect wires and cables. Such components are small, bespoke and dispersed; however, some reuse is certainly possible, therefore 20% has been assumed.

3.2.4 Reuse in metal products

Packaging goods (food and drink cans, aerosols etc.) are single-component products. As reuse is component based, returnable packaging is instead classed as life extension and has not been included in this analysis.

The majority of the steel and aluminium used in domestic appliances is used in fridges and washing machines. The metal-intensive components in these products are mechanical components, such as motors and compressors, and the structure (paneling). The replacement of domestic appliances is typically prompted by the failure of small mechanical components, such as wear of the bearings in a washing machine drum or wear of the carbon brushes in the fridge compressor. Ideally, at appliance end-of-life, the paneling and functioning mechanical components could be reused in a new appliance. However, despite the overall dimensions of appliances being standardised to fit under kitchen units, the interfaces between the various components have not been standardized across either products or brands and this prevents the interchange of reusable parts.

Given sufficient incentives in the future, however, this situation could change.

Electric motors and fridge compressors can be remanufactured, and the sheet metal panels could be reformed into alternative shapes if not directly relocated onto a new machine. A 50% yield on the reforming or relocation of the structural paneling and a potential 40% yield on remanufacturing of the mechanical components (analogous to car components), results in an overall potential reuse of approximately 50% (the structure accounting for more metal than the mechanical components).

Lithographic plates are used to repeatedly print an image and/or text. The aluminium plate is covered in photosensitive emulsion and a negative of the intended image placed onto the surface. The plates are quickly redundant as the hardened emulsion only corresponds to one printed image. The hardened emulsion cannot be easily removed and melting must be used to recycle the aluminium. Consequently, it is assumed no reuse of lithographic plates can take place.

The potential to reuse aluminium that deoxidises liquid steel is, in effect, the potential to reuse the steel in which it has been used. Consequently, the potential reuse of aluminium used for deoxidation is estimated at 27%.

3.3 Discussion

The potential reuse of components in metal intensive products is derived using the product descriptions and interviews with industry experts. The descriptions were informed by an extensive product specific review of academic and company literature and up to three interviews were conducted for each product, ensuring that the majority of reuse opportunities are considered.

3.3.1 Physical strategies for component reuse

From the interviews, two key factors emerge to determine the type of component reuse that can occur: the performance of the component and the demand for the service it provides. The service is the function of the component, and the performance is the success or efficiency with which the component completes this function. For example, a worn engine block has low performance despite the demand for the service (automotive power) remaining high.

When demand for the service provided is high and the component is in a good condition it may simply be **relocated** (typically a large single component) into another product with little refurbishment, such as cleaning and simple repairs/adjustments. When both demand is low and the condition poor or unknown, the component may be **cascaded** to a less demanding use, or **reformed** (re-shaped) to form a new, more useful, geometry. If demand exists but the component has suffered significant degradation, or an upgrade is needed, the component/sub-assembly may need to be **remanufactured**. Remanufacture typically entails further disassembly (of a sub-assembly), re-drilling and metallic spraying/thermal techniques to recover worn and fatigued surfaces. Relocation and remanufacture are the most effective strategies; they maintain the value of the component in its second use. Reforming and cascading, however, typically apply when downgrading required properties is acceptable. Greater cascading reuse opportunities are possible with stronger alloys. For example, 7xxx series aerospace aluminium alloys could be reused in automotive applications.

These reuse opportunities, with examples, are structured in Table 3.5. The potential application of each strategy on 2008 end-use production, summed from Figure 3.1 and Figure 3.2, is also shown.

	…and are used in the same type of product	….and are used in a different type of product
The component(s) undergo extensive reconditioning…	**Remanufacture** 25Mt steel; 2Mt Al E.g. Remanufactured engines and electrical transformers	**Reform** 60Mt steel; 1Mt Al E.g. Ship plate and line pipe to reinforcing bar
The component(s) undergo superficial reconditioning…	**Relocate** 170Mt steel; 9Mt Al E.g. Recovered aluminium alloy wheels and transmission casing put on another car	**Cascade** 15Mt steel; 3Mt Al E.g. Reclaimed structural steel used as shoring; building classing used on agricultural sheds

Table 3.5: Reuse strategies and potential application on 2008 end-use production

The remaining metal must be recycled. However, application of other material efficiency strategies – discussed in the introduction and explored in Allwood et al. (2010b) – will help lower the absolute metal mass for recycling.

Reuse is often used synonymously with remanufacture, whereas Table 3.5 shows that remanufacture offers relatively little potential for reuse. The greatest potential reuse strategy is relocation. For steel, this is dominated by the potential to relocate hot rolled structural steel, typically requiring deconstruction rather than demolition of a building or piece of infrastructure. This activity is currently inhibited not only by health and safety concerns (as discussed in section 2.1.2), but by deconstruction's relative slowness compared to demolition, which could delay the new construction programme and consequently the site owner's revenue. Anecdotal evidence from a leading demolition contractor suggests that up to thirty times more man-hours and additional equipment (a crane and cherry picker opposed to only a demolition machine) is needed to deconstruct rather than demolish a typical 3-story steel building. There is also anecdotal evidence, both from the interviewed demolition contractor and from Kay and Essex (2009), that new build planning decisions are taken long before demolition takes place and that there is a long period in which buildings are empty (as shown in Figure 3.3). A different sequence of decisions could, therefore, allow time for deconstruction without delaying construction of replacement buildings/infrastructure.

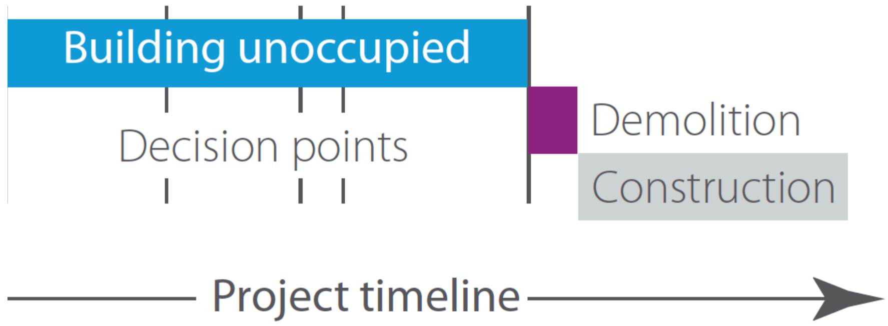


Figure 3.3: Decision points when a building is replaced

For aluminium, potential relocation of aluminium extrusions used in buildings (curtain walls and window frames), and car wheels are dominant. These items are all large single components (as opposed to more complex sub-assemblies) and therefore do not have moving parts. This generally limits degradation by wear and fatigue, and remanufacture is not required. For steel, the other significant reuse strategy is reforming the metal. An existing example is the re-rolling of discarded ship plate into construction products in India. There is also potential to re-roll retrieved line pipe into construction products. Such 're-rolling' opportunities account for 40Mt of steel, two-thirds of the reforming potential. With a global demand for reinforcement steel of 210Mt this reformed steel would not saturate the market. In addition to re-rolling of plate, it is assumed some reshaping of steel sheet from cars, trucks and domestic appliances could happen in the future. Such reforming of small sheet metal has already been demonstrated by Tekkaya et al. (2008) and was discussed in chapter 2.1.

Any businesses or policy makers who wish to maximise reuse activities should therefore first examine the opportunity to relocate metal directly. Associated technology development may include automated disassembly and machines or processes to validate properties. For example, coupon tests can determine the mechanical properties of reclaimed structural steel; however, these tests are typically too expensive and instead the allowable stresses are currently identified through the use of a historic sections book and the lowest grade assumed. Such downgrading mitigates the environmental benefit of reuse; the relative emissions associated with primary and secondary production (3:1) means that reusing a steel section in an application for which it is 30% over-sized causes greater CO_2 emissions than if the section had been recycled, as primary production must be increased to make up for the short fall of scrap to the supply chain. Over-sizing structural steel will also increase the mass of the steel frame, demanding larger foundations and causing further increases in emissions.

If an accurate and affordable testing method could be devised it would maximize the value of the steel and the carbon savings associated with reuse. A Vickers hardness test could be used to determine the strength: a cone indenter is pressed into the surface of a material, with the Vickers hardness defined as the applied force divided by the area of the indented shape. The yield stress can be estimated as a third of this value. This relationship between hardness and the yield stress arises due to the local yielding in a constrained stress field beneath the indenter, as described by Ashby and Jones (1980). Portable Vickers hardness testing could be a much cheaper and quicker method of determining the properties of reclaimed steel than coupon tests. However, the error between hardness testing results and the actual yield stress is often greater than 20%, which is an unacceptable level of error for insurance companies. Potentially this error could be reduced without dramatically increasing the cost of testing: Tekkaya (2000) has shown that the error can be reduced by considering the changing behaviour of the material as it deforms around the indenter. By computer modeling of an elastic-plastic material, Tekkaya (2000) reduced the error to less than 4%. For a given bath of reclaimed beams, a combination of portable hardness testing (using Tekkaya’s method of converting to a yield stress) and a small number of coupon tests could allow a satisfactory degree of confidence in the properties of the material.

The welding properties could be determined by chemical tests or, alternatively, the connection method in the original use inspected, and the steel bolted if necessary.

3.3.2 Constraints to reusing metal

Barriers to reuse were also considered in the interviews. The performance of the component is again important and, in addition, the value of the component to the designer may have decreased. Component reuse demands that the component or sub-assembly is **retrievable** from the rest of the product at end-of-life. Even components that can be easily recovered and are neither damaged nor obsolete may be **incompatible** with new products because the component design is not standardised, or because the component is of unknown specification. Both these constraints reduce the value of the old component to the designer.

The performance of the retrieved component can prevent reuse if its condition is degraded beyond repair or remanufacture. Products with a high rate of technological evolution are difficult to reuse due to falling demand for older products, and their components performance can be classed as inferior. These constraints, with examples, have been structured in Table 3. The prevalence of each barrier against the potential reuse of 2008 end-use production, summed from Figure 3.1 and Figure 3.2, is also shown.

	…relative to before product fabrication	…relative to new components
The component's performance has declined…	**Degraded** 170Mt steel; 6.5Mt Al E.g. Offshore corroded steel; structural steel in bridges	**Inferior** 10Mt steel; 6.5Mt Al E.g. Building cladding and car engines
The components value has declined…	**Irretrievable** 200Mt steel; 0.5Mt Al E.g. Rebar in foundations; purlins from industrial sheds (without damage)	**Incompatible** 335Mt steel; 10.5Mt Al E.g. Bespoke fabricated structural sections; building gutters and spouts

Table 3.6: Reuse constraints and prevalence of these barriers against reuse of 2008 consumption

Note that the sum of all steel or aluminium in Table 3.5 and Table 3.6 equals the total sum of end-use products minus the metal associated with packaging and rail track (as single component-products they are deemed to be applicable for life extension).

The greatest constraint on the reuse of components is incompatibility. For example, bespoke or irregular lengths and depths of hot rolled and fabricated structural steel limit reuse in new designs. Also, relocation of steel and aluminium paneling in domestic appliances is limited, as the profiled paneling and connections to the interior components are brand and product generation specific. Car closures and body panels are also incompatible with new car designs. Therefore, the upper technical limit on reuse is limited predominantly by the degree of standardisation possible across business, products and time. The other major constraint to reuse is degradation of components. For example, steel in infrastructure, such as in bridges and offshore structures, is subject to severe corrosion and fatigue loadings; for aluminium building components corrosion is not a problem, but the appearance of anodized or painted frames may change (water staining), impeding reuse; cast aluminium engine blocks wear; and aluminium and steel electric cables corrode and anneal. With suitable efforts, most products can be dismantled and the components retrieved, and projecting design changes to 2050 a lot of components could be standardised across both brands and products. The only significant components limited by the 'inferior' constraint are aluminium drive-trains and metal cladding on buildings. Aluminium drive-trains are being downsized with widespread implementation of hybrid and turbocharger technology, and changing gearbox design also drives obsolescence of aluminium transmission housings. Cladding is subject to improving thermal rating regulations, preventing reuse in commercial buildings and currently limiting it to agricultural sheds.

This chapter focuses on the technical potential of reuse. However, significant economic and behavioral barriers also limit uptake. These include concerns over increased labour costs and time in deconstruction, logistical challenges of returning and sorting components, the lack of an established supply chain, and consumer trends and habits. Prior to implementation, this technical assessment of potential reuse must be evaluated against such socio-economic considerations, but without the technical analysis in this chapter it would not be possible to evaluate the scope of potential change.

3.3.3 Can component re-use be greatly expanded to reduce demand for new metal?

Only a small fraction of metal components is currently reused. To move close to the potential reuse figures discussed in this chapter will require aggressive pursuit of the strategies outlined in section 3.3.1.

The most immediate and significant areas of opportunity are the relocation of steel building components and the reforming of ship plate and line pipe. Ship plate and line pipe are both corroded at end-of-life, but as demonstrated by Tilwankar et al. (2008), this does not prevent them being reformed into construction products. Extracting line pipe can be difficult if underground or offshore, but technically feasible. Given design changes in the future, many aluminium building components may also be reused: window frame and curtain wall extrusions would need greater standardization and a connection that would allow deconstruction without compromising future seal quality. Realization of the above opportunities alone, to the intensity depicted in Figure 3.1 and Figure 3.2, would reuse 180Mt of steel (18%) and 5.5Mt of aluminium (12%).

Design for future reuse must consider the barriers presented in Table 3.6. For example, components that would otherwise fail due to wear could be designed to be more **durable** to prevent excessive degradation, and **standardised** across brands and time to allow compatibility. It must be possible to **disassemble** products and to acquire **knowledge** of the original component specification through either product marking at the time of fabrication (many steel mills already stamp sections to enable tracking in-house), or post-disassembly testing.

The durable properties of the alloy (corrosion, fatigue and wear resistance) should be considered when designing for future reuse that is currently constrained by degradation. There is a case, then, for using stainless steel in select locations in infrastructure. For components susceptible to wear, each application must be considered on a case-by-case basis to determine the trade-off between selection of a harder alloy and recovery/replacement of the worn surface.

Standardised and durable components may limit bespoke optimisation and require more material. If use phase emissions are dominant and largely dependant on mass - such as in transport applications - optimisation may be a preferable strategy. However, for the majority of products, the steel content determines embodied carbon only, and in order to achieve the large carbon savings associated with reuse modest increases in component mass may often be worthwhile.

The largest single end-use of steel is as reinforcement in concrete, using 210Mt in 2008 (approximately one fifth of all steel). A top priority for increasing the potential reuse fraction of metal is to investigate reusing reinforcement steel. Currently, reinforced concrete requires crushing to recover steel bars for recycling, whilst sub-surface reinforcement in foundations is left in the ground at end-of-life and cannot be recycled. Developing reusable foundations for multiple building types and loadings could potentially reuse this steel effectively. For above-surface concrete, Wace et al. (1993) investigate cracking the concrete and recovering the rebar using microwaves; however, creating sufficient penetration is problematic, and this technology is in its infancy. The steel bars are unlikely to be recovered from the concrete undamaged, but by developing modular pre-cast designs that are easier to disassemble and reuse, greater reuse may occur. Research on dry connections to enable disassembly of pre-cast concrete could help maximize reuse of the largest single end-use of steel.

4 Component level strategies for exploiting the lifespan of steel in products

The work presented in this chapter was conducted in collaboration with Alexandra Skelton and Muiris Moynihan, both of the Low Carbon and Materials Processing Group at the Department of Engineering, University of Cambridge. Contributions to this chapter that are the outcome of their work, and not my own, are clearly referenced in the text. Specifically, they are the design of Figure 4.5 (Muiris Moynihan), nine of the twelve case study interviews detailed in Appendix C (five by Muiris Moynihan, four by Alexandra Skelton), and all collation and interpretation of cost data (Alexandra Skelton).

Over two million fridges and freezers are thrown away in the UK each year. The average lifespan of these refrigerators is eleven years, with newer models often only lasting half that time (BBC, 2004). Such swift replacement is often attributed to compressor failure. Over a period of ten years, lubricant loss from the compressor causes the small bearings to wear out. With compressor replacement cost comparable to that of a new refrigerator, consumers typically choose to replace rather than repair. The other components in a refrigerator, which account for the majority of the metal content, are still functioning at product end-of-life: the outer case, door, interior fittings and heat exchanger are all working when the fridge is discarded. These components could be used for longer, and are therefore currently under-exploited. The refrigerator is just one example of how the potential lifespan of the components in a product are poorly exploited; the discarded goods in nations' scrap yards suggest this is inherent in 'throwaway societies'.

The replacement of discarded products drives production and emissions from industry. This chapter investigates how to increase the lifespan of a product's **steel** components, as reducing steel production would have the greatest impact on industrial emissions; the production of steel accounts for more emissions than any other material. Moreover, Allwood et al. (2010) predict that from 2008 to 2050 the share of steel production required to replace buildings, equipment, transport and other steel products will increase from 40% to 80%. In light of this, reducing demand by exploiting the lifespan of steel in products could help meet the IPCC's target of reducing global emissions to half of 1990 levels by 2050. An analysis equivalent to that set out in this chapter could be conducted for sources of embodied emissions other than steel.

The literature review presented in section 2.2 concluded that there have been no studies that analyse the causes of failure of steel products and that assess the extent to which failure occurs at the product rather than the component level. In light of these findings, this chapter addresses the following questions:

1. Why are steel intensive products replaced?

2. Do we exploit the steel in products?

3. How can we reduce demand for steel by better exploiting the steel components in products?

4. What pragmatic strategies are associated with these objectives?

5. What would motivate us to adopt these strategies?

4.1 Why are steel intensive products replaced?

A set of failure modes is required that applies to all the key end-uses of steel, and is pertinent to both household and commercial product replacement decisions. A review of the literature on reasons for product replacement/failure was conducted in section 2.2, concluding that Skelton's (2013) framework, shown in Table 4.1, satisfied the above criteria. Skelton's framework is therefore used to examine steel products' failure modes in this chapter.

The performance of the product has declined …	**DEGRADED** … relative to when it was bought	**INFERIOR** … relative to what is currently available
The desire for the product has changed …	**UNSUITABLE** … in the eyes of its current user	**WORTHLESS** … in the eyes of all users

Table 4.1: Product failure framework (Skelton, 2013)

The two rows of the framework distinguish between failure that arises from a change in the state of the product, and failure that arises from a change in the desires of the user. The columns distinguish between changes that affect only the current individual product and user, and more systemic changes that come about through developments elsewhere in the market. These systemic changes could be due to the performance of rival products, changes to the environment in which the product is used, or alterations in the regulations that govern its use.

The failure modes – *degraded*, *inferior*, *unsuitable* and *worthless* – have been applied to the catalogue of steel products produced in Chapter 3, which includes all products that account for at least 1% of end-use demand for steel. This was done by mapping the catalogue's detailed causes of failure onto the failure framework using the definitions presented in Table 4.2.

Degraded • Wear • Fatigue • Accidental damage • Product spent • Product repair not economically viable • Scheduled life reached	Inferior • Rival product offers enhanced functionality • Rival product offers lower costs • Technology superseded
Unsuitable • Change in circumstance • Change in preferences • Changes in legislation that affect requirements placed on products	Worthless • Legislation that prohibits use • Changes in the environment in which immobile products are used

Table 4.2: Mapping detailed reasons for product failure onto the failure framework

Figure 4.1 combines the resultant information on product failure with data on the final destination of global steel production and the average life of steel products from the product catalogue. The share of total production accounted for by each product is plotted on the y-axis; the expected lifespan of the products in each category is shown on the x-axis; and examples of the causes of product failure are given on the right hand side of the figure.

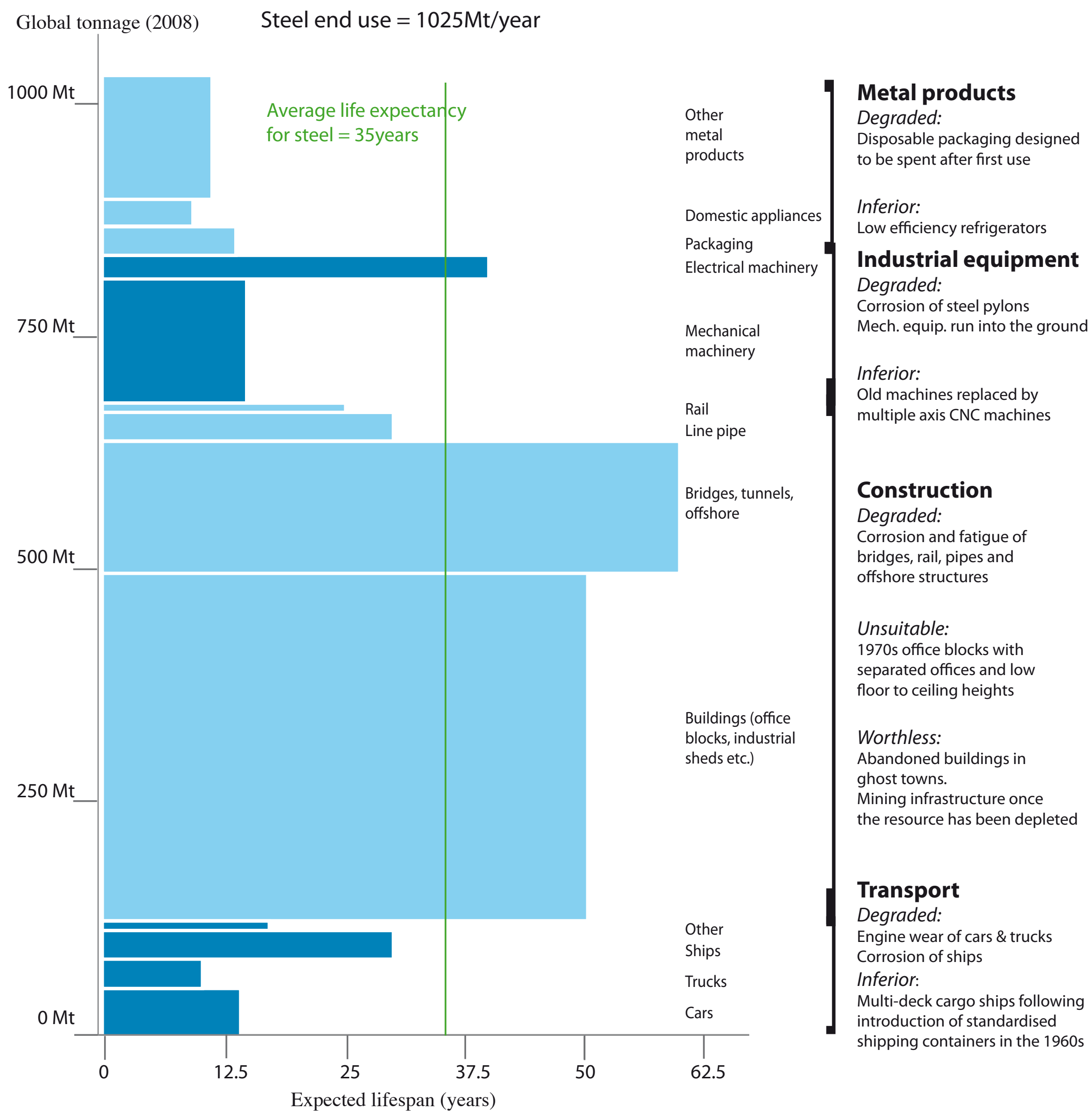


Figure 4.1: Expected lifespan and causes of failure of steel products

Figure 4.1 shows that the average expected product lifespan is thirty-five years, ranging from fifty-two years in construction to eleven years in metal products. The relatively short lifespan of metal products is due to short-lived domestic appliances, such as refrigerators, and disposable steel packaging, such as food cans.

Degraded was the most common failure mode of steel products included in the catalogue including: corrosion and fatigue in infrastructure (for example line pipe); packaging designed to be 'spent' after first use (for example aerosol cans); wear of mechanical sub-assemblies in a transport or industrial product (for example engine wear causing a whole car to be scrapped). Due to established product reuse routes (e.g. for second hand cars) *Inferior* failures were found to be relatively rare but do occur, for example, when refrigerators with poor efficiency are replaced with newer, more efficient versions. A significant share of product replacements occur because of a change in users' desires. Buildings are the most significant example: their steel elements undergo negligible deterioration and they are demolished because they become *Unsuitable* (for example open plan offices are now preferred over individual units) or *Worthless* due to more systemic changes in preferences (for example derelict buildings in ghost towns).

4.2 Do we exploit the steel in products?

To assess whether steel components are fully exploited, a comparison between the actual life of steel products and the potential life of their components is required. In order to make this comparison, four products—which represent the four major end-use steel sectors—are analysed at the component level. This analysis first identifies the products' actual lifespans, reasons for failure and key components. Typical data on the key components' steel content (by mass), and potential lifespan are then collected from industrial partners and from published, product-specific literature. The representative products are a washing machine (metal products), a car (transport), an office block (construction), and a 5m steel plate rolling mill (industrial equipment). Table 4.3 shows the data sources that were used to compile the component level information.

Product	Steel mass	Potential lifespan and failure mode of components
Washing machine	Park et al. (2006)	ISE Appliances (2011) Product Lifespan Institute (2008) U.S. Department of Housing and Urban Development. (2000)
7-storey Office block	Goodchild (1993)	Scheuer (2003) Sturgis and Roberts (2010) Treloar et al. (1999) Arup (2011)
Car	Information received from a car manufacturer	Information received from a car manufacturer MVDA (2010)
5m Steel Plate Rolling mill	Information received from an industrial equipment manufacturer	Information received from an industrial equipment manufacturer

Table 4.3: Component level data sources

Data from the industrial equipment manufacturer and car manufacturer were supplied on condition of anonymity

The mass and lifespan data for the products' components are presented in Table 4.4.

Product	Component	Mass	Potential lifespan (years)
Washing machine	Drum	3kg	6
Initial steel mass = 40kg	Motor	8kg	6
Actual lifespan = 6years	Heating element	1kg	7
Failure mode: *Degraded*. Wear of drum bearings / motor brushes	Other	7kg	18
	Structure: frame & panels	21kg	18
Car	Suspension	87kg	4
Initial steel mass = 960kg	Other	163kg	8
Actual lifespan = 13years	Transmission	48kg	12
Failure mode: *Degraded*. Engine cylinder wear	Interior & trim	87kg	13
	Engine	200kg	13
	Structure	375kg	21
Office block	Internal finishes	100t	10
Initial steel mass = 1,000t	Service	80t	10
Actual lifespan = 50years	Internal planning	10t	13
Failure mode: *Unsuitable*. Internal plan incompatible with the owner's new desires	Roofing & cladding	10t	45
	Structure	800t	110
Rolling mill	Spindles	200t	5
Initial steel mass = 4,700t	Work rolls	500t	5
Actual lifespan = 100years	Back-up rolls	800t	15
Failure mode: *Degraded*. Fatigue failure of the steel housing structure	Hydraulic system	300t	20
	Other	400t	20
	Structure	2400t	100

Table 4.4: Mass and lifespan data for the four representative products

Table 4.4 presents a single lifespan for each product and component. This is a highly simplified view of component failure, with components performing perfectly until they fail and the timing of failure being a defined point that can be known in advance. In reality, a component will often deteriorate up until the point of the failure. A more advanced analysis could consider lifespan distributions; however, the purpose of the analysis in this section is to determine the scale and circumstances under which components and products are under-exploited, for which using these mean lifespans is acceptable.

The data presented in Table 4.4 are used to create ‘step-graphs’ of each product’s cumulative mass over time, accounting for both the initial steel content used in production and the steel within replacement components. These ‘step-graphs’ are shown in Figure 4.2 and Figure 4.3. Each coloured line represents the cumulative mass of a component over time. Any vertical slice of the graphs sums to their products’ cumulative mass. The length of each flat section represents a component’s lifespan, and each ‘step’ indicates component replacement, increasing that component’s and product’s cumulative mass. The failure of a critical component (always shown in red) causes the product to be discarded. The dashed vertical line shows product end-of-life; any horizontal line to the right of this shows residual lifespan of a functioning component currently discarded with the rest of the product. A product’s steel demand rate – its cumulative mass divided by its lifespan – is equal to the gradient of the grey line from the origin to the intersection of the cumulative product mass and product end-of-life lines.

Figure 4.2 shows the cumulative mass over the lifespan of a washing machine.

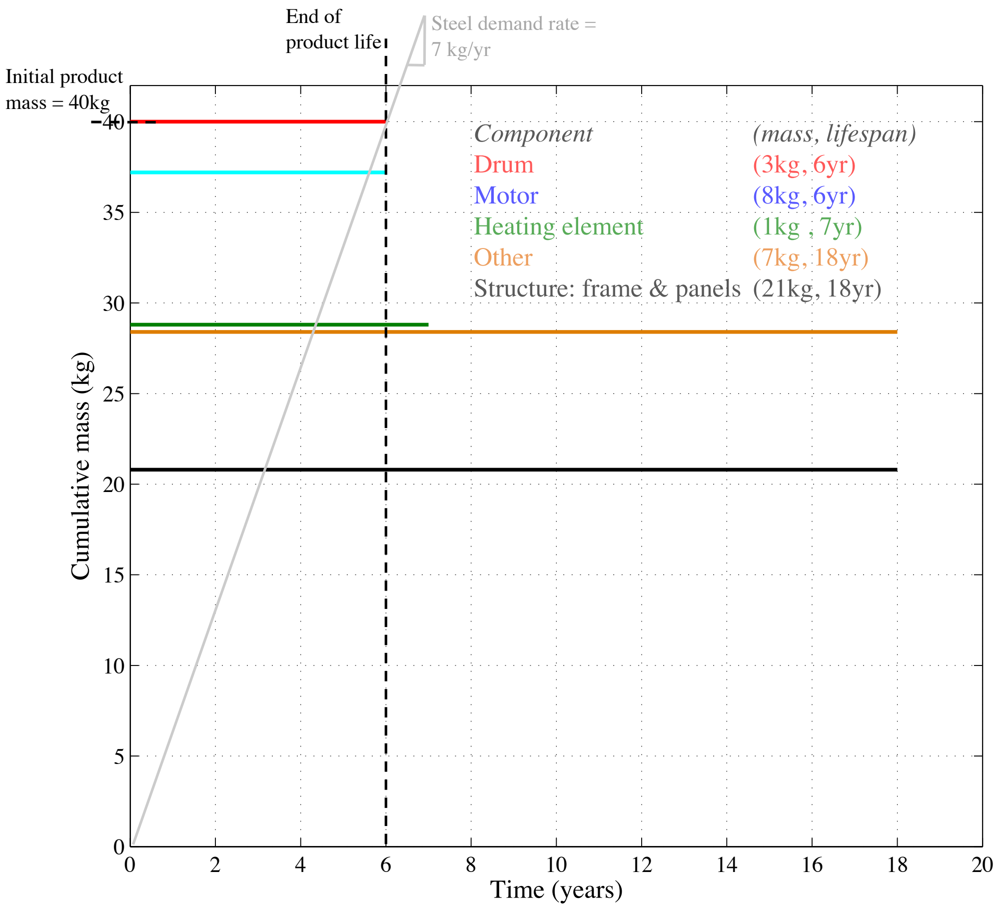
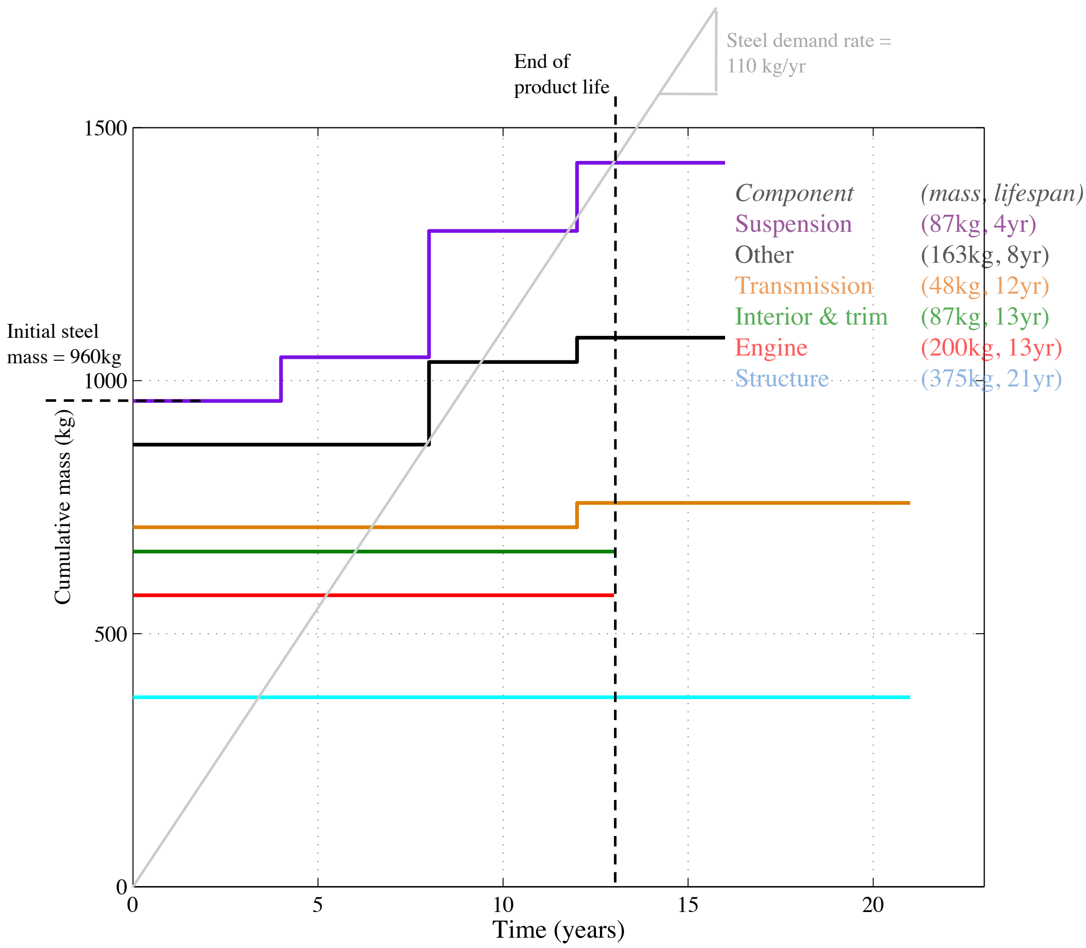


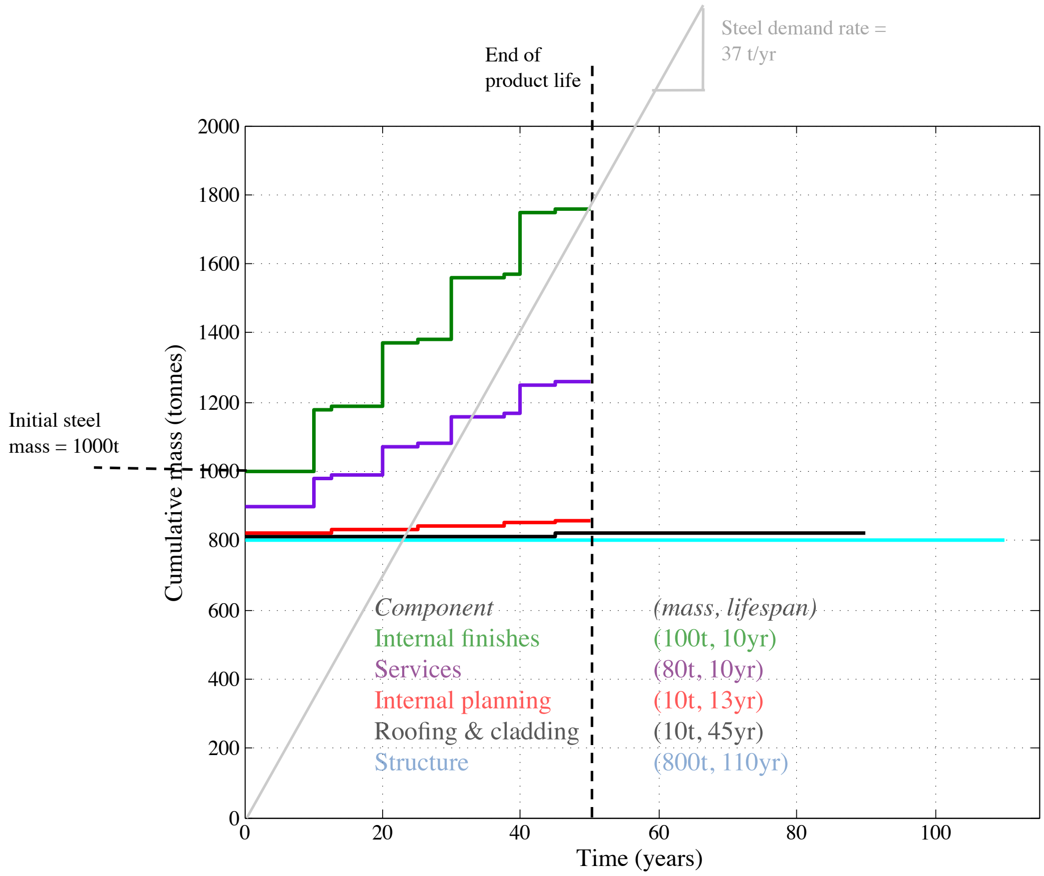
Figure 4.2: Cumulative mass of washing machine components over the product's lifespan

Typically, no components in a washing machine are replaced before it is discarded. Subsequently, there are no 'steps' in Figure 4.2, and the cumulative product mass is equal to the initial mass of 40kg. Washing machines are typically discarded after six years, due to wear of inaccessible bearings within the drum casing. The structure, accounting for over half of the steel, has a potential lifespan of eighteen years, but is used for just six years. This twelve year residual life (the difference between the actual life of the structure and its potential life) means that a significant share of the steel in the washing machine is under-exploited.

