INDUSTRIAL INTEGRITY & SUSTAINABILITY*

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Abstract

This paper is a composite. It describes research performed initially in Singapore on the integrity of lightweighting (magnesium) alloys and on the sustainability of industrial systems. The work is based upon an approach to engineering integrity and plant operations which incorporates the concept of Industrial Ecology. The first stage of the research was undertaken within an international consortium "Precision Processing of Ultra-Light Alloys and Composites" (PULAC) in Nanyang Technological University and GINTIC, Singapore. Initially this involved studies of lightweighting and enhanced recyclability of engineering cast components for microelectronics and vehicles, focussing on structural integrity and high-pressure die-casting of magnesium alloys. The work then took a new departure in the arena of simulation and modelling. Several case studies were undertaken including the processes of a complete metal supply chain. It involves a pilot plant in Australia (ILM) and a die casting company in Singapore (DYNACAST). The research work has further evolved via a programme at University College Cork within the new Environmental Research Institute -- with a focus on cleaner production, environmental security and industrial sustainability. The paper is organized into three main sections. The first section describes fatigue, fracture and stress-corrosion research on high-pressure die cast magnesium alloy specimens. The second section describes research on the simulation and modelling of industrial processes, which focuses on the sustainability of the light metals industry. The third section describes how the work might evolve through current research developments at the Environmental Research Institute of University College Cork, Ireland. The general idea is to look at the overall integrity of the various projects as a "retrospect and prospect" and to generate this theme for future research and development, as a discussion paper for this Conference.

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Introduction

This is designed as a discussion paper. The paper addresses a pattern of research which began in Singapore in 1997, continued in Queensland, Australia and has now linked to Cork, Ireland in 2002 – with other threads in Greenwich, England and Harvard, USA. We believe that this represents an interesting international programme which has an underlying thread of industrial sustainability. The beginning was reasonably "conventional" in 1997 in Singapore – via work on the structural integrity and high pressure die-casting of magnesium alloys. This was initially driven by ideas created by Gordon Dunlop and driven by Australian Magnesium Corporation via "CAST" a Cooperative Research Centre based in Queensland. The work initially focused on lightweighting of vehicles to reduce fuel consumption and thus overall carbon mitigation but developed within the manufacturing industries of Singapore based on consumer electronics industries.

This initial ***fracture*** work, (the core topic of this Conference) was conducted within a programme on "Precision Processing of Ultra-Light Alloys and Composites" (PULAC) based at NTU & GINTIC Singapore. Thus the first main section explores the work on fracture and fatigue of these magnesium alloys. The work then developed in a new arena on simulation and modelling of industrial processes driven by additional ideas of sustainability and Industrial Ecology. The second main section explores this work. The third section outlines a new application of the work in the Environmental Research Institute at University College Cork related to Cleaner Production.

There is an interesting evolution and coherence in this pattern of work which we envisage might direct towards thinking of possible new approaches to the theme of this conference in terms of "industrial and asset sustainability and integrity" which may yield new overall thinking via further discussion here at the conference and also benefit agreed themes for ICF11 in March 2005 in Torino, Italy.

We are all now highly conscious of the need to address carbon mitigation in industries and engineering design. This has had a major effect on our thinking within Materials and Manufacturing Engineering, including Structural Integrity and Fracture practice, research and education. The rapid development of industries, including the metal supply and production sectors, has resulted in considerable environmental degradation. There is observed to be a shift of focus – from the integrity and reliability of materials and metals to the products' environmental consequences including recyclability and lightweighting. A core thrust of Australian Magnesium Corporation resides in this arena. For example, studies have been carried out to investigate the recycling activities and scrap processing of a series of metal casting companies. The concerns of the studies were the detrimental effects of the over-consumption of resources and energy [1], as well as the processing costs of the recycling activities [2]. This paper thus aims to address this new paradigm for research in fracture mechanics and structural integrity. It is designed to engage in extending product and industrial "integrity" to "sustainability", by incorporating concepts of Industrial Ecology. The overall idea is to generate some discussion on the work performed and open new areas for future research and development ("retrospect and prospect").

The paper is organized into three main sections. The first section of the paper describes fracture research on high-pressure die cast magnesium alloy specimens, referencing the range of work accomplished in this arena. The second section describes the research work performed on the simulation and modelling of industrial processes based on the concept of Industrial Ecology. In this section, three simulation studies are presented, involving a case studies performed in Singapore and in Queensland, Australia. The third section describes how this work is evolving through the current research developments at the Environmental Research Institute of University College Cork, Ireland.

Fatigue & Fracture of Magnesium Alloys

This section explores the work performed on the fracture and fatigue characteristics of magnesium alloy components. This started in 1997 in Singapore. This was initially driven by work performed on the lightweighting of vehicles to reduce fuel consumption and thus addressing carbon mitigation. The work was performed through a programme, "Precision Processing of Ultra-Light Alloys and Composites" (PULAC) [3], based at the Nanyang Technological University of Singapore. The objective of PULAC was to develop research activities and achieve research deliverables in the processing of new ultra-light alloy and composite components for a range of industries – focusing initially on magnesium die casting for the electronic and telecommunication sectors and then on magnesium die castings for automotive components. The research scope at PULAC covered parameter and process optimisation, alloy improvement, material properties and environmental issues, such as recycling. The main concern was on magnesium die casting alloys due to its many advantages, including: the recyclability and end-of-life properties, light weight, availability, low-toxicity, ease of casting, electro-magnetic radiation shielding, dematerialization and de-manufacturing.

Magnesium die casting is a very healthy and growing segment of the precision processing industry with current and projected growth in the range of 15-20% per annum. The driving need for weight reduction, particularly in portable microelectronics, telecommunication and automotive applications, has stimulated engineers to be more adventurous in their choice of materials. Magnesium, with one quarter the density of steel and only two thirds that of aluminium, and a strength to weight ratio that far exceeds either, fulfills the role admirably as an "ultra-light" alloy, and possible applications of its composites can also be envisaged (*e.g.*, when wear resistance is an important requirement). Table 1 shows the advantages of magnesium die casting alloy over aluminium alloy, mild steel, typical polymer and ceramic.

