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Deformation and Fatigue Behaviour of Aluminium Alloys for High Specific Power IC Engine Applications

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Abstract

The development towards higher specific power and lower displacement engines in recent years has placed increasingly high thermal loads on the internal combustion engine materials. Further, the advent of hybrid power trains placing higher demands on quick starts and a rapid approach to maximum power necessitates the automotive industry to move towards a more robust computational thermo-mechanical fatigue life prediction methodology to develop reliable engines and reduce developmental costs. The cylinder heads of the internal combustion engines are often made with primary A356 cast aluminium alloys subjected to an ageing (T7) heat treatment. The overarching goal of the research work is to develop a deeper understanding of the continuum deformation and fatigue behaviour of the improved A356-T7+0.5 % Cu aluminium alloy. Understanding the influence of various factors on the mechanical properties of the cast aluminium alloy should enable improved thermo-mechanical fatigue prediction methodology of the highly loaded engine cylinder heads using computer aided design methods.

Samples for testing are extracted from the highly loaded valve bridge regions of specially cast cylinder heads. The deformation and fatigue behaviour of the alloy is predominantly determined by the cast microstructure characterized by the dendritic arm spacing, the size of the secondary precipitates, the defect distribution and by the temperature during deformation. The scope of this study covers uniaxial isothermal tests to establish the cyclic deformation behaviour and fatigue properties of the alloy at temperatures ranging from ambient temperature up to 250 °C. The material exhibits decreasing strength and increasing ductility with increasing temperatures under monotonic loading. The material exhibits cyclic hardening at room temperature for all tested load levels and cyclic softening with strain load cycles at all the elevated test temperatures of 150, 200 and 250 °C. The material exhibits yield strength and peak stress asymmetry under cyclic loading with the stress response in compression higher than in tension under fully reversed strain controlled cyclic load cycles at all load levels. Mean stress relaxation is observed in the material for all test temperatures when run with a tensile or compressive mean strain. Tensile mean strain has a deleterious effect on the number of cycles to failure at temperatures below 200 °C.

Hold time effects mimicking the in-service loads (dwell in compression loading for 10 minutes or 1h) are examined to study their influence on the deformation and fatigue behaviour of the alloy. The material exhibits a significant stress relaxation during the dwell periods at all temperatures and load levels with a rapidly decreasing stress relaxation rate. The dwell times at constant compressive strains have no discernible influence on the following cyclic hardening behaviour or the fatigue life of the material, even at elevated temperatures. The visco-plastic deformation behaviour can be modelled using a combination of the Chaboche combined non-linear kinematic and isotropic mixed hardening model and the rate dependent Cowper-Symonds overstress power law model. The role of artificial and natural ageing is explored and both time and temperature associated changes in the microstructure result in transient states of both the continuum deformation and fatigue behaviour of the alloy. The effect of strain rate on the cyclic deformation behaviour of the alloy is studied by testing at strain rates of 1% s^{-1} and 10% s^{-1} at room temperature, 150 and 200 °C. The influence of the strain rate on the cyclic peak stress development is small, but it has a significant influence on the development of cyclic mean stress, especially at room temperature. Fractographic investigation of the fracture cross-section highlights the role of porosities, silicon rich phase in the eutectic region and the intermetallics on the crack initiation process. The larger precipitates are preferentially cracked highlighting the importance of refining the microstructure and minimizing the shrinkage porosity.

Keywords: cylinder head, aluminium, A356, mechanical behaviour, fatigue, constitutive models, thermo-mechanical fatigue, ageing.

In “god” we trust, all others must bring data.

– Dr. W. Edwards Deming

Preface

This work was carried out at the Department of Industrial and Materials Science, Chalmers University of Technology, Gothenburg, Sweden between April 2015 and July 2020 under the supervision of Professor Christer Persson and Professor Johan Ahlström.

The research was financially supported by FFI and Volvo Cars under the project 'Utveckling av analysmodeller för termomekanisk utmattning', project no 37807-1.

The doctoral thesis is based on a summary of the research papers by the author. A general introduction to the topic, placing the presented work in context and the following publications or manuscripts at various stages (in press, submitted, or in draft) are presented.

List of appended papers

A. Deformation and Fatigue Behaviour of A356 - T7 Cast Aluminium Alloys Used in High Specific Power IC Engines.

Elanghovan Natesan, Johan Ahlström, Stefan Eriksson, and Christer Persson
Journal article: Materials 2019, Vol. 12 (18), 3033.

B. Effect of Temperature on Deformation and Fatigue Behaviour of A356 - T7 Cast Aluminium Alloys Used in High Specific Power IC Engine Cylinder Heads.

Elanghovan Natesan, Johan Ahlström, Stefan Eriksson, and Christer Persson
Journal article: Materials 2020, Vol. 13 (5), 1202.