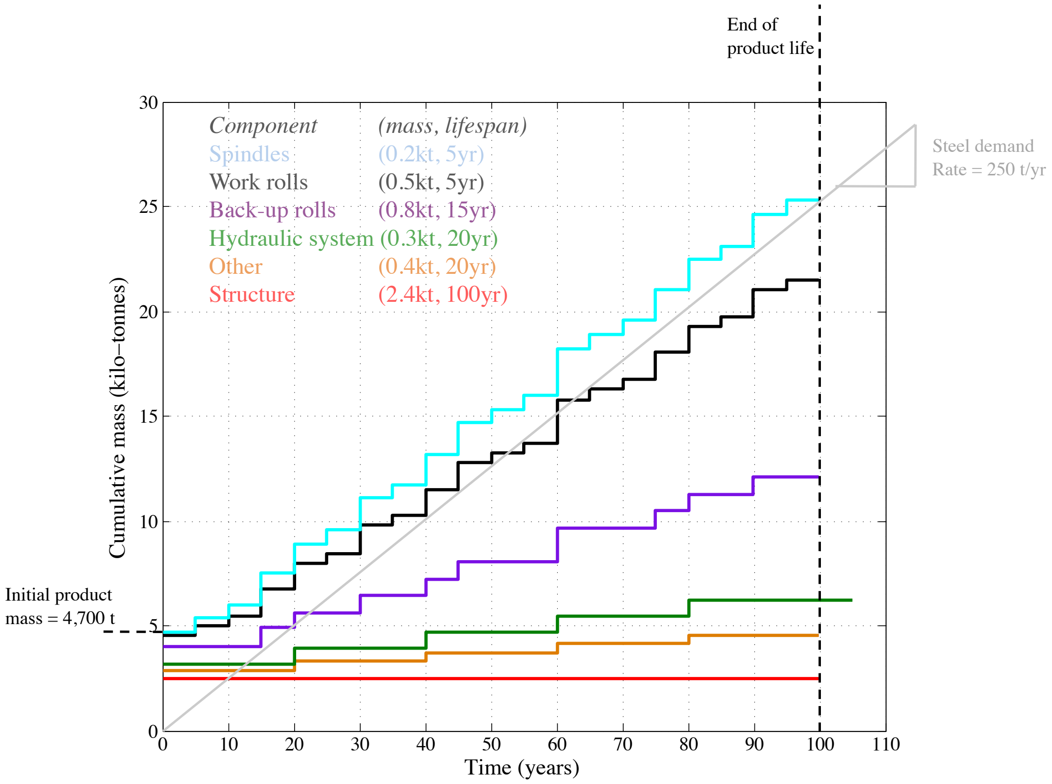
Trends towards sealed sub-assemblies have deterred individual replacement of washing machine components; however, for other products component replacement is more common and this helps exploit the long-lasting structural steel. Figure 4.3 presents the cumulative steel mass over time for a car, office block and rolling mill respectively.



(a) car



(b) office block



(c) rolling mill

Figure 4.3: Cumulative mass of components over the products' lifespans

A car's engine is scrapped due to cylinder wear after thirteen years, when the structure has eight years of potential life remaining, and the transmission (gearbox) maybe relatively new. The internal planning of an office block has usually been replaced a number of times until the owner's desired internal plan becomes incompatible with the structure and it is favourable to demolish and rebuild. The structure of the office block, however, could last twice as long as the current building life of fifty years. The rolling mill is the only product for which the structure is fully exploited (no residual lifespan), finally failing due to fatigue after one hundred years.

The y-intercepts of the step-graphs show that all four products have a long-lasting structure that accounts for the largest initial steel mass share. Structural components will often have the longest potential lifespan because they are subject to minimal wear, fatigue and corrosion.

Comparing the y-intercepts to the cumulative masses at product end-of-life reveals that components that have a relatively low steel mass, but which are regularly replaced, can have a large impact on the steel demand rate. These are typically mechanical sub-assemblies, failing due to wear. The clearest example is the work rolls in a rolling mill which, over the mill's hundred-year lifespan, account for two new mills' worth of steel.

4.3 How can we reduce demand for steel by better exploiting the steel components in products?

The mass of steel required for a product to operate depends on the steel mass in initial production and the steel mass in component replacements. Reducing the demand for steel, therefore, depends on reducing the average steel demand rate (the steel used in a product spread over its lifetime), which is a function of both these quantities. For products where there are no component replacements (such as the washing machine), comparing Figure 4.2 and Figure 4.3 reveals that the steel demand rate is the mass of the product divided by the lifespan of its shortest-lived component. For products with component replacements (such as the rolling mill), it is the cumulative product mass divided by the product's lifespan. In this case, the cumulative product mass depends on the mass of the components and the rate at which they are replaced. The product lifespan will correspond to the failure of one or more components.

In both scenarios, increasing the actual lifespan of high cumulative mass components will reduce the steel demand rate significantly. The structure, if under-exploited, typically accounts for a high proportion of the cumulative mass. Therefore, there are two complementary objectives for reducing steel demand by increasing the average lifespan of steel in products:

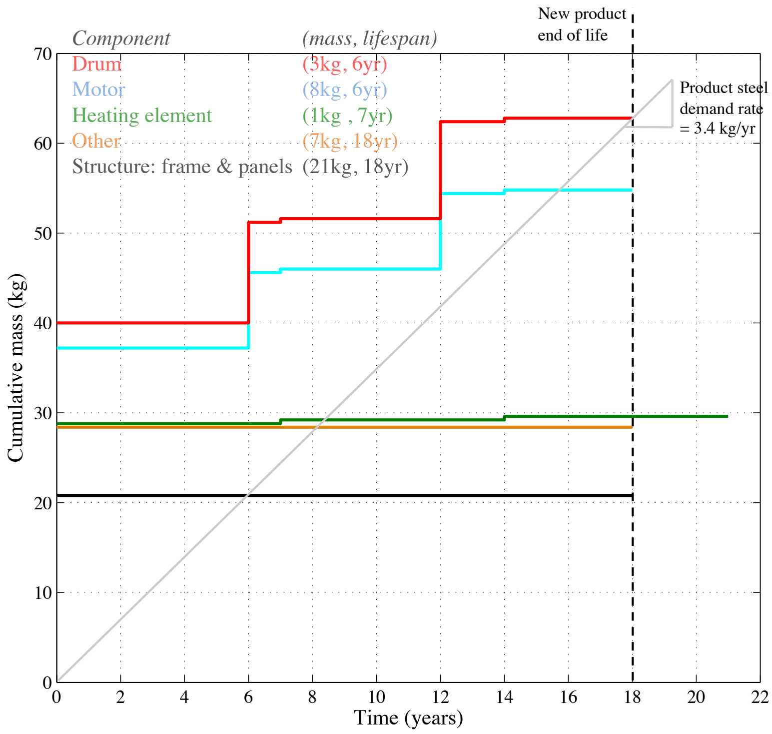
1. **Reduce the residual lifespan of under-exploited structural components**

(a) By facilitating replacement of short-lived components

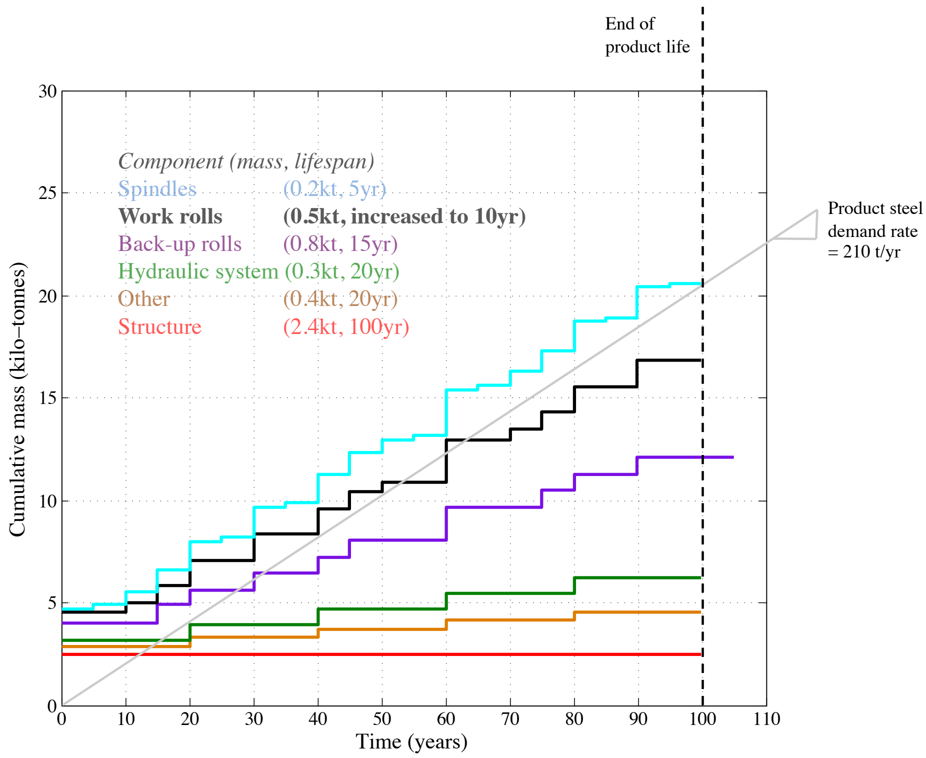
(b) By extending the lifespan of short-lived components

2. Increase the lifespan of components with high cumulative mass

Figure 4.4 shows how the calculation for the cumulative mass step-graphs of the washing machine and rolling mill (Figure 4.2 and Figure 4.3c) changes when these strategies are applied to the same mass and lifespan data set. Light weighting of components, without any increases to their lifespan, would also reduce the steel demand rate. This has been addressed by Carruth et al. (2011) and is not studied further here.



(a)



(b)

Figure 4.4: (a) Reducing the residual lifespan of the washing machine structure by replacing short-lived components (b) Reducing the steel demand of rolling mill work rolls by increasing their lifespan

Figure 4.4a shows the modeled cumulative mass over time of a washing machine assuming that the drum, motor and heating element can all be easily replaced, fully exploiting the potential lifespan of the steel rich structure. This reduces the washing machine's steel demand rate from 7kg/yr to 3.4kg/yr. Therefore, the structure's residual lifespan, and the product's steel demand rate, can be reduced by either extending the lifespan of shorter-lived components, or allowing them to be easily replaced. Increasing the potential lifespan of a component with residual life (such as the washing machine structure in Figure 4.2 and Figure 4.4a) will have no effect on the steel demand rate because it will neither decrease the cumulative mass nor increase the product's actual lifespan.

Increasing the lifespan of short-lived components decreases their cumulative mass and can greatly reduce the product's steel demand rate. Figure 4.4b represents a rolling mill where the lifespan of the work rolls has been increased from five to ten years. This decreases the rolling mill's steel demand rate from 250t/yr to 210t/yr.

An office block structure (Figure 4.3b) has a high residual lifespan and dominates the cumulative mass. Applying the objectives above, either the lifespan of the internal planning should be increased or it should be made easily replaceable, reducing the structure's residual lifespan. Similarly, either increasing the lifespan of a car's engine or making it easier to replace would reduce the residual lifespan of a car's structure (Figure 4.3a). Increasing the lifespan of a car's suspension would also be worthwhile as the suspension can account for a large proportion of a car's cumulative mass.

Implementing these strategies could be encouraged by a shift from consumer product ownership to leasing, incentivizing the product owner to refurbish products. Parker and Butler (2007) describe two business-to-business examples of this model: Rolls Royce offer 'power by the hour' jet engines, and Balzers retain ownership of their machine tools, providing a 'pay-per-hole' service. In the future, similar business models applied to consumer products, such as cars and white goods, may result in product life extension.

4.4 What pragmatic strategies are associated with these objectives?

To achieve the objectives set out in section 4.3, designers and maintenance engineers require practical strategies. They also need to know which product failure mode each strategy is applicable to. A set of twelve 'case study interviews' with industry and academic experts (who are experienced in extending the lifespan of products and components) was conducted in order to identify strategies to address product and component failure. Each interview covered the causes of failure, the technical strategies that had or could be applied to extend product or component life, and the motivations for these strategies. The resulting evidence on motivations is used in section 4.5. Table 4.5 provides a summary of the interviews conducted.

Case study	Sector	Interviewee/Source
Refurbishing modular buildings	Construction	Technical Manager, Foreman's Relocatable Building System
Steel rolling mills: replaceable work roll sleeves	Industrial equipment	Technology Manager, Siemens VAI
Adaptable foundations	Construction	Director, Arup
Adaptable, robotic packaging equipment	Industrial equipment	A fast moving consumer goods manufacturer
Durable infrastructure	Construction	Professor, Cambridge University
Hard-wearing rails, replacing rails & resurfacing tram rails	Construction	Programme Manager, Network Rail
Carbon-fibre aircraft body	Transport	Technical Fellow, Boeing
Restoring supermarket equipment	Metal goods	Development Manager, Tesco
Office block refurbishment	Construction	Associate, Expedition Engineering
Steel mill upgrade	Industrial equipment	Senior academic, Manchester Business School
Upgradable washing machine	Metal goods	Director, ISE appliances
Component reuse of oil rigs	Construction/Industrial equipment	Project Director, Able UK

Table 4.5: Interviews undertaken to investigate lifespan extension strategies

Details of each case study interview can be found in Appendix C. Transferable lessons were identified from each case study and the resulting strategies were tailored to the four types of failure: *degraded*, *inferior*, *unsuitable* and *worthless*.

From the interviews it became apparent that knowledge of the anticipated failure mode determines the type of life extension strategy that can occur. When the cause of failure can be foreseen, measures can be taken to *design-out* the features that cause failure. For example, high strength, hardwearing rail track can be used to mitigate against rail-head wear that causes failure. When the exact failure is less certain, or when design-out solutions do not exist, features can be incorporated into the design that prevent product failure by providing sufficient flexibility to adapt or replace components. These strategies are referred to as *design-in* strategies (e.g. designing foundations to allow for different building configurations). The interviews revealed that maintenance strategies are the same as design strategies, but applied during the product's life. Figure 4.5 shows the strategies and their relevance to each of the four failure modes.

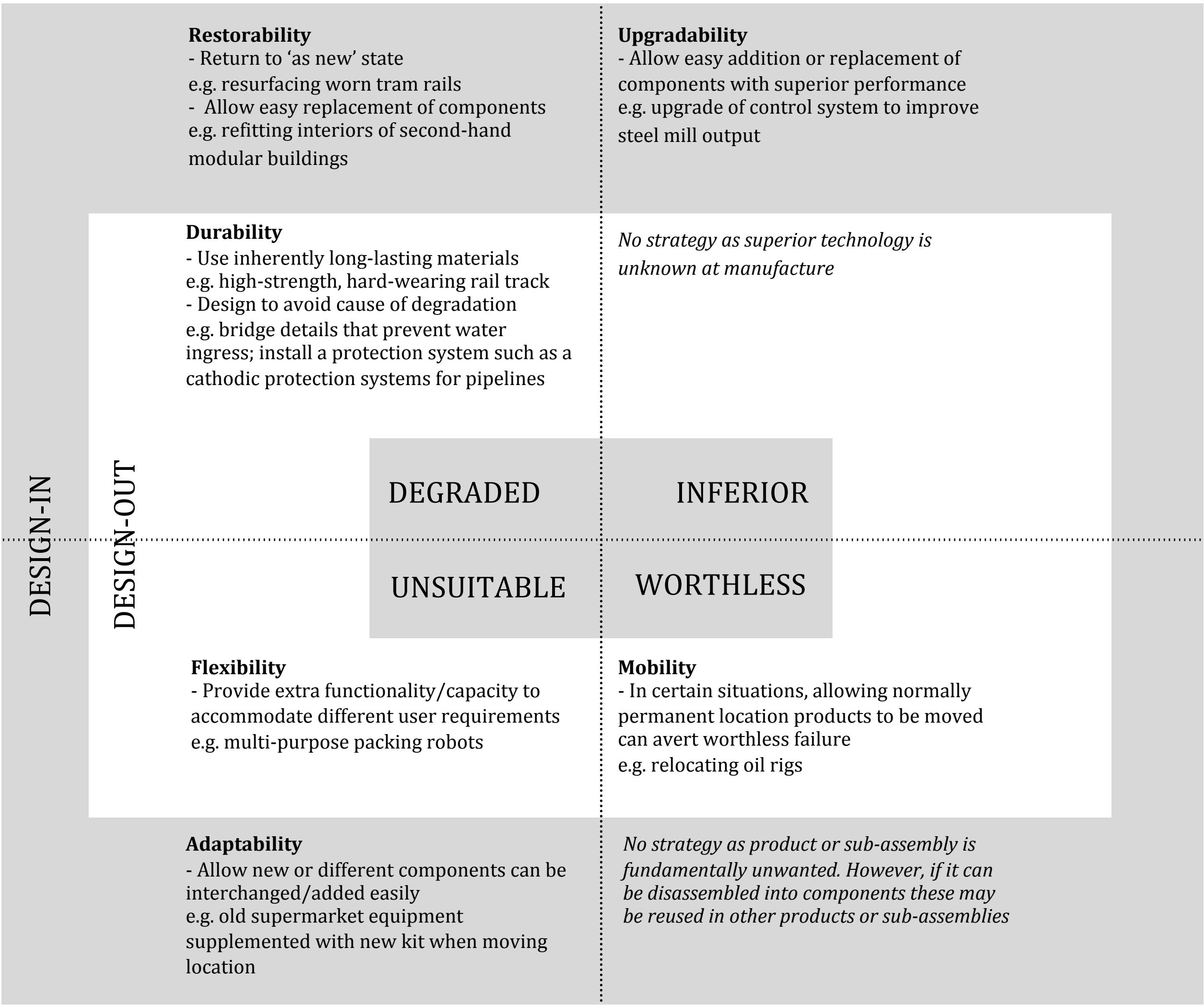


Figure 4.5: Targeted strategies to address product and component failure (figure designed by Muiris Moynihan)

4.5 What would motivate us to adopt these strategies?

(Section 4.5: Text based on interpretations by Alexandra Skelton, Figures by Daniel Cooper)

Section 4.3 identified two objectives to reduce demand for steel: (1) components that fail early should be easily replaceable or have their life extended (to exploit the long lived structure) and (2) the life of steel rich components should be extended. Consumers are likely to help meet these objectives if component costs and component steel content are positively correlated: this would mean that light, short-lived components could be replaced at relatively low cost and that it would take longer to write-off steel rich components. Producers, however, are more likely to contribute to meeting these objectives when high margins can be made on short-lived replaceable components. This business strategy has been adopted, for example, for printers (where margins are made on cartridges), coffee machines (where margins are made through the sale of coffee capsules, for example nespresso) and cameras (where margins are made on film, for example the sale of Polaroid film prior to the dominance of digital photography).

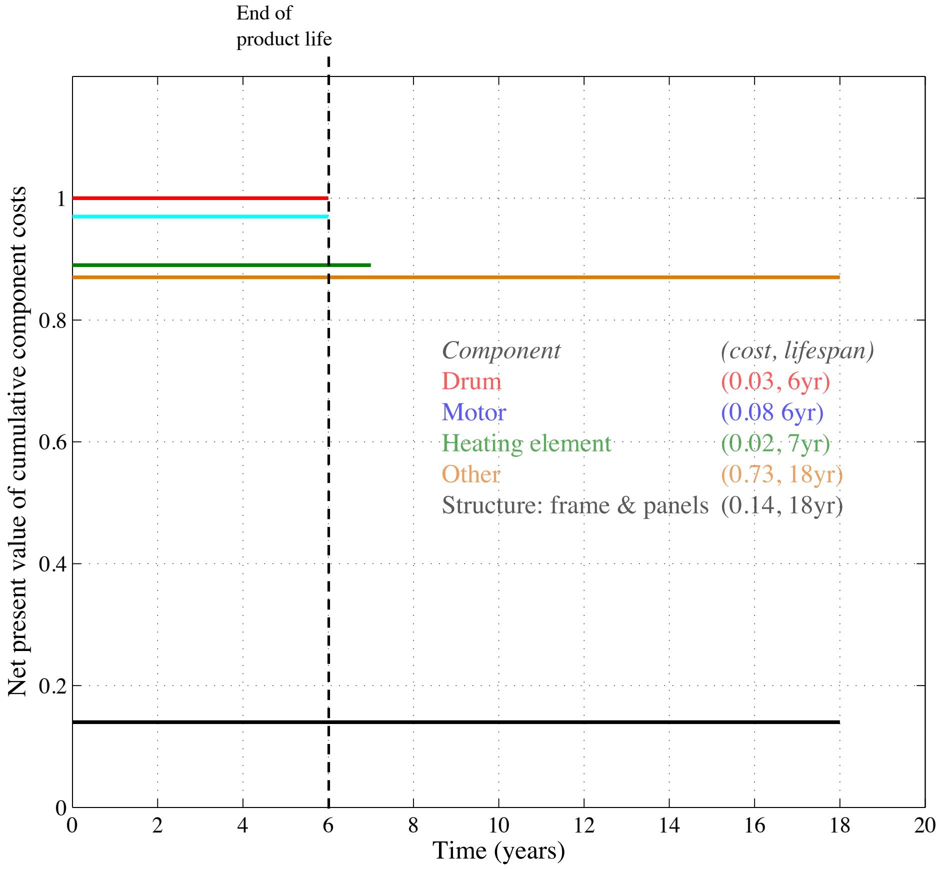
This section presents findings on the configuration of product component costs and explores the extent to which the above statements apply to the four case study products. The cost data for the products are presented in Table 4.6.

Product	Component	Cost (indexed to total component cost of 1)
Washing machine	Drum	0.03
	Motor	0.08
	Heating element	0.02
	Other	0.73
	Structure: frame & panels	0.14
Car	Suspension	0.12
	Other	0.22
	Transmission	0.07
	Interior & trim	0.18
	Engine	0.18
	Structure	0.21
Office block	Internal finishes	0.09
	Service	0.5
	Internal planning	0.03
	Roofing & cladding	0.24
	Structure	0.14
Rolling mill	Spindles	0.04
	Work rolls	0.01
	Back-up rolls	0.01
	Hydraulic system	0.08
	Other	0.55
	Structure	0.31

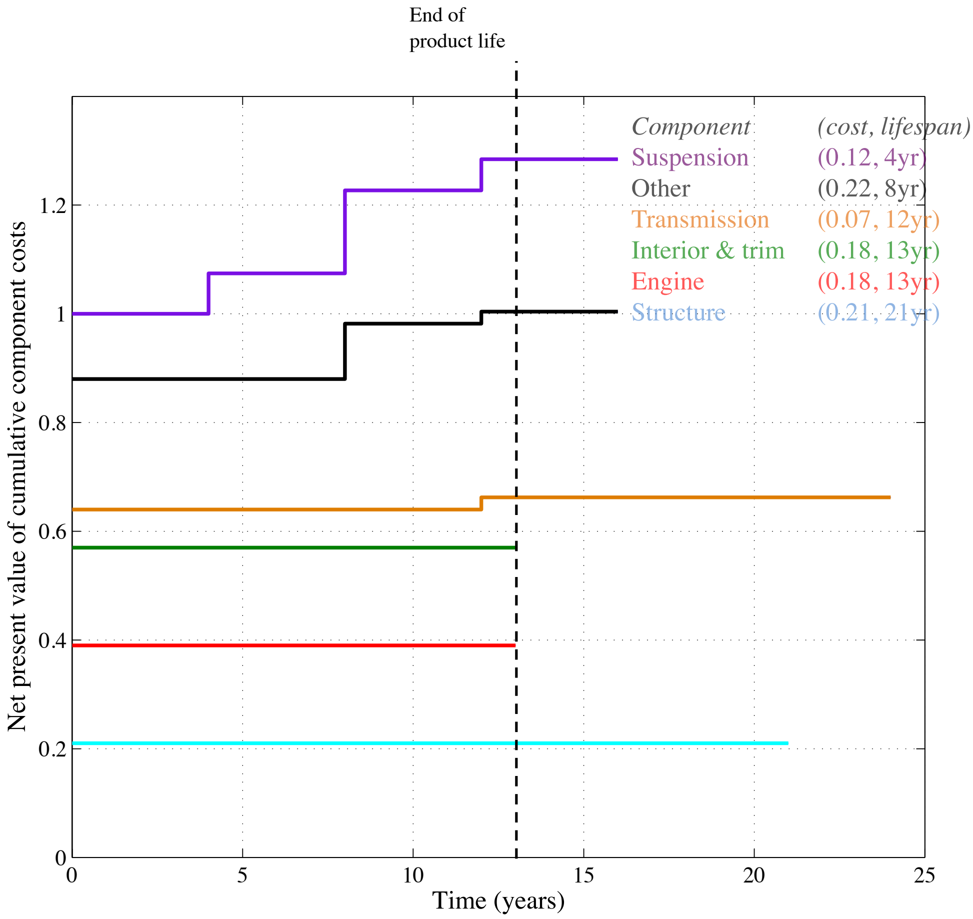
Table 4.6: Cost data for the four representative products (data were collated by Alexandra Skelton)

The data for the car and the steel rolling mill were supplied by a car manufacturer and an equipment manufacturer under the condition of anonymity. Office block and washing machine component cost data were taken from Goodchild (1993) and Siemens (n.d.) respectively. The cost data for the car reflects the component costs faced by a luxury car manufacturer: it includes the cost of raw materials, the cost of intermediary inputs (including profits charged by suppliers on these), and value added (e.g. component labour costs); it excludes any margins that could be charged by the car manufacturer on selling these components individually to customers. The cost data for the steel rolling mill, the washing machine and the office block reflects the price that is paid by the purchaser: in addition to all producer component costs, profit margins charged by the supplier are included. In all cases costs are expressed as an index, with initial total component costs equal to one.

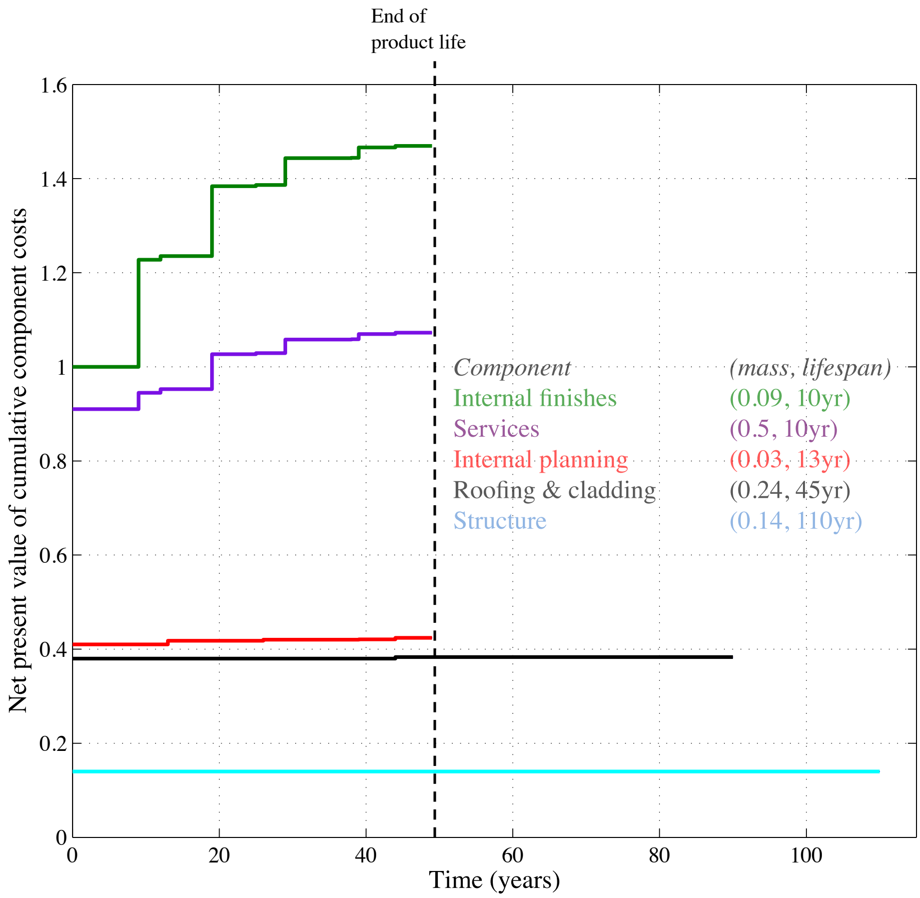
Figure 4.6 presents cumulative cost step-graphs for the four representative products, analogous to the cumulative mass step-graphs reported in Figure 4.2 and Figure 4.3. As replacement costs for components are incurred at different points in time, future costs must be discounted to reveal their current value. The appropriate discount rate depends on factors such as the cost of capital to the user, risk preferences and opportunity costs. In Figure 4.6 a rate of 10% was used. This lies between the 3.5% recommended by the UK Treasury (HM Treasury, 2003) for evaluating government projects and the 15% used by a fast moving goods manufacturer to justify purchasing decisions (Appendix C, case study 4). The discount rate makes the consumer less concerned about the cost of future component replacements.



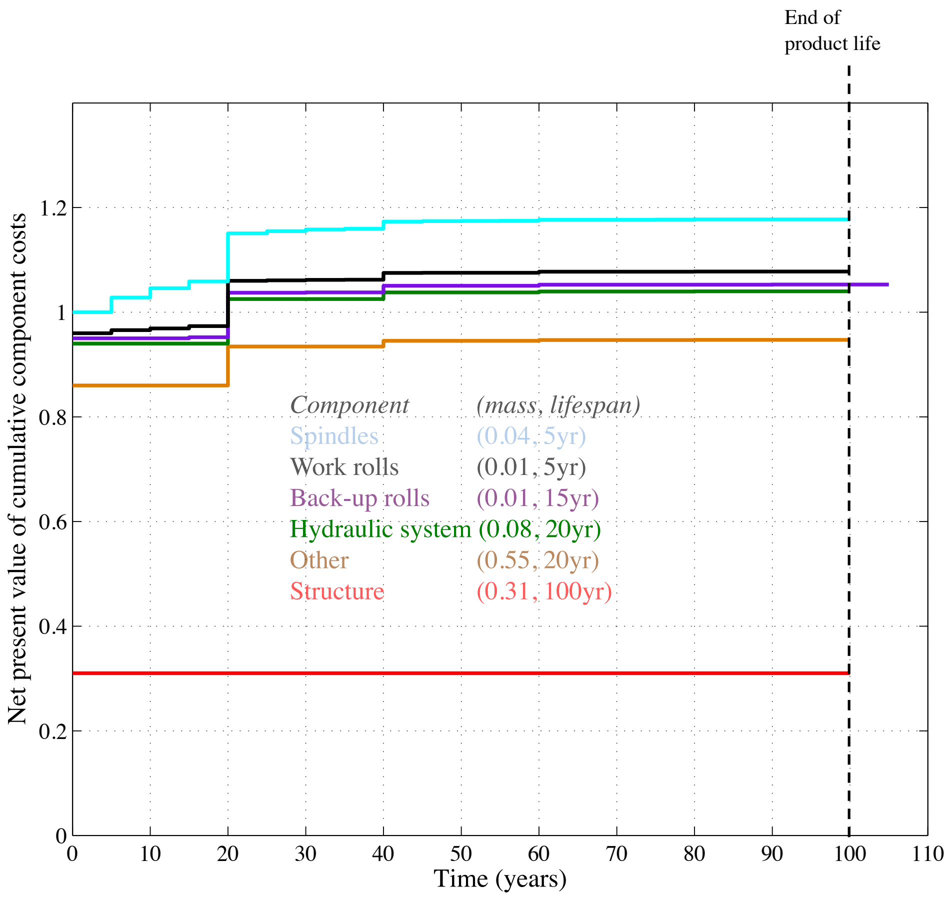
(a) washing machine


End of
product life
Component
(cost, lifespan)
Suspension
(0.12, 4yr)
Other
(0.22, 8yr)
Transmission
(0.07, 12yr)
Interior & trim
(0.18, 13yr)
Engine
(0.18, 13yr)
Structure
(0.21, 21yr)
Net present value of cumulative component costs
Time (years)
0
0.2
0.4
0.6
0.8
1
1.2
0
5
10
15
20
25

(b) car



(c) office block



(d) rolling mill

Figure 4.6: Net present value of cumulative component costs over the products' lifespans. All costs indexed to initial product cost = 1

Figure 4.6 includes the same steel rich components for each product as in Figure 4.2 and Figure 4.3. For all products except the car, the most expensive component does not contain the most steel (either initially or over the lifetime of the product). The components with the highest cumulative cost shares are the services in the office block and the electronic and control systems (part of the 'other' category) in the rolling mill and the washing machine. The car is the only product for which the most expensive component also has the highest steel content; this is likely due to the high quality of the material used by this luxury car manufacturer. For the car and the washing machine the most expensive components are not replaced. However, for the rolling mill and the office block these relatively high cost services and control systems are replaced when they become inferior. This suggests that the relatively high cost of manufacturing and installing components does not deter replacement if the replacement parts offer enhanced functionality.