Table 1 Comparison of material properties

Property	**Mg alloy AM60B**	**Al alloy A380**	**Mild Steel**	**Typical Polymer**	**Typical Ceramic**
Mass density ($g \cdot cm^{-3}$)	1.79	2.8	7.85	0.91-0.925	3.99
Young's modulus (GPa)	45	71	210	0.055-0.172	393
Yield strength 0.2% (MPa)	130	200	440	-	-
Ultimate tensile strength (MPa)	220	275	540	15.2-78.6	206
Specific Young's modulus ($GPa/kg/dm^3$)	25	26	27	0.059-0.189	98
Specific yield strength ($MPa/kg/dm^3$)	73	73	57	-	-
Specific ultimate tensile strength ($MPa/kg/dm^3$)	123	100	70	16.4-86.3	52

The electro-magnetic radiation (EMR) shielding capability of magnesium is particularly desirable for microelectronics applications, e.g., hand phone casings. Legislation in the hand phone industry is very likely to push for better electromagnetic shielding capabilities -- a role readily taken by magnesium alloys.

Being resistant to both flexing and heat deformation and with minimal creep at higher temperatures (e.g., 100-150 °C), magnesium alloy housings eliminate leakage problems often encountered with metal-coated plastics.

In production, magnesium's low heat content and low reactivity to steel provide fast cycle times with minimised die wear and a high tolerance capability due to low thermal distortions. This latter point often renders secondary machining unnecessary and thus improves the precision processing economics. This coupled with the high fluidity of magnesium alloys allows complex, thin-walled and finely detailed component fabrication. In Japan, many top of the range products, such as lap-top computers, hand phones, pagers, cameras, video cameras, CD and DVD players have already utilised magnesium die casting technology. Examples of magnesium alloy applications are shown in Figures 1-2 and Table 2.

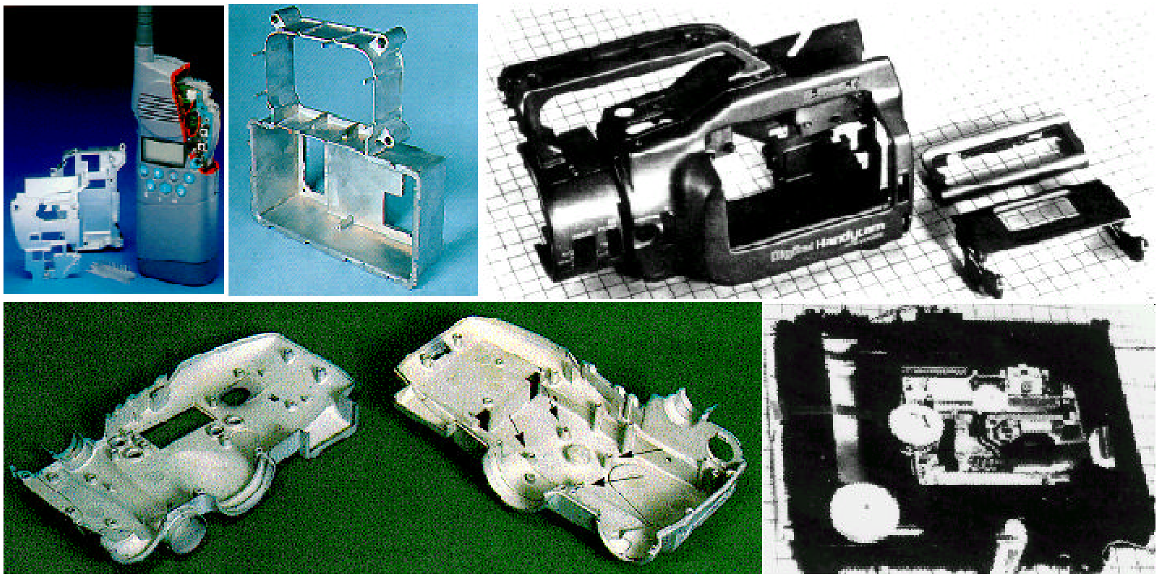
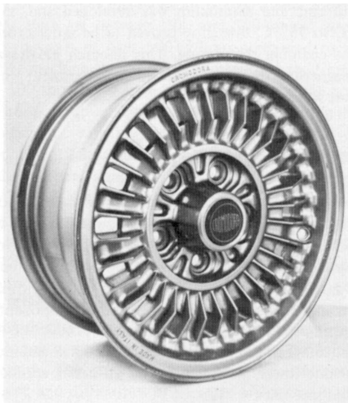
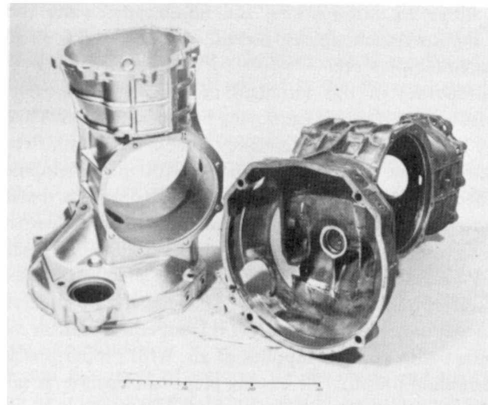


Figure 1. Examples of magnesium castings, top left - handphone chassis, top middle - thin wall chassis, top right - video camera case, bottom left - camera body, bottom right DVD chassis.