C. Evolution of Yield Surface and Stress Asymmetry in A356 - T7 Cast Aluminium Alloys Used in High Specific Power IC Engine Cylinder Heads.

Elanghovan Natesan, Johan Ahlström, Stefan Eriksson, and Christer Persson
In manuscript.

D. Effects of Dwell Time on the Deformation and Fatigue Behaviour of A356 - T7 Cast Aluminium Alloys Used in High Specific Power IC Engine Cylinder Heads.

Elanghovan Natesan, Knut Andreas Meyer, Johan Ahlström, Stefan Eriksson, and Christer Persson
Journal article: Materials 2020, Vol. 13 (12), 2727.

E. Effect of Strain Rate on the Deformation Behaviour of A356 - T7 Cast Aluminium Alloys at Elevated Temperatures.

Elanghovan Natesan, Johan Ahlström, Swathi K. Manchili, Stefan Eriksson, and Christer Persson
Journal article: Metals 2020, Vol. 10 (9), 1239.

F. Effect of Natural and Artificial Ageing on the Deformation and Fatigue Behaviour of A356 - T7 Cast Aluminium Alloys Used in High Specific Power IC Engine Cylinder Heads.

Elanghovan Natesan, Monika Vogler, Adrianna Lozinko, Stefan Eriksson, Johan Ahlström and Christer Persson
In manuscript.

Contribution to the appended papers

I. The author planned and performed the experimental and modelling work and wrote the paper in cooperation with the co-authors.

II. The author planned and performed the majority of the experimental and modelling work and wrote the paper in cooperation with the co-authors.

Ageing studies were performed by M.Sc. Monika Vogler, University of Stuttgart, Germany.

Dilatometric tests were performed by Dr. Johan Wendel, Chalmers University, Sweden.

III. The author planned and performed the experimental work and wrote the paper in cooperation with the co-authors.

IV. The author planned and performed the experimental and modelling work and wrote the paper in cooperation with the co-authors.

V. The author planned and performed the experimental and modelling work and wrote the paper in cooperation with the co-authors.

Electron Microscopy work was performed by Lic. Eng. Swathi Kiranmayee Manchili, Chalmers University, Sweden.

VI. The author planned and performed most of the experimental work and wrote the paper in cooperation with the co-authors.

Ageing studies were performed by M.Sc. Monika Vogler, University of Stuttgart, Germany.

Heat Treatment for samples used for mechanical testing was performed by Lic. Eng. Adrianna Lozinko, Chalmers University, Sweden.

Contents

Chapter 1

Introduction

1.1 Background

"Modern technology has become a total phenomenon for civilization, the defining force of a new social order in which efficiency is no longer an option but a necessity imposed on all human activity" said the famous French philosopher Jacques Ellul. The industries of the world have constantly strived to increase their energy efficiency and move towards renewable and more sustainable sources of power with the glaring exception of the transportation industry over the last few decades [1].

Mechanical power trains with more than 150 year old internal combustion engines (ICE) have remained largely inefficient with average efficiencies of about 20 % [2]. With the ever tightening environmental regulations since the 1970s in Europe and around the world [3] to improve the quality of ambient air with a focus on urban air quality in particular, auto manufacturers have been increasingly looking at electrification of the vehicle power trains to meet the emission norms [4], [5]. The Volkswagen emissions scandal has brought about a renewed focus on the topic of air pollution from combustion engines and its consequences on public health and the environment [6]. While the concept of electric or electrified powertrains have been around for well over a century [7]–[9], the advent of electric powered means of private transportation has been hindered primarily by the prohibitively expensive prices, the size and capacity of the traditional batteries coupled with long charging durations and several other practical challenges [1], [8]. Remarkably, electric cars were a third of all road vehicles sold around the 1900s in the USA [8] at a time when the society was gradually moving away from horse drawn carriages with steam powered, electric and internal combustion engine cars getting increasingly popular. While the steam powered cars were notoriously difficult to operate, the internal combustion engine cars with their manual cranks, difficult to operate gear system and noxious fumes were not too popular either. Electric cars were getting increasingly prevalent owing to their ease of use and practicality before the introduction of the first mass produced internal combustion engine car, the Ford Model T that made personal vehicles accessible to the general public with its significantly lower cost. Coupled with the introduction of the electric starter motor by Charles Kettering obviating the need for hand cranks in ICE cars and the cheaper and more easily accessible petroleum fuel products in comparison to electricity that was only available in the cities, there was a gradual decline in interest in electric powered cars until they virtually became non-existent by 1935 [8]. While there was a brief resuscitation of interest in the electric and hybrid technology during the 1973 oil crisis [10], the eventual stabilization of the oil prices and the underperformance, limited range and still prohibitive cost of manufacturing electric vehicles ensured that the idea of electrified powertrains never took off [8]. Continuing technological advances in the battery technology primarily driven by the consumer electronic industry, and especially those that of the lithium ion chemistry and solid state batteries, has been leading to a gain in traction of battery electric vehicles in recent years [11], [12]. Developments in both lithium ion chemistry and the solid-state battery arenas will only improve the outlook for hybrids and electric vehicles.