Just as high component cost shares do not necessarily deter replacement, low component cost shares do not necessarily mean that replacement will occur. For example, the bearings in a washing machine drum are relatively cheap but are not replaced because they are inaccessible due to integrated design. Products that fall into this category are prime candidates for redesign by applying the strategies mentioned in the previous section.

Comparing the y-intercepts to the cumulative costs at product end-of-life reveals that the proportions do not vary between initial and final stages as much as the corresponding cumulative mass graphs. This is best illustrated by considering the work rolls (Figure 4.3c and Figure 4.6d). The work rolls dominate the cumulative steel mass but are only 2% of the cumulative cost. Lower discount rates would result in a greater positive correlation between cumulative component costs and steel content.

Based on the limited data provided here it is not possible to draw broad conclusions, but the findings suggest that the rolling mill template – in which the long-lived structure accounts for a relatively high share of costs and short-lived components can be easily replaced (offering profit to the producer and enhanced utility to owners) – encourages product life extension.

4.6 Discussion

In this section recommendations are made for extending the lifespan of the steel in the four representative products by applying the strategies presented in Figure 4.5 and drawing on specific examples discussed in the case study interviews (detailed in Appendix C). More generally, the impact of applying long-life strategies on the designed level of modularity is then discussed.

A washing machine's drum bearings, a car's engine, and a rolling mill's work rolls all fail because they become *degraded*. Both *restorable design-in* and *durable design-out* strategies could be applied to prevent failure. For example, the lifespan of the washing machine (see case study 11) could be increased by designing for the motor and bearings to be replaced (easy access to motors/compressors in white goods would also allow them to be upgraded if they were superseded) or by installing more durable bearings; car engine cylinders could be made from a more durable alloy, or replaceable inserts could mitigate wear. In the case of rolling mill work rolls (see case study 2), the outer layer is already made of a hard chrome steel, meaning that increasing their durability may be difficult. However, the worn surface could become restorable by using a replaceable, short-lived work roll 'sleeve' around the long-lived structural core, as suggested by Hadjduk et al. (2010). This latter principle could be applied more generally to address other types of failure e.g. replaceable aesthetic skins could be used to tackle failure of products or components that become *unsuitable* because their aesthetics are dated.

The office block is demolished due to an *unsuitable* internal plan that is incompatible with the structure. Applying the strategies for an *unsuitable* failure from Figure 4.5, the structure could be made more *adaptable*, with standard interface architecture so that modules could be replaced or extended from the existing structure to cater for new requirements (see case study 1). *Flexible* buildings also include: extra space, flexible floor to ceiling heights, and extra load capacity in areas where this provision is likely to be required (see case study 9).

The design strategies summarised in Figure 4.5 show that all four types of failure could be tackled through some form of modularisation (isolating the components that have failed and so extending the life of the remaining components). Examples from the interviews include restoring worn tram rails, upgrading steel rolling mill control systems, adapting building design whilst retaining the foundations and, (in the case of unequivocal product failure) by reusing components. Considering the different causes of failure, Table 4.7 summarises which components should be isolated in products that fail for different reasons.

DEGRADED Isolate short-lived components (typically those that are subjected to wear or corrosion)	INFERIOR Isolate components that are most likely to suffer due to technological change (typically electronics)
UNSUITABLE Isolate components that target the product to specific consumer groups (for example the internal space plan of buildings or the aesthetics)	WORTHLESS Isolate components with the highest residual value (typically standardised components (e.g. structural components) with multiple alternative uses but also more complex bespoke units for which a buyer can be found)

Table 4.7: Modular design responses to product failure

The economic viability of these strategies will have to be assessed on a case-by-case basis and take into account the multiple influences on these decisions, not only the component cost structure. Nevertheless, this chapter has presented some preliminary evidence to suggest that product upgrade strategies are most likely to be viable when the source of product failure can be isolated to a subset of replaceable components that offer high value to users (as they enhance the functionality of the product) and can generate high margins for producers.

5 Solid-state aluminium welding

The case studies presented in section 5.1 of this chapter were conducted in collaboration with Technische Universität Dortmund and various aluminium companies. Most of the analysis presented in section 5.1 was conducted at the companies and this is clearly referenced in the text.

The concept of aluminium solid-state recycling has existed for nearly seventy years. However, only one industrial application of this concept has been found, and no predictive model of chip extrusion profile strength has been produced. In order to evaluate potential applications for scrap extruded profiles four case studies are conducted in collaboration with aluminium producers and product manufacturers (section 5.1). A new predictive model of weld strength is then presented which, building on the well-known work by Bay (1983), takes account of all the relevant deformation parameters in bond formation (section 5.2-3). This model is then evaluated using a new experiment in which the interface strain and normal contact stress are decoupled, and the friction hills between both the tooling and the samples and between the samples themselves minimized (section 5.4-5.6).

5.1 Applications for extruded aluminium scrap

In order to evaluate potential applications for extruded scrap, four products are produced from manufacturing scrap and their resulting properties compared to current product specifications. The products are decorative car bright trim (transport), drinks cans (metal products), hollow structural sections (construction) and circular rods (industrial equipment). In all the trials the cleaning, compaction and extrusion of the scrap was conducted at Technische Universität Dortmund (TUD). The scrap was cleaned by submerging it in aqueous degreaser for 30 minutes at 60°C and it was compacted with a 100te hydraulic press to produce billets approximately 10cm long, Ø60mm. These compacted billets were extruded in a Collins Technology 250te extrusion press with an extrusion chamber Ø60mm. Conventional flat dies were used during extrusion of the car trim, drinks can material, and circular rods. A two-hole porthole die was used to produce the hollow section.

5.1.1 Decorative car bright trim

Trials in collaboration with Technische Universität Dortmund (TUD), Jaguar Land Rover (JLR), Erbslöh Aluminium and Boeing have aimed to produce decorative car bright trim (transport sector). Saw trimmings from the extrusion of car trim, produced from AA6060, were supplied by Erbslöh Aluminium and hot extruded into a trim profile designed by JLR, presented in Figure 5.1. In parallel trials, trim was produced from AA6061 aerospace machining chips provided by Boeing. Both sets of extrusions were analysed at Erbslöh Aluminium, establishing the dimensional accuracy, mechanical properties, surface quality, and grain structure. These were compared to profiles produced from as-cast AA6060 billets, provided by TUD.

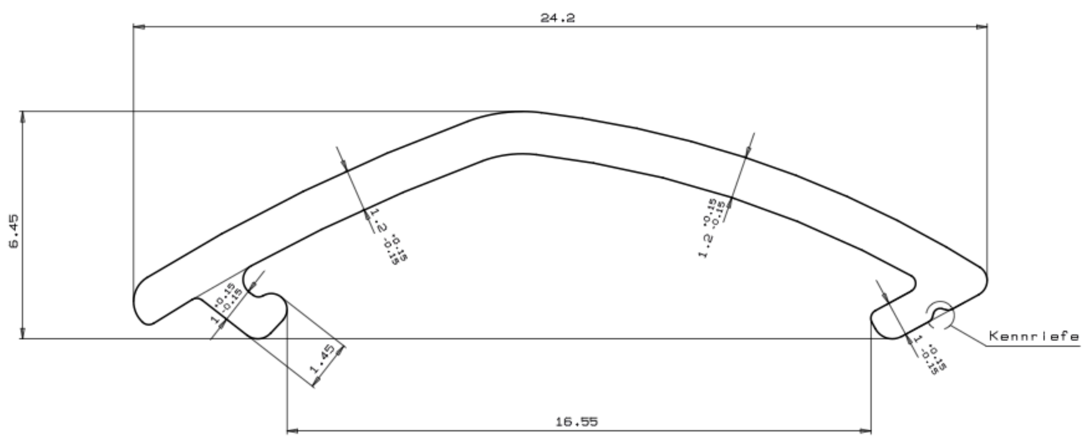


Figure 5.1: Car trim profile design provided by Jaguar Land Rover (all dimensions in mm)

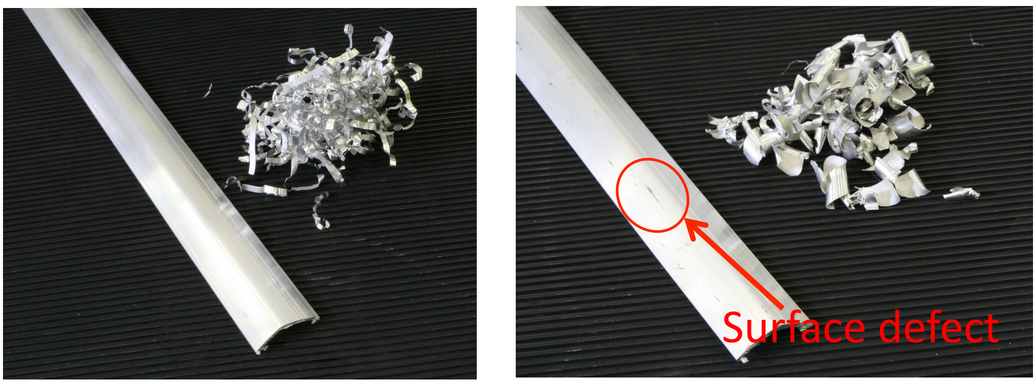
Scrap supply and extrusion process

The AA6060 saw trimmings are flat and approximately 60mm long, 2.5mm wide and 0.15mm thick. The AA6061 machining chips are approximately 22mm long, 10mm wide, 0.7mm thick and have a 360° twist along the length.

The same extrusion parameters were used in all the trials, and were chosen to maximise bonding based on the literature review presented in section 2.3.2. The parameters were a high billet pre-heat temperature (500°C), a high tool temperature (450°C), a high extrusion ratio (70) and a slow ram speed (1mm/s). Three 2.5m profiles from each set of extrusions (AA6060 as-cast, AA6060 trimmings, AA6061 chips) were sent to Erbslöh Aluminium for analysis.

Results and discussion

Examples of the car trim profiles produced from AA6060 extrusion saw trimmings and AA6061 aerospace machining chips are presented in Figure 5.2a and Figure 5.2b respectively.



(a) (b)

Figure 5.2: Decorative car bright trim extruded from (a) AA6060 extrusion saw trimmings (b) AA6061 aerospace machining chips

All the profiles' cross-sectional dimensions were within the tolerance specified by JLR (see Figure 5.1) and were therefore compatible with the connection system used on JLR's vehicles.

The strength and ductility of the trim profiles is presented in Figure 5.3 and Figure 5.4 respectively. The lower strength and ductility of the extruded AA6060 saw trimmings, compared to profiles produced from a cast AA6060 billet, was probably due to imperfect bonding decreasing the strength of the scrap profiles and producing cracks that propagate through the structure when loaded, reducing the ductility of the material. Profiles extruded from AA6061 chips were both stronger and more ductile than the AA6060 cast billet equivalents. The higher strength is probably because AA6061 is a stronger alloy than AA6060 and therefore, even with imperfect bonding, it has a higher strength and ductility. Car trim does not need to be particularly strong or ductile. The opinion of experts at Erbslöh Aluminium was therefore that the mechanical properties of the profiles produced from scrap were sufficient for a commercial application.

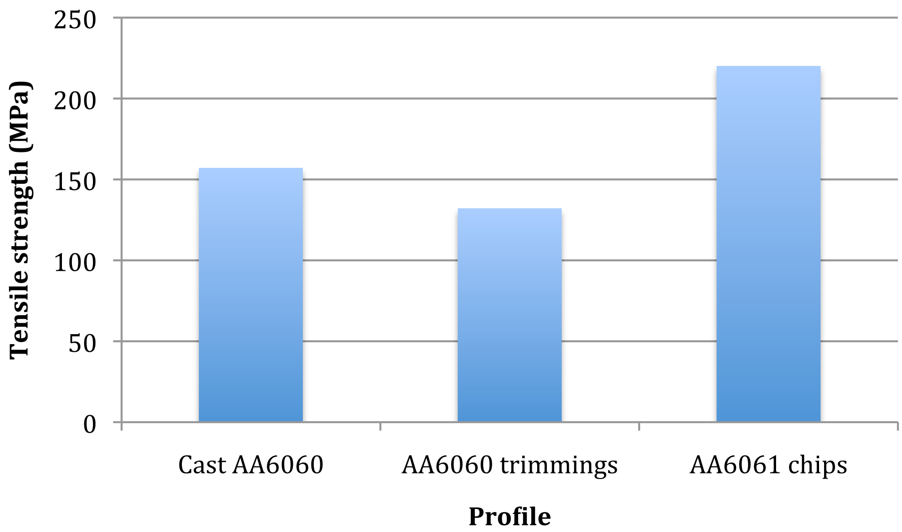


Figure 5.3: Tensile strengths of car trim profiles (Erbslöh, 2011)

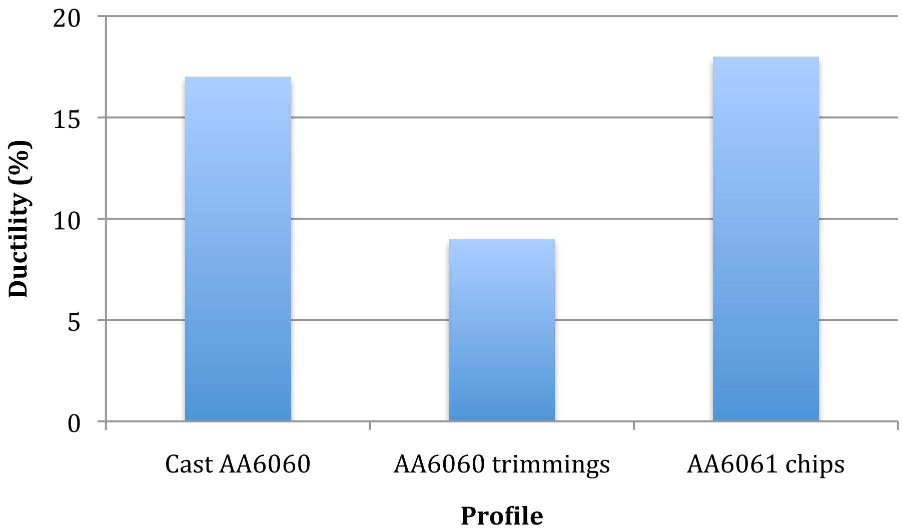


Figure 5.4: Ductility of car trim profiles (Erbslöh, 2011)

In order to protect the car trim profiles from corrosion they are typically painted or anodized. Erbslöh Aluminium specify the root mean square surface roughness of the profiles must not be greater than 9μm for painting and not greater than 5μm for anodizing. In order to evaluate the suitability of the scrap extruded profiles for undergoing these surface treatments roughness measurements were taken at three different points along each 2.5m sample, finding an average roughness on the as-cast profiles of 14μm, on the AA6060 trimming profiles of 39μm, and on the AA6061 chip profiles of 52μm (Erbslöh, 2011). These values of surface roughness are all outside Erbslöh's current product specification for painting or anodising. However, experts in the surface finishing department at Erbslöh recommend other surface finishing processes could be used to make the scrap profiles commercially viable: abrasive blasting could be used to smooth out the surface or a thick powder coating could be applied.

The surface roughness of profiles produced from cast billets, although much lower than on the scrap profiles, was too large for painting or anodising to be appropriate surface treatments. This suggests that the high surface roughness on the scrap profiles was at least partly due to the use of extrusion conditions poorly optimized for surface finish.

In order to increase the understanding of the bonding process the top apex of one of the AA6060 trimmings profiles was polished and etched to reveal the grain structure, shown in Figure 5.5. The regular horizontal lines running along the extrusion direction are likely to be micro-porosity on the boundaries between the chips. These features are not visible on profiles from as-cast billets, so these lines must be the chip boundaries. The weld lines run parallel to the extrusion direction because the trimmings are stretched as they are squeezed through the die in the extrusion process. There is a heterogeneous grain structure varying in size from 5 to 110µm. The equiaxed grains suggest recrystallisation has taken place during the extrusion process, which is likely given the high extrusion ratio (and therefore strain) and temperature. Grain growth has typically stopped at the boundary between the chips, presumably impinged by either the micro-porosity or the oxide layer between the chips. This challenges the recrystallisation theory, proposed by Parks (1953) and reviewed in section 2.3.1, which claims that welding occurs because crystal growth during recrystallisation eliminates the oxide films as a non-metallic barrier.

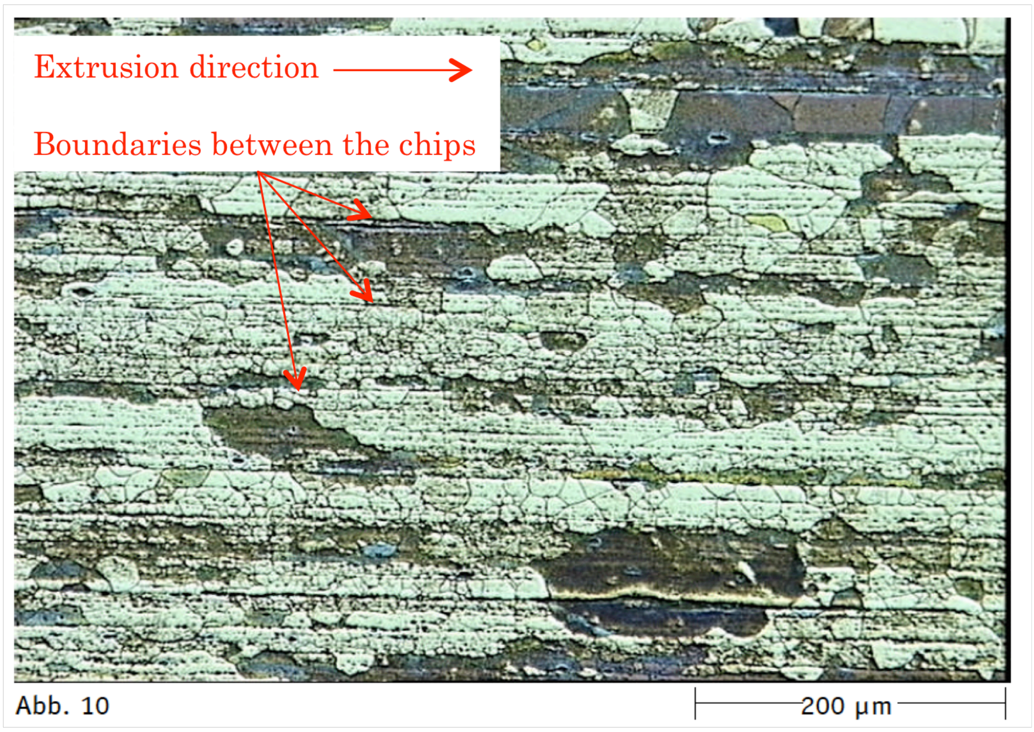


Figure 5.5: Polished and etched sample from the apex of AA6060 trimmings profile (Erbslöh, 2011)

This case study has shown the potential for car door trim to be produced from extrusion saw trimmings and aerospace machining chips. The macroscopic dimensions and mechanical properties of the extruded scrap profiles were suitable for commercial use. However, the surface roughness of both sets of profiles was too high for conventionally surface treatments to be applied.

5.1.2 Drinks cans

Trials in collaboration with Novelis and Crown Packaging have aimed to determine whether drinks cans, produced from AA3104, could be manufactured using solid bonded material: solid bonded bar is produced at TUD from chopped can making skeletons provided by Crown. This bar is then cross-rolled to blank thickness at Novelis prior to cup drawing at Crown.

Scrap supply and forming processes

Can making skeletons are chopped into small flat scrap fragments approximately 10mm long, 5mm wide and 0.3mm thick. These fragments were extruded to produce a rectangular profile (34x10mm), shown in Figure 5.6.

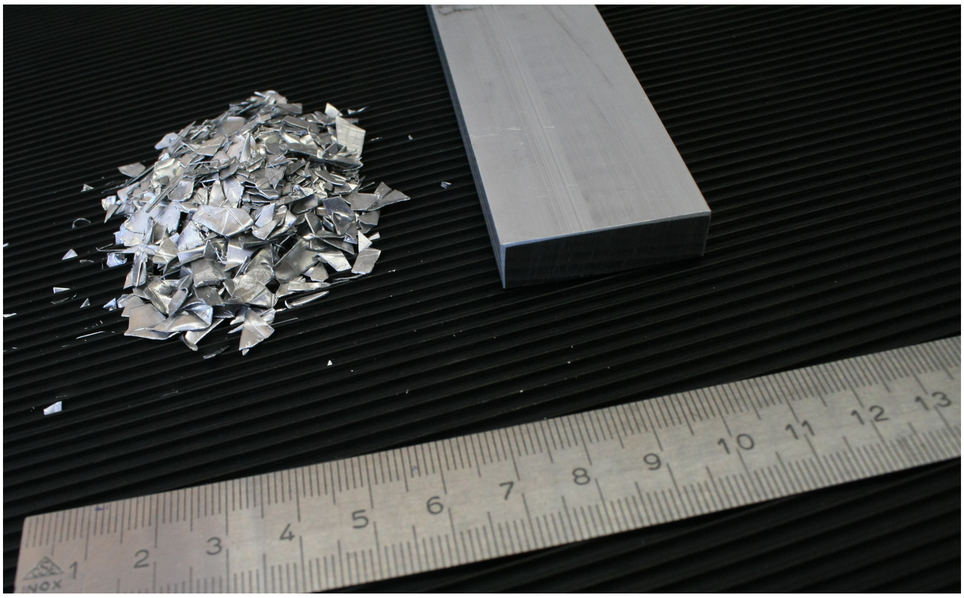


Figure 5.6: Rectangular profile bar (34x10mm) produced from AA3104 scrap fragments

The cross-sectional area of this profile is relatively large compared to the billet diameter (Ø60mm), resulting in a low extrusion ratio equal to 8. A low ram speed (1mm/s), high billet pre-heat temperature (500°C) and high tool temperature (450°C) were used to maximise bonding.

Two 30cm lengths of this profile were cold rolled - perpendicular to the extrusion direction - to a sheet thickness of 0.3mm, the usual thickness for drinks can blanks. Circular blanks (Ø50mm) were then produced from the sheet and attempts were made at Crown to produce a drinks can body and base using the standard procedure, as described by Hosford and Duncan (1994): Blanks 5.5cms in diameter are cut from the sheet; a punch draws the circle to form a 3.5cm-diameter cup; a second machine then redraws the blank, irons the walls and gives the base its dome.

Results and discussion

Initial attempts to draw the blanks into cups had limited success, with only 1 out of 4 attempts avoiding ‘punching through’, or wrinkling. Figure 5.7 presents the outcome of this initial attempt. Split cup ‘3a’, shown in Figure 5.7a, shows small imperfections on the sidewall, which are similar to the imperfections on the fully formed cup shown in Figure 5.7b.

(a) **(b)**

Figure 5.7: (a) Punched through and badly wrinkled samples; (b) Successful drawing with some ironing on base. (Crown, 2010)

In order to understand why the bonded material would not readily be formed into a cup, tensile tests were conducted on the bonded sheet and compared to conventional can blanking material. Figure 5.8 presents the tensile tests, showing that the solid bonded sheet has a much higher strength than the conventional can body stock. This is to be expected when the work hardening during hot extrusion and cold rolling of the bonded material is taken into account.

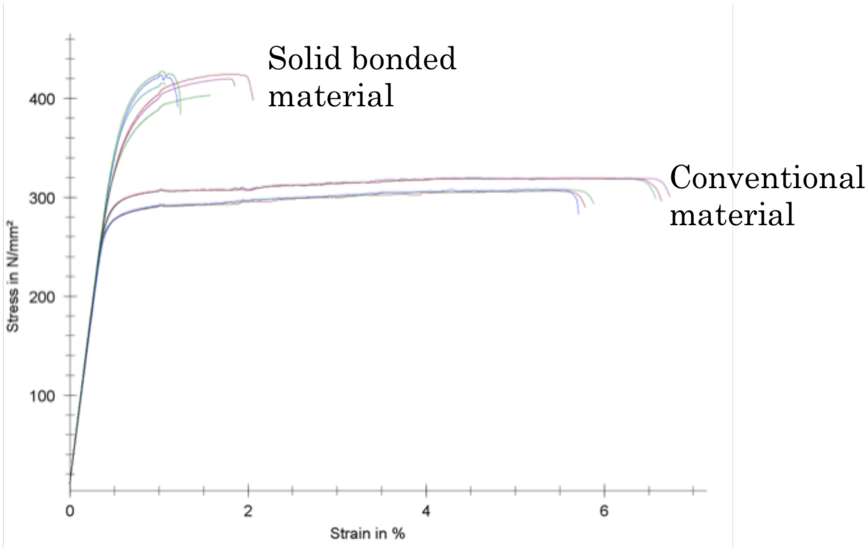
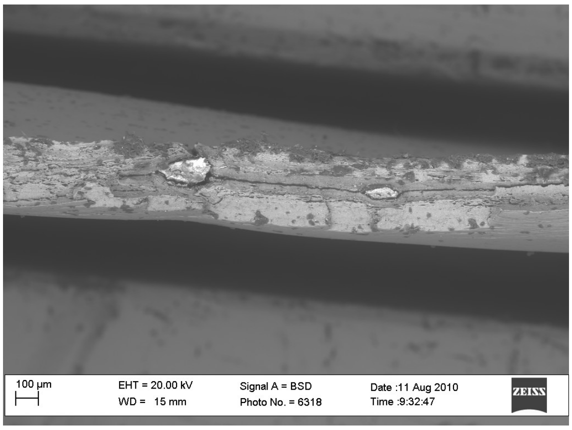


Figure 5.8: Tensile tests on bonded sheet and conventional can blank sheet (Crown, 2010)

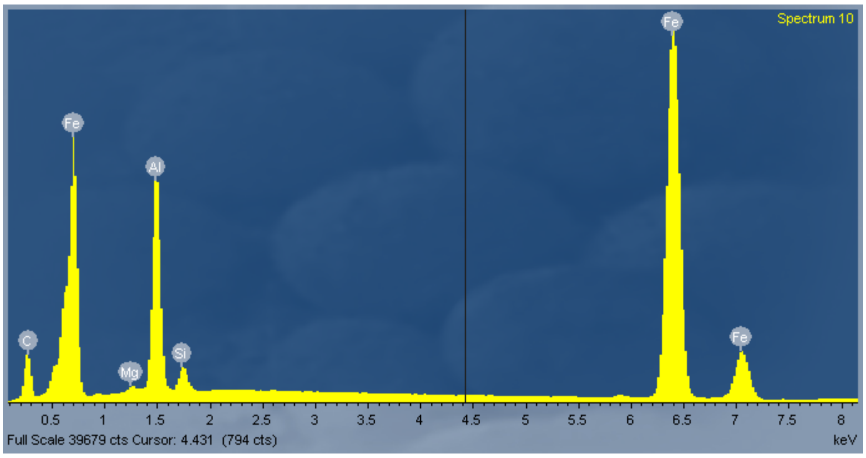
In an effort to increase the ductility of the bonded material it was annealed at a low temperature (≈200°C). This lowered the yield stress by approximately 25MPa. This material was successfully drawn into cups, presented in Figure 5.9. However, any redrawing resulted in the cups immediately splitting.

Figure 5.9: Cups drawn from rolled AA3104 solid bonded material reheated at low temperature (Crown, 2010)

In order to understand the reason for the inferior formability of the bonded material the wrinkled area of a split cup was cut out and bent across the defect area until the piece fractured. The fracture surface was examined under the microscope and is shown in Figure 5.10a. Two inclusions, which are relatively large compared to the thickness, are clearly visible in Figure 5.10a. Energy-dispersive X-ray (EDX) spectroscopy of the fracture surface clearly indicates that the inclusions are iron based (see Figure 5.10b). The scrap material is likely to have become contaminated either during collection and chopping at Crown or iron fragments may have come off the inside of the tube used to compact the chips at TUD. It is likely that this ferrous contamination was the limiting factor on the formability of the material.



(a)



(b)

Figure 5.10: (a) Fracture surface of split cup showing large inclusions (b) EDX analysis of this region showing ferrous contamination (Crown, 2010)

This case study has shown the potential to further deform solid bonded material after extrusion; 0.3mm sheet was successfully produced by cold rolling of 10mm thick profiles perpendicular to the extrusion direction. The fact that a full can body could not be drawn from the bonded sheet because of ferrous contamination highlights the importance of quality control in avoiding contamination of the scrap.

5.1.3 Hollow structural section (HSS) and circular rod

Trials in collaboration with Boeing and Alcoa have produced a hollow structural section and circular rod from AA6061 aerospace machining chips provided by Boeing. Material testing of these extrusions was then performed at Alcoa.

Scrap supply and extrusion process

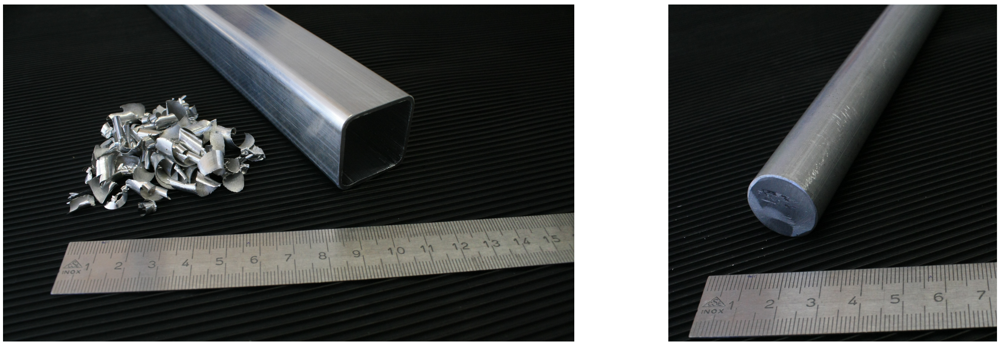
The aerospace chips provided by Boeing were the same chips as used in the car trim case study, approximately 22mm long, 10mm wide, 0.7mm thick and having a 360° twist along the length. These chips were extruded to produce a hollow structural section and solid circular rod. The extrusion conditions used are shown in Table 5.1.

Profile	Extrusion ratio	Ram speed (mm/s)	Billet pre-heat temp. (°C)	Tool temp. (°C)
Hollow profile (30x30x2)mm	13	5	500	450
Circular rod (Ø20mm)	10	5	500	450

Table 5.1: Extrusion conditions for producing the hollow section and circular rod

Results and discussion

Examples of the hollow section and circular rod profiles produced from the AA6061 aerospace machining chips are presented in Figure 5.11a and Figure 5.11b respectively.



(a) **(b)**

Figure 5.11: AA6061 aerospace chips extruded into (a) hollow section (b) circular rod

Analysis at Alcoa revealed that the hollow section displayed poor bonding near the corners of the section (see Figure 5.12), and has a blistered surface finish (see Figure 5.13). The poor bonding, porosity and blistered surface finish mean that these hollow sections would not be suitable for any safety critical or even decorative applications.

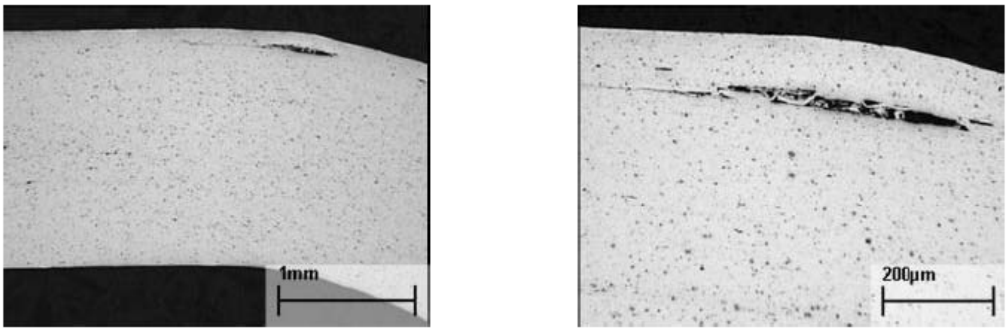


Figure 5.12: Optical microcopy image of hollow section profile showing porosity and poor bonding (Alcoa, 2010)

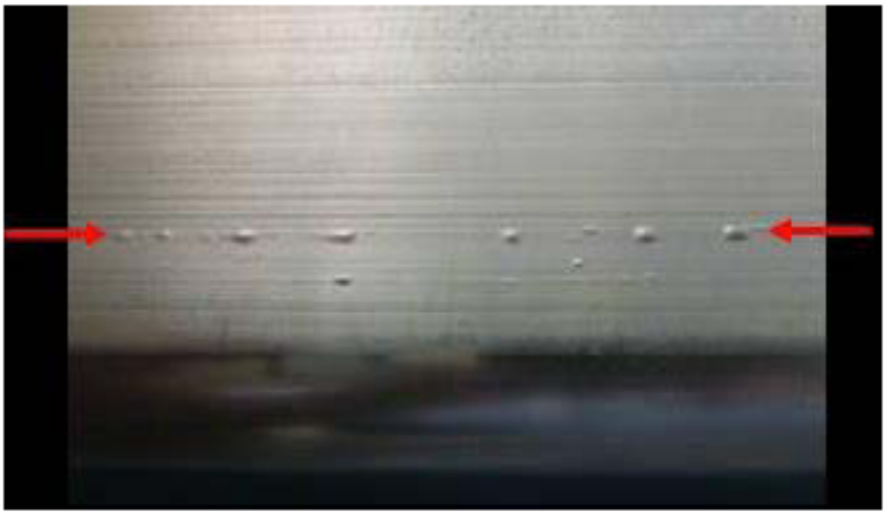


Figure 5.13: Blistered surface of the hollow profile (Alcoa, 2010)

The round profile displayed very poor bonding, as shown in Figure 5.14. Porosity between the chips is very clear and again this profile would be unsuitable for any safety critical applications.