Table 2 Applications of magnesium alloys in automotive industry

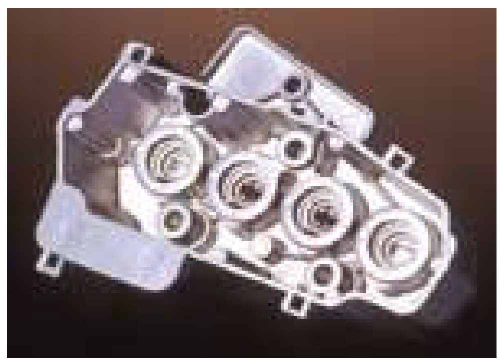
Application	Examples
Interior	Instrument Panel Structure Steering Wheel Seat Frame
Exterior	Roof Frame Door Frame Fuel Filler Lid
Chassis	Wheel Brake Pedal Bracket Brake Pedal Arm
Powertrain	Transmission Housing Intake Manifold Valve/Cam Cover





(a) Wheel [4]

(b) Transmission housing [4]



(c) Engine valve cover [5]

(d) Valve body [5]

(e) Brake support bracket [6]

(f) Parts of assembled steering column [6]

Figure 2. Examples of magnesium alloy applications in automotive industry

Compared with aluminium die casting, magnesium die casting reduces casting machine cycle time by 25% (thus 25% higher productivity) and increases die life by 2-4 times (from 150,000 to 700,000 shots). In addition, magnesium alloys also have a tighter dimensional tolerance of 0.001 mm/mm and design freedom with a smaller draft angle than aluminium (0-1.5° Vs 2-3°).

In spite of the many advantages of magnesium alloys, several aspects hinder the growth of magnesium casting industry. These consist of:

- raw alloy supply problems;
- highly unstable processing aspects;
- coating and corrosion protection requirements;
- fracture and fatigue in highly stressed structural applications;
- ageing and creep at high operating temperatures (e.g., in the extremely hostile working conditions experienced by Formula One racing cars, the average working temperatures of brakes and clutches could go up to 750 °*C* and 500 °*C* respectively, and even wheels have to endure temperatures as high as 125 °*C*);
- high cost.

The cost problem is somewhat addressed through solving the others whilst the alloy supply problems are already being eliminated by fast expansion in the magnesium smelting industry -- spurred on by the considerably increased demand. The paper will present an overall summary of the major problems tackled by PULAC and then focuses on fracture and fatigue of AZ91D alloy. The researches under PULAC can be broadly classified into the following three categories:

(1) Highly unstable processing aspects in magnesium die casting. This was studied both by extensive experimental work using a hot chamber die casting machine [7-10] and by numerical simulation [11-14]. Over the past four years, scrap rates of between 10% and 90% (typically 30%) have been reduced and stabilized to predictable and acceptable levels.

(2) Corrosion mechanisms and corrosion prevention [15-19].

(3) Mechanical properties, including tensile, fatigue and creep properties and long-term ageing behaviour [20-21]. An example of the researches in this area is given below.

The example mainly deals with fracture and fatigue behaviour of AZ91D alloy [20]. Magnesium alloys have high specific strength, but their low fatigue strength under service conditions has been a major factor in limiting the wider use of magnesium alloys in highly stressed designs. Magnesium has a H.C.P. (Hexagonal Close-Packed) crystal structure. The ductility of H.C.P. metal is usually not good compared with other metals, because it has less slip systems than F.C.C. or B.C.C. metals. Primary objective of the study was to establish microstructure-property relationship for AZ91D, which is one of the highest strength magnesium alloys.

The alloy was subjected to solution heat-treatment at 380 °C for 8 hours and then at 420 °C for 24 hours in argon atmosphere followed by water quench to room temperature. Some of the solution treated specimens were then aged at 200 °C for 24 hours in a vacuum oven.

Uniaxial tensile test was carried out at an initial strain rate of 1×10^{-4} /s using cylindrical specimens with 6 mm gauge diameter and 30 mm gauge length on an Instron machine equipped with a computer data acquisition system. Fatigue life of each of the microstructures was then characterized using cylindrical tension-compression type specimens at a fixed frequency of 25 Hz and stress ratio (R) of 0.1 using a servo hydraulic universal testing machine of 25 kN capacity in the laboratory environment.

The fatigue crack growth rates were studied using half-sized compact tension (CT) specimens as described in ASTM standard E647-93 [23]. All the specimens were optically polished using 0.5-micron diamond particles before testing. Fatigue crack growth rates as a function of the alternating stress intensity factor range ($\Delta K=K_{max} - K_{min}$) were determined on the fabricated specimens under load control mode in a servo-hydraulic machine. These tests were conducted in the laboratory air at room temperature using a sine-wave cyclic frequency of 10 Hz and a load ratio of R=0.1. The crack extension in the test specimens was monitored using a stereo microscope on the optically polished specimen surfaces. The major emphasis in these studies was laid on crack path morphology and determining the ΔK_{th} values. In order to achieve these values, all tests were started with an initial $\Delta K \approx 5$ MPa√m, and load-shedding was done in steps keeping the constant load-ratio of R= 0.1. The tests were terminated at the ΔK value where no physical crack growth could be discerned for 1 million cycles of loading.

The microstructures in the as cast, solution treated and aged conditions were studied under the optical microscope. The as-cast microstructure was observed to consist of β phase ($Mg_{17}Al_{12}$) along the α grain boundary and eutectic α phase adjacent to β phase, as shown in Figure 3. In the solution treated condition, little β phase remains at the grain boundaries. In the solution and aged condition, β phase precipitates again at the grain boundaries.

Tensile properties of AZ91D alloy in three different heat treatment conditions are shown in Table 3. It can be seen from the table that the tensile and yield strength of the material are significantly improved after heat treatment. However, the elongation to failure is lowest in the case of solution and aged condition. Under the SEM the fracture surfaces were observed to be predominantly cleavage fracture, as shown in Figure 4.

The *S-N* data obtained from the compression-tension fatigue test (Figure 5) show that the solution treated microstructure has improved fatigue strength at any given stress level as compared to as-cast or aged microstructures.