1.2 Challenges in Complete Electrification & Hybrid Technology

The primary challenges in complete electrification is the cost of the batteries used in the vehicle, range anxiety, charging infrastructure and need of specialized charging stations to have shorter recharge time, the cost and sustainable mining of the rare earth elements used in the batteries, battery recycling among others [13].

Hybrids offer a desirable balance owing to their high performance, lower cost of operation and the ability to run with petroleum fuel thus mitigating the range anxiety that has proved to be one of the biggest obstacles in complete electrification of our vehicles. With increasing oil prices, governments worldwide are offering subsidies and policy changes to help adopt electrified vehicles faster. Unlike conventional combustion engine cars, performance does not come at the cost of fuel efficiency and air pollution in hybrid vehicles. They currently offer a more practical solution to the transportation problem compared to bio-fuel and hydrogen powered vehicles. While future vehicles will probably, to a large degree, be electrified, hybrids offer a perfect balance between the worlds old and new. As part of the new adoption of wide scale hybrid powertrains, automakers are continually looking at engine downsizing and induction charging techniques to reduce the weight and increase efficiency and performance simultaneously.

1.3 Aim of the Study

This constant drive towards higher specific power and lower displacement engines in recent years place increasingly higher thermal loads on the internal combustion engine materials. Further, the advent of hybrid power trains placing higher demands on quick starts and a rapid approach to maximum power necessitates the automotive industry to move towards a more robust computational thermo-mechanical fatigue life prediction methodology to develop reliable engines and reduce developmental costs. The study aims to develop a wide-ranging understanding of the material deformation and fatigue behaviour under service-like loads to enable reliable development of constitutive and lifetime prediction models to help predict the thermo-mechanical fatigue life of the highly loaded engine cylinder heads used in the new generation of hybrid power trains.

Chapter 2

Thermo-Mechanical Fatigue

2.1 Fatigue: An Introduction

Repeated loading of engineering structures, even at load levels much lower than a material's yield strength, can lead to microstructural damage initiation and accumulation leading to fatigue failures. An estimated 80% of all structural failures have some contribution from fatigue related damage and its cost, amongst industrialized nations, is estimated at about 3% of their GDP [14]. Owing to engineering efforts in the last 150 years, fatigue is a well explored subject with broadly three different approaches adopted for designing structures against fatigue failure [14], namely:

- stress based approach that uses the nominal stress in the region of interest,
- strain based approach that takes a more detailed look at localized plasticity,
- fracture mechanics approach that explicitly deals with the growth of cracks.

The development of numerical simulations and the incredible leaps made in computing technology in the last decades have enabled engineers to compute structural responses and predict component life in vastly shorter times.

2.2 Thermal Fatigue in IC Engine Cylinder Heads: An Introduction

2.2.1 Thermal Fatigue

Spear [15] in his introductory text on the topic, describes thermal fatigue as "a gradual deterioration and eventual cracking of a material by alternate heating and cooling during which free thermal expansion is partially or completely constrained." It can broadly be classified under the term 'low cycle fatigue', as thermal fatigue often involves significant plasticity in the material and cracks often initiate and grow after a few thermal load cycles in the material.

2.2.2 Thermo-Mechanical/Thermal-Stress Fatigue

The constraint to free thermal expansion/contraction is a key element of thermal fatigue in materials. In an engineering component operating at elevated temperatures, this resistance to free thermal expansion/contraction comes from the surrounding adjacent volume of material that could:

1. Have a different temperature than the material volume in focus, or
2. Have a different co-efficient of thermal expansion by virtue of a different chemical makeup
3. A combination of both.

Such constraints to thermal expansion/contraction are often observed in components operating at high temperatures and those which are subjected to rapid thermal heating-cooling cycles, often by fluids used for operation that are in direct/indirect thermal contact with the material volume [15], [16]. Such fatigue in material structures are referred to as "Thermal-Stress Fatigue". Such failures are often termed "Thermal Shock" if the failure is from a single cycle of severe thermal stress and "Thermal Fatigue" if the failure is attributed to several thermal stress cycles [17]. Interestingly, Boas et al. [18] showed that anisotropic materials can exhibit thermal fatigue failures through self-generating internal thermal stresses from heating-cooling thermal cycles, even without thermal gradients in the material test volume or the presence of external deformation constraints. This highlights the role of differential thermal expansion/contraction, even at sub-micron levels, inducing damage and failure of the material when subjected to cyclic thermal stresses.