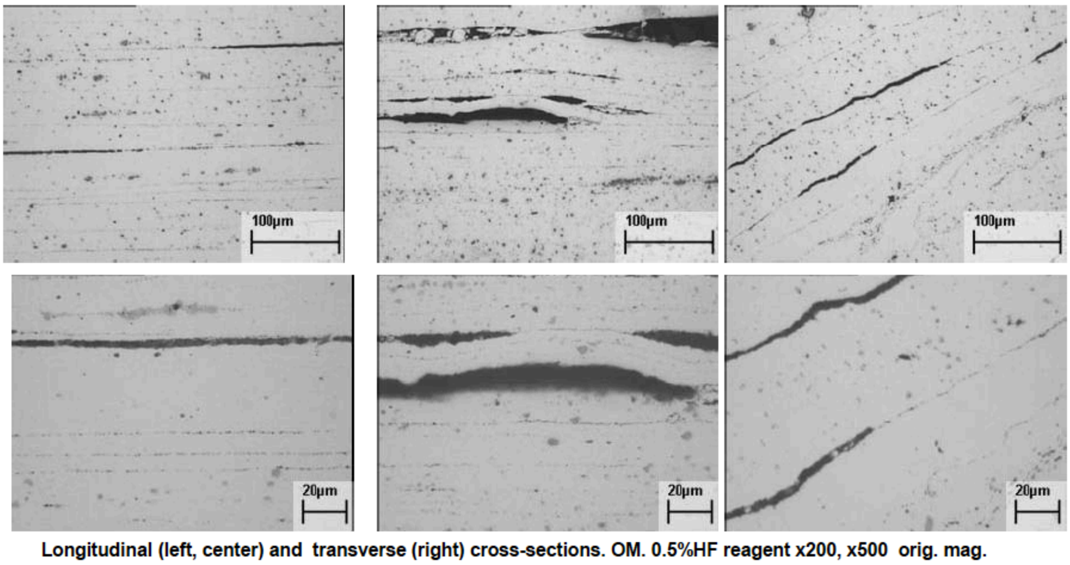


Figure 5.14: Poor bonding in both longitudinal and transverse directions of circular rod section (Alcoa, 2010)

5.1.4 Conclusions

These case study projects have shown that imperfect bonding and a poor surface finish are major issues when finding potential applications for solid bonded products. Applications that require neither a predictable high strength nor decorative surface do exist, but are limited to very low volume markets. Examples include solar frames (used to support solar panels) and internal window frame extrusions.

The properties of extruded scrap profiles might be improved by optimising the extrusion conditions. For example, reducing the extrusion temperature typically improves the surface finish of profiles in conventional extrusion of cast billets (Sheppard, 1999), and could help to improve the surface finish of the car trim profiles studied in section 5.1.1. However, this is at odds with the high extrusion temperature found by Suzuki et al. (2005) to promote good bonding between the chips. A medium extrusion temperature may exist which promotes both a good surface finish and results in sufficient bonding. The limit diagram for such a trade-off may look something like Figure 5.15. A model of profile strength would allow a more structured search of appropriate extrusion conditions for a given profile and application.

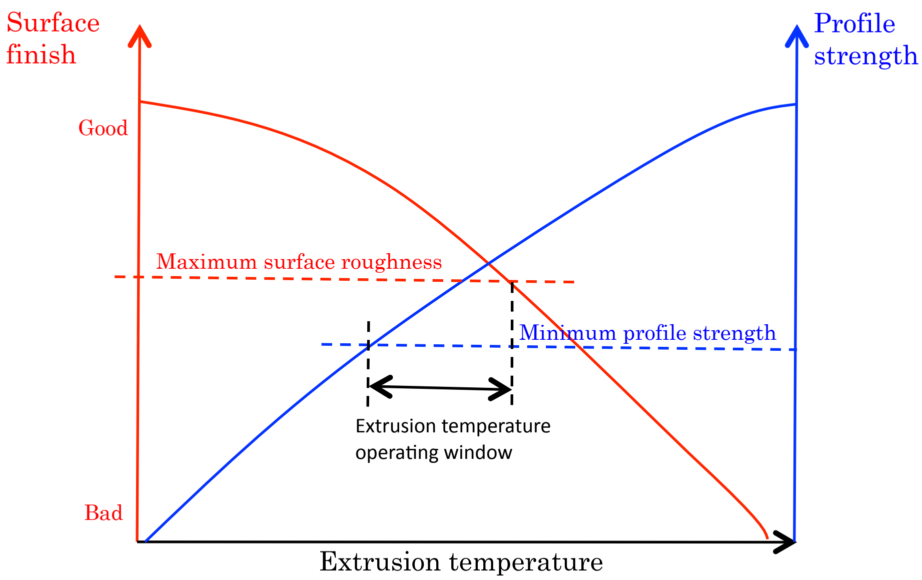


Figure 5.15: Suggested form of extrusion temperature limit diagram for satisfactory strength and surface finish

5.2 The influence of deformation conditions in solid-state aluminium welding processes on the resulting weld strength

The review in section 2.3 reveals that no general model of solid bonding exists, so in the rest of this chapter the first aim is to produce a bonding model that addresses the limitations of previous attempts. The second aim is to devise an experiment where aluminium can be solid bonded whilst as many as possible of the relevant deformation conditions (*strain*, s*train rate, normal contact stress*, *temperature* and *shear*) are controlled independently. Analysing the resulting bond strengths can inform understanding of the role of each deformation parameter on the resulting solid weld. The experimental results can also be used to validate or challenge aspects of the model.

5.3 Proposed model for solid bonding

The following is proposed: that a combination of normal contact stress and shear establishes close contact between two surfaces. The oxide remains along the interface, but as an applied strain stretches the material, clean metal becomes exposed. Entrapped air oxidizes some of the exposed metal; however, provided the strains are great enough, some of the clean metal will be extruded through the ever-widening cracks in the oxide. A bond forms, the strength of which is equal to the strength of the base metal at room temperature, once clean metal surfaces are within atomic distances.

The model presented in the following sub-sections considers plane strain deformation and a perfectly plastic material.

5.3.1 Establishing close contact between the surfaces

When two aluminium surfaces are pressed together, initial contact is only made between the asperity tips. Examining force equilibrium between two surfaces has led most researchers to conclude that the area in contact (A_c), as a fraction of the nominal area (A_n), is equal to the normal contact stress (σ_n) divided by the aluminium flow stress (Y). The results of Conrad and Rice (1970), however, suggest that the true area of contact is about 80% of this ratio. This discrepancy is most likely due to a tri-axial stress state in material around contacting asperities, constraining plastic flow. In light of this, true contact area in this model as a fraction of nominal area is taken as 80% of the effective stress between the surfaces divided by the flow stress, as shown in equation 5.1.

$$A_c = 0.8\frac{\sigma_n}{Y}A_n \qquad (5.1)$$

where in the case of $A_c > A_n$, set $A_c = A_n$.

It is acknowledged that this percentage is approximate and that experimentation or detailed contact modeling could improve its accuracy.

The application of a nominal shear stress, τ_{app}, in addition to a normal contact stress, results in an effective von Mises stress of $\sqrt{\sigma_n^2 + 3(\tau_{app})^2}$. For equilibrium to be maintained the area in contact must increase to

$$A_c = \frac{0.8A_n}{Y}\sqrt{\sigma_n^2 + 3(\tau_{app})^2} \qquad (5.2)$$

where in the case of $A_c > A_n$, set $A_c = A_n$.

The flow stress of the metal (Y) is dependent on the strain, strain rate and temperature (Hosford and Caddel, 2007).

Initial contact will be between the oxide films. Nicholas (1990) investigates ceramic-ceramic and ceramic-metal bonding, finding no bonding at temperatures below 1000°C or in the presence of air. Aluminium and its oxide are mutually insoluble (Tylecote, 1968);

therefore, there is no diffusion through the oxide films to help create a weld. Bonding must be due to stretching of the interface exposing substrate aluminium.

5.3.2 Initial stretching of the interface and oxidation by entrapped air

As discussed in section 2.3.3, there is a threshold stretching deformation of the interface before which welding will not occur. Researchers have typically assumed this corresponds to the deformation necessary to crack surface films. However, aluminium oxide is very brittle: a tensile strength of 260MPa and Young's modulus of 350GPa suggests that it has a failure strain of less than 1%. As would be expected given such brittleness, Sherwood and Milner (1969) find that the threshold reduction for welding aluminium in a vacuum is less than 1%. In light of this, it is proposed in this work that the significant threshold strains observed in atmospheric conditions are due to entrapped air oxidising aluminium exposed at low strains. Only when all the entrapped oxygen has chemically bonded to this aluminium can any aluminium exposed at higher strains exist in an inert atmosphere. To quantify the fraction of the surface that the entrapped air will oxidize requires an estimate of its oxygen content and therefore its volume.

The contact geometry between two aluminium surfaces is complex. For simple analysis, however, O'Callaghan and Probert (1987) argue that it may be regarded as equivalent to the contact between an imaginary rough surface, with an appropriate triangular topography, against a flat surface. Roughness is characterised by the root mean square of the asperity heights (r) and the asperity inclination angle (ψ). For a machined aluminium surface, typical values for r range from 1-5μm and ψ is typically less than 0.2°. O'Callaghan and Probert assume that the equivalent rough surface has a root mean square asperity height, r_{eq}, and asperity inclination angle, ψ_{eq}, of $\sqrt{2}r$ and $\sqrt{2}\psi$ respectively. Estimating the entrapped air volume is possible with this simplified geometry. 1.7×10^{-4} moles of oxygen (O_2) are required to oxidize a $1m^2$ aluminium surface to a depth of 2.9nm (ten aluminium atom spacings), which would prevent inter-atomic forces creating a bond. The number of O_2 moles in the entrapped air is determined by its volume and temperature. The fraction of the surface that will be oxidised by the entrapped air, η, is then given by equation 5.3 (see Appendix D for derivation), where T is the process temperature in Kelvin.

$$\eta = 50{,}000 \times r_{eq} \times \cos(\psi_{eq}) \times \frac{298}{T} \tag{5.3}$$

A typical value of η is 0.35 (r=5μm, ψ=0.18°, T=298K).

The fraction of the final contact area that is exposed aluminium without a protective oxide layer is therefore given by ν in equation 5.4.

$$\nu = \frac{\varepsilon - \eta}{1 + \varepsilon} \tag{5.4}$$

A typical value of ν is 0.3 (ε=1,η=0.35).

The area of exposed substrate aluminium (A_{ex}) is, therefore, given by equation 5.5.

$$A_{ex} = \nu A_c \tag{5.5}$$

where A_c is given by equation 5.2.

5.3.3 Further stretching of the interface

Further stretching cracks the oxide films in an oxygen-free environment. For bonding to occur exposed aluminium on both sides of the interface must be overlapping. Force equilibrium analyses on oxide fragments (see Appendix E) show that the fragments experience a greater maximum tensile stress when adjacent oxide layers break-up together. It is therefore assumed that substrate aluminium exposed on one side of the interface is always adjacent to—completely overlaps with—substrate aluminium exposed on the other side, as shown in Figure 5.16.

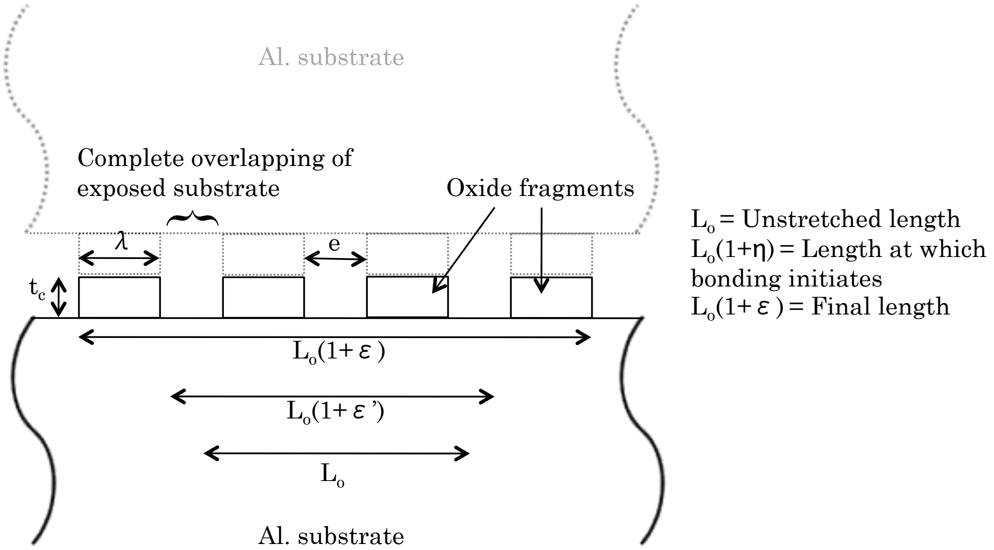


Figure 5.16: Aluminium surface of original length L_0 stretched to length $L_0(1+\varepsilon)$

This is consistent with the findings of Vaidyanath et al. (1959) on examining the welding interface. The aspect ratio of the resulting oxide fragments is

$$\frac{\lambda}{t_c} = \frac{2\sigma_{oxide}}{k} \tag{5.6}$$

where λ and t_c are the length and thickness of the oxide fragments respectively (as defined in Figure 5.16), σ_{oxide} is the failure stress of aluminium oxide and k is the aluminium shear flow stress. Equation 5.6 shows that the length of the oxide fragments increases for thicker oxides and for weaker substrate aluminium (alloys).

In the presence of a shear stress, τ_{app}, at the interface, the aspect ratio increases to

$$\left(\frac{\lambda}{t_c}\right)_{shear} = \frac{2\sigma_{oxide}}{k} \times \left(1 - \frac{\tau_{app}{}^2}{k^2}\right)^{-1} \qquad (5.7)$$

The length of oxide fragments therefore increases still further for higher shear stresses at the interface. Derivations of equations 5.6 and 5.7 are shown in Appendix E. Substituting typical AA1050-O parameters into equation 5.6 (σ_{oxide}≈260MPa, k≈37MPa, t_c≈10nm) produces an oxide fragment aspect ratio of approximately 14 (λ≈140nm). This compares to an aspect ratio of up to 13 observed by Barlow et al. (2004) in a transmission electron microscopy (TEM) analysis of the internal surfaces of roll bonded AA1050 foil. The similarity between the calculated and observed aspect ratios suggests that the methodology used to model the fracture of the oxide layers is valid.

Having worked out when fracture will occur, the crack width can now be calculated. This is equal to the area of exposed aluminium divided by the number of cracks. The number of cracks is the stretched area at which bonding is initiated divided by the length of the oxide fragments, equal to

$$\frac{L_0(1+\eta)}{\lambda} \qquad (5.8)$$

Dividing the final area of exposed aluminium by the number of cracks (equation 5.8) gives an average crack width (e) of

$$e = \frac{\lambda(\varepsilon - \eta)}{1+\eta} \qquad (5.9)$$

A typical value of e is 65nm (ε=1, η=0.35, λ=140nm).

Having worked out the crack width, the pressure required to micro-extrude the substrate aluminium through the cracks can be calculated. This could be done in a number of ways, including finite element or slip line field analysis, as outlined in Hill (1950). For simplicity, a slab analysis, as outlined by Hosford and Caddel (2007), is used here. Plane strain and square dies (dead zone angle approaching 90°) are assumed. The pressure required to micro-extrude the substrate aluminium through the cracks is given by p_{ex} in equation 5.10.

$$p_{ex} = Y \ln\left(\frac{\lambda + e}{e}\right) + \left(\frac{Y t_c}{e}\right) \quad (5.10)$$

A typical value of p_{ex} is 95MPa (Y=74MPa, λ=140nm, e=65nm, t_c=10nm).

The difference between the nominal normal contact stress (σ_n) and p_{ex} is the contact stress that forces the substrates together, establishing an area of contact between the substrate aluminium (A_s) of

$$A_s = 0.8 \frac{\sigma_n - p_{ex}}{Y} A_{ex} \quad (5.11)$$

where in the case of $A_s > A_{ex}$, set $A_s = A_{ex}$.

A_{ex} is given by equation 5.5.

5.3.4 Nominal weld strength

The components of the model are combined in this sub-section to provide an estimate of the final weld strength. The area of contact between clean aluminium surfaces (A_s) is assumed to bond to the strength of the cold, bulk aluminium (σ_0). Force equilibrium implies equation 5.12.

$$\sigma_b A_n = \left(\frac{0.8 A_n}{Y} \sqrt{\sigma_n^2 + 3\left(\tau_{app}\right)^2}\right)_{\leq A_n} \times \nu \times \left(0.8 \frac{\sigma_n - p_{ex}}{Y}\right)_{\leq 1} \times \sigma_0 \quad (5.12)$$

where p_{ex} is given by equation 5.10 and ν is given by equation 5.4.

The derived model therefore predicts a nominal room temperature bond shear strength, τ_b, given by equation 5.13.

$$\tau_b = \frac{1}{\sqrt{3}}\left(\frac{0.8}{Y}\sqrt{\sigma_n^{\,2} + 3\left(\tau_{app}\right)^2}\right)_{\leq 1} \times \nu \times \left(0.8\frac{\sigma_n - p_{ex}}{Y}\right)_{\leq 1} \times \sigma_0 \qquad (5.13)$$

The effect of each deformation parameter on the bond strength is accounted for in equation 5.13. For example:

- A higher *strain* increases the exposed area and oxide crack width, increasing ν and decreasing $\mathbf{p_{ex}}$ respectively.
- Increases in *strain rate* increase the flow stress of the metal, increasing both **Y** and $\mathbf{p_{ex}}$.
- Increases in *normal contact stress* increase $\boldsymbol{\sigma_n}$.
- Increases in bonding deformation *temperature* decrease the threshold strain (η) and flow stress of the metal. The reduced threshold strain increases ν, and the reduced flow stress of metal decreases both **Y** and $\mathbf{p_{ex}}$.
- A higher *shear stress* increases $\boldsymbol{\tau_{app}}$ and increases the oxide crack width, decreasing $\mathbf{p_{ex}}$.

5.4 Methodology for evaluating the new model of bond strength

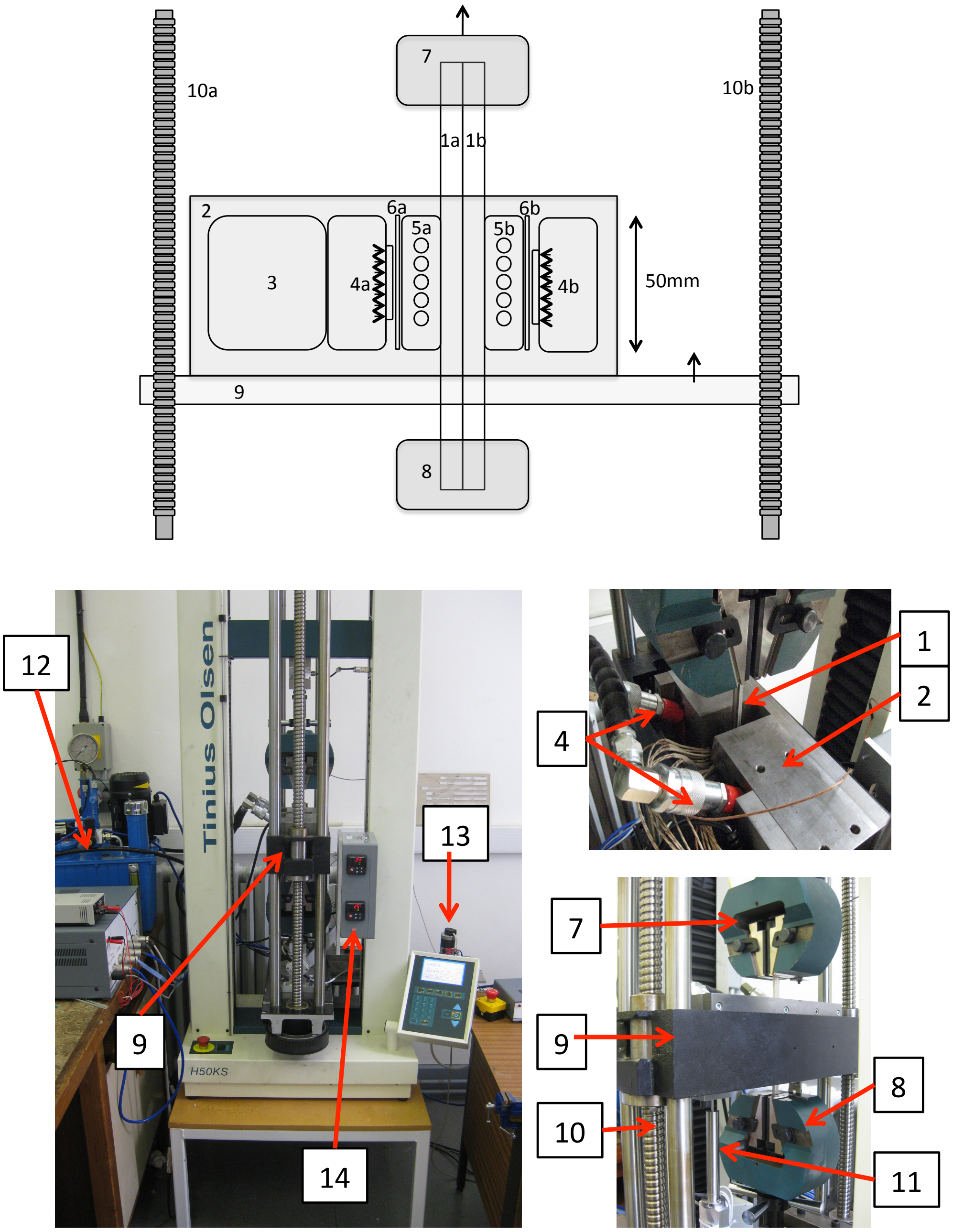
Evaluating the model requires that the strength of welds produced under various deformation conditions are compared to the model's predictions of these welds' strengths. Section 5.4.1 describes the physical experiments performed to bond aluminium samples and to test the strength of the weld. In order to use the model to make predictions of the weld strength, it is necessary to understand the deformation conditions in the physical experiments. This was achieved by simulating the experiments using finite element (FE) software. Details of these FE simulations are presented in section 5.4.2. The full range of physical and simulated experiments is described in section 5.4.3.

5.4.1 Physical experiments

In rolling, extrusion (and forge) welding the extension of the interface is the result of the perpendicular compressive strain. Therefore, although many deformation parameters can be varied in processes such as accumulative roll bonding (ARB) and porthole die extrusion (PDE), they are strongly dependent on each other. For example, increasing the pressure between the rolls in ARB (and hence the normal contact stress between the sheets) also increases the reduction ratio and therefore strain at the interface. In this work's experiments, in addition to an interfacial force, a tensile stress was applied parallel to the welding plane, decoupling the interface strain from the normal contact stress.

Equipment design

Adjacent aluminium strips were stretched in a tensile testing machine and simultaneously squeezed in a perpendicular direction by two heated flat tools, pushed together by hydraulic pancake rams. The flat tools and pancake rams were contained in a tool steel housing situated in a carriage that was mounted on two vertical lead screws. The carriage could be moved up and down via a motor. Figure 5.17 presents a schematic and photograph of the experimental set-up.



1a & 1b	Adjacent aluminium samples
2	Tool steel housing
3	Load cell
4a & 4b	Pancake rams
5a & 5b	Heated tools (holes for cartridge heaters and thermocouple)
6a & 6b	Ceramic plates to insulate the pancake rams from the heated tools
7	Top crosshead (moves upwards during tests)
8	Bottom crosshead (remains stationary)
9	Carriage
10a & 10b	Lead screws
11	LVDT
12	Hydraulic power pack
13	Carriage motor
14	Cartridge heaters controller

Figure 5.17: Equipment set-up

The *strain* and *strain rate* were dependent on the top crosshead displacement and speed. These could be controlled using the tensile testing machine software. The *normal contact stress* was dependent on the interfacial force between the samples, set using an input current to a proportional control valve on the hydraulic power pack. Before testing, the valve setting was calibrated to the resulting force using a load cell located in the steel housing. The force could be controlled within ±0.3kN.

During testing, the carriage must remain equidistant from the top and bottom crossheads to prevent the samples buckling. A linear variable differential transducer (LVDT) was situated between the rig base and carriage, providing feedback on the carriage's position. Proportional and integral control was used to adjust the power sent to the motor, maintaining positional accuracy within ±0.25mm.

The *temperature* was controlled using eight 95Watt ∅1/8" cartridge heaters. These heat the flat tools, which were pressed against the aluminium samples for two minutes prior to testing, ensuring the contact region was at the tool temperature (up to 200°C). Four heaters, and one thermocouple, were inserted into each tool. The thermocouple provided feedback for full proportional-integral-derivative control of the power sent to the heaters, setting their temperature to within 1 Kelvin. The specification of the heaters was determined using a generic fin analysis of conductive and convective heat loss from the aluminium samples, as outlined by Incropera and Dewitt (1985). Ceramic plates (6mm thick) separated the heated rams from the hydraulic pancake rams, ensuring the oil remained cool.

The above system was integrated and synchronized using a National Instruments compactRio real-time system controlled with Labview2012.

Preparation of the aluminium samples

Three related factors determined the choice of the samples' alloy, temper and geometry. Firstly, the force capability of the hydraulic system (≤32kN) must be sufficient to compress the samples by at least 35% (the threshold reduction for bonding found in the literature). This capability depends on the material strength and cross-section geometry. Secondly, the samples must not buckle under this interfacial force. Lastly, during the tests, friction hills are present between the rams and the aluminium samples, and between the samples themselves. These friction hills are unwanted as they produce differential strains and normal contact stresses both along and across the interface. The sample and interface design must minimize these friction hills.

Annealed AA1050 samples (shear strength of 37MPa) were used in these experiments. This material was chosen because it is soft and a non-heat treatable alloy; the post-bonding analysis of weld strength was simplified by avoiding precipitation-hardening effects. The geometry and material properties are shown in Figure 5.18 and Table 5.2 respectively. A water-jet was used to cut rectangular cross-section samples from 5mm thick sheet. A 3-axis CNC milling machine was then used to create the geometry shown in Figure 5.18. The samples were cleaned using ethanol (removing the machining coolant) and fully annealed at 500°C for 30 minutes.

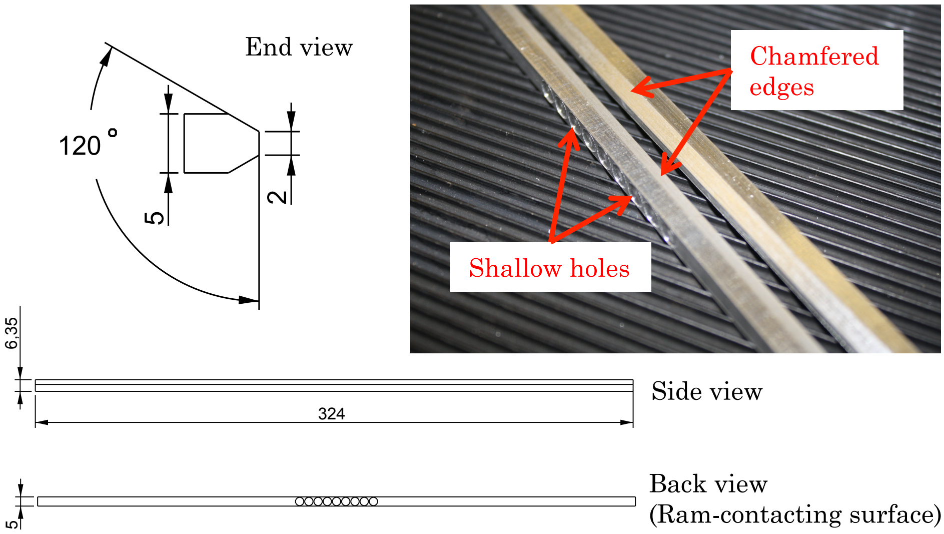
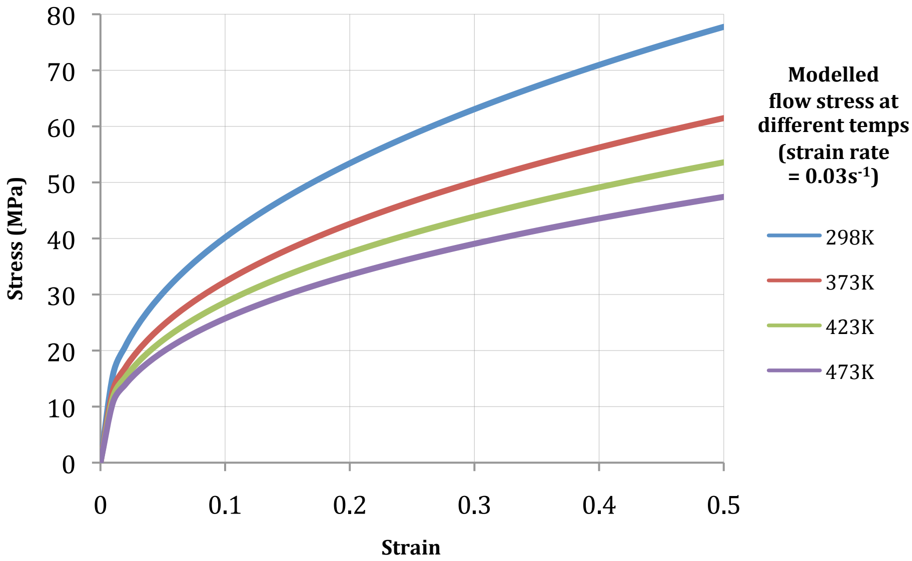


Figure 5.18: Aluminium sample geometry (all dimensions are in mm)



Temperature (K)	Flow curve (MPa)*
298	$\sigma = 107 \times \varepsilon^{0.41} \times \dot{\varepsilon}^{0.01}$
373	$\sigma = 87 \times \varepsilon^{0.40} \times \dot{\varepsilon}^{0.02}$
423	$\sigma = 78 \times \varepsilon^{0.39} \times \dot{\varepsilon}^{0.03}$
473	$\sigma = 71 \times \varepsilon^{0.38} \times \dot{\varepsilon}^{0.04}$
Roughness of 2mm wide surface	
Machined finish R=5μm ψ=0.18°	

***Flow curve proportionality constants and strain hardening exponents determined by tensile tests. Strain rate exponents from Hosford and Caddel (2007). However, these are higher than is usually expected.**

Table 5.2: Aluminium sample properties.

To reduce the friction hill across the bonding interface the width of contact was only 2mm. This also increased the maximum normal contact stress that could be applied via the hydraulic system. The aluminium samples had a trapezoidal cross-section. This prevented out of plane buckling of the specimens as they were compressed.

Two different methods could have been used to decrease the friction hills between the tools and samples: a series of rollers could have been placed between the rams and the samples, switching the friction regime from sliding to rolling friction; alternatively, lubricant reservoirs could have been placed in shallow holes on the softer, aluminium, surface.

The effect of a series of rollers on the deformation of the aluminium samples was simulated using finite element analysis. Figure 5.19 presents a screenshot of this simulation. Details of the finite element simulations are presented in section 5.4.2. It was found that rollers would significantly indent the aluminium surface, 'trapping' material between the rollers and causing unpredictable deformations at the interface. Rollers were not, therefore, used in these experiments.

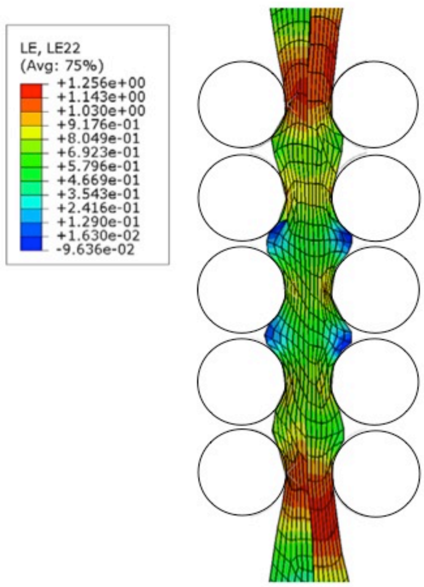


Figure 5.19: Finite element simulation of aluminium samples compressed using rollers

Lubricant reservoirs are used in Rastegaev upsetting tests, where a metal's flow curve is determined via the force-displacement relationship when compressing a cylinder of the metal. Recesses are machined into the top and bottom of the cylinders and filled with lubricant, greatly reducing friction and subsequent barreling of the compressed cylinders (Freire and Vieira, 1992). Inspired by Rastegaev tests, lubricant reservoirs were used in this work's experiments. The samples' ram-contacting surfaces were polished and had nine 4.5mm diameter holes (0.1mm depth) running along their centre. During testing, these shallow holes were filled with Teflon, chosen because it exhibits very low friction (static coefficient of friction≈0.04) and is stable up to 200°C, the maximum temperature in these tests.

Evaluating the bond

The bond strengths were determined using shear tests. The shear tests were conducted on a tensile testing machine at 298K, with a crosshead speed of 10mm/min. Narrow 1mm wide slots were cut on both sides of the bonded samples so that, when pulled, the bonded areas experienced only a shearing force. The distance between the two slots was 15mm, as shown in Figure 5.20.

During the bonding experiments, high interfacial forces meant that the chamfered surfaces of adjacent samples sometimes made contact. When this occurred the bonded samples were machined, reducing the interface width to 2mm (Figure 5.20). This eliminated the possibility of any bonding of the chamfered edges affecting the shear test results. The nominal bonded area was therefore a consistent 30mm^2.

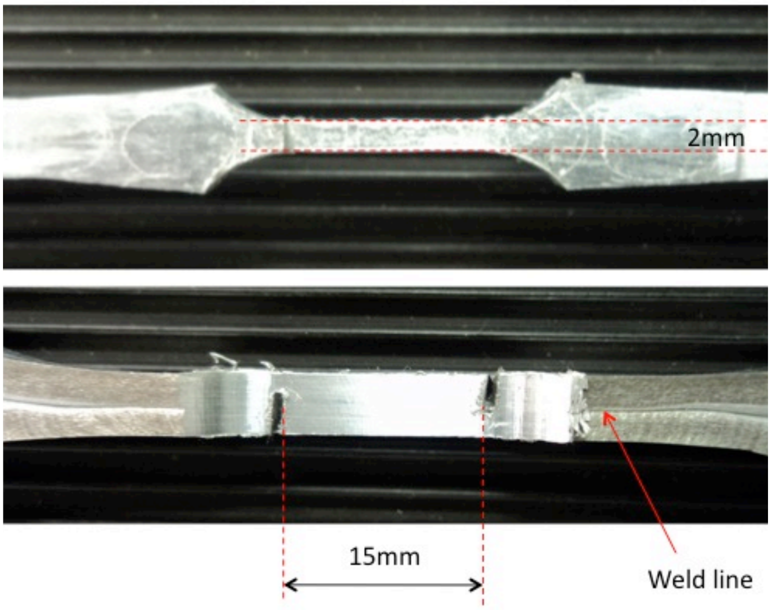


Figure 5.20: Machined shear test samples. Interface width reduced to 2mm

In order to assess the quality of the weld and interpret the way in which the bond forms, Scanning Electron Microscope (SEM) images were taken of the welded samples' cross-sections (showing the weld line between the two samples).