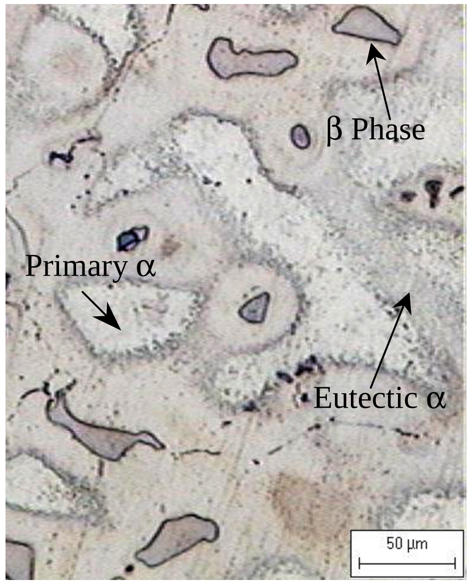


Figure 3. Optical micrograph of AZ91D magnesium alloy in as-cast condition.

Table 3. Tensile properties of AZ91D alloy in three different heat-treated conditions

Condition	0.2% Y.S (MPa)	UTS (MPa)	Elongation (%)
As-cast	112	166	5.3
Solution	124	185	8.4
Solution & Aged	155	209	3.5

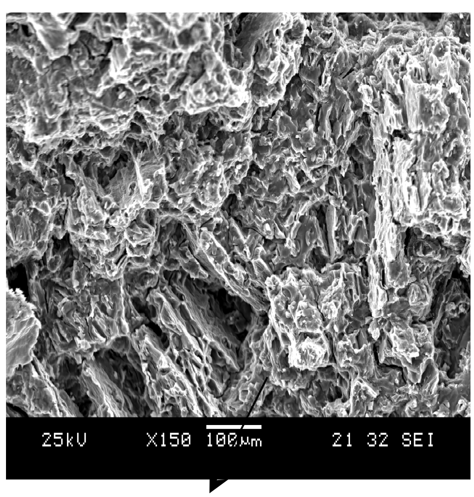


Figure 4. SEM fractograph of typical tensile fracture surface of AZ91D magnesium alloy showing predominately cleavage fracture.

The typical relationship between fatigue crack growth rate, da/dN and stress intensity factor range ΔK for aged microstructure is shown in Figure 6. The fatigue crack propagation (FCP) resistance of heat treated material is superior to that of as cast material at any ΔK region. The high FCP resistance of the heat treated material is mostly due to a larger deviation of the crack path from the maximum stress plane. The crack path divided into many branches (Figure 7(a)) as compared to as-cast material (Figure 7(b)), and the crack front no longer advanced in a planar fashion, which results in reduction of effective stress intensity at the crack tip, and hence lower crack growth rate.

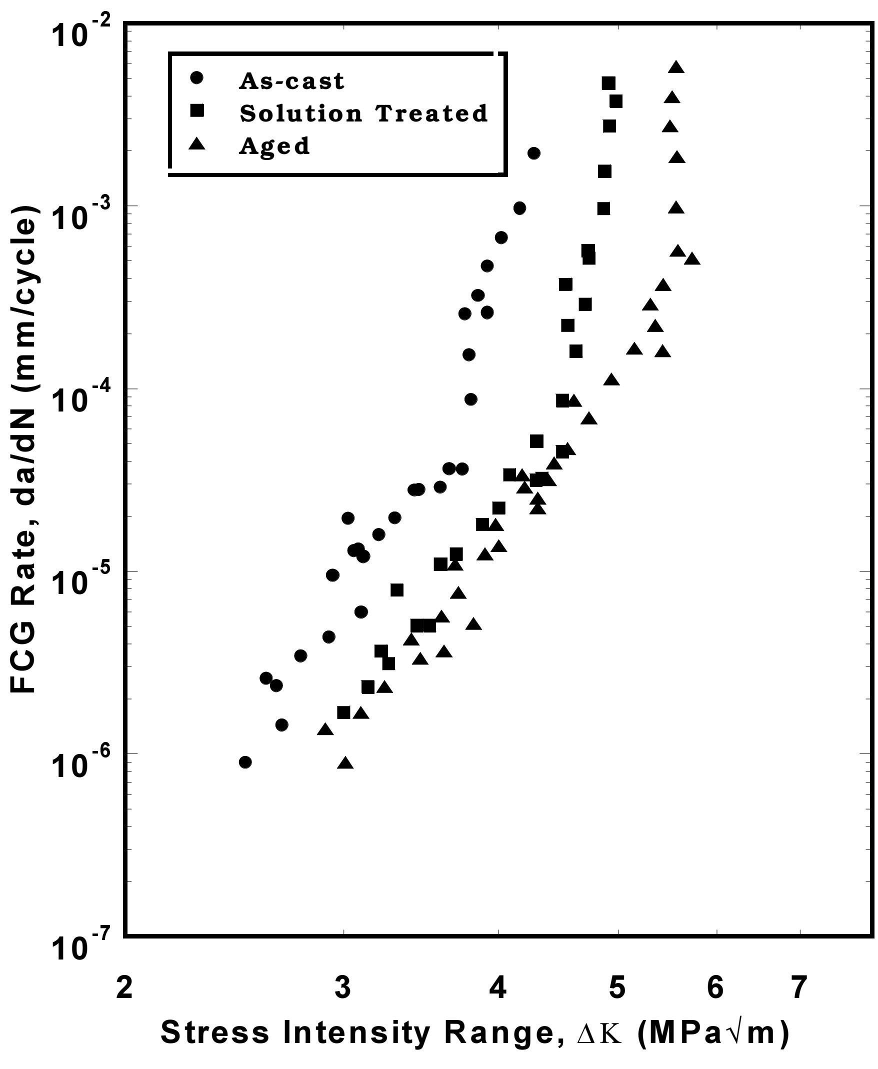


Figure 6. Variation in fatigue crack growth rate (da/dN) with stress intensity range (ΔK) for the AZ91D in three different microstructures at R= 0.1, 10 Hz, in air and at 25 °C.