To study thermal fatigues in a laboratory setting, external constraints are often placed on the test specimens that are subjected to thermal cycles as a convenient way to generate thermal stresses in the material. This helps with an alternative and easier way to simulate the "internal" constraints to thermal expansion/contraction observed in real life engineering structures. Such testing is referred to as "Thermo-mechanical fatigue testing", and has evolved from the first reported test apparatus by Coffin [19] with simple semi-rigid test frames that only constrained the specimen ends, to the more advanced modern variations with servo-hydraulic systems which enable us to apply complex temperature and/or force/strain load cycles independent of each other.

2.2.3 Thermal-Stress Fatigue in Cylinder Heads

A cylinder head is part of an internal combustion engine and sits on top of the engine cylinder block as illustrated in Figure 1. It serves as the upper deck of the combustion chamber and houses the cam shaft, inlet and exhaust valves, cooling channels and other assorted components. It also serves as a passageway for the inlet and exhaust gases. Further, with non-uniform engine/cylinder head cooling, variations in the combustion flame front, variations in surface geometry of the cylinder head flame deck, etc., different parts of the cylinder head experience different temperature cycles during a typical operation [20]. Thermal-stress fatigue damage is induced in cylinder heads during the engine start-run-stop thermal cycles. The cylinder head material experiences steep thermal gradients in the structure that cause cycles of alternating tensile and compressive stresses that progressively damage the structure leading to an increased risk for premature crack growth and structural failure [21]–[24].

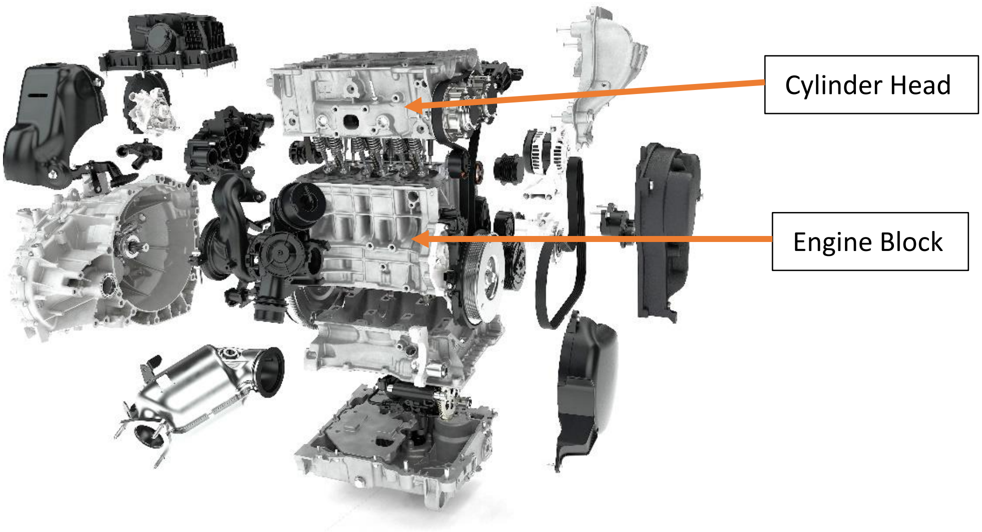


Figure 1: Internal combustion engine architecture. [Source: Volvo Cars]

The temperatures in parts of a cylinder head can surpass 230 °C during operation [20] and during winter months, the cylinder head material can get cold to temperatures well below 0 °C. When such start-run-stop cycles are repeated, we induce thermal damage to the structure that could lead to gradual loss of combustion pressure and eventual structural failure [20], [21]. This problem is further aggravated in the new generation of hybrid engines, where there is a stronger emphasis on rapid approach to maximum power coupled with the magnitudes higher start-stop cycles compared to conventional IC engines.

Besides the thermal loads associated with the combustion processes and the stresses in the material owing to steep thermal gradients, a cylinder head material should also support the mechanical assembly loads from bolts, gaskets, and operational mechanical loads from the valve operations that load the cylinder head through the valve seats [25]. Consequently, the cylinder head undergoes high cycle fatigue (HCF) associated with the combustion cycles at a loading frequency corresponding to the engine rotational speed [26] and low cycle fatigue (LCF) associated with the engine start - stop cycle that is a combination of the thermal and mechanical loads resulting in thermo-mechanical fatigue failures (TMF) [25], [27], [28].

Chapter 3

Thermo-Mechanical Fatigue Life Prediction – A Literature Review

3.1 Design Methodology of Structures Subjected to Thermo-Mechanical Loads

Physical TMF testing of cylinder heads is an expensive routine and so, development of a reliable simulation model is desirable to reduce developmental times and associated testing costs. Thermo-mechanical fatigue life prediction using computer aided engineering (CAE) methods can broadly be brought under the umbrella of the three following steps [21]:

1. Thermal analysis
2. Mechanical structural stress-strain response analysis
3. Fatigue life prediction

For IC engine cylinder heads, the transient temperatures associated with the start-run-stop cycles induce the low cycle, TMF crack initiations. So, combustion simulations involving computational fluid dynamics (CFD) to determine the transient thermal loading in a cylinder head forms a vital first step and is described under the umbrella term “thermal analysis”. The results of this step set important boundary conditions for the final thermo-mechanical fatigue life prediction [29].