5.4.2 Simulations

In order to use the model to predict weld strength, the deformation conditions (*strain, normal contact stress* etc.) experienced during weld creation must be known. This was achieved by conducting a finite element simulation of each physical experiment. The deformation variables used to plot the figures in the results section were the average of their values over the 30mm^2 area (varying by a maximum of ±10%). For example, Figure 5.21 shows the finite element simulation of an experiment that created a weak weld at 373K.

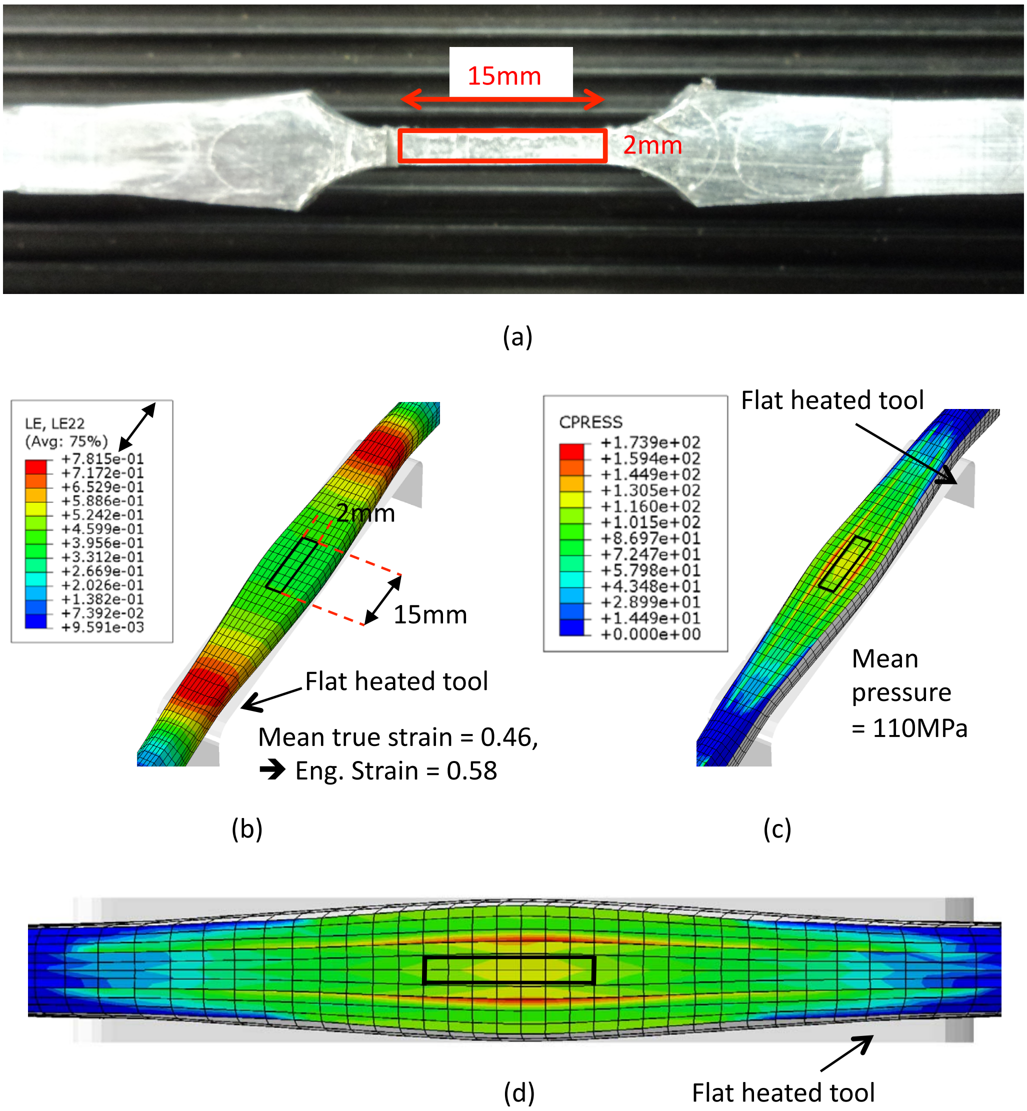


Figure 5.21: (a) Machined test sample showing 2x15mm zone. Finite element simulation of (b) real strains and (c) pressures (normal contact stresses) on the welding plane for 373K, 28kN squeeze, crosshead displacement of 30mm. (d) enlarged image of pressure distribution, same contour definition as in (c)

The finite element simulations were conducted using Abaqus/Standard v6.10, implementing an implicit time integration analysis with 'Static, General' steps. Each aluminium sample was modeled as a 3D deformable body and meshed using around 8,000 brick elements (C3D8R). A convergence study was performed to ensure that this number of elements is sufficient to provide accurate results, and to avoid excessive element distortion. The tools (flat or rollers) were simulated using analytical rigid surfaces.

The material model for the aluminium samples assumed a von Mises material with isotropic hardening. Different flow curves were used for simulating different process temperatures. The flow curves corresponded to the equations shown in Table 5.2.

The friction coefficient between the samples and heated rams needed to be determined so that the finite element analysis accurately simulated the deformations. This was done by performing a tensile test while compressing the specimen, analogous to open die forging with the addition of a tensile stress stretching the forged material as it is pressed. A standard slab analysis of this process (as outlined by Hosford and Caddel, 2007) was used to identify the friction coefficient value that correctly predicted the compressive (forging) force. A Coulomb friction coefficient of 0.15 was calculated using this method. This value was used in all simulations with a Coulomb (penalty) friction law, and a contact stabilization value of 0.001.

Several checks were performed to ensure the accuracy of the simulations. Within the model it was ensured that both the stabilization energy (due to the contact stabilization) and artificial energy (associated with hourglass control) were small compared to the internal energy. Comparing the predicted geometry of bonded samples to the results from experimental trials provided final validation of the simulations. Table 5.3 presents this comparison for simulations and experimental tests over a range of temperatures, pressures and strains. The simulated and experimental results agree to within a maximum error of 10%. An example result from the finite element model is shown alongside the equivalent experimental result in Figure 5.22.

Transverse force (kN)	Cross-head disp.* (mm)	Temp. (Kelvin)	Experimental results		Finite element results		Mean error (%)
			Max. width (mm)	Max. thick-ness (mm)	Max. width (mm)	Max. thick-ness (mm)	
32	50	298	8.4	4.6	8.5	4.4	3
32	42	373	9.0	4.1	9.2	4.5	6
20	42	423	8.0	5.9	7.9	5.3	6
28	22	473	10.8	4.1	9.9	4.5	9

Table 5.3: Comparison between experimental and finite element simulation results. *Cross-head speed of 100mm/min

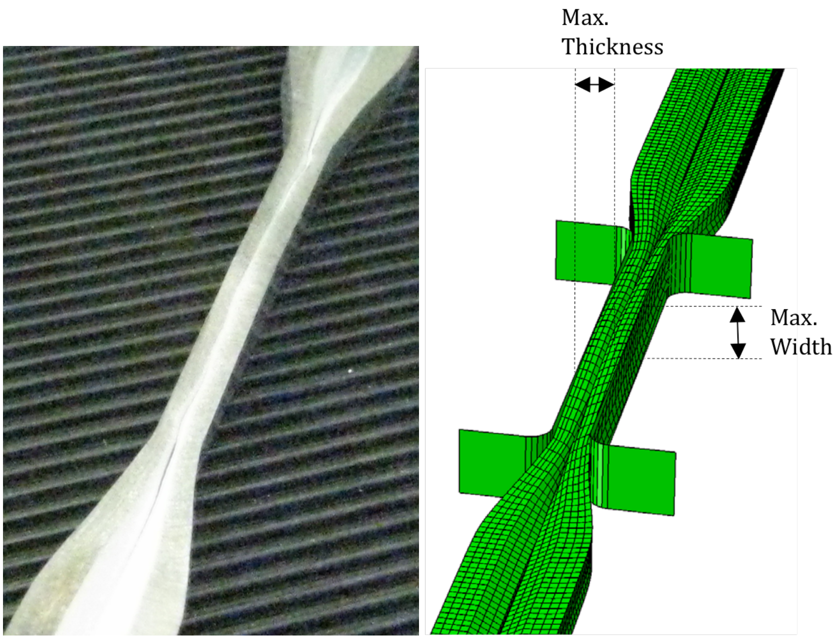


Figure 5.22: Comparison of finite element and experimental results from a Set A experiment (see table 5.4, section 5.4.3)

A sensitivity analysis was performed to investigate the effect of experimental error on the accuracy of the simulated deformation conditions (*strain, normal contact stress* etc.). There are two main sources of experimental error: the hydraulic force applied to the samples can only be controlled within ±0.3kN, and the position of the carriage within ±0.25mm. Finite element simulations were conducted of 3 physical experiments performed at 298K with a 50mm crosshead displacement and interfacial force of 20, 26 and 32kN. In the simulations of each experiment the interfacial force and carriage position were varied by ±0.3kN and

±0.25mm. It was found that the simulated strain and normal contact stress varied by a maximum of 2%. The experimental errors were not, therefore, expected to have a significant effect on the results.

5.4.3 Experimental plan

The tests conducted were designed to reveal the accuracy of the new model, and with it increase understanding of the influence of each deformation parameter on the resulting weld strength. Table 5.4 presents a list of the experiments conducted in this study. Each row of the table represents a matrix of experiments, where an experiment was conducted for each combination of temperature, crosshead displacement and hydraulic force. Each successful experiment was repeated three times and the repeatability shown in the results as error bars.

The independent variation of normal contact stress and interface strain was limited due to the inherent instability of large tensile strain deformation: significant deviations from pure shear caused necking, as shown in Figure 5.23. The Levy-Mises flow criterion was used to define an experimental normal contact stress versus strain envelope, limiting the crosshead displacement to a practical maximum of 54mm.

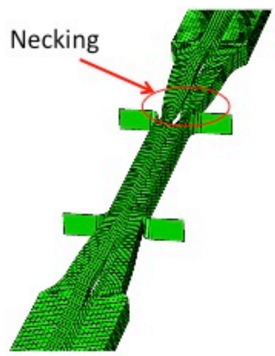


Figure 5.23: Necking of the samples outside of the rams at high crosshead displacements

Set A: Crosshead speed = 1.7mm/sec No macroscopic shear between samples

Temperature (K)	Crosshead displacement (mm)	Hydraulic force (kN)
298	[46, 48, 50, 52, 54]	[28, 32]
373	[26, 30, 34, 38, 42, 46, 50]	[20, 24, 28, 32]
423	[16, 20, 26, 34, 38, 42, 44]	28
473	[16, 20, 26, 34, 38, 42, 44]	28

Set B: Crosshead disp. = 54mm No macroscopic shear between samples

Temperature (K)	Crosshead velocity (mm/min)	Hydraulic force (kN)
[423, 473]	[100, 150, 200]	28
[298, 373]	[100, 150, 200]	32

Set C: Crosshead speed = 1.7mm/sec 7mm macroscopic sliding with 3kN hydraulic force

Temperature (K)	Crosshead displacement (mm)	Hydraulic force (kN)
373	[22, 26, 30, 34, 38, 42, 46, 50]	28

Table 5.4: Experimental tests conducted

Set A investigated the effect of varying *strain* (proportional to crosshead displacement), *normal contact stress* (proportional to hydraulic force) and *temperature*. Set B investigated the effect of increasing the *strain rate* at different temperatures. Set C investigated the effect of a *shear stress* applied between the samples during bonding. High shear and normal contact stresses alone caused the samples to distort and neck before bonding had occurred; therefore, in the Set C experiments a two-step process was performed, as shown in Figure 5.24. Firstly, the end of one sample was gripped in the bottom crosshead and the other end left unconstrained. Asymmetrically, one end of the other sample was gripped in the top crosshead and the other end left unconstrained. The top crosshead then moved vertically upwards by 7mm while a 3kN interfacial force was applied to the samples. This caused a small shear stress to develop across the interface. In this stage of the process the top crosshead displacement was limited to 7mm as greater movement caused severe distortion of the samples. In the second part of the process, the unconstrained ends of both specimens were gripped in the crossheads and the test proceeded to the final crosshead displacement and interfacial force, as defined in Table 5.4.

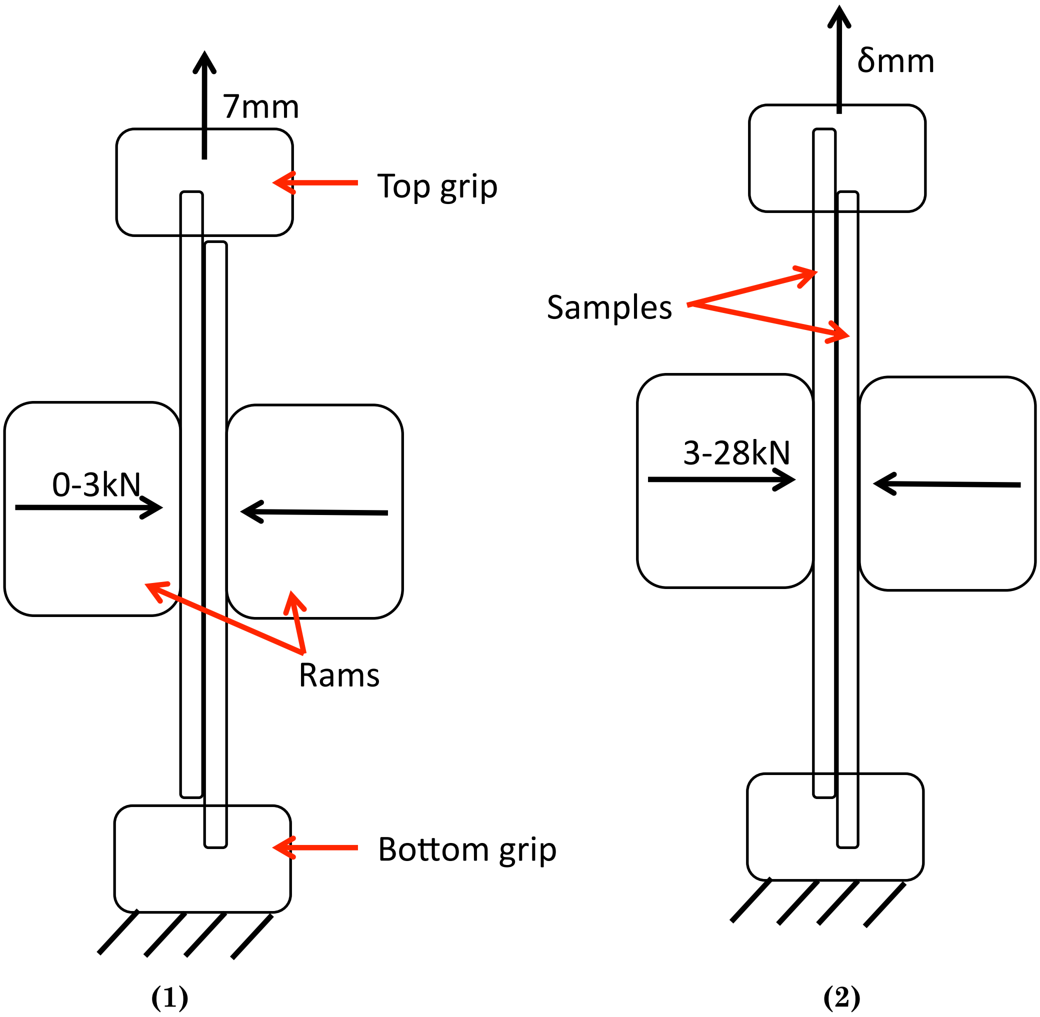


Figure 5.24: Set C tests
(1) A normal contact stress combined with a top crosshead displacement of 7mm causes a shear stress to develop across the bonding interface (2) Both ends of both samples are then gripped in the crossheads and stretched to a final crosshead displacement (δ)

5.5 Results

This section presents the results of the experimental shear tests on solid-state welds created under various deformation conditions. The resulting measured bond strengths are compared to those predicted by the new model (equation 5.13). Table 5.5 presents the material parameters used in the new model.

*AA1050 flow stress (strain rate=0.03s^{-1}) = $Y_{temp.}$ AA1050 flow stress (strain rate=0.045s^{-1}) = $Y_{temp.}$ AA1050 flow stress (strain rate=0.06s^{-1}) = $Y_{temp.}$	(Y_{298K}, Y_{373K}, Y_{423K}, Y_{473K}) (Y_{298K}, Y_{373K}, Y_{423K}, Y_{473K}) (Y_{298K}, Y_{373K}, Y_{423K}, Y_{473K})	(74, 60, 54, 49)MPa (74, 60.1, 54.5, 50.2)MPa (74, 60.3, 55.1, 51.4)MPa
**Oxide tensile strength, thickness	σ_{oxide}, t_c	260MPa, 10nm
***Machined samples surface roughness parameters	R, ψ	5μm, 0.18°

*Flow stresses calculated from the flow curves presented in Table 5.2 (equal to the stress at the maximum load in the tensile test; when the strain is equal to the strain hardening exponent).
**Oxide strength and thickness taken from Shackelford and Alexander (2000) and Vargel (2004) respectively.
***Roughness parameters measured using a stylus profiler

Table 5.5: Parameters used for predicting weld strengths.

The new model predicts solid-state weld strengths as a function of 5 deformation variables: *strain, normal contact stress*, *temperature, strain rate* and *shear.* This section is structured around examining the influence of each of these deformation conditions on the weld strength.

The results of the experiments show that, as predicted by the model, a minimum strain is required for bonding and that increasing the temperature, normal contact stress or shear stress can reduce its value and increase the strength of any subsequent welds. The new model often predicts bond strengths within the range of strengths created in the physical experiments. At higher temperatures, however, it underestimates bond strengths and the effect of increasing the strain rate on decreasing the bond strength.

5.5.1 Influence of strain and normal contact stress

Figure 5.25 presents experimental and predicted bond strengths (y-axis) as a function of strain (x-axis) and normal contact stress (coloured datapoints/dashes). Figure 5.25 shows a positive correlation between increasing the normal contact stress or strain and the resulting bond strength. A high normal contact stress alone is unable to create a weld and, similarly, even at relatively high strains, some normal contact stress is required to create a weld. Increasing the normal contact stress reduces the minimum (threshold) strain required for bonding. This has not been observed in previous literature due to the coupling between normal contact stress and strain in roll bonding experiments. The model correctly predicts the observed trends and in Figure 5.25 the predicted weld strengths typically lie within the error range of experimental results.

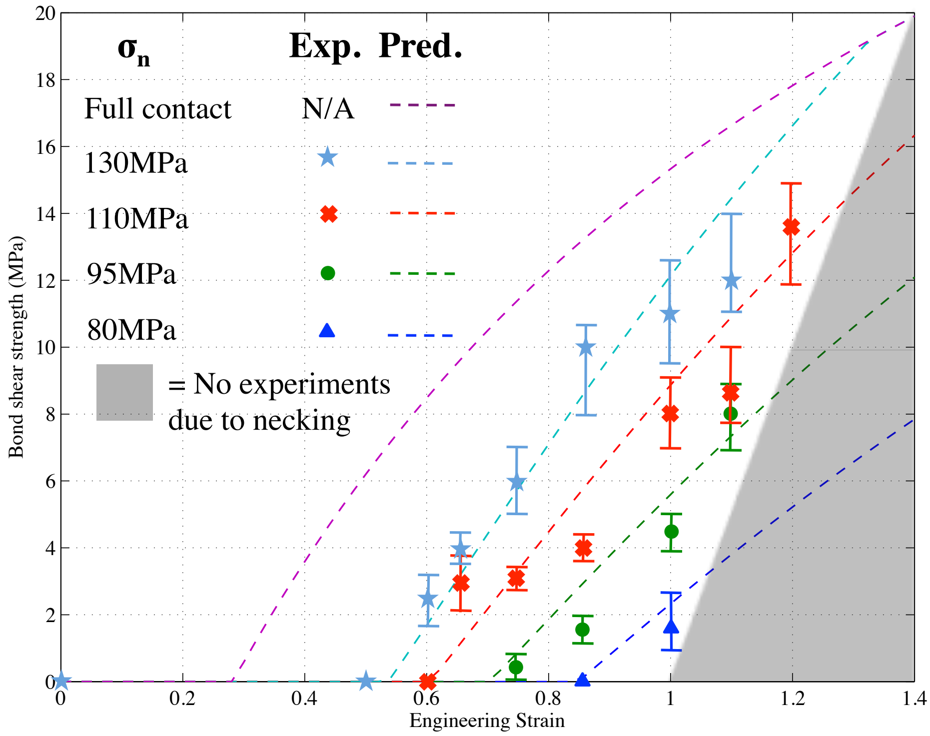


Figure 5.25: Effect of normal contact stress on the bond shear strength. Temp. = 373K, Strain rate ≈ 0.03s-1, Interfacial shear stress = 0MPa

Figure 5.25 contains a theoretical contour for 'full contact' stress. This stress corresponds to complete macroscopic contact between the surfaces, and complete micro-extrusion of the substrate through any cracks in the oxide. At this normal contact stress, bonding is initiated when the strain reaches the same value as η (the fraction of the surface that will be oxidised by the entrapped air), equal to 0.28 in this case.

Figure 5.25 (and Figure 5.26) contain grey regions where no experiments were successfully performed due to the material necking just outside of the rams (as discussed in section 5.4.3). It was also found that necking occurs at lower strains for high normal contact stresses. This may be because high frictional forces developed due to the high contact stresses involved, restraining the flow of material from between the rams.

5.5.2 Influence of temperature

Figure 5.26 presents the experimental and predicted room temperature bond strengths for deformation temperatures ranging from ambient (298K) to 473K. Figure 5.26 confirms that both the threshold strain and bond strength are very sensitive to temperature, with the threshold strain reducing from 72% at 298K to 25% at 473K. The model correctly predicts these trends, but underestimates the room temperature strength of bonds created at the highest deformation temperature. A prediction of the bond strength at 923K (650°C) is also shown on Figure 5.26. The melting temperature of aluminium is 660°C; therefore, this prediction represents the limiting case of solid bonding.

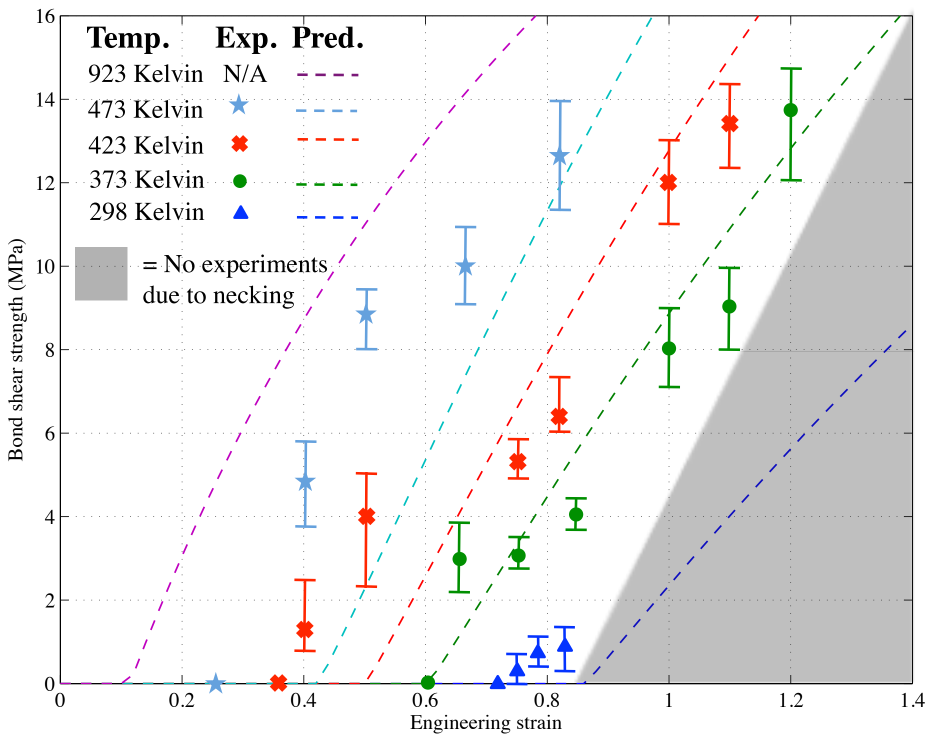


Figure 5.26: Effect of temperature on the bond shear strength. Normal contact stress of 110MPa, Strain rate = 0.03s-1, Interfacial shear stress = 0MPa

5.5.3 Influence of strain rate

Figure 5.27 presents the experimental and predicted weld strengths as a function of strain rate. The bond strengths are expressed as an index, with the strength of welds created at a strain rate of $0.03s^{-1}$ equal to 100. The effect of strain rate variations is predicted by modeling the aluminium flow stress as a function of strain rate (as shown in Table 5.5).

Figure 5.27 shows that increasing the strain rate significantly reduces the weld strength at higher temperatures. At lower temperatures the weld strength still reduces, but by less than 10% for process temperatures of 298K and 373K. The model predicts strengths that lie within the experimental error range at these lower temperatures. At 423K and 473K, however, there are significantly larger decreases in the bond strength than predicted by the model.

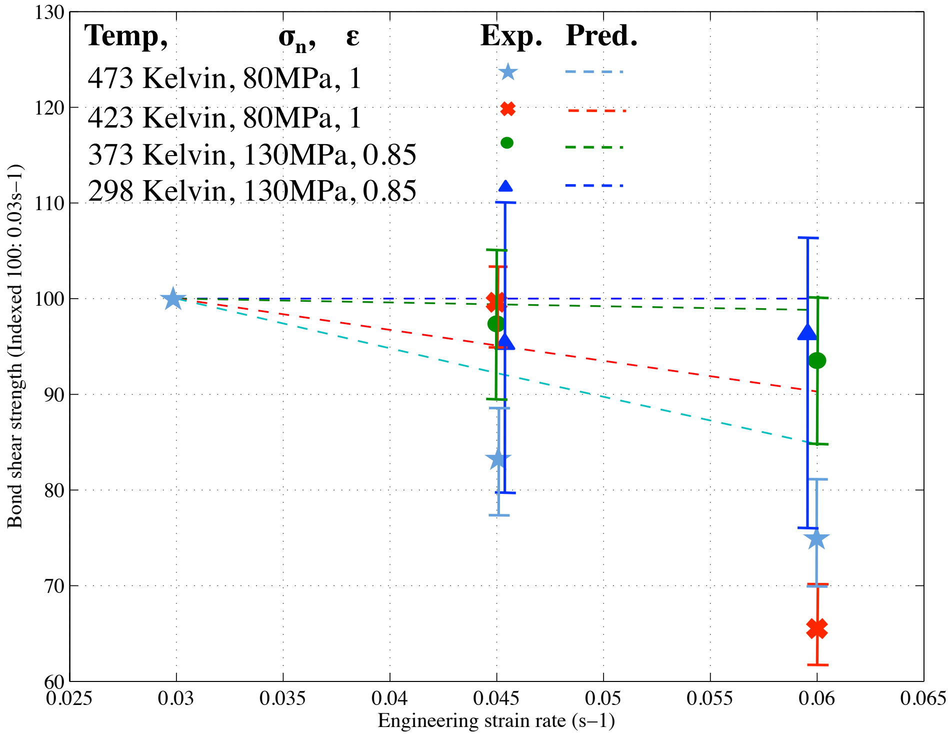


Figure 5.27: Effect of strain rate at different temperatures on the bond shear strength. No interfacial shear

5.5.4 Influence of shear

Figure 5.28 presents the experimental and predicted strengths of welds created with and without a 30MPa interfacial shear stress. The shear stress increases the subsequent bond shear strength, and decreases the threshold strain from 60% to 42%.

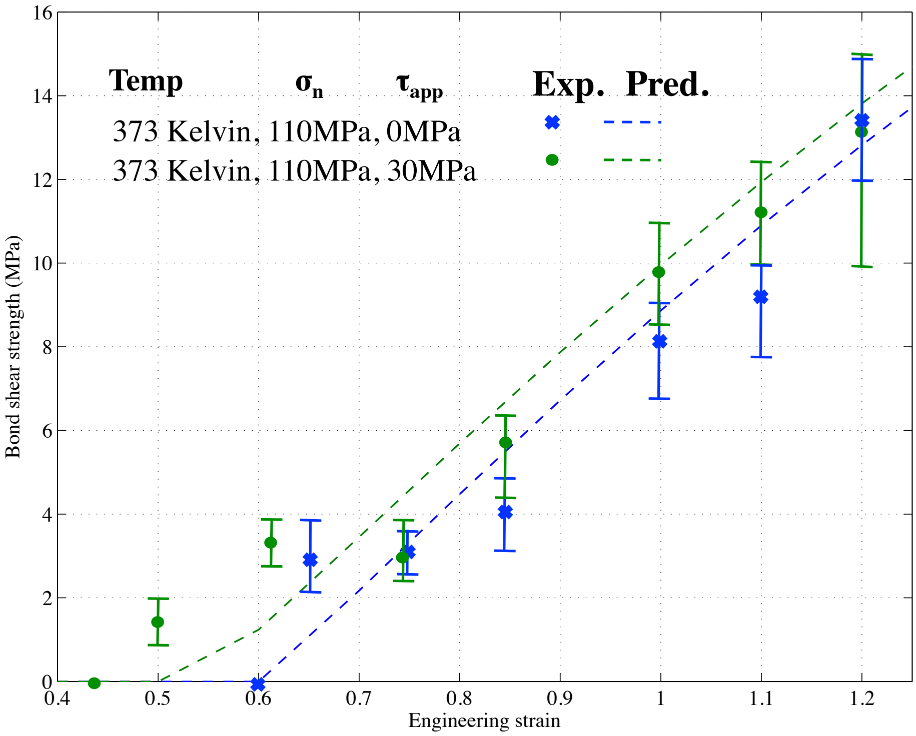
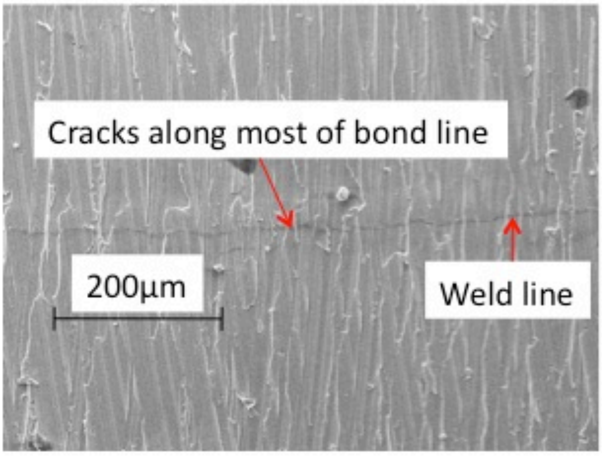


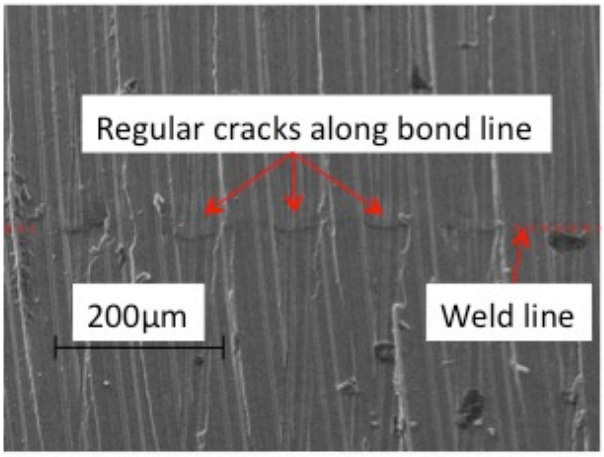
Figure 5.28: Effect of interfacial shear at different temperatures on the bond shear strength

5.5.5 Microscopy results

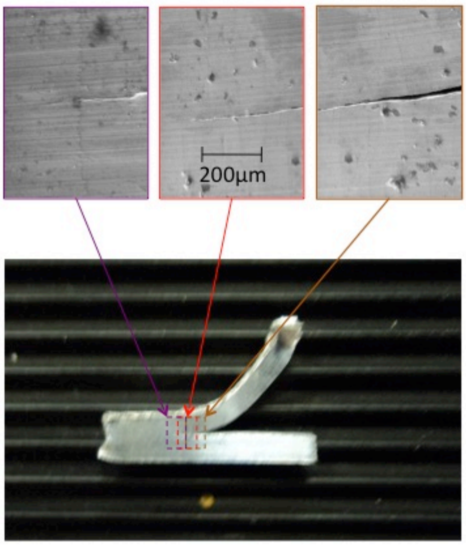
As an additional measure of weld quality, alongside bond strength, microscopy images were taken of welds produced at different temperatures. Figure 5.29 presents SEM images of welded samples' cross-sections (showing the weld line between the two samples). Figure 5.29a shows the cross-section of a sample created at 373K. The weld line is clearly visible with only small regions where the interface line disappears. Figure 5.29b shows a bond created at 423K. Approximately half of the interface is not visible, with intermittent 50μm long cracks spaced along the weld line. Figure 5.29c presents the cross-section of a weld created at 473K. The weld line could not be found by scanning the cross-section alone, so a peel test was partially performed, cracking some of the weld. The left hand image of Figure 5.29c shows that no weld line can be seen, indicating very good bonding.



(a)



(b)



(c)

Figure 5.29: Cross-sections. σ_n=110MPa, ε=0.8, T= (a)373K, (b)423K, (c)473K

Figure 5.29 shows that, as expected, the bond line becomes less visible for stronger welds created at higher temperatures. In addition, Figure 5.29b presents evidence of the film theory of bonding; the presence of regular cracks is consistent with the existence of unbonded oxide islands along the welded interface. The regular cracks are more easily seen when looking at a polished specimen under an optical microscope. An example is shown in Figure 5.30.