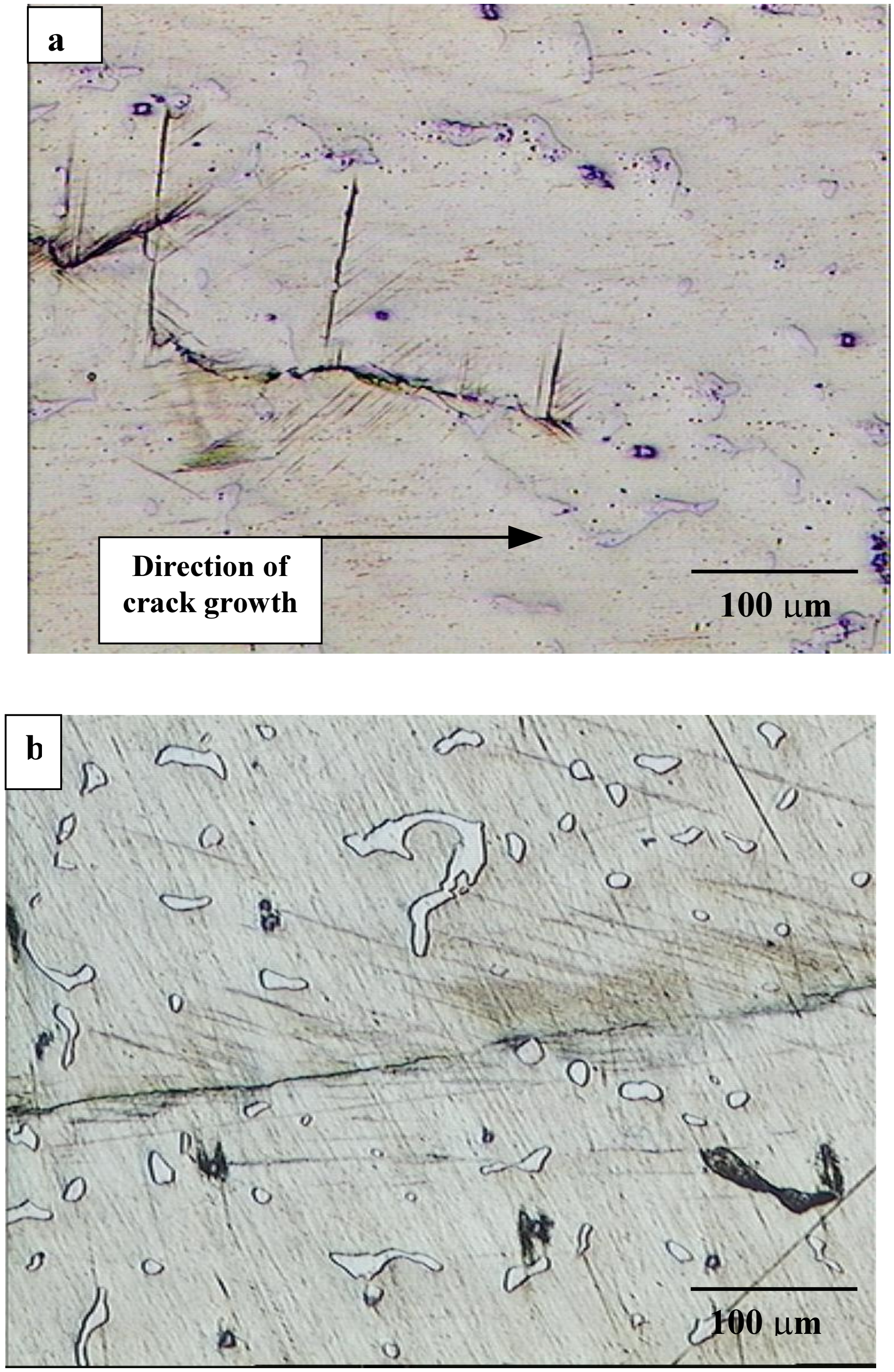


Figure 7. Optical micrographs showing fatigue crack paths formed in (a) solution treated and (b) as-cast AZ91D magnesium alloy at ΔK=3.2 MPa$\sqrt{m}$ in laboratory air at 25 °C.

It can be concluded from the above experimental results that AZ91D magnesium alloy exhibits highest elongation with moderate strength and fatigue behaviour in the solution treated condition. The superior fatigue behaviour of heat treated AZ91D alloy is mostly due to crack branching. The magnitudes of fatigue threshold of AZ91D alloy are found to lie between 2.6 to 3.2 MPa√m for the three different microstructures. It is interesting to note that if 10% SiC is added to AZ91D to produce a magnesium composite by squeeze casting then the comopsite has more or less similar fatigue threshold (ΔK_{th}) in the range between 2 and 3 MPa√m [21].

The research on magnesium die casting eventually evolved to incorporate the second stage: the simulation and modelling of industrial processes driven by additional ideas of sustainability and Industrial Ecology.

Simulation And Modelling Of Industrial Processes

The second research stage describes the use of computer simulation tools for the purpose of modelling industry as a dynamic and ecological system. Simulation models allow the reproduction of actual events and processes under test conditions. Within the model, a set of logical rules, relationships and operating procedures are specified, along with other variables. Simulation tools can be used to quantify and measure the environmental performance and the associated costs in industry, and demonstrate the potential savings or incentives achieved when implementing cleaner or greener technology [24, 25].

Case Study of A Metal Supply Chain, Singapore-Australia

A main development in this arena was the design of a complete metal supply chain, which spreads across two continents, Singapore and Australia. It starts with the Metal Supplier (Refinery and Smelter), proceeds to the Casting Plants, and finally to the End User (Market). This kind of approach focused on creating green supply chains by viewing the entire production series as a single enterprise [26, 27]. The supply chain simulation study is displayed in Figure 8. The model demonstrates the internal and external operations of two main companies, a pilot plant in Australia, and die casting company in Singapore, and how the two companies relate to each other. Analysis of the internal operations of the individual plants are modelled separately and then integrated into a complete supply chain model so that the interrelationships between the separate components of the enterprise can be established. The individual component models are detailed below.