This study focusses on the subsequent two steps, namely, of the mechanical response of the structure to the transient thermal loads and the fatigue behaviour of the material in the operating conditions expected in the cylinder head.

During a typical TMF load cycle, the temperature of different parts of the structure varies from ambient to several hundred degree Celsius and since the material’s mechanical behaviour varies with temperature, it is imperative to create temperature dependent constitutive and fracture models from the ambient to the maximum temperatures in the structure expected during operation to get reliable simulation results [28], [30], [31]. To model the mechanical behaviour of the structure, one tactic is to take a micro-mechanical approach that relates to the behaviour of the material at microstructural level. But it is often intricate and computationally expensive in an industrial context [30]. This study instead uses the other popular technique of macroscopic, phenomenological approach that is a much faster and computationally inexpensive method in comparison.

As there is significant plastic deformation during the thermo-mechanical loading of the structure, a strain-life approach is often taken to model and predict the fatigue life of the cylinder heads [14], [28]. Since the strain based approach could also be used for long lives with mostly elastic deformation, it is a wide-ranging methodology [14] and is the topic of interest in this study. The strain-based approach to predict the fatigue life employs the strain life Coffin-Manson type model. It is especially suitable for applications that involve cyclic loading associated with thermal stresses and strains [14].

Thermo-mechanical life prediction by Thomas et al. [21] involved a comprehensive approach starting with thermal analysis to obtain the load history which was then combined with an elasto-viscoplastic mechanical analysis to predict the structural response. This was then used to predict the crack initiation points by using a suitable damage criterion coupled with fatigue life models. The prediction of the cylinder head life under thermo-mechanical loads is vital before the commencement of the mass production process. The temperatures in the cylinder head can vary from the environmental temperature in cold climates to over 250 °C in highly loaded areas. To make things complicated, literature and internal studies have shown that the material exhibits an ageing behaviour at temperatures above 150 °C [21], [32]. Often, in modelling, a stabilized response of the material is assumed. But with ageing, studies have shown the effect on the life curves for instance [33], [34] and this muddles the process even further. To keep the simulations at a complexity level that is suitable in an industrial context, certain simplifications need to be made in the simulation process to obtain workable results [21].

A thermo-mechanical fatigue life prediction simulation can be briefly condensed to the following steps according to Thomas et al. [21]:

- Choosing appropriate cyclic visco-plastic model and calibration of the model parameters using isothermal and non-isothermal tests.
- Modelling of the ageing behaviour of the alloy.
- Choosing a suitable fatigue criterion based off isothermal and non-isothermal uniaxial tests with suitable loading conditions.
- Finite element simulation of the structure or sub-structure with realistic load and boundary conditions. The accuracy of the prediction is heavily influenced by the load and boundary conditions used when the constitutive and fatigue models are suitably calibrated.
- Use the chosen damage and fatigue criterion to analyse the structural response and determine the thermo-mechanical fatigue life of the component.

While in real life these scenarios play out simultaneously, to reduce the complexity of the simulation process, a decoupled approach is often suggested and has shown to give satisfactory results [21], [28], [35]–[37]. So, the thermal analysis and the mechanical analysis are handled separately and in the structural simulations, a further decoupling is assumed between the various phenomena, for example, the ageing evolution and the mechanical behaviour, the constitutive behaviour and the fatigue life modelling.

3.2 Constitutive Modelling

Since the thermal fatigue in the cylinder heads is fundamentally associated with the thermal loading associated with the engine start-stop, it is imperative to model the behaviour at elevated temperatures where the flow stresses are significantly lower than at room temperature. Dwell times enhance time dependent relaxation of the material and the cyclical nature of the thermal loads lead to high stresses and plasticity in confined regions like the exhaust valve bridges. This necessitates a visco-plastic model that is temperature dependent. To simplify the simulations, the visco-plastic model does not need to include damage accumulation as several previous studies [21], [38] have showed that such a coupling is often unnecessary and often leads to difficulties in parameter calibrations and lengthy calculations without any improvement in the life estimations. The calibration can often be done on steady state cycles and the constitutive law should be robust enough to allow large time step integrations [21].

3.3 Fracture Modelling

The failure criteria in a thermo-mechanical context should be capable of predicting failures in applications with transient operating temperatures and isothermal loads under uniaxial and multi-axial load conditions [23]. Once the mechanical response of the structure has been determined using the load history, the natural ensuing step in the design cycle is to determine the life of the component using a pertinent fatigue life criterion. While the constitutive behaviour could be coupled with the material damage in the material model, it is unnecessarily complex without offering any improved life prediction [21]. Hence, a decoupled constitutive behaviour and fatigue life modelling is often adopted in the industry.