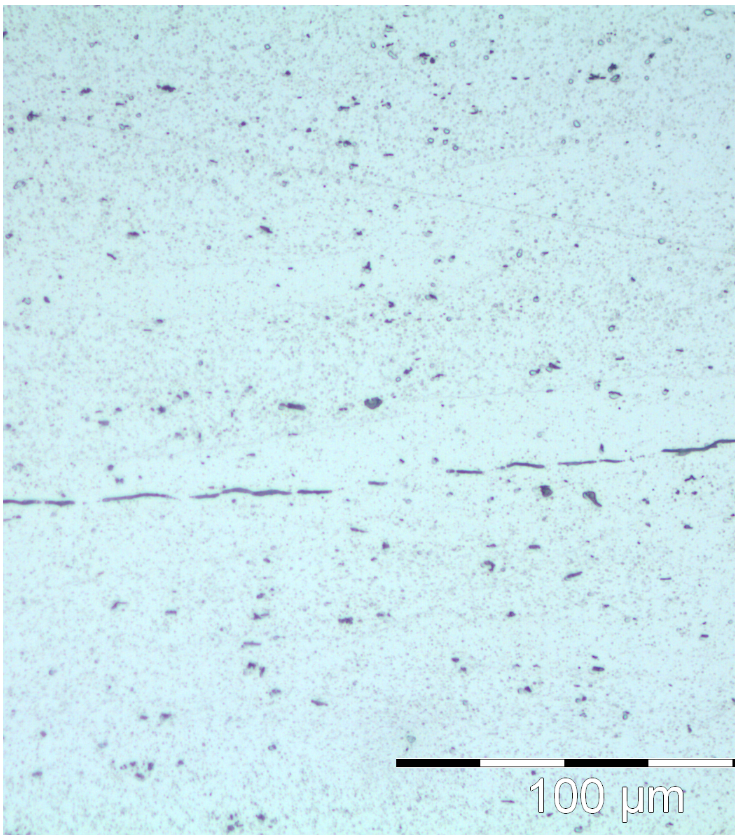


Figure 5.30: Cross-section of welded interface created at 423K (σ_n=110MPa, ε=0.8)

5.6 Discussion

In this work a new model of bonding strength is presented which, building on the well-known work by Bay (1983), takes account of all the relevant deformation parameters in bond formation. An experiment was designed and built that successfully decouples the application of the relevant parameters. Over 150 tests were conducted to evaluate the model and investigate the effect of each deformation parameter on the weld strength.

The experiments have established the basic relationships between deformation parameters and weld strength, of which it is important for engineers to be aware when considering solid-state fabrication, forming and recycling processes. The relationships are as follows: (1) An aluminium interface must be stretched by a threshold strain for it to weld. (2) Increasing the normal contact stress, temperature, or shear stress decreases the threshold strain and increases the strength of any welds. (3) Normal contact stresses above the yield strength of the material are necessary to create strong bonds. This is most likely due to a higher normal contact stress increasing the real contact area and micro-extruding more substrate aluminium through cracks in the oxide layers. (4) Increases in strain rate have little influence on the bond strength at low temperatures, but significantly decreases the bond strength at temperatures over 423K. (5) The weld strength is very sensitive to temperature. For example, for a bond created with an interface strain of 80% and normal contact stress of 110MPa an increase in temperature from 298K to 473K corresponds to a shear strength increase from 1.3MPa to 12.5MPa.

A key reason for conducting solid-state recycling research is the potential to reduce energy use. The dependence on a high temperature to create a strong bond conflicts with the aim of minimizing energy use. However, over a third of the energy required to melt aluminium is the latent heat of melting, not the energy to heat the material to its melting point. Even high temperature solid-state processing of scrap could, therefore, save energy compared to conventional recycling.

The proposed model correctly predicts the experimental trends. Evidence for the film theory of bonding (used to derive the proposed model) can be evaluated using microscopy analysis. Figure 5.30 shows the cross-section of a weld with welded zones interspersed with cracks 2 to 10μm long. The film theory of bonding suggests that these cracks are either the oxide fragments that remain along the weld line after the interface is stretched, or that they are due to the bonding process failing to establish close contact between the surfaces in these regions. Equation 5.6 in the model derivation predicts an oxide fragment length of approximately 140nm; therefore, the 2 to 10μm long cracks in Figure 5.30 are more likely to be due to the absence of close contact between the two surfaces in these regions. Transmission electron microscopy of roll bonded AA1050 foil by Barlow et al. (2004) suggests that, at a finer length scale than observable with optical microscopy, the regions of good bonding shown in Figure 5.30 are likely to resemble that of Figure 5.31, with perfect bonding obtained between islands of oxide fragments between 40 and 200nm in length. The fragment length predicted by equation 5.6 is within the range of observed fragment lengths in Figure 5.31, suggesting that the mechanisms assumed in the proposed model (based on the film theory of bonding) are valid.

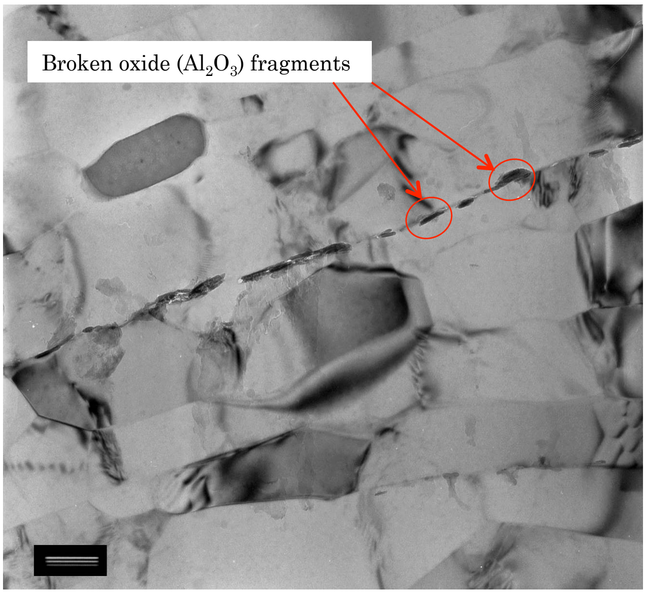


Figure 5.31: TEM micrograph showing dispersion of Al_2O_3 fragments in a matrix of roll bonded AA1050 aluminium foil (Barlow et al., 2004). Scale bar is 0.2 μm. Rolling direction ↔.

For temperatures up to 423K predictions from the model typically lie within the experimental error range. However, the agreement between the two gets worse at higher temperatures. Figure 5.26 shows that predicted weld strengths are consistently too low at high temperatures, and Figure 5.27 shows that the influence of strain rate at higher temperatures is underestimated. These results imply that diffusion plays a significant role at higher temperatures. Doubling the strain rate halves the process time, and results in a 30% decrease in diffusion distance by equation 5.14 (Callister, 1999).

$$x \propto \sqrt{Dt} \qquad (5.14)$$

Where x is the characteristic diffusion distance, t is time, and D is the diffusion coefficient. Consistent with diffusion being important to bonding at higher temperatures, Figure 5.27 shows an average 35% and 25% drop in shear strength when the strain rate is doubled at 423K and 473K respectively. Aluminium and its oxide are mutually insoluble; therefore, diffusion is unlikely to create contact between substrate aluminium, but may act to decrease the surface mismatch and improve the quality of the weld once contact has been made.

In these experiments the maximum strain was limited by the onset of unstable necking. The strain rates were also very low because of the low maximum crosshead velocity. It would be worthwhile conducting similar roll bonding experiments, which would cause large friction hills to be developed between the sheets, but would allow high strain and strain rates to be tested. A back-tension could be applied to the sheets to decouple the normal contact stress and strain, and independent control of the rolls' speeds could produce shearing at the interface.

5.6.1 Comparison of the new model to Bay's model

The new model presented in this work (equation 5.13) builds on the work of Bay (1983), whose model of weld strength in accumulative roll bonding (equation 2.3) was reviewed in section 2.3.3. In order to compare the two models, Figure 5.32 presents weld strengths predicted from both models and measured weld strengths from the Set A experiments. Bay's model assumes that aluminium surfaces consist of an oxide film covering a fraction, ψ, and a brittle cover-layer of work-hardened aluminium, created by scratch brushing, covering the remaining area. As no scratch brushing took place in this work's experiments ψ is taken as equal to one for the sake of constructing Figure 5.32.

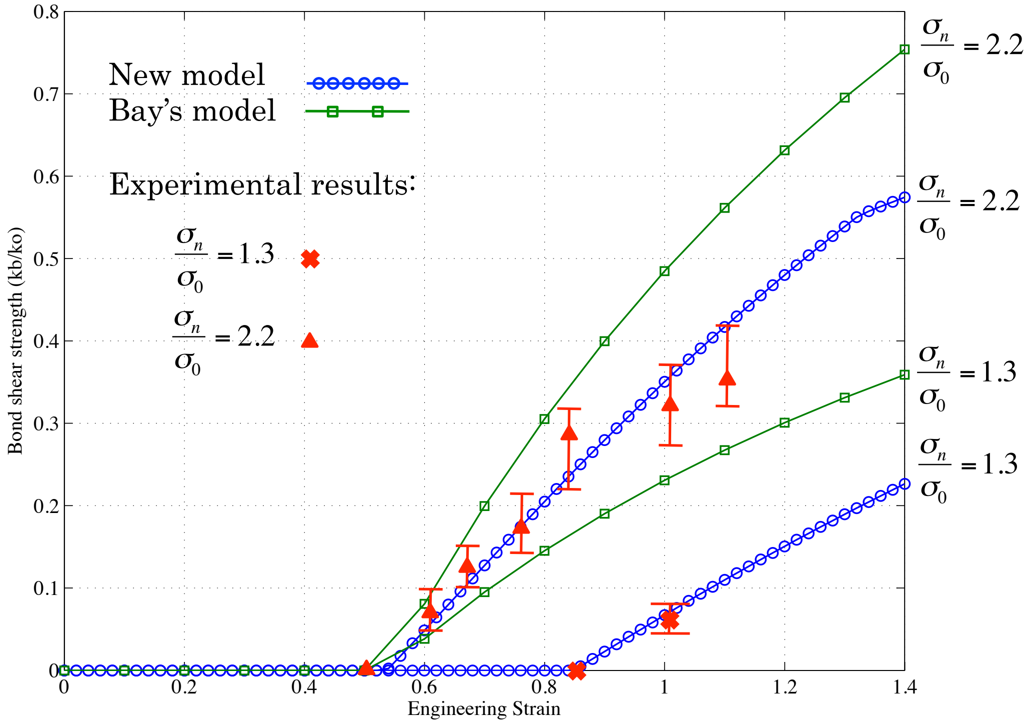


Figure 5.32: Comparison between new model (equation 5.13) and Bay's model (equation 2.3) for bonding experiments at 373K (no shear)

Figure 5.32 shows that the new model is better at predicting the strength of solid-state welds than Bay's model. Bay's model assumes a constant threshold strain before the onset of welding, whereas the new model calculates threshold strain as a function of the temperature and normal contact stress, resulting in a variable threshold strain. The new model predicts a shallower rise in bond strength (with increasing strain) than Bay's model. This is mainly because the calculated value of the pressure that is required to micro-extrude the substrate aluminium through the cracks in the oxide layer is higher in the new model than Bay's model. This is due to the new model accounting for the fragmentation of the oxide layer, resulting in islands of oxide (as shown in Figure 5.33a). In contrast, although Bay's model estimates the total area of exposed aluminium substrate, inherent in his calculation of the micro-extrusion pressure is an assumption that all the exposed aluminium is grouped together (as shown in Figure 5.33b), resulting in a relatively low micro-extrusion pressure being calculated.

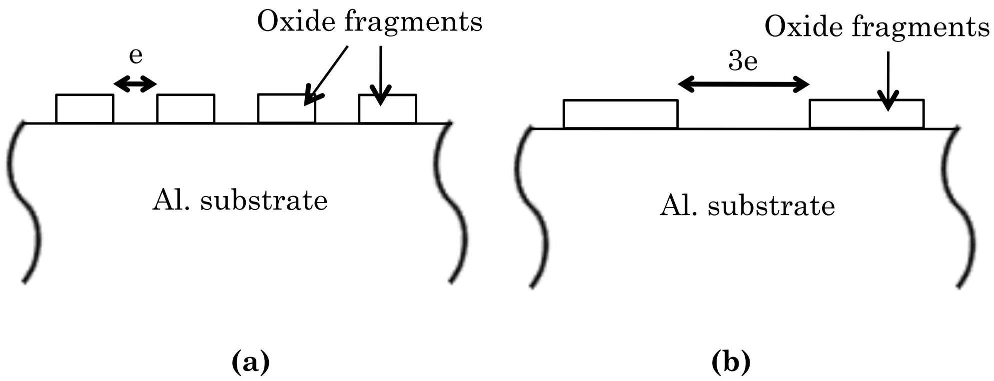


Figure 5.33: (a) Fragmentation of the surface layer in the new model (b) fragmentation of the surface layer in Bay's model

Physical evidence for oxide fragmentation, of the type shown in Figure 5.33a, was presented in the TEM image in Figure 5.31, which shows fragments of aluminium oxide dispersed along a AA1050 roll bonded weld line.

5.6.2 Relevance of the new model to chip extrusion

The new model presented in equation 5.13 could be used to predict the strength of profiles produced from extruding compacted aluminium machining chips. A possible method would be to model the compaction of the porous chip billet into a fully dense solid and then use finite element analysis to determine the five deformation parameters—relevant to the new model—along streamlines of fully dense metal. The profile strength could then be estimated by aggregating the results from the model across multiple streamlines.

Before extensive bonding of the chips can take place they must be compacted by the extrusion ram, increasing the density of the chip billet. The chip billet porosity and yielding behaviour, as a function of hydrostatic and deviatoric stresses, could be determined by compacting aluminium chips and measuring force-displacement curves under different stress states, as described by Hellier (2013).

Fully compacted chips could then be analysed as a solid billet. Finite element analysis of solid billet extrusion can determine the deformation conditions along streamlines of solid metal flowing through the extrusion die, as shown in Figure 5.34.

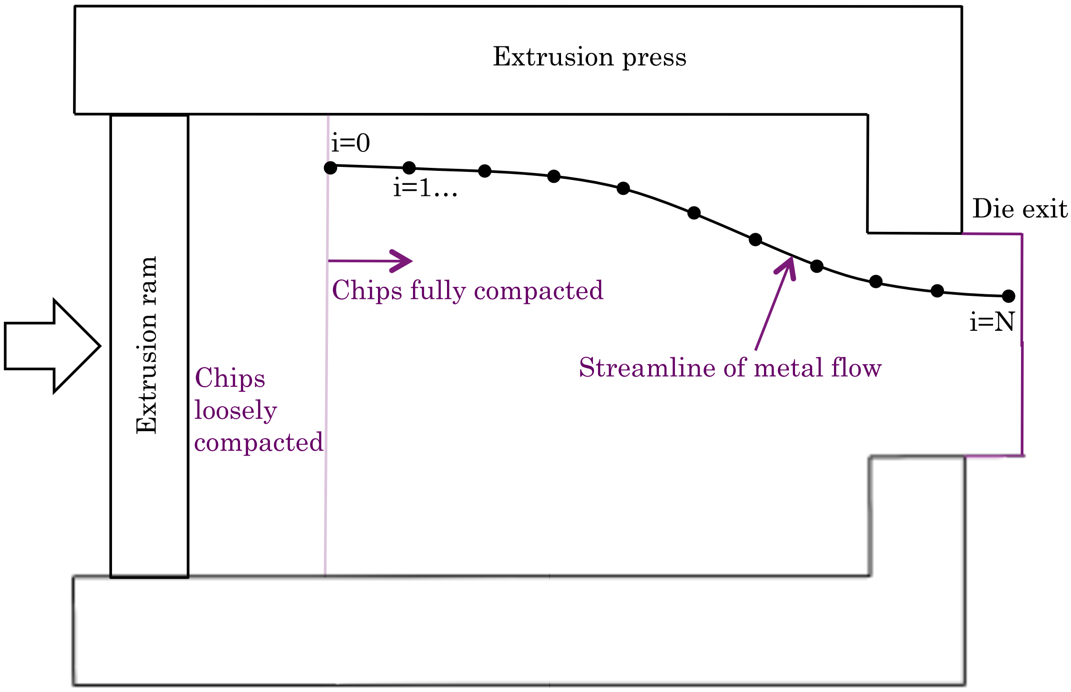


Figure 5.34: Streamline of fully compacted chips extruded through an extrusion die

Equation 5.13 (the new model) could be evaluated at a number of points along the streamline, with the final bond strength equal to the maximum bond strength calculated at any of the points, as shown in equation 5.14.

$$\tau_{streamline} = \max\left(\tau_b(i)\right) \tag{5.14}$$

Averaging the results across several streamlines would provide a prediction of profile strength. This modeling could help optimize the chip extrusion process and minimize the technical barriers (imperfect bonding and a blistered surface finish) that have so far hampered industrial application of chip extrusion.

6 Conclusions and further work

This thesis has investigated the reuse of steel and aluminium without melting, structuring technical opportunities for, and barriers against, reuse worldwide, and developing technical contributions that might help reuse become widespread. This chapter summarises the contributions in this thesis to the knowledge on reusing steel and aluminium without melting (section 6.1) and then outlines some further work (section 6.2).

6.1 Contributions in this thesis

The motivation for this thesis is the potential for reuse to become a major carbon dioxide abatement strategy for the steel and aluminium industries. Given the wide scope of this topic, the three areas within reuse identified in Chapter 1 (component reuse, product life extension and reuse of manufacturing scrap) and the literature reviews presented in Chapter 2 are themselves contributions to understanding such a vast topic.

Chapter 3 presents two new frameworks with which to analyse reuse: the first defines a hierarchy of technical strategies for reusing metal, and the second structures the physical barriers that constrain reuse. These frameworks can help businesses and organizations that wish to reduce the carbon emissions associated with their metal use and can help to inform policy makers of where reuse may have the largest impact. The results on the global potential of reuse suggest that approximately 30% of steel and aluminium could be reused, far short of the 92% calculated by Allwood et al. (2010) as necessary for reuse alone to halve emissions in the steel industry by 2050. Therefore, other material efficiency strategies (light-weighting products and improving manufacturing yields) should be pursued concurrently with reuse to help meet the IPCC's target.

In Chapter 3 a global assessment of steel and aluminium end-use is presented. Previously, global analyses of metal end-use have only presented the destinations of intermediate metal products at a sector level, rather than attributing demand to final products. The global assessment is used to create a catalogue of product descriptions. Together, the global assessment and catalogue have provided a valuable archive, which has proved helpful to other researchers. For example, they were used in mapping a global flow of steel (Cullen et al., 2012) and aluminium (Cullen and Allwood, 2013) from liquid metal to end-use products, and in estimating future material efficiency limits (Milford et al., 2013; Allwood et al., 2012).

Chapter 4 shows how products are often replaced because a component/sub-assembly becomes *degraded*, *inferior*, *unsuitable* or *worthless*, with the majority of steel components underexploited, that is to say, they are still functioning when the product is discarded. It is found that a product template in which the long-lived structure accounts for a relatively high share of costs while short-lived components can be easily replaced (offering profit to the producer and enhanced utility to owners) encourages product life extension.

Solid-state bonding of aluminium chips in an extrusion process presents an opportunity to reuse aluminium scrap. In Chapter 5 a new model of solid-state bond strength is presented. A new experiment is designed with which to evaluate the model, successfully decoupling the application of different deformation parameters. The experiments establish the basic relationships between deformation parameters and bond strength, which can aid engineers when considering solid-state fabrication, forming and recycling processes. The proposed model correctly predicts the experimental trends and could be used as an indicator of solid-state bond strength in chip extrusion and other solid-state welding processes.

6.2 Further work

Several opportunities for further research have emerged from the work in this thesis. These are outlined in the sub-sections below.

6.2.1 Component reuse

Two areas for further technical research have been identified in this area: development of a cheap method to identify and certify the properties of reclaimed structural steel; and development of reusable pre-cast reinforced concrete, facilitating reuse of both the concrete and steel reinforcement.

The reuse of structural steel is currently limited due to the uncertainty of the reclaimed steel's properties. If an accurate and affordable testing method could be devised it would maximize the value of the steel and the carbon savings associated with reuse. As discussed in section 3.3.1, for a given batch of reclaimed beams, a combination of portable hardness testing—using Tekkaya's (2000) method of converting to a yield stress—and a small number of coupon tests may provide a satisfactory degree of confidence in the steel's properties. There is, therefore, potential for a EU or UK specific project to develop a test methodology that meets the statistical certainty required for certification from either British Standards or European CE marking. If a cheap, certified test could be developed it would not only maximize the environmental benefit of any structural steel that is reused, but would also encourage greater reclamation because certification would increase the reclaimed steel's value.

Further research could develop reusable pre-cast concrete systems to replace in-situ concrete. For example, floor systems in multi-storey buildings are usually composite floors consisting of steel decking covered with in-situ reinforced concrete, as shown in Figure 6.1a. The bond between the concrete and steel is strong enough that the two materials act compositely together, making this system structurally efficient. However, the strong bond between the concrete and steel makes separating them difficult, reducing the chances of any of the components – including the steel beams – being reused. Pre-cast equivalents exist, comprising of pre-stressed slabs supported on steel beams. However, in-situ concrete is still poured on top of this system to guarantee a secure connection between the slabs, as shown in Figure 6.1b. The development of a practical reversible connection between the pre-stressed slabs and the steel beams could lead to reuse of both the slabs and of the steel beams.

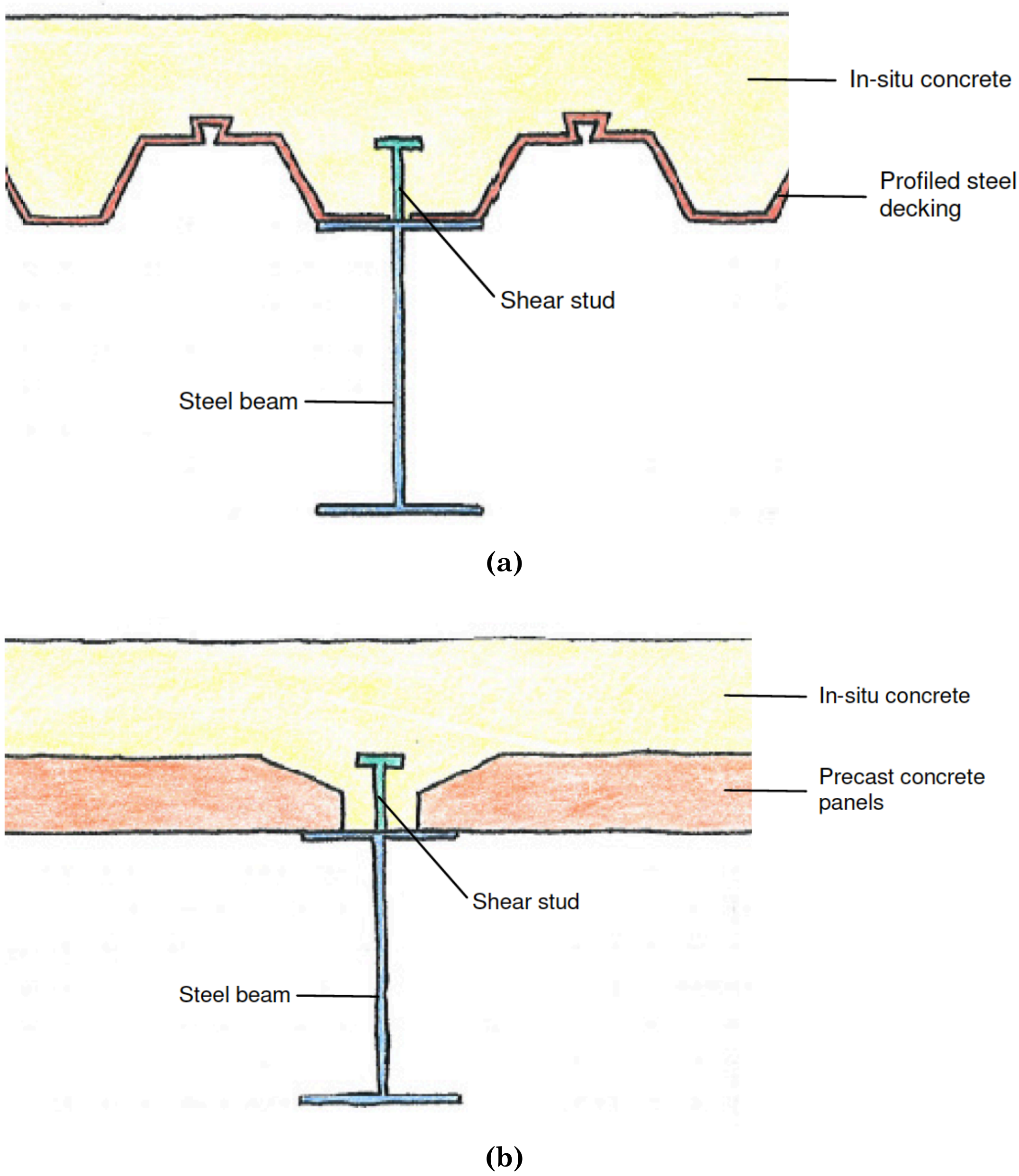


Figure 6.1: (a) Conventional composite floor (b) Pre-cast equivalent (Arup, 2010)

6.2.2 Exploiting the lifespan of steel and aluminium

In Chapter 4 a discarded functioning product is described as "under-exploited". It is under-exploited because it could provide more services to the owner (in the way of transportation, shelter etc.) if it continued being used. Further research could examine the impact of the intensity with which we use products (the **loadings**—power output of an engine, weight on a bridge, people in an office—and the **frequency** of use—hours per day, miles per year etc.) on both the product lifespan and the total level of service derived from the product. Exploring these interactions could inform behavioural options to reduce the demand for liquid metal.

For example, Figure 6.2 presents the total service output provided by a car, in thousands of passenger-miles, as hyperbolic contours on a chart of the vehicle lifespan (x-axis) against the intensity of use, passenger miles per year (y-axis). In the UK, the average number of passengers in a car is 1.6 and cars are driven for an average of approximately 10,000 miles per year for 13 years before physical (degraded) failure of the engine (Allwood et al., 2011) .

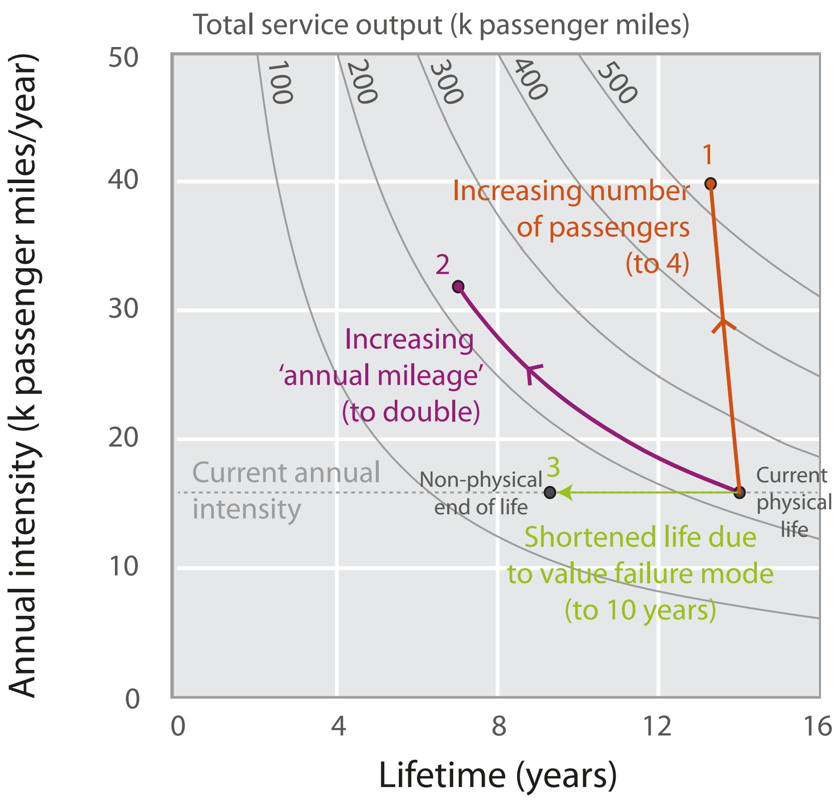


Figure 6.2: Total service output (passenger-miles) for a car.

Figure 6.2 shows that increasing the average passenger loading from 1.6 to 4 (orange line) makes little difference to the physical life of the car (because the car weighs more than the passengers) but more than doubles the service output. Doubling the annual mileage (pink line) halves the physical life of the car because the engine wears out twice as fast, therefore the service output remains the same. Finally, a reduced lifespan from 13 years to 10 years with no change in intensity of use (for example, due to an accident or as promoted, for example, by the expired UK scrappage scheme) decreases total service output by 30% (the green line). Assuming people want services, and not products for their own sake, this approximate analysis suggests that car sharing schemes (represented by the orange line) could reduce the demand for cars and therefore save liquid metal.

6.2.3 Reuse of manufacturing scrap

Two areas for further research have been identified in this area: investigation of the role of diffusion in increasing the weld strength in high temperature, high strain rate solid-state welding processes; and assessment of reusing large sheet blanking scrap from manufacturing processes.

Further work could include investigating the role of diffusion in solid-state welding processes, and adapting the new model of weld strength presented in Chapter 5 (equation 5.13) to take account of these findings. It was discussed in section 5.6 that at high temperatures the new model not only underestimates weld strengths but also the effect of increasing the strain rate on decreasing the weld strength. These results imply that diffusion plays a significant role at higher temperatures. Diffusion distances are predominantly a function of the material, temperature and process time. In light of this, a sensible series of tests to assess the significance of diffusion in solid-state welding would be to vary the process time and temperature in otherwise identical bonding experiments, and then to compare the strengths of the resulting welds.

Further work could include an assessment of reusing steel and aluminium blanking scrap. This opportunity was identified in section 1.4.1; Abbey Steel is a company that buys process scrap from the automotive industry and resells it as blanks to manufacturers of smaller components. This activity is currently constrained because manufacturers tend to chop up their large blanking skeletons into smaller pieces for ease of handling (Corus Automotive, 2010). This could be avoided, however, by changing scrap handling systems. Mapping the shapes and sizes of blanks and skeletons in different industries is required to identify in which situations the skeleton scrap from one manufacturer could be reused as smaller blanks for another. Allwood (2011), in an assessment of the steel and aluminium industries in a low carbon future, suggests that such mapping could take the form of Figure 6.3. Robust manufacturing data must be collected and collated in order to draw Figure 6.3 accurately and to elucidate significant opportunities for reuse. This activity would be a good starting point for future research in this area.

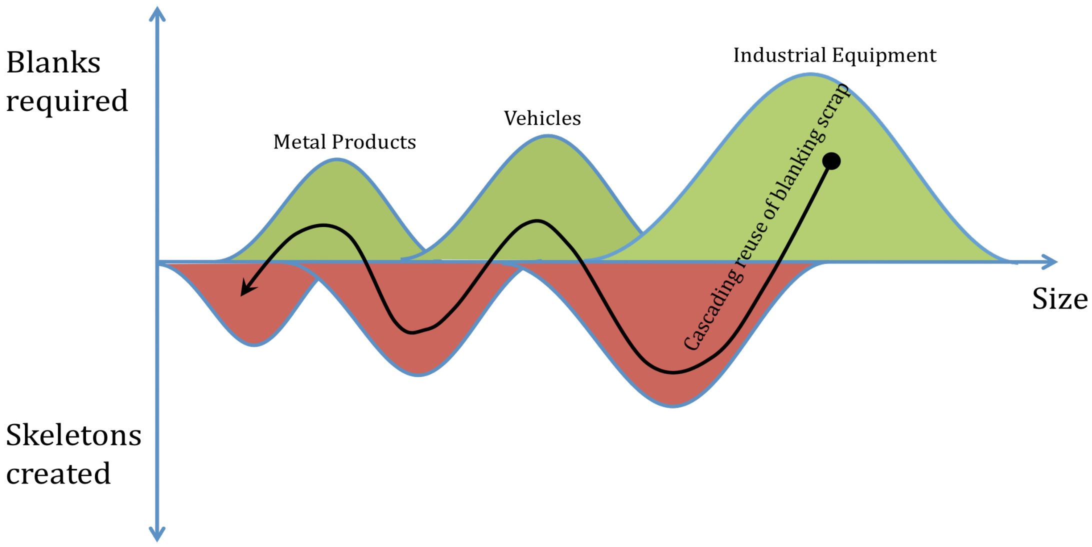


Figure 6.3: Form of schematic map of blank and skeleton sizes (Allwood, 2011)

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Appendix A: In which final products is steel and aluminium used?

This section summarizes the methodology and data sources used to estimate the final products in which steel and aluminium is used. To simplify clustering of products across both metals this work uses 4 product groups: transport; construction (including buildings and infrastructure); industrial equipment (including mechanical and electrical equipment); metal products (containing packaging, consumer durables and miscellaneous metal goods).

The only top-down analyses with a global scope are the World Steel Association (WSA, 2009) and the International Aluminium Institute (IAI, 2008). These top-down estimates are summarised in Table A.1 and Table A.2, with average forming yields taken as 86% for steel (Wang et al., 2007) and 73% for aluminium (IAI, 2008), and fabrication yield losses taken from Hatayama et al. (2010) for steel and IAI (2008) for aluminium.

Sector	Intermediate (%)	Fabrication yield (%)	End use (%)
Construction	50	94	52
Automotive	12	81	11
Other transport (inc. shipping)	3	81	3
Mechanical machinery	14	86	13
Metal products	14	95	15
Electrical equipment	3	81	3
Domestic appliances	4	95	4
1330Mt liquid production	1145Mt intermediate products		1040Mt end use products

Table A.1: Global top-down estimates of steel use

Sector	Intermediate (%)	Fabrication yield (%)	End use (%)
Construction	22	90	24
Transport (Auto & light truck)	17	84	18
Transport (truck, bus, marine, rail)	9	80	9
Other transport (Aerospace etc.)	1	60	Negligible
Machinery & equipment	8	75	7
Packaging – cans	8	75	7
Packaging - foil	7	75	6
Consumer durables	7	80	7
Electrical – cable	8	90	9
Electrical – other	5	80	5
Other (ex. destructive uses)	4	80	4
Other (inc. destructive uses)	4	80	4
73Mt liquid metal production	53Mt intermediate products		45Mt end use products

Table A.2: Global top-down estimates of aluminium use

The rest of this appendix summarises the data sources and methods used to increase the resolution of these global top-down analyses to final products.

Transport

Table A.1 and Table A.2 present global top-down estimates of metal use in transport: 141Mt (14%) of steel comprising of 113Mt in *automotive applications* and 28Mt in *other transport*; 12.2Mt (27%) of aluminium comprising of 8Mt in *cars and light trucks*, 4Mt in *trucks, busses, marine applications and rolling stock*, and negligible use in *other transport*. Bottom-up studies and scaling of regional data were used to improve the resolution of this data to final products, as reported below.