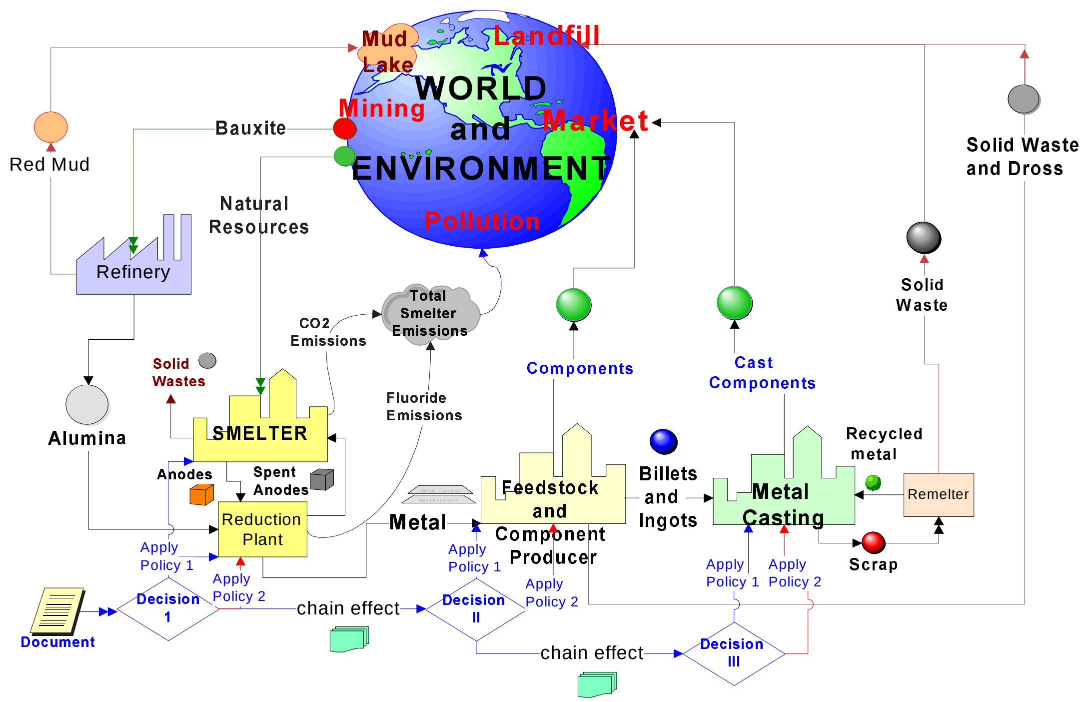


Figure 8. Case study of a complete metal production chain

ILM, Australia

This analysis involves a pilot plant, International Light Metals (ILM), based in Queensland, Australia. Within the pilot plant's casting process, various types of casting structures were available to produce cast components for filling a marketing niche where the demand for weight reduction in material is sought. This type of light metal provides a sustainable and environmentally friendly solution for improving energy efficiency in the aerospace, electronics and automotive industry. The second simulation model, displayed in Figure 9, was developed to investigate the processing of orders, in the form of billets, for the objective of meeting customer demands as well as reduced material, energy and costs.

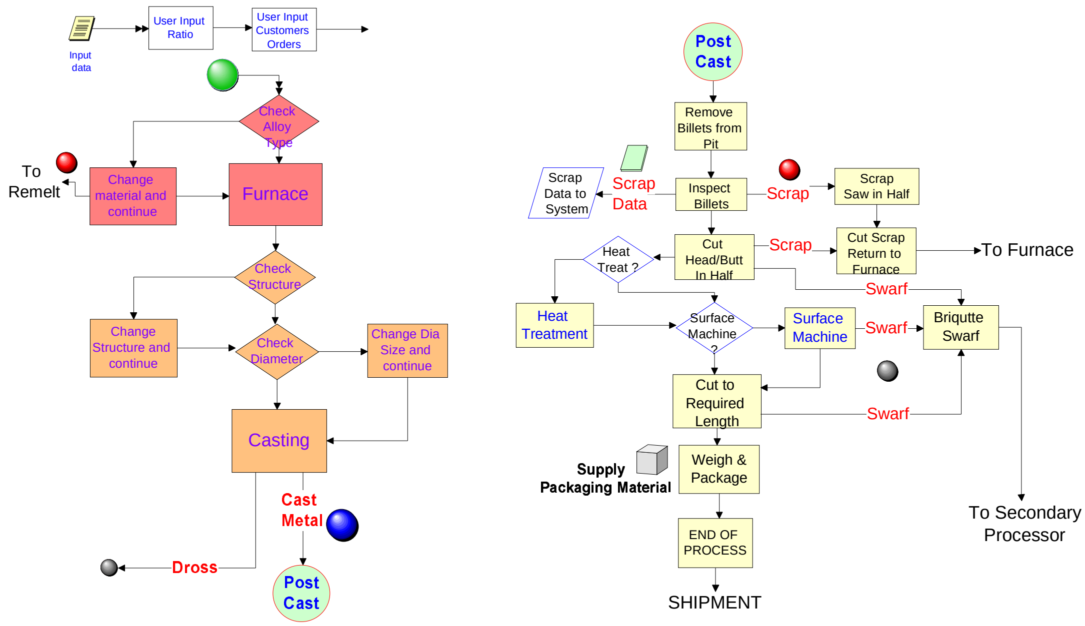


Figure 9. Simulation model of the casting plant at ILM, Australia

The simulation results of the second case study revealed how material and energy savings, as well as the reduction of machine set-up costs and production time, could be achieved from the matching of customer orders. The simulation model provided a methodology for addressing both sustainable issues and marketing needs, such as meeting Just-In-Time (JIT) demands.