Due to the multiaxial and anisothermal nature of the real life structural loads in a thermo-mechanical fatigue context, there is a continuous discussion over the suitability of multiple different techniques that can be used to predict the life of the components once the stress and strain history of the geometry is known. Coffin-Manson parametric models based on the plastic strain amplitude ($\Delta\varepsilon_{pa}$) have historically been used for fatigue life determination in the low cycle fatigue regimen. To account for mean strain and stress effects, the Smith-Watson-Topper [39] revisions or the Ostergren fatigue criterion applying the maximum tensile stress are often used in the fatigue criteria. These laws are empirical in nature and work well for most engineering metals but, do not have direct physical couplings in terms of deformation and fracture. Generalization of these classical laws for multi-axial and anisothermal loads can often be tedious because of the varying yield in isothermal conditions and with them not being intrinsic in general [37].

To tackle such issues, Morrow et al. [40], [41], Benham et al. [42] pioneered the use of an energetic criterion for determining the fatigue lives of engineering metals. Broadly speaking they propose quantitative relations between the plastic strain energy (per cycle or the total plastic strain energy) to the fatigue life of metals with the assumption that the plastic strain energy in cyclic loading is a measure of the fatigue damage. Subsequently many researchers have studied the suitability of the energy criterion in a TMF context with varying temperatures and mechanical loads. Charkaluk et al. [21], [37] propose dissipated energy per cycle from the saturated state as a more suitable and better fatigue criterion for the multi-axial anisothermal loads in the cylinder head compared to the classical Coffin-Manson or Ostergren fatigue criteria. In order to account for strain rate effects in TMF, Takahashi et al. [31] propose using the dissipated energy rate per cycle as a suitable criterion for complex loads with different loading rates. Energetic approaches despite being deemed suitable for anisothermal and complex multi-axial loads are often criticized for failing to distinguish between the dissipated heat energy in a load cycle and the portion contributing to tangible material damage [37].

Chapter 4

Material: Cast Aluminium Alloys

4.1 Aluminium Alloys: An Introduction

Aluminium alloys are extensively used in structural components owing to their low density, good thermal and electrical conductivities, good corrosion resistance and a number of other desirable properties, but, are often limited in their use in high temperature applications owing to their low melting point [43]. The mechanical properties can be tailored with alloying and cold working, with most alloyed materials being capable of heat treatment through precipitation of different phases in the microstructure.

Aluminium alloys in their various forms are widely used in the aircraft, automotive, food and numerous other industries. Aluminium has especially gained traction in the automotive industry in recent years owing to its impressive specific material properties. Its low density and high mechanical performance leads to an improved performance on a per weight basis compared to traditional materials like steels enabling the vehicle manufacturers to drastically cut down the weight of their products and in turn improving the vehicle efficiency and lowering the environmental impact [43].

4.1.1 General Introduction & Classification

Aluminium alloys are broadly categorized as cast and wrought alloys. The compositions and purity levels are often indicated with three or four digits indicating the principal alloying elements and the purity level of the alloy. The temper designation follows these numerals after a hyphen and is specified with a letter followed by a number indicating the various mechanical and heat-treatment that the material is subjected to. For example, F, H and O are used to indicate as-fabricated, strain hardened and annealed states in that order [43]. A T7 temper designation indicates a solution treatment followed by over-ageing of the material [43].

4.1.2 Aluminium Alloys in the Automotive Industry

Besides the automotive chassis, aluminium alloys are widely used for producing various parts of the internal combustion engine like the engine blocks, cylinder heads, pistons, inlet and exhaust manifolds among many others.

Cylinder blocks and cylinder heads often owing to their complicated geometry are mass produced by casting processes. Different casting processes like sand casting, die casting, investment casting, lost foam casting, etc. are often used depending on the volume of production, quality of casts required, mechanical properties desired among other considerations [43].

4.1.3 Microstructure of A356 Alloys

The microstructure of the A356 family of alloys can be broadly classified down to three different components [44]:

1. primary α-Al solid solution phase,
2. Al-Si eutectic,
3. other intermetallics and secondary phases arising out of components not dissolved in the primary solid solution.

The size, volume, morphology and distribution of these microstructural features have a profound impact of the deformation behaviour of the alloy and are largely determined by the specific alloy composition, manufacturing methods, post-treatment and service conditions [44].

4.1.4 Role of Alloying Elements

Silicon

Owing to the eutectic formation in the binary Al - Si alloy, silicon is added in cast aluminium alloys to reduce the melting point of the alloy. It also has the added advantage of reducing the volumetric shrinkage of the structure during solidification [44]. The amount of silicon present in the alloy primarily determines the proportion of the Al-Si eutectic formed in the microstructure. Silicon addition also improves the wear properties and the dimensional stability of the structure. It further improves the strength and toughness of the alloy [45].