Global bottom-up analyses were performed for cars, light trucks, heavy trucks, and buses. Production statistics for each product were multiplied by data on product composition to calculate the metal intensity of each product type. Production statistics for these products are presented by the *Organisation Internationale des Constructeurs d'Automobiles (*OICA, 2007), who represent all major automobile manufacturing countries. Average product composition data is available for the metal content in cars (steel: MCI, 2011; aluminium: Bertram et al., 2009), light trucks (steel: MCI, 2011; aluminium: US Department of Energy, 2007), heavy trucks (steel: MCI, 2011; aluminium: Cullen et al., 2011) and buses (steel: MCI, 2011; aluminium: Cullen et al., 2011).

No reliable production statistics were found on the manufacture of rolling stock. Regional studies on aluminium use in China (Wang et al., 2010) and Connecticut (Recalde et al., 2008), however, suggest that only a negligible amount of aluminium production is destined to rail applications (<<1%). In the absence of more robust data these studies have been taken as representative of world aluminium use in rolling stock. For steel, the *Japanese Iron and Steel Institute* (JISF, 2007) reports that less than 0.1% of steel used in Japan is used in rolling stock. When scaled using steel production statistics to the global level this implies that the amount of steel used in rolling stock is negligible.

A global bottom-up estimate of aluminium used in aircraft was calculated using production statistics from Boeing (2010) and Airbus (2009) and product composition data from IAI (2011), finding that 0.02Mt of aluminium (<<1%) was used in commercial aircraft in 2008.

In order to estimate the global quantity of steel used in shipping, European top-down data on steel use in shipping (Eurofer, 2009) was combined with European ship production statistics (BRS, 2013). An average steel content per shipping gross tonnage was calculated from this data. This was scaled using global ship production statistics (BRS, 2013) to calculate a total of 31Mt. This is 3Mt higher than the top-down estimate for *Other transport* presented in Table A.1. Given that the fabrication yield in shipping is likely to be higher than the 81% transport average used in Table A.1 (as ship plate is typically just cut into rectangles), 31Mt is a reasonable estimate.

No analyses on aluminium used in shipping were found. However, the IAI (2008b) report that aluminium is almost exclusively used in the superstructure of cruise ships and hulls of yachts and car and passenger ferries. There have been approximately ten newly-built cruise ships every year since 2001, all at 100,000te or greater, and made mostly from aluminium. Therefore, approximately 1Mt of aluminium is used in cruise ships each year. A regional study on aluminium use in Connecticut (Recalde et al., 2008) suggests that 4% of aluminium production is destined for marine applications (which would scale to 1.8Mt globally). As aluminium is used in car and passenger ferries as well as cruise ships, 1.8Mt, in the absence of more robust data, is a reasonable global estimate.

	Steel (Mt)	Aluminium (Mt)
Cars & light trucks	70	8.9
Heavy trucks & buses	15	1.9
Ships	31	1.8
Other (Rolling stock, aerospace etc.)	1	0.2
Total Bottom-up	117	12.8
Top-down estimates (Tables 1 and 2)	146	12.2

Table A.3: Summary of transport breakdown bottom-up estimates

The top-down and bottom-up estimates presented in Table A.3 are consistent for aluminium (less than 5% error). However, there is a discrepancy of 20% for steel, originating with the discrepancy for automobiles (113Mt top-down estimate vs 70Mt bottom-up estimate). It is likely the real figure is somewhere in between, as the top-down estimate assumes a relatively high yield for car manufacture (81%), when the fabrication of the steel bodywork on cars (accounting for over 30% of the mass) can have a yield as low as 50% (Corus Automotive, 2010). On the other hand, the bottom-up estimate does not account for any military production, which may be significant. Therefore, an average of the bottom-up and top-down estimates (131Mt) is used in the final product allocation, shown in Table A.4.

	Steel (Mt)	Aluminium (Mt)
Cars & light trucks	70	8.9
Heavy trucks & buses	15	1.9
Ships	31	1.8
Other (Military, rolling stock, aerospace etc.)	15	0.2
Total	131	12.8

Table A.4: Steel and aluminium use in transport (final allocation)

Construction

Table A.1 and Table A.2 present global top-down estimates of metal use in construction: 540Mt of steel and 10.8Mt of aluminium per annum. Construction includes both buildings—structures to provide shelter—and infrastructure—supply and communication networks.

Five groups of products dominate steel use in construction. These are structural steel, reinforcement steel, sheet (cladding, floor decking, sheet piling, cold formed sections), tube (linepipe, structural, non-structural and conduits for air or gas flow), and rail track (Ley, 2003; Wang et al., 2007). Aluminium used in construction is dominated by building use, with window and door frames, curtain walling (commercial building glass facades) and cladding the dominant users of aluminium (American Aluminium Association, 2007).

Many of the steel products used in construction are produced as intermediate products, which are cut to length by the fabricator (for example, rail track). The fabrication yields for such products are consistently high (>90%); therefore, global top-down estimates are likely to be accurate. However, smaller volumes of these products are fabricated from more generic intermediate products (for example, structural steel welded together from plate). Therefore, World Steel Association (WSA, 2009) top-down estimates (of production of structural steel or reinforcing bar) were augmented with estimates scaled from regional studies. Hatayama et al.'s 94% fabrication yield in construction was used throughout.

Structural steel is produced as a hot rolled intermediate product and is also fabricated by welding together steel plate. WSA (2009) record global production statistics for heavy and light sections. Applying a 94% yield ratio to these values provides an initial estimate of structural steel use. In an integrated top-down and bottom-up study of steel flow in UK construction, Moynihan and Allwood (2012) find that 5% of heavy sections are fabricated from welded plate. Therefore, the figure calculated from the WSA data was increased by 5%. Moynihan and Allwood (2012) also report that 10% of the mass of a steel framed construction is connections (nuts, bolts and fin plates), accounting for additional constructional steel.

Reinforcing bar is produced as a hot rolled intermediate product (recorded by WSA, 2009) and is also fabricated from wire rod. Production of wire rod is also recorded by WSA (2009) and contact with a major UK wire rod producer indicates that 50% of wire rod is fabricated into reinforcement steel (Howells, 2010). In the absence of more robust data this UK statistic was taken as indicative of the global market. The remaining 50% of wire rod is drawn into wire. Some of this wire is also added to in-situ concrete to add tensile strength. *Bekaert* are a world leading supplier of drawn wire products and 19% of their products are used in construction, largely as reinforcement, but also as cables and fences (Bekaert, 2010). Bekaert's production mix was taken as indicative of the world's drawn wire products.

The integrated top-down and bottom-up analysis on construction by Moynihan and Allwood (2012) presents a breakdown of final construction products in which steel tube is used, reporting that 11% of steel in construction is tube. The largest single end-use product is large diameter linepipe. Moynihan and Allwood's statistics were used in this analysis.

The World Steel Association publishes statistics on rail track production (WSA, 2009). The final amount of steel used in rails was calculated as this value multiplied by the 94% fabrication yield from Hatayama et al. (2010).

The total quantity of sheet used in construction is calculated using a mass balance (total steel in construction minus total steel in structural steel, reinforcement steel, tube and rail track). In construction, sheet is used for cold-formed sections, cladding, metal decking for composite floors, and sheet piling. The flow of steel into each of these products was taken from Moynihan and Allwood (2012).

Tonnages of each product were allocated to 'buildings' or 'infrastructure' according to regional data which, in the absence of more robust data, is taken as indicative of worldwide metal use. The allocation of structural sections is taken from the *European Convention on Constructional Steelwork* (ECCS, 2008). No global, regional or even national data exists on the relative use of reinforcement steel in buildings and infrastructure. However, cement use is taken as a proxy for rebar consumption and so data is combined on cement use from the UK (MPA, 2008), USA (PCA, 2011) and Turkey (Akcansa, 2012), and used to assign tonnages to buildings and infrastructure. The allocation of connections was proportional to the allocation of sections, the allocation of sheet and tube was taken from Moynihan and Allwood (2012), and drawn wire was assigned equally to both buildings and infrastructure.

The final allocation of steel products in construction is shown in Table A.5.

	Buildings (Mt)	Infrastructure (Mt)	Total (Mt)
Sections	61	20	81
Connections	6	2	8
Rebar	110	98	208
Drawn wire	7	7	14
Sheet	152	6	160
Tube	27	33	60
Rail track	0	10	10
Total	363Mt (67%)	176Mt (33%)	540Mt

Table A.5: Steel use in construction (final allocation)

No global statistics on aluminium products in construction were found. However, the American Aluminium Association provides a breakdown of aluminium use in construction in the USA and Canada (American Aluminium Association, 2007). In the absence of more robust data this has been scaled to a global level, shown in Table A.6. Scaling data from one region like this inevitably introduces errors. However, the results presented in Table A.6 show that aluminium use in construction is dominated by extrusions in glass frames (window and door frames and curtain facades) and sheet cladding. Therefore, even if the scaled worldwide allocations are inaccurate it is likely that the dominant aluminium products used in North American construction are representative at a global level.

	American Breakdown (%)	Scaled worldwide tonnages (Mt)	Shape
Windows & door frames	33	3.5	>85% extrusions
Curtain walls & facades	19	2	>90% extrusions
Cladding	23	2.5	All sheet and plate
Other (Mainly gutters and spouts)	25	2.5	Mainly sheet and plate

Table A.6: Aluminium use in construction—all in buildings (final allocation)

Industrial Equipment

Table A.1 and Table A.2 present global top-down estimates of metal use in industrial equipment: 166Mt (16%) of steel (consisting of 135Mt in *mechanical equipment* and 31Mt in *electrical equipment*) and 9.5Mt (23%) of aluminium (consisting of 3.2Mt in *mechanical equipment,* 4Mt in *electrical cable* and 2.3Mt in *other electrical equipment*).

Steel is used in a plethora of 'mechanical machinery' products. No reliable statistics were found that assigned steel to specific products. This is a well known problem when allocating data for machine parts, also reported by authors such as Recalde et al. (2008). It was decided that the best of way of sourcing information on the reusability of components in this sector was to conduct a case study. A product description on rolling mills was produced, and interviews conducted with a mechanical machinery design company (Siemens VAI).

Similarly, for aluminium, no global production analyses could be found on its use in mechanical machinery. However, Wang and Graedel (2010) provide Chinese in-use stock estimates of 35 aluminium products across manufacturing equipment, agricultural equipment and construction equipment. Production statistics were calculated from Wang and Graedel's (2010) study. This required calculation of the annual replacement demand to replenish current stock levels. This was then added to the annual new demand required for Chinese stocks to continue growing at the calculated rate. Such an analysis was possible because Wang and Graedel provide lifespan estimates for the products (allowing an estimation of replacement demand) and stock data for both 2000 and 2005 (allowing an estimate of the new demand as stock levels increased). For full details on these calculations please refer to the supporting information accompanying the journal article, Cooper and Allwood (2012). Analysis on the Chinese aluminium stock data showed that manufacturing equipment accounted for 90% of the aluminium used in mechanical machinery. Of this 90%, most was attributed to ordinary workshop machinery (lathes and pillar drills etc.) or to use in petrochemical industries, most likely to be used in heat exchangers etc.

Discussions with the UKs National Grid (National Grid, 2010) produced the following list of key metal intensive products in electrical equipment: steel pylons (steel), steel reinforced cables (steel and aluminium), transformers (electrical steel and aluminium), busbars (aluminium), and conduits (aluminium).

For aluminium, 2.3Mt is used in electrical applications other than electric cables. This is split between transformers, busbars and conduits.

The quantity of steel used in aluminium-clad-steel-reinforced (ACSR) electric cables can be calculated by multiplying the known quantity of aluminium used in these cables (4Mt) by both the ratio of steel to aluminium densities (3:1) and by the average ratio of steel to aluminium cross-sectional areas in these cables (0.25:1, National Grid, 2010).

Global production statistics for electrical sheet and strip are provided by WSA (2009). Applying a fabrication yield ratio of 81% (Hatayama et al., 2010) results in an estimate of the steel used in transformers and motors. A mass balance on the remaining steel used in electrical equipment is assigned to steel towers and wire sheathing.

Table A.7 presents a summary of final allocations of steel and aluminium to products in the industrial equipment sector.

	Steel (Mt)	Aluminium (Mt)
Mechanical machinery	135	3
Electrical Equipment	31	6
Electrical cables	/	4
Transformers and motors	17	/
Transmission cable reinforcement	2.5	/
Other (steel pylons/wire sheathing etc.)	11.5	N/A
Other (transformers, busbars, conduits)	/	2
Total	166	9

Table A.7: Steel and aluminium use in industrial equipment (final allocation)

Metal Products

Grouping *metal products* and *domestic appliances,* Table A.1 presents a global top-down estimate of 187Mt (19%) of steel used in metal products. Grouping *packaging*, *consumer durables* and *other*, Table A.2 presents a global top-down estimate of 13Mt (28%) of aluminium used in metal products.

Discussions with a major packaging manufacturing (Crown, 2010) produced the following list of steel-intensive packaging products: shipping containers, food cans, aerosols, and drinks cans.

No global production statistics on shipping containers were found. However, the *Japanese Iron and Steel Institute* (JISF, 2007) report that 4% of steel used in Japan, equivalent to 1.4Mt, is used in making containers. 4% is likely to be higher than the global average as Japan is one of the world's major export economies and therefore will manufacture more shipping containers to export its goods than most countries. Therefore, the 1.4Mt used in Japanese shipping containers was scaled using according to world export figures; 8% of the world's exports come from Japan so it is assumed Japan accounts for 8% of the world's shipping container production.

Global bottom-up analyses were performed for steel food cans, aerosols, and drinks cans. Production statistics for each product were multiplied by data on product composition to calculate the metal intensity of each product type. Production statistics for these products are available for food cans (Allwood et al., 2010), aerosols (BAMA, 2011), and drinks cans (BAMA, 2011). Average product composition data is also available for food cans (Crown, 2010), aerosols (Crown, 2010), and drinks cans (Crown, 2010).

The top-down global analysis presented in Table A.2 estimates that 6Mt of aluminium is used in packaging products (3.2Mt in drinks cans, 2.7Mt in foil). The fabrication yield for packaging products is relatively low (<80%). Global bottom-up studies and scaled regional analyses were therefore used to confirm that these top-down estimates are sensible. Regional product production statistics are reported for European drink can production (EAFA, 2011) and European packaging foil production (Alufoil, 2011) . These European figures were scaled to a global level using GDP data from the IMF (2010). The error between the global top-down estimates and the scaled regional estimates is approximately 30%. This was considered a low error considering the method of scaling and therefore the global top-down estimate was used in the final product allocation.

Contact with a leading manufacturer of aluminium packaging (Crown Cork and Seal) established that foil is used in three main products: household foil, semi-rigid 'take-away' containers, and laminated foil drinks and food pouches. Tonnages were not assigned to these end-use products but a product description was written for each.

Table A.1 and Table A.2 present global top-down estimates of metal use in consumer durables: 42Mt (4%) of steel and 3.2Mt (7%) of aluminium. Bottom-up studies are needed to improve the resolution to individual products. Once again, no global production statistics could be found so Wang and Graedel's (2010) study of Chinese in-use stocks was used to calculate production statistics for aluminium used in consumer durables. Wang and Graedel define 25 consumer durable products over three groups of products: household durables (white goods), other household durables, and commercial durables. Analysis of the Chinese aluminium stock data—please refer to Cooper and Allwood's (2012) supporting information for details—reveals aluminium use in consumer durables is dominated by household white goods (60%), with fridge and washing machines accounting for nearly 30% of the total. The only non-white goods that are significant are televisions, accounting for 13% of aluminium that is used in Chinese 'consumer durable' products. In the absence of more robust data these statistics were taken as representative of global aluminium use in consumer durables. Having calculated a global aluminium tonnage allocated to washing machines, televisions and fridges, production data on steel used in these products was calculated using data on their material composition from Truttmann and Rechberger (2006). Scaling data from one region like this inevitably introduces errors. However, the results show that aluminium use in consumer durables is dominated by white goods. Therefore, even if the scaled worldwide allocations are inaccurate it is likely that the dominant aluminium products used in Chinese consumer durables are representative at a global level.

Table A.2 presents a global top-down estimate of aluminium use in sectors defined as 'Other (ex. Destructive uses)' and 'Other (inc. destructive uses)'. Contact with the International Aluminium Institute (Bayliss, 2010) established which products are included in these categories:

- **Other (ex. destructive uses):** mainly lithographic plate, but also includes powder metallurgy applications, paints, and pigments
- **Other (inc. destructive uses):** Mainly aluminium used for the deoxidation of liquid steel, but also includes aluminium used in explosive applications (rocket fuel, fireworks etc.)

A lithographic plate is used to repeatedly print images and text. The total world market volume grew from 390kte in 2002 to 414kte in 2004 (Bayliss, 2010). If this annual growth rate of just over 3% continues, there will be a worldwide demand of 0.47Mt in 2008. This estimate is consistent with company specific figures from Novelis. A third of aluminium production is in rolled products, of which Novelis is a global leader. Just 3% of Novelis' rolled products are lithographic plate (Mayr, 2010), implying approximately 1% (0.45Mt) of total aluminium production per year is used in lithographic plates.

On average approximately one kilogram of aluminium is required to deoxidise every tonne of liquid steel (Ofendenden & Nesterovich, 1958). 1330Mt of liquid steel was produced in 2008 (WSA, 2009), implying 1.3Mt of aluminium was needed to deoxidise the steel.

Table A.8 presents the summary of the analyses on metal products.

	Steel (Mt)	Aluminium (Mt)
Packaging	26	6.5
Shipping containers	16	/
Foil	/	2.5
Drinks cans	1	3
Aerosols	3	0.5
Food cans	6	/
Domestic Appliances	28	3
Fridges	12.5	0.5
Washing machines	8	0.5
TV	2.5	0.5
Other	138	2
Lithographic plate	/	0.5
Steel Deox.	/	1.5
Other (powder metallurgy – paint, pigments etc.)	/	1.5
Total	187	13

Table A.8: Steel and aluminium use in metal products (final allocation)

The allocation of ‘other’ steel products in Table A.8 is calculated using a mass balance. ‘Other’ includes a range of miscellaneous goods, including all commercial durables that are not domestic appliances (baths, chairs, filing cabinets, electric heaters, fax machines, pots and pans, sewing machines, computers, printers, copiers, fax machines, telephone sets etc.)

Appendix B: Catalogue of product design descriptions (abridged version)

Transport example: Steel Ship (Production≈31Mt/yr, 3% Total)

The majority of the world's ships (by tonnage) are of the following varieties[1]: container, cruise, diversified, tanker, dry bulk, and offshore. The top 20 public shipping companies in the world own a combined fleet mass of 472Mt distributed between over 9000 ships[1]. The mass of a typical Very Large Crude Carrier (VLCC) is 30-36 thousand tonnes[1].

Dimensions are typically constrained by economical feasibility and the maximum geometry permitted by the likely sea route (for example: 32.2m widths and 12m drafts are the upper limits determined by the Panama canal, and a maximum height of 40m above waterline is determined by bridges in New York and San Francisco)[2].

The majority of the steel is in the hull, formed from welded steel plates attached to a framework of sections comprised of steel bars (flat, channel, tee and angle)[2]. The description below concentrates on the most used component, steel ship plate.

Ship Plate

Design Constraints: Dimensional consistency and flatness[3], a good combination of high strength, toughness, and weldability[4].

Dimensions[3]: Thickness of 6-20mm, tending thinner. The width is as wide as possible, with demand a main driver for 5m plate rolling mills.

Material: Steel for hull construction is usually mild steel containing 0.15 to 0.23 percent carbon and a reasonably high manganese content[2]. Both sulphur and phosphorous in the steel are kept to a minimum (<0.05%); higher quantities are particularly detrimental to welding[2]. In highly stressed regions of large tankers, container ships and bulk carriers high tensile steels[2] are used, though weldability and fatigue endurance are concerns. Other alloying elements may include boron, copper, and nickel[4].

Coatings: Paints and coatings are often used to prevent ships rusting. Alternatively, cathodic protection on ships is often implemented using galvanic anodes attached to the hull.

Process supply chain of predominant material (Ship Plate)

Steel ship plate is currently only produced from ore, not recycled steel[2]. After the production of the steel, the challenge is to roll the steel thin and flat at maximum width[3]. Thermo-mechanically controlled rolling (TMCR) produces high strength and low temperature properties[5].

Reasons for End of Life[2]

Deterioration of the ship with age causes more costly and frequent repairs, and ultimately the ship is no longer a viable commercial option. Given a favourable scrap price as well, the owner will scrap the ship for demolition, typically in the Far East. Technical obsolescence can also cause the relatively quick scrapping of vessel categories, such as multi deck ships in the late 1960s made obsolete by containerization.

Economics[1] The material accounts for approximately 60% of the total shipbuilding cost, labour 40%. Approximately $150billion was directly invested in shipping in 2007. Many banks and financial institutions value ships at their scrap value after a certain age. A relatively small number of companies own the majority of the worlds shipping. For example, five companies own 55% of the worlds cruise ships. Classification societies (such as Lloyds Register in London) provide assurance to the underwriter against the maritime risk. Approximately 10 large classification societies exist.

Historical development of metal and energy use Airlines cut passenger ships in the 1950s. Aluminium is now commonly used for cruise ships, as the higher specific strength allows a greater height above the water line for a given draft.

Current Reuse[6] One of the largest examples of metallic reuse results from ship dismantling in India. Approximately 50% of the world's discarded ships are broken in India, the majority in Alang, Gujarat. Tilwankar et al's (2008) analysis finds the ship breaking industry contributes 10- 15% of India's steel demand in 2008. Up to 80% of the steel recovered from the vessels is in the form of re-rollable ferrous sheets. These percentages imply reuse of ship plate provided up to 12% of India's steel demand in 2008. The steel is converted (without melting) into flattened plates, bars and rods that are used in the construction sector, offering a 66% emissions saving on conventional recycling.

Current Life Expectancy from Production to Disposal[1] 25-35 years. In 2007, 216 vessels scrapped, average of 27 years for tankers and 32 years for dry cargo vessels (wide spread in each case). There are a few examples of vessels scrapped after 60 or 70 years.

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Construction Example: Steel Sections (Production ≈ 96Mt/yr, 9% Total)

Steel sections are used as both beams and columns in the construction industry, as well as in large machinery applications. Beams are usually referred to as I-sections and columns as H-sections (note that some structural sections are tubes).

The section may be considered as consisting of flange and web components:

Sections are very effective at carry web plane bending and compression, but the open section is poor in torsion.

Dimensions Typically, the flange thickness will be greater than the web thickness.

Overall Design When a structural engineer is choosing a beam or column, the strength requirement is typically checked first. For beams of significant length, however, the stiffness will likely be the limiting criteria. The maximum permissible central deflection of a structural beam under live loading with brittle finishes is L/360 (where L is the length of the beam) and L/200 for non-brittle finishes, as specified by British Standards[1].

Hot rolled sections typically come in standard sizes, known as universal beams (UBs) and universal columns (UCs). UBs are designed so that flange buckling can typically be assumed not to occur, and the full moment capacity of the beam may be realized when assessing ultimate limit states. This assumption requires the beam to be in a low shear state, defined as shear<0.6*shear capacity and the plastic moment capacity<1.2*elastic moment capacity[2].

Web

Design Constraints: Strength to resist shear forces; corrosion and fire resistance; the web depth, in combination with flange width and thickness, should provide sufficient web plane bending stiffness (realizing a central deflection less than L/360).

Material[3]*:* Structural steels contain small amounts of the useful alloying elements, carbon (0.17%) and manganese (1.4%). Sulphur (0.04%) and phosphorus (0.04%) are harmful elements present in the steel; their levels are closely controlled. In the UK, structural steels are designated by a code such as "S275-JR" where the 2nd to 4th characters present the material yield strength in MPa, and the last 2 characters represent fracture toughness properties. The ultimate strength of S235 sections is a minimum of 430MPa.

Coatings: Coatings provide fire protection to the steel. If not encased within brickwork or concrete, the beam is typically coated with intumescent paint. Alternatively, it is covered with mineral wool boards or coated with cementitious sprays. Coatings may also be used to increase corrosion resistance (intumescent paint and sprays offer some corrosion protection*).

Flanges

Design Constraints: Strength and geometry to resist web plane bending moment, and provide sufficient web plane bending stiffness (realizing a central deflection less than L/360); slenderness ratio constraint (b/2t<18, where b is the breadth and t the thickness of the flange) preventing local buckling[2]. The flange width and thickness may also be sized to allow attachment of secondary beams and services.

Material: As for the web

Coatings: As for the web

Process chain of predominant material

For sections of non-standard sizes, some steel fabricators will cut and weld in appropriate plates to create the desired shape. However, the majority of sections are mass-produced as shown in the schematic above.

Blooms are continuously cast and then cut when the centre has solidified. The blooms are then reheated and hot rolled at approximately 1200°C. Multiple passes through reverse rollers are required. Little work hardening is imparted during rolling because the temperature is sufficient for the steel to self-anneal. The rolling acts to transform the cross-section, align grains and reduce porosity.

Direct hot rolling after continuous casting could conserve some of the energy already invested in heating the material. However, it is important that the centre of the bloom has solidified before hot rolling commences. Additionally, without removal of cut blooms to a rolling shed, multiple series-aligned rollers would be needed to reduce the cross-section.

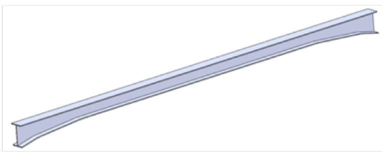
Tata Steel Europe is exploring nearer-net shape casting of I-beam blooms, reducing the mechanical work necessary to create the cross-section. This may also allow the removal of intermediate reheating during rolling.

Economics A steel portal frame typically accounts for 15% of the total structural cost of a warehouse[4]. The frame usually accounts for 10-15% of the cost of a typical multi-storey building[*].

Historical development of metal and energy use The first sections produced in the 19th century consisted of riveted plates, forming the web and flanges. In the mid-20th century, rolled sectional joists (RSJs), with tapered flange thicknesses, were used. However, British and European standards now refer to standard section universal beams (UBs) and universal columns (UCs), produced with parallel inner flange faces.

Significant Variations from Design

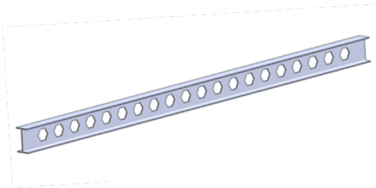
The shear force and bending moment requirements of a beam typically demand only 2/3 of the material currently used. By varying the cross section of the beam along its length, considerable material savings could be made. Fabsec beams (shown opposite) are manufactured by welding flange and web plates to produce a beam that may have tapered sections, forming nearer optimal beams (it should be noted that the majority of fabsec beams produced do not have tapered sections). Fabsec beams offer a potential weight saving of 14-18%, depending on end loading conditions[5]. Fabsec beam production



Fabsec™ Beam

is relatively small; the logistical issues of additional cutting, welding etc is uneconomical in most cases.

Cellular beams (shown opposite) are standard universal beams, produced with cells cut out of the web at regular intervals to reduce weight. These beams offer a weight saving of up to 22%[5], and integration of services within the web depth of the beam. However, the material yield loss increases.



Cellular Beam

Current Reuse: There is minimal reuse of hot rolled steel sections. The limited activity centres on cascading reuse, with larger sections reused in the shoring and bracing industries[6]. In certain high fatigue loading cases, such as bridges and offshore structures, direct reuse may not be applicable.

Current Life Expectancy: Typically determined by the life expectancy of the construction, rather than of the steel section. Building life expectancies are typically 50years. The life of a steel section is often extended through building/infrastructure adaption and upgrade[6].

References

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Industrial Equipment Example: Aluminium Electric Cables (Production ≈ 4Mt/yr, 9% Total)

Dimensions Individual aluminium strand diameters typically range from ∅5-20mm. Individual steel core wire diameters typically range from ∅1-5mm.

The two predominant types of electrical aluminium cable are shown above. Aluminium conductors are used widely in overhead electrical transmission and distribution. Transmission lines conduct high voltage power from a generating source to substations, and distribution lines from these substations to individual homes and businesses. There are currently over 22,000 km of overhead cables in the UK[1]. Aluminium was briefly used as a conductor in household wiring, but is no longer used due to household fires linked with improper installations.

Aluminium Conductor – Steel Reinforced (ACSR): used as bare overhead power lines in long span, medium and high voltage lines[2]

Design constraints: High strength and low weight for the long span, high conductivity, flexibility to withstand deflections due to self-weight, and corrosion resistance

Material and construction[2]: Concentrically stranded aluminium wire (typically AA1350-H19) of one or more layers around a high strength coated steel, of single or stranded wire. The central steel core supports the weight of the transmission line, whilst the aluminium is used for its conductive properties. ACSR cables are available in specific sizes and varying amounts of central steel and outer aluminium, achieving desired capacity and strength. The number of aluminium strands typically range from 3 to 100, and the number of steel wires from 1 to 20.

Coatings[2]: The core wires are usually galvanized, aluminium coated, or aluminium clad. Additional corrosion protection is available through the application of grease. The coating of the steel core typically accounts for 11-18% of the core weight.

All Aluminium Conductor (AAC): used as bare overhead power lines for short spans where maximum current transfer is required[2]

Design Constraints: Moderate strength and low weight for short spans, good conductivity, flexibility to withstand deflections due to self-weight, and corrosion resistance

Material and construction[2]: Concentrically stranded aluminium wire (typically AA1350-H19) of multiple layers. The alloy provides good conductivity, equivalent to 61.2% IACS (61.2% of the conductivity of annealed copper).

Other Aluminium Cables

Other transmission cable varieties include the use of AA6201-T81 aluminium alloy, used as the main conductor or support, depending on the design[2].

Trap wire construction (where the strands have trapezoidal cross-sections) developed in the early 1990s, allows a smaller cross-sectional area of cable for a given conductivity[2]. This decreases environmental loadings on the cable.

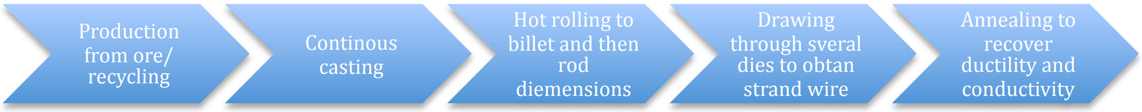
ACCC (aluminium conductor composite core) overhead lines were developed recently. The steel core is replaced with a pultruded carbon and glass composite. This allows a greater cross-section of aluminium for a given diameter (increasing conductivity); it improves sag resistance caused by high loading induced high temperatures; and it allows greater spans between supporting pylons, also preventing bi-metallic corrosion.

Aluminium vs. Copper Conductors[4]

The use of aluminium instead of copper is predominantly due to lower overall cost (the rising cost of copper in the 1960s and 1970s prompted the switch from copper to aluminium). Additionally, aluminium cables weigh less than copper. This is despite the conductors needing to be larger due to the higher electrical resistivity of aluminium (the conductivity of annealed copper being 100% IACS).

Reasons for End of Life*: The importance of a continuously robust transmission network demands electrical equipment is typically maintained, rather than replaced, causing minimal disruption to the network. However, greater power demands cause higher temperatures, in turn causing structural sag and efficiency problems, prompting replacement.

Process supply chain of predominant material (Pure aluminium or 1xxx series alloy)



Economics: Conductors represent 20 to 40% of the installed cost of a line[3]. The cost of overhead transmission lines is £1.4-1.8million/km for a 400kV double circuit line (this includes the installation cost)[5].

Current Reuse*: Negligible. The cables have typically lost their mechanical strength on replacement and therefore are not reused (they would sag too much)*.

Current Life Expectancy: 30 years

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[*] National Grid (UK)

Metal Products Example: Aluminium Beverage Can

(Mass≈14grams; Production≈3.2Mt/yr, 7% Total)

Dimensions[1] Typically (330-500) ml, ∅(52-65) mm; for soft drinks and beers; global

The can consists of a drawn can body and base attached to a can lid that is riveted to the tab. It is not unusual to find cans in which the opening on the lid fractures, and the bottom dome and lid bulge at nearly the same pressure (typically 100-115psi)[2]

Can body and base

Design constraints[1,2]*:* Strength to resist internal pressure (>90psi); Ductility and texture to allow drawing and wall ironing process; Axial strength to withstand the vertical loads imparted by filling, seaming and stacking; An inert internal surface for product contact (health and safety); External print capability (a near 100% surface for brand decoration and consumer information).

Material: Internally coated AA3004/AA3104/3204 H19 (containing both magnesium and manganese)

Mass: Accounts for approximately 80% of the total empty mass of the can

Coatings: The majority of internal coatings are epoxy-based lacquers[3] (approximately 120mg per can[1])

Process[2]*:* Circular blanks are punched from wide aluminium coil (generating a yield loss of approximately 20%). The base and body are formed from a single blank by DWI (drawing and wall ironing). The base is domed to resist internal pressure and the top edge of the body trimmed to remove ears, then necked and flanged. The can then undergoes washing, lacquering and printing.

Can lid

Design Constraints[2]*:* Strength to withstand internal pressure (>90psi); Stiffness to prevent excessive deflections; Provision of an inert surface for product contact (health and safety)

Material: Coated AA5182-H48/H49 (containing more magnesium and less manganese than the can body material, increasing strength).

Mass: The (relatively thick) lid accounts for approximately 20% of the total mass of the empty can

Coatings: Similar to those for the "Can body and base"

Process[1]: Circular blanks are punched from wide, pre-lacquered aluminium coil. The drinking aperture is scored, a bubble is drawn from the lid to provide tab location, and then the tab attachment is achieved by riveting. The lid is seamed to the body after filling to provide an hermetic seal; seaming consists of two roll forming stages that clinch a rubber compound (on the lid) between tight lid and body curls.

Tab[1] Separate Piece of Metal (AA5182, i.e. same as end).

Scored opening[1,2] Controls the load that is needed to open the drinking aperture by the consumer (but also prevents premature opening/leakage).

Process supply chain of predominant material (Can body/base AA3004/AA3104/AA3204 H19)[2]

Elements of the supply chain are geographically widespread, preventing the use of heat developed in one process in subsequent stages. Wide strip coil is hot and cold rolled from 30" thick ingots. Casting aluminium in thinner slabs has been investigated, but due to the faster cooling and reduced rolling reduction, the desired textures (for easy DWI and low earing) have been difficult to achieve.

Suggestions from the literature include altering the cooling rate and the composition of the alloy.

Economics[1,4] The aluminium material accounts for approximately 75% of the cost of the can.