DYNACAST, Singapore

The component involves a metal casting company, DYNACAST, based in Singapore. The company produced small precision components, with specialized design, tooling and production processes for aluminium and zinc components. Simulation and modelling tools were used to analyse the outcome of their production rates, scrap metal and waste generated; and establish an understanding of how high waste streams within the system may be reduced. A systems approach was used to develop a holistic view of the enterprise, starting from decision making at the top management level, and determine how these decisions affect the operational changes at the manufacturing level. The simulation model, shown in Figure 10, was used to generate the essential information required to achieve the targets of reduced inventory levels and material cycle time and costs.

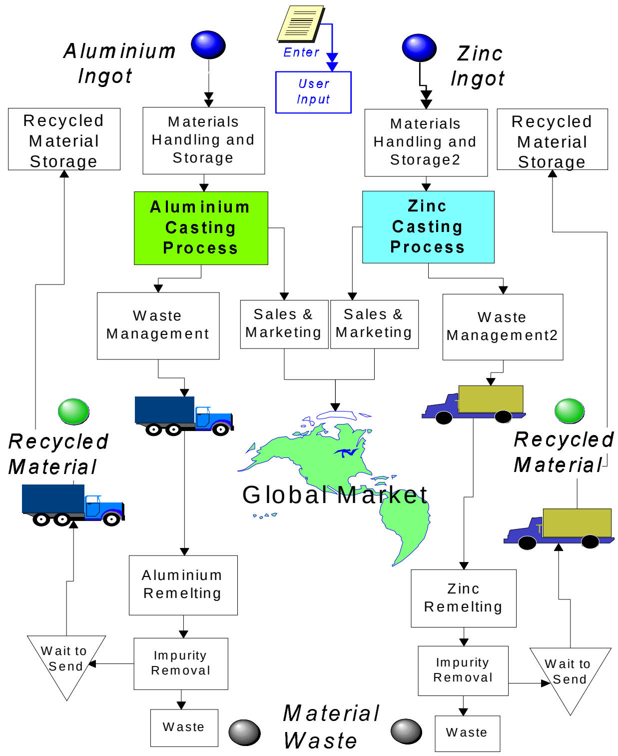


Figure 10. Simulation models of casting processes

In the study of ILM, the simulation results demonstrated the possible areas of cost savings when material was used more efficiently. The study illustrated how sustainability could fit with the overall policy of better material handling and consumption, thus resulting in reduced waste, increased productivity and reduced operating cost. It was proposed that due to heightened business competition, sustainability should be integrated into the objective of developing an efficient and lean enterprise.

Discussions

In the case studies, simulation tools were used to "operationalise" casting processes (operating time, flow of material, etc) and sustainability rules (energy, wastes, etc). This type of tool is especially appropriate for problems where uncertainty, such as random activity timings, regarding states and inputs can be modelled probabilistically. The robustness and integrity of the approach can be further enhanced by incorporating intelligent and interactive systems into the simulation models.

The integration of artificial intelligence and soft computing techniques into simulation models provides mechanisms for the models to “learn” from a dynamic set of input conditions the operating conditions which optimise the environmental performance of an enterprise. This type intelligent simulation model has the ability to evolve with the company activities and its environment [28].

Intelligent Simulation provides an opportunity to develop a balanced scorecard approach to defining key performance measures in terms of quality, cost, productivity and environmental sustainability. Enterprise Resource Planning (ERP) systems which provide and integrated information and control system for enterprises and their supply chain offer the potential or also managing and controlling the environmental performance of an enterprise once the key environmental measures and then relationship to the other performance measures have been established.

An exiting prospect here is that the new generation of simulation modelling packages offer "hooks" to facilitate on-line data acquisition data from ERP systems and hence generate a real-time simulation of the activities of an enterprise. The simulation model can then be "fast forwarded" into the future to obtain operational and strategic measures of environmental performance in relation to the other key performance drivers of the enterprise.

Future Research And Development

The evolving programme of research on Asset Sustainability at the Environmental Research Institute, National University of Ireland – Cork, builds on work by various research teams and researchers of the Environmental Research Institute: in the Department of Civil and Environmental Engineering on the sustainable management of water resources in Cork City [29] and of buildings and their construction process by the Informatics Research Unit for Sustainable Engineering (IRUSE) [30]; on food packaging in the Department of Process Engineering [31]; and on research detailed below at the Cleaner Production Promotion Unit (CPPU) [32].

This section of the paper will concentrate on work undertaken by CPPU as the most immediately relevant to the research carried out by the co-authors of this paper. CPPU's research related to Asset Sustainability is based on waste minimization; product design and life cycle management; material flows analysis; the analysis and control of industrial environmental risk; and the sustainable development of regions. Underlying this work is an understanding of Sustainable Development as integrating economic, environmental and socio-cultural factors for industrial performance optimisation.

In the early 1990s CPPU coordinated EU-funded research, by an international consortium comprising the International Institute for Industrial Environmental Economics in Lund, Sweden, the Polytechnic of Milan, Italy and UCC, into the end-of-life management of complex durable products [33]. This research re-conceptualised products at end-of-life not as waste or waste products but as a combination of materials that in themselves are at various stages of their own life cycles. This implied a paradigm shift from the then conventional, and still prevalent, understanding of production as a linear process of a product's life from cradle-to-grave.

Figure 11. Linear process of product

The new paradigm requires a more dynamic understanding of the production process, embedded in the product's life as a cycle, affording multiple opportunities during the product's life, including design and manufacture, for intervention to recover, re-use, dis-assemble, re-manufacture and re-cycle the constituent materials and components of the product. Most important among these opportunities is the opportunity for designers of both product and production process to avail of the information provided by analysis of the environmental impact of the product throughout its life and including end-of-life. (See Figures 11 and 12).