Copper

Copper addition typically promotes the formation of copper rich intermetallics like the θ (Al_2Cu) that improve the high temperature strength of the alloy even though it comes at the cost of reduced ductility. Copper rich precipitates are more resistant to shearing by dislocations, thus providing increased hardening [46], [47]. Increasing the copper content also results in an increased volume fraction of porosity due to the increased solidification interval in the castings [44].

Magnesium

Age hardening behaviour is induced in Al - Si castings by the addition of magnesium as a vital alloying element. It forms Mg - Si precipitates that are highly effective in strengthening and can be heat treated to tailor the mechanical properties of the alloy [48], [49]. However, studies have indicated that the dimensional stability of the casting is affected by increased magnesium content [50].

Iron

Iron is treated as an impurity in the Al - Si cast alloys in general. Due to the low solubility of iron in the aluminium alloys, it forms brittle intermetallic particles that tend to have a deleterious effect on the ductility of the material. Low magnesium content in the range 0.3 - 0.5 % aids marginal improvement in ductility by partially transforming the brittle iron containing intermetallics to fine scale β particles during the heat treatment [44]. Studies have shown the influence of such β precipitates in the formation of porosities [51]–[53].

Manganese

Manganese serves to mitigate the deleterious effect of iron in Al - Si castings. In the presence of manganese, iron forms an intermetallic α phase in place of the β platelets with the former improving the ductility of the material [44]. α phase also reduces the shrinkage porosity in the cast structure [54].

Other Alloying Elements

Sodium is often added to modify the microstructure and produce fine interconnected fibrous phase distribution in the eutectic structure [55], [56] that gives better toughness and ductility. Boron and titanium are added to refine the grain size of the cast structure by promoting the nucleation rate during solidification [56], [57]. Strontium is often added to the alloy to modify the Al-Si primary eutectic to a fine fibrous phase brought about by changes in nucleation and growth of the eutectic phase [55], [58].

4.1.5 A356 Cast Aluminium Alloy in Cylinder Heads

Cast aluminium alloys of the Al - 7 Si - Mg type, like the A356 family of alloys, are widely used for structural castings with complex geometries owing to their good castability, high strength, high toughness and a reduced tendency to form casting defects [44]. For applications like cylinder heads in the internal combustion engines, where the ductility takes lower priority than the high temperature strength, copper is often added to varying degrees to improve the elevated temperature mechanical properties even if it comes at the cost of increased porosity and susceptibility to cracking during the casting process [44].

4.1.6 Influence of Microstructural Features

A number of factors besides the chemical composition affect the mechanical deformation and fatigue behaviour of the A356 family of alloys [44]. The as-cast microstructure is influenced by various factors like chemical composition, cooling rates, the heat treatment that the structural material is subjected including others. The resulting material microstructure and the service temperatures have a significant impact on the mechanical behaviour of the material [48], [59]–[63]. The life of the A356 - T7 aluminium alloy cylinder heads is found to be often dictated by the casting defects and other microstructural features like the secondary dendrite arm spacing, the morphology and size of the secondary particles [64]. Studies on fracture surfaces by Fuoco et al. [65] on fatigue cracks in aluminium cylinder heads show cracks originating from micro-porosities and oxide film inclusions. Fatigue damage studies by Koutiri et al. [66], [67] on A356 - T7 alloys identified two competing fatigue damage mechanisms with the micro-shrinkage pores playing a very fundamental role in dictating the fatigue behaviour. In the absence of the micro-shrinkage pores, the fatigue behaviour was controlled by other microstructural inhomogeneities like the secondary precipitates that affect the crack initiation. In addition, they found no significant difference in the fatigue strength of the material under uniaxial and biaxial stress states in A356 + 0.5 % Cu - T7 group of alloys contrary to the prediction of most multi-axial fatigue criteria [66], [67].

4.2 Material for Testing

4.2.1 Material Chemistry and Microstructure

The material for testing was extracted from specially cast cylinder heads made of A356 + 0.5 % Cu cast aluminium alloys subjected to a T7 heat treatment. The average chemical composition of the alloy as determined using a modified ASTM E1251 [68] analysis of Al-base using optical emission spectrometry [69] on two specimens extracted from the cylinder head is as presented in Table 1. The microstructure of the alloy indicating the primary α-Aluminium phase, the Al-Si eutectic and the visible intermetallics of the Mg, Cu, Fe, Mn, etc., elements whose solubility exceed that of the α - Al phase are shown in Figure 2 (a) and (b). The material exhibits a dendritic microstructure with the primary aluminium skirted by the Al-Si eutectic interspersed with the intermetallics formed by elements exceeding the solubility limit in the primary aluminium.