Historical development of metal and energy use The industry has continually focused on light weighting due to the large economic incentive to reduce cost. The mass has reduced by 30% from the 1960s. In recent times, the mass has decreased from 16.55gms in 1992 to 14.7grms in 2005[5].

Current Reuse[1] Negligible. The can design would need to be strengthened against accidental crushing/damage. A key consideration would be removal and re-attachment of the end - double seaming may have to be replaced. Coating removal and relacquering would not be necessary, but a returned can would need to be washed thoroughly to remove debris, then washed with a fluid to deactivate remnant microbes, then rinsed in water. The internal coating would survive (it is already designed to survive such treatment).

Current Life Expectancy from Production to Disposal[2] < 6weeks

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Appendix C: Chapter 4—case study interviews

Case Study 1: Refurbishing modular building (conducted by Muiris Moynihan)

Interview with Technical Manager, Foreman's Relocatable Building System

Modular buildings are manufactured in a factory, transported to site and erected to form an office, school, hotel, retail unit (these are the most common structures, but almost any are possible). Modular buildings are constructed in a controlled factory environment, resulting in health & safety, quality, cost and time benefits, as well as reduced time on site, minimising disruption.

Foremans Relocatable Buildings Systems are a UK company that specialises in refurbishing modular buildings. Owners of building modules contact them to sell on their units; if the unit has certificates to show it was made by a reputable manufacturer, then Foremans will inspect and potentially buy it. Its team disassembles and removes it to their plant in Yorkshire, where it undergoes refurbishment. Firstly, the module is stripped back to its structure and a thorough check undertaken with any repairs made – this allows the structure to be guaranteed for 10 years, regardless of its age on arrival. It is then held in stock until a client purchases it, at which point modern interior finishes & services are installed in accordance with the client's specifications and the building regulations. Module components can even be combined in a 'kit-of-parts' approach to meet non-standard requirements. The finished modules are then transported to the new site and erected in any feasible geometry. In this way, approximately 80% of the steel in each module is retained and kept past the lifetime of its parent building.

Case Study 2: Replaceable roll sleeves (conducted by Daniel Cooper)

Technology Manager (rolling mills and process lines), Siemens VAI

The cylindrical work rolls in steel and aluminium rolling mills weigh up to 90te, and exert loads up to 10,000te. The typical specification for (5m) plate mills work rolls is a ø1.2m roll weighing approximately 90te. The work rolls in a mill weigh up to 450te (including chocks). The roll is made from forged steel with the inner grey steel surrounded by a thick outer layer of chrome steel. The rolls quickly wear, causing problems with surface quality of the rolled product and a danger of explosive disintegration of the rolls. The rolls are consequently replaced every 8 hours of operation. They are then ground down to remove the damaged outer layer, and returned to the mill. This cycle is repeated over a period of 5 years until the radius has reduced by approximately 100mm, prompting full replacement with the old roll being scrapped.

Acknoweldging that performance degradation is only applicable to the outer surface of the roll, can the life of the remaining steel be prolonged by modularising the inner and outer core? Sleeved rolls consist of an arbour and a sleeve that are joined by a shrink fit. These sleeved rolls facilitate repair of older rolls and multiple use of the arbour. Carefully designed and manufactured rolls have proved to be equivalent to solid rolls in terms of rolled kilometres and tonnages at rolling mills in the Czech Republic. They have only been used occasionally thus far, due to the problems of induced tensile stress from the shrink fit. However, this problem is being slowly overcome with careful design, better materials and FEM analysis.

According to Hajduk et al (2010), sleeved rolls are used to repair older rolls and to manufacture large rolls that cannot be made as a solid roll. They offer a cost advantage as the structural core (the “arbour”) can be reused.

Case Study 3: Adaptable foundations (conducted by Muiris Moynihan)

Interviews with two Directors, Infrastructure Division, Arup

Two aspects of the foundations were explored: how to design them so that they are adaptable, and how to adapt them once installed so they can be used beyond the life of their original superstructure. Every structure requires some form of foundation. These were mainly shallow footings until the 1950s, when deep foundations (mainly piles) came into the main stream as taller buildings became more common. Since then concrete has been the material of choice for the industry, as it has a major cost advantage over the main alternative, steel.

Adaptable foundations

A large developer in London usually requires foundations that can take a number of different building layouts, based around the likely core layouts and column grids. Design teams are commissioned to develop concept designs for each one with foundation designs worked out which give a maximum of overlap (a ‘totally’ flexible foundation would be at least twice as expensive, if not more). On one project 15% more piles were added to achieve this flexibility, which added less than 1% to project cost. On another project the individual piles were designed with 10% extra capacity, which barely added to project costs; this is possibly going to be used to add extra storeys.

At the end of building life the foundations are much more likely to be kept for the next building, as it can be quite different to the previous. Considering a typical pile contains 700-1100 kg of steel, and that there may be hundreds on a site, the potential steel saving is huge, especially given that London’s tall buildings last less than 25 years in places and the ground is slowly filling up with piles.

The developer’s reason for specifying adaptable foundations was that foundation work could start without the superstructure being fully decided, giving programme advantages as well as allowing a greater pool of potential clients.

Adapting foundations

At building end-of-life, the superstructure can be readily removed and potentially reused; however, this is very difficult and expensive for piled foundations. Instead, there are three options: dig out, leave in place, or use again. Digging out concrete piles is a difficult and expensive task as they cannot be pulled out and go to great depth, so currently many piles are simply left in place and the next set of foundations merely fit in around them. The Reuse of Foundations on Urban Sites (RuFUS) project highlighted the congestion present underground at certain sites in London, where two or three generations of concrete piles have left almost no space for new foundations to go in. Concrete piles are very difficult and costly to remove, as well as damaging to the ground to do so – new foundations must go deeper and deeper to get the same capacity. The RuFUS project championed the reuse in-situ of existing concrete foundations, and listed examples where this has been successfully done, but identified the key barriers of suitability, information and liability.

- Suitability: obviously the existing foundation must be able to accommodate physically the new superstructure, i.e. have sufficient capacity in the right locations.
- Information: to re-use the foundations safely, engineers must know what they are. If the original design calculations and drawings are available this makes the task much easier, as small investigations and checks can be done to verify these. If not, however, then much larger investigations and testing must be done to ascertain what is there before the foundations can be used with confidence.
- Liability: when a new foundation is installed, the contractor provides a warrantee for it. However, with an existing one the original warrantee has expired and no designer or contractor is likely to take responsibility for it, as they cannot be certain what is there. The client therefore must shoulder the risk or take out a 'latent defects' insurance policy to cover any claims related to the foundation.

Case study 4: Adaptable, robotic packaging equipment (conducted by Alexandra Skelton)

Interview with the Procurement Director European Equipment for a fast-moving consumer goods firm

Industrial equipment, predominantly made from steel and stainless steel, is purchased for processing, filling, palletising and packaging food and detergent.

Reliability, efficiency and price govern purchasing decisions. The requirements of the equipment changes often as the products and packaging are updated frequently. The cost of ownership is assessed over a 10-year period and the equipment must have a payback period of 5 years and exceed the internal rate of return of 15%. Increasing the durability of equipment beyond this 10-year mark is not a priority and the potential resale value of equipment has no significant influence on purchasing decisions. This is the case despite the fact that packaging equipment is typically used for 5-7 years in house and has an expected life of 20-30 years. Flexible, robotic packaging equipment could be used to adapt to changing product needs. However, robotic packers are 2-3 times more expensive than dedicated packers and require forward planning to ensure a second use in order to be cost effective. The company currently favours dedicated packers given the price differential between the two and uncertainty over future product lines. However, the potential to reduce the time-to-market for future products by using adaptable, robotic packers is under consideration.

Case Study 5: Durable infrastructure (conducted by Muiris Moynihan)

Interview with Professor for Construction Engineering, Cambridge University

Most major transport installations, such as train tunnels or motorway bridges, cannot be allowed reach end-of-life and get replaced like buildings or other products, as the disruption caused would be too severe – they are, in effect, 'essential'. Therefore, they are undergoing constant maintenance to keep them functional, and a growing part of this is condition monitoring to identify problems and determine the best solutions before they become critical. Focusing on UK motorway bridges, the next generation of structures can avoid the degredation being seen currently by implementing novel design features.

Condition monitoring involves the attachment of small wired or wireless sensors, which detect changes in strain, inclination, displacement, humidity, etc. and feed this information back to a central hub. Analysing this data points towards likely causes of any problem, and can recommend the best method of addressing it, be it repair or replacement of a section. Before this technology, more manual inspections were necessary, causing more disruption, and components were replaced on a scheduled basis where this was impossible, regardless of actual deterioration, or when a problem was not understood and replacement was the only option. The technology is not at a stage where it should be applied everywhere; it is preferable to target a specific problem and place sensors to best quantify it. As well as allowing efficient maintenance strategies, monitoring also leads to individuals believing maintenance can be postponed until the situation is almost critical, in order to reduce costs.

UK motorway bridges suffer physical failure, most commonly corrosion of rebar. Left untreated this can cause loss of strength and even collapse, while remedies for it are difficult and expensive to implement. While most bridges projects have a 'design life' of 120 years, in fact due to poor design and construction some not half that age require major interventions. More considered design and higher quality construction could, at minimal extra cost, increase the lifespan of a structure by a significant portion.

As water ingress leads to corrosion, design strategies to limit this will improve matters. Examples of this are minimising joints (increasing internal stresses, however) or the specification of stainless steel (or other corrosion resistant) rebar at high risk locations, both of which are done in cases where extended warrantees are requested by the client. Poor quality construction, where substandard placing of rebar or concrete lead to insufficient cover depths, or where concrete mixes were not to the specification required, has caused the majority of repairs historically. Especially for installations built in the 1960s, a lack of supervision and checking on site led to these errors, and now the structures are showing more defects than bridges built correctly in the 1920s and before. Proper quality assurance procedures and inspections during construction are required to ensure the current generation of bridges do not suffer the same fate.

Case Study 6: Hard-wearing rails, replacing rails & resurfacing tram rails (conducted by Alexandra Skelton)

Interview with Programme Manager, Network Rail

Three strategies to extend the life of rails are documented: engineering harder-wearing rails, cascading rails from main lines to branch lines, and a new technology to replenish worn tram rails.

Harder-wearing rails

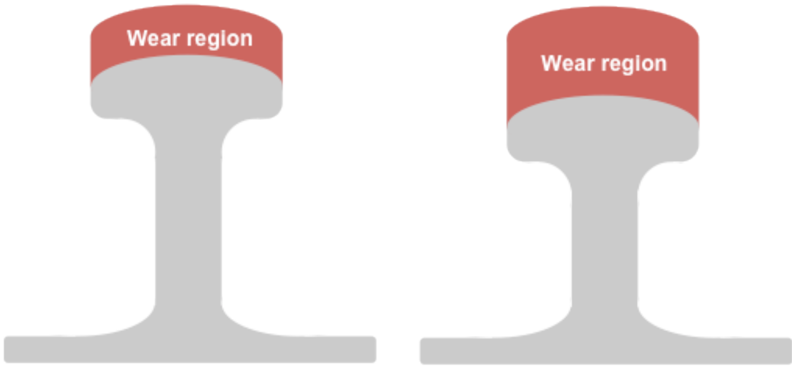
Replacing and maintaining rail track is an expensive business, not just because of the cost of materials and the logistics of transporting materials and equipment to and from the work site, but also because of the economic penalty from lost track time when the line is closed. Therefore, increasing the life of rail track and decreasing the frequency of maintenance are important economic and environmental strategies for the rail industry. Heat-treated or non-heat treated premium grade rail, with a higher wear resistance, can be used in the place of conventional rail to extend the service life and reduce the frequency of maintenance. Table C.1 shows that total emissions for the premium grade rails are less than half of the emissions for conventional rail due to significantly reduced maintenance.

	Conventional rail	High performance rail (non-heat treated)	Heat-treated rail
Material production, processing and recycling	Produced as 108m length rails at Scunthorpe. At its end-of-life, the rail is collected and recycled. The rail has a mass of 60.21 kg/m. **52 kg CO_2/m rail**	Produced using the same process route as conventional rail but with additional alloying elements. At its end-of-life, the rail is collected and recycled. **53 kg CO_2/m rail**	Steel produced in Scunthorpe is transported by rail to France for rolling into rail and heat treatment. The rail is then transported by sea back to the UK before welding to length. At its end-of-life, the rail is collected and recycled. **56 kg CO_2/m rail**
Maintenance (over a life of 1000 EMGT* for a curve of radius less than 2500m)	Rail grinding is performed every 15 EMGT of traffic for curves with a radius smaller than 2500m. ≈ 1 kg CO_2/m rail. 66 grinding schedules over rail life. **66 kg CO_2/m rail**	High performance rail has a wear rate of about 3% of the value for conventional rail. ≈ 1 kg CO_2/m rail. 2 grinding schedules over rail life. **2 kg CO_2/m rail**	Heat-treated premium rail has a wear rate of less than 1% of the value for conventional rail. ≈ 1 kg CO_2/m rail. <1 grinding schedules over rail life. **0 kg CO_2/m rail**
Total	**118 kg CO_2/m rail**	**55 kg CO_2/m rail**	**56 kg CO_2/m rail**

*equivalent million gross tonnage carried by a section of track

Table C.1: Embodied carbon calculations for different rail options

Another strategy is to increase the proportion of weight worn away during service by increasing the thickness of the rail head, shown in Figure C.1. Assuming the wear rate is identical for both conventional and thicker head rail, extending the rail life would save metal by reducing the need for the manufacture of a completely new rail.



a) Conventional rail – wear region ≈ 20% of weight b) Thicker head rail – wear region >20% of weight

Figure C.1: Schematic diagram of thicker head rail

In environments where corrosion may significantly reduce the life of a rail, high purity zinc coated rail can be used to extend its life. In one such environment, a crossing made of conventional rail required replacement every 3 to 6 months due to corrosion. By replacing it with high purity zinc coated rail, the crossing has been in service for the last 16 months without needing to be replaced.

Rail Mainline to Branch

Cascading of rails was performed in the UK until recently, and is still practiced on German railways. Worn mainline rails undergo non-destructive, ultrasonic testing to establish integrity. Existing welds are then cut, and the remaining lengths welded into long strings. These are resupplied to the network for use on secondary routes. Cost can limit the motivation for this reuse as the rails themselves represent only 7% of track renewal costs. Historically, the rail life was also increased by transposing the rail: provided head wear was not too close to the limit the non-active gauge face was made active by turning through 180 degrees. Other than transport and welding emissions, this prevents emissions associated with the production of branch line rails

Metal decomposition on tram rail

The cost of replacing grooved tram rail in the UK may be up to £3000 per metre; digging up old and laying new embedded tram rail often necessitates the closure of roads, causing significant disruption to traffic. An alternative strategy to replacing a rail is to extend its life. A submerged arc welding process is used to restore the rail profile by depositing steel onto the worn rail surface. Careful temperature control during processing and alloy choice produces a high integrity weld. Additionally, the deposited steel has a higher carbon content than the original rail, which results in a more wear resistant surface.

Figure C.2: Photograph of welded grooved rail

Case Study 7: Carbon-fibre aircraft body (conducted by Muiris Moynihan)

Interview with Technical Fellow, Boeing

Boeing's new 787 Dreamliner aircraft makes significant advances in the use of composite materials in the aircraft's main structure. Around 50% of the aircraft by weight is made of composite materials, and most significantly the fuselage is made from a single fabricated piece. This change in design was motivated by the desire for weight savings and resulting fuel savings and has the co-benefit of increasing the life of the aircraft. The Dreamliner is anticipated to have a service life of 30-35 years, compared to 20-25 years for a conventional metal aircraft. This extension is principally due to the elimination of large numbers of connections and fasteners through the use of composite materials. Fasteners such as rivets act as stress concentrators and can also be sources of corrosion, which limit the fatigue life of an aircraft. The use of composites allows much more complicated sections to be made as single pieces, thereby eliminating large numbers of fasteners and extending the life of the aircraft. The smaller number of fasteners also simplifies maintenance checks, where each fastener must be checked for signs of corrosion or cracking.

Case Study 8: Restoring supermarket equipment (conducted by Daniel Cooper)

Interview with Development Manager, Tesco

Tesco has been operating a reuse program for 18 months and has realised great benefits from the process; capital savings on investment in new kit and product lifetime extension. Currently as store closures and refreshes are identified, those stores are surveyed and kit is removed for refurbishment to be placed back into new and existing stores. Items currently removed from stores include mechanical handling equipment, checkouts, and refrigeration units. The greatest challenge to the success of this process has been the perception of kit as 'second hand' and Tesco Design Standards that change frequently to keep the stores and brand contemporary.

Case study 9: Office block refurbishment (conducted by Muiris Moynihan)

Interview with Associate, Expedition Engineering

55 Baker St. is a concrete-framed office block originally built in the 1950s. By the early 21st Century it had become outmoded – its long, narrow corridors and enclosed offices were no longer suitable to the needs of the modern workplace. Because of its city-centre location, a conventional demolition and rebuild project would have taken too long to meet developers' profitability targets, so instead an ambitious major refurbishment programme was undertaken. This involved stripping the building back to its structure; filling in the many stair and lift voids dispersed throughout the floorplates to create open-plan office and replacing them with a new centralised circulation and stability system; expanding the floorplate into spaces between the 'wings' of the existing building and creating atria; and removing columns at certain locations to improve flows around the final building. The servicing was entirely redone; the low floor-ceiling height of the existing building was overcome by a chilled beam system which gave maximum headroom over most of the floorplate. In all 70% of the original building structure was reused, saving 3,500t of rebar.

Unusually, the design team had access to extracts of the original design calculations and drawings for the existing building, which greatly aided understanding and justification of what was there and why, hence only limited testing and investigation was required. Even so, some unexpected challenges arose on site which were difficult, but none that could not be surmounted by careful thinking and intelligent detailing.

More generally, two commonly cited ways of increasing a building's adaptability are having longer spans and increase imposed loading. This enables a wider range of activities to be accommodated and could prevent demolition in future. However, the extra resources used to deliver the longer spans and higher loads should be balanced against the likely benefit from them. It is thought preferable to consider where capacity is most probable to be useful, for example putting extra load allowances towards the back of building where storage is likely, or adding capacity along edges (e.g. atria) where extension is possible. This has been successfully done on high-rise office blocks in London and additions subsequently made, once the user request them, with reduced costs and time.

Case Study 10: Steel mill upgrade (conducted by Alexandra Skelton)

Interview the Jonathon Aylen, senior academic at Manchester Business School

80% of the product range rolled on the modern wide strip steel mill has been developed in the last 20 years meaning that 60 year old mills have had to adapt to deliver this more diverse product range (Aylen (2011)). Higher strength steels have put pressure on the power, torque and load limits of mill stands and have been accompanied by demanding quality standards, rising energy costs and the need to increase output in order to reap economies of scale in competitive markets. Aylen (2011), in a study of 7 strip mills built using Marshall Aid following the second world war, identifies four means by which mills have been upgraded or "stretched" in response to these pressures: (1) improved intensity of hardware use through experience and better maintenance e.g. through better scheduling and condition monitoring; (2) system wide effects of improvements in material feedstock and downstream processing e.g. accepting higher piece weight inputs that allow the production of longer, heavier coil; (3) modular improvements to existing plant e.g. rotating quick roll change rigs that reduce downtime and control systems that predict strip quality and accurately determine the number of passes required; and, finally, (4) physical reconstruction of existing plant e.g. a switch from a semi-continuous or continuous layout to a ¾ continuous layout that allows greater utilization of the finishing train. As a result of this activity, the average ratio of current installed capacity relative to initial design capacity is found to be 1.8 i.e. the capacity of these mills has close to doubled over their lifetimes to-date. The single outlier is the Linz mill in Austria, which has a stretch capacity ratio of 8.3 achieved through over 30 significant performance enhancing modifications and by accepting heavier piece weight inputs. Productivity is not compromised in these upgraded mills relative to newly designed mills; in fact, there is some evidence that established mills have an advantage. Aylen (2011) briefly discusses the possibility that mill stretch has been facilitated by initial overdesign, e.g. the mill in Linz had a low initial rolling capacity but was contained in an excessively large building allowing the rolling line to increase within the building by just under 40%. In their paper on plate mill upgrade Bhooplapur et al. (2008) point to a second reason why mill upgrade has been possible. Microalloying is the favoured process for making modern high strength plate grades and in this process the greater strength of the steel is exhibited only in the late stages of rolling and cooling, limiting pressure on the mill stand and so allowing high strength steels to be rolled on mill stands that were built before these grades were envisaged.

Case study 11: Restorable washing machine (conducted by Daniel Cooper)

Interview with Director, ISE appliances

The main washing machine sub-assemblies are the housing, drum unit, motors and transmission, and pipes and pumps. Although customer misuse may damage the housing, this is rare. The pipes and pumps will clog over time, but with reasonable maintenance these components should not limit the life of the machine. The drum unit is typically made from plastic (though some more expensive machines are made from stainless steel). The steel bearings in the drum are typically contained within a sealed plastic housing. When these bearings wear and fail, the sealed drum unit must be replaced, as there is no access to the bearings. Drum replacement is expensive; therefore, bearing failure typically leads to the washing machine being replaced. The motors used in washing machines are typically carbon brush motors (90% of domestic washing machines use carbon brush motors) contained within a sealed unit. The carbon brushes wear out and the sealed unit again means motor replacement is necessary to prolong the life of the machine. The expense of replacing the motor means that wearing of the carbon brushes often leads to whole machine replacement.

For a washing machine to be inherently long life and easy to repair the design must mitigate the two predominate failures discussed above – wear of the bearings in the drum and the carbon brushes in the motor. More durable bearings would provide inherent long life and an "old-fashioned" spilt-ring drum design would allow them to be easily replaced when they do fail. As for the motors, these should not be put in a sealed unit, allowing replacement of the carbon brushes if they wear out. Alternatively, more expensive, and longer lasting, induction motors could be used.

Case study 12: Disassembly and component reuse of oil rigs (conducted by Alexandra Skelton)

Interview with Project Director for North West Hutton, Able UK

North West Hutton is an oil rig that was built by Amoco in 1981 in order to exploit reserves in the northern most section of the British North Sea. BP inherited the installation through the takeover of Amoco in 1998 and North West Hutton was subsequently owned by a joint venture - 26% BP Amoco, with the remainder held by Shell and others. Despite being designed to process up to 130,000 barrels of oil per day, the reservoir underperformed. Production peaked in 1987 before hitting the characteristic production cliff with production decreasing by 42% 1988-1989 and successive step decreases (with the odd minor production push) until, in 2003, production ceased altogether (BP (2009)). In 2007 the rig was decommissioned and dismantled by Able UK. Able UK sought to reuse as much of the rig as possible in order to maximise residual value. The accommodation block was refurbished and is now used as the Able UK offices, at the time of interview buyers were being sought for the heli-pad, and sections of the jacket (the legs) of the structure were cut into sections and sold on to be re-rolled into plate that could be reused.

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Appendix D: Calculation of η

The contact geometry between two aluminium surfaces is complex; however, O'Callaghan and Probert (1987) argue that it may be regarded as equivalent to the contact between an imaginary rough surface, with an appropriate topography, against a flat surface. Roughness is characterised by the root mean square of the asperity heights (r) and the asperity inclination angle (ψ). O'Callaghan and Probert argue that the equivalent rough surface has a root mean square asperity height, r_{eq}, and asperity inclination angle, ψ_{eq}, of $\sqrt{2}r$ and $\sqrt{2}\psi$ respectively, as depicted in figure D.1.

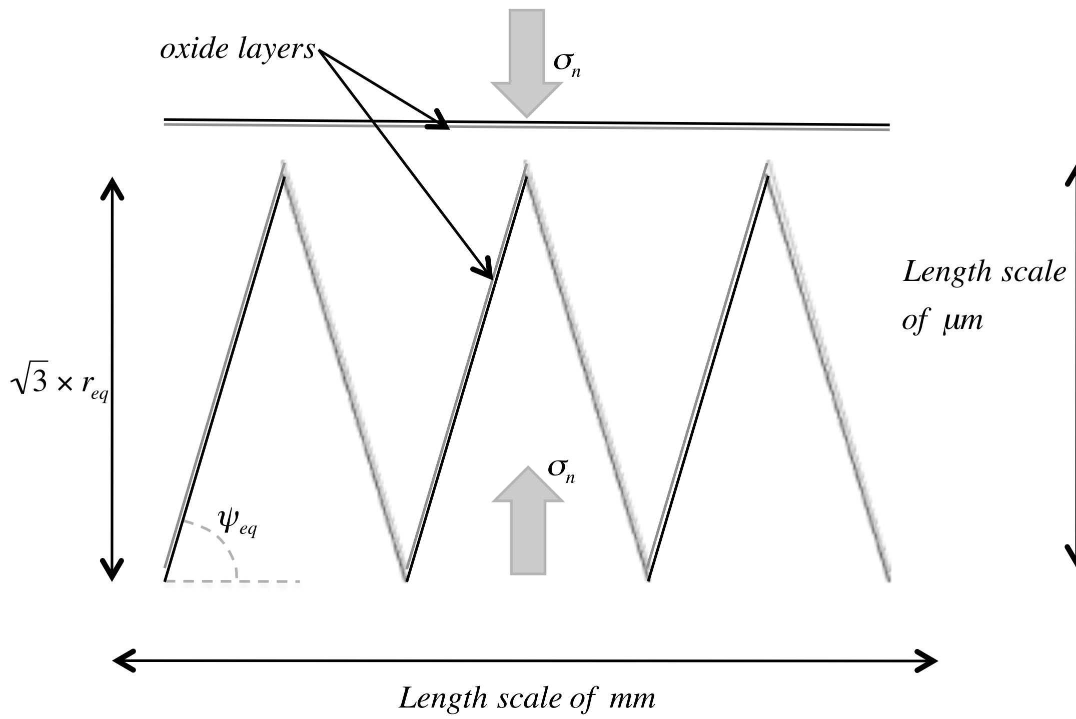

Figure D.1: Simplified contact geometry from O'Callaghan and Probert (1987)

Estimation of the entrapped air volume in a single 'valley' (per unit depth) is now possible. The volume of oxygen is 21% of the volume of the entrapped air:

$$Volume_{O_2} = 0.21 \times \sqrt{3}r_{eq} \times \frac{\sqrt{3}r_{eq}}{\tan(\psi_{eq})} \qquad \text{(D.1)}$$

There is one mole of gas molecules in 22.4 litres ($0.0224m^3$) of volume at standard pressure and temperature. Therefore, the number of O_2 moles in this volume is given by the following equation.

$$Moles_{O_2} = \frac{Volume_{O_2}}{0.0224} \times \frac{298}{T} \qquad \text{(D.2)}$$

An oxide layer 2.9nm thick (equivalent to ten aluminium atom spacings) is enough to inhibit bonding (Tylecote, 1968). The molar mass of Al_2O_3 is $0.102kgmol^{-1}$, and its density is $4000kgm^{-3}$, therefore $1.7x10^{-4}$ moles of O_2 are required to oxidize a $1m^2$ surface to a depth of 2.9nm (ten aluminium atom spacings). The area of the 'valley floor' (per unit depth) from one peak to the next is given by the following equation.

$$Area = 2 \times \frac{\sqrt{3}r_{eq}}{\sin(\psi_{eq})} \qquad \text{(D.3)}$$

Therefore, the number of moles of O_2 for complete oxidation of this surface:

$$Moles_{\substack{complete\\oxidation}} = \left(1.7 \times 10^{-4}\right) \times 2 \times \frac{\sqrt{3}r_{eq}}{\sin(\psi_{eq})} \qquad \text{(D.4)}$$

The fraction of the surface that can be oxidised is therefore given by the following equation

$$\eta = \frac{Moles_{O_2}}{Moles_{\substack{complete\\oxidation}}} = 50{,}000 \times r_{eq} \times \cos(\psi_{eq}) \times \frac{298}{T} \qquad \text{(D.5)}$$

Appendix E: Equilibrium analyses on oxide fragments

Figure E.1 depicts a scenario in which the oxides do not break together. In this scenario, as depicted in Figure E.1, the top oxide restrains the separation of the bottom oxide, reducing the maximum tensile stress experienced in the bottom oxide and therefore making it less likely to crack in the first place. In the case of the oxides cracking together, however, there is no frictional restraint provided by the adjacent oxide and a higher maximum tensile stress will develop in the oxides causing them to crack. Therefore, in this work it is assumed that adjacent oxides crack together, resulting in complete overlapping of exposed aluminium substrate.

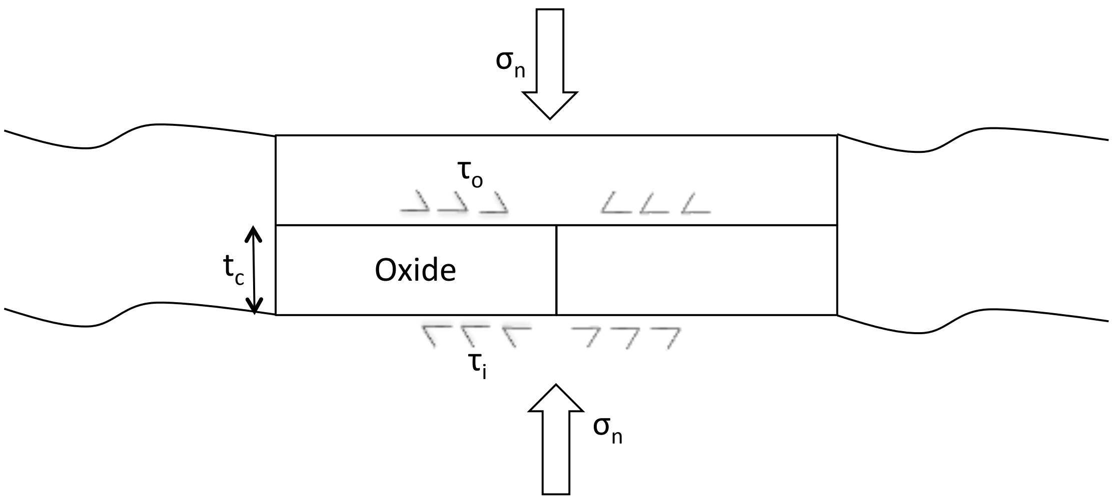

Figure E1: Scenario in which adjacent oxides do not crack together

As the aluminium is stretched the aluminium oxide will crack and substrate aluminium will 'flow' into the cracks. The oxide will continue to crack until the tensile stress within the oxide is less than the oxide tensile strength. The aspect ratio of the oxide fragments can therefore be calculated by considering the force equilibrium on an oxide fragment as depicted in Figure E.2.

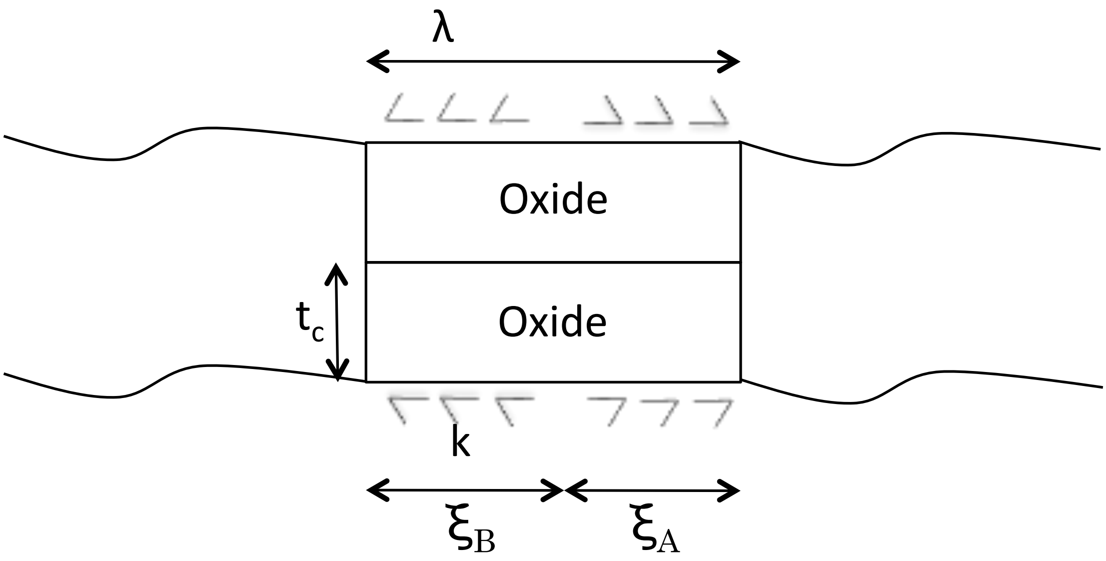

Figure E.2: Forces acting on oxide fragments

ξ_A and ξ_B are the distances between the trailing and leading end of the oxide fragment and the neutral point of the friction hill on the oxide fragment. Horizontal force equilibrium implies $\xi_A = \xi_B = \frac{\lambda}{2}$. The maximum tensile stress, σ_m, in the oxide occurs at the neutral point, with a value of $\frac{\lambda k}{2t_c}$. The aspect ratio of the resulting oxide fragment is therefore given by the following equation.

$$\left(\frac{\lambda}{t_c}\right)_{\substack{no\\shear}} = \frac{2\sigma_{oxide}}{k} \qquad \text{(E.1)}$$

When a shear stress is present at the interface, the forces acting on the oxide are as depicted in Figure E.3.

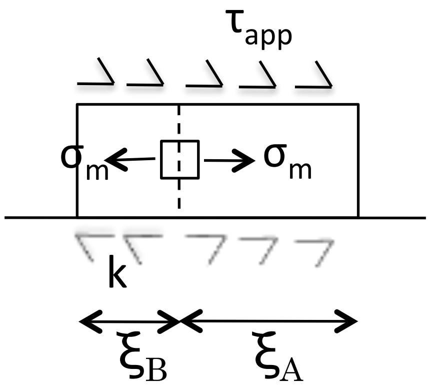

Figure E.3: Force equilibrium on fragment with interfacial shear stress, τ_{app}

From horizontal force equilibrium:

$$\xi_A (k + \tau_{app}) = \xi_B (k - \tau_{app}) \tag{E.2}$$

Since $\xi_A + \xi_B = \lambda$, the neutral point is located at:

$$\xi_A = \frac{\lambda}{2}\left(1 - \frac{\tau_{app}}{k}\right) \tag{E.3}$$

Subsequently the maximum tensile stress in the sample is:

$$\sigma_m = \frac{\lambda k}{2t_c}\left(1 - \frac{\tau_{app}{}^2}{k^2}\right) \tag{E.4}$$

And the aspect ratio of the oxide fragments is

$$\left(\frac{\lambda}{t_c}\right)_{shear} = \frac{2\sigma_{oxide}}{k} \times \left(1 - \frac{\tau_{app}{}^2}{k^2}\right)^{-1} \tag{E.5}$$