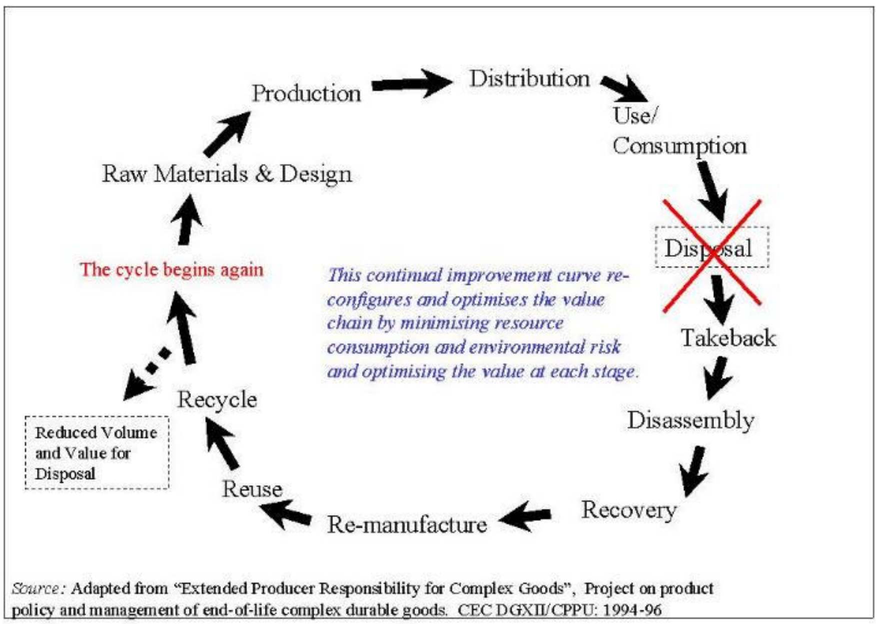


Figure 12. Cyclical process of product

CPPU has since the early 90s applied a systems approach to the reduction at source of environmental risk in various sectors of manufacturing, service and agricultural enterprise. As a consequence, CPPU focused its research on the theme of Asset Sustainability in the following ways.

CPPU addresses the relationship between how an asset – a town, a service unit such as an hotel, or an industrial enterprise – metabolises its materials and energy flows and the economic, environmental and socio-cultural context within which it operates with the objective of optimising the sustainable development of that asset. Most research on material flows analysis has been done at the level of nation states or regions. In its research on Sustainable Destinations [34] CPPU is adapting material flows analysis to the micro-level in two case studies, a tourist caravan park as a service industry site and a small town as a tourism destination, both in the south-west of Ireland.

CPPU analyses the environmental risk associated with a particular asset – a town, a building, an industry, an industrial manufacturing site, a supply-chain or a socio-geographic region - and identifies the points at which control of these risks must be exercised [35]. A research pilot in a major food processing plant led to the development of a tool, ERACCP (Environmental Risk Analysis Critical Control Points), which consciously mirrors the HACCP (Hazard Analysis Critical Control Points) approach widespread in process industries, e.g., the pharmaceutical and food processing sectors, but adapts it for environmental concepts and risks which are very different from those pertaining to product safety and quality issues.

CPPU's work on sustainability profiling of materials and components used in building construction is of particular interest as a construction site combines the characteristics of a manufacturing and a service industry [36].

This theme of CPPU research supports that by other UCC research teams referred to above in providing a platform from which the ERI can collaborate with the co-authors of this paper in furthering research on Asset Sustainability.

The UCC ERI programme is focused on underpinning the sustainable development of assets, where an asset may be a product, a technology, an industry, a supply chain, a city, a socio-geographic region or indeed natural capital. As such the programme meshes well with the evolution of the materials engineering/Industrial Ecology simulation and modelling/ERP systems approach detailed in the preceding sections of this paper.

The programme will address key stages of material flows in an illustrative range of business applications to investigate optimal routes to Asset Sustainability: sustainable products – design for environment (DFE), light weighting, de-materialisation, life-cycle performance of materials; sustainable packaging – design for end-of-life (EOL) management; sustainability evaluation of construction materials and components; evaluation of emergent re-cycling, re-use technologies, e.g. Advanced Fluidised Composting, heat/pressure conversion technologies; use of Virtual Reality technology and techniques as an integrative ICT tool for planning, decision-making and public education

An exciting dimension of the ERI research [37] is the development of Virtual Reality tools that focus on decision-making for prediction, minimisation and control of environmental risk; deliver rapid, flexible resolution of complex, differentiated data sets into a range of scenarios that provide an instantaneous basis for decision-making and can be adapted as an effective training tool. The research addresses the integration of data sets from current and emerging environmental risk management tools with virtual reality technology and expertise on multiple issues and levels – community/society, single or series of enterprises, product or process life-cycles for goods and services, etc. This innovative approach represents the potential to progress from decisions made on the basis of an iterative “What if” analysis to decisions made on the basis of a virtual scenario planning system.

Conclusion

This papers describes research which began in PULAC, Singapore, in 1997, proceeded to include ILM of Queensland, Australia, and DYNACAST in 1999/2000 and next, further work at Central Queensland University has been performed to generalising these approaches. The research work has now linked to Cork, Ireland in 2002 – with other threads in Greenwich, England and Harvard, USA. It represents, we suggest, an interesting international programme which contains within its approach an underlying thread of industrial sustainability. The initial research stage involved work carried out on the structural integrity and high pressure die casting of magnesium alloys, which was driven by the need for the lightweighting of vehicles to reduce fuel consumption and thus overall carbon mitigation. This has resulted in a series of papers as referenced including a new review on Ultra Light Alloys in Vehicles. The first stage eventually evolved into the second stage – a new arena on simulation and modelling of industrial processes, driven by sustainability and Industrial Ecology. This work is also continuing. The third section outlines a new application of the work in the Environmental Research Institute at University College Cork relating to cleaner production. There exists an interesting evolution and coherence in this pattern of work which has the potential to generate new approaches to the theme of "industrial and asset sustainability and integrity".

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