The dendritic arm spacing, size, shape and morphology of the secondary phases are a function of the chemical composition, cooling rates and the heat treatment and it tends to vary over the geometry of the cylinder head. All the micrographs and other measurements presented in this work pertain to the highly loaded valve bridge area of the cylinder head which is expounded in the succeeding section detailing the specimen extraction zones. The secondary dendrite arm spacing determined using the mean linear intercept method on the aligned sets of the secondary cells was between 30-32 µm at the centre of the specimen and with about 5 % reduction closer to the mould walls where the associated cooling rates are higher.

Table 1: Chemical composition of A356 + 0.5 % Cu - T7 cast aluminium alloy as tested in wt. %

Si	Cu	Mg	Ti	Fe	Mn	B	Others	Al
6.8	0.53	0.35	0.12	0.10	0.07	0.0012	<0.05	Bal

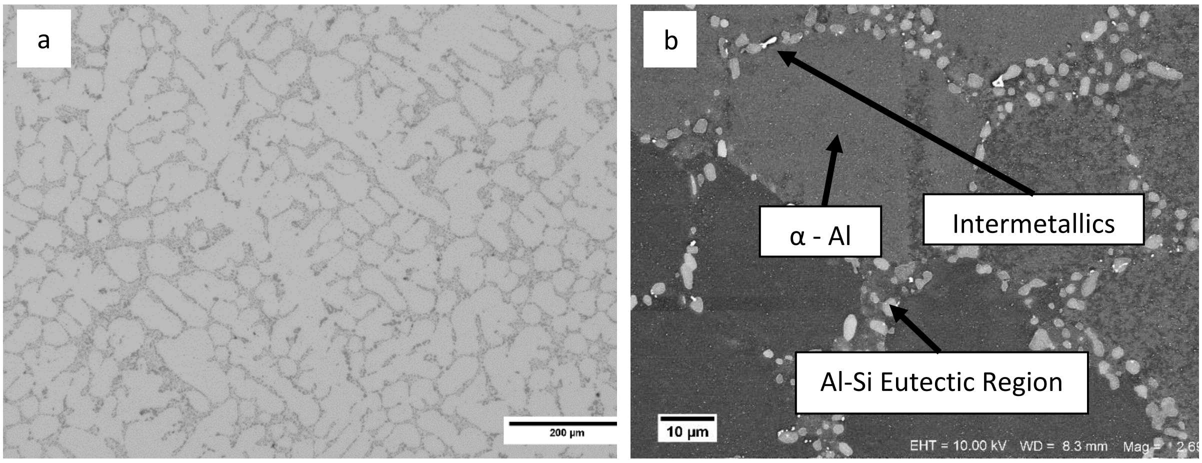


Figure 2: Representative optical micrograph from the tested A356-T7 alloy.

4.2.2 Manufacturing Process Parameters

The material for testing was extracted from specially cast cylinder heads made of A356 cast aluminium with additions of about 0.5% copper and subjected to a T7 heat treatment. To ensure the high quality of the casts, the melt temperature was maintained quite low at temperatures between 690-710 °C with the die temperature maintained between 200-240 °C. The combustion chamber side was water cooled for quicker directional solidification and for obtaining a finer microstructure. The degassing procedure was carried out with graphite rotors and a steady flow of nitrogen gas at 2-10 l/min into the melt and rotor speeds of up to 300 rpm. The eutectic modification was controlled using strontium and the grain size was refined using titanium additions. The T7 heat-treatment involved solutionizing at temperatures of about 500-530 °C for about 3-5 h followed by quenching the structure in air. Further, artificial ageing was carried out at temperatures in the range of 200-230 °C for about 2-5 h.

4.2.3 Sample Extraction from Cylinder Heads

It is desirable to extract the test specimens for testing as close to the region of interest as possible to be able to examine the correct microstructure to accurately mimic the material deformation behaviour in the CAE simulations. The specimens used in this study were extracted directly from Volvo Cars' (Gothenburg, Sweden) inline VEP4 series of engines with four cylinders. A cylinder head has a highly complex geometry with the material thickness differing from region to region. When such an intricate structure is cast, the cooling rate is different in different parts of the mould. As a result, the dendritic arm spacing and consequently, the deformation behaviour, damage mechanisms and the fatigue lives of the material varies through the geometry [23], [44] and is highly dependent upon where the test specimens are extracted from. It is of interest to study the deformation behaviour of the material that is critically loaded in the thermo-mechanical fatigue (TMF) context that which is the focus of the current research work. Numerous studies have shown that the material in the valve bridge areas experience the steepest thermal gradients during the engine start-stop cycle and tends to crack first [25], [64], [70] and hence is the region of interest in this study. Figure 3 shows the location of the extracted material that was used for establishing the deformation behaviour of the alloy. The test bars were carefully extracted, such that the test volume corresponded to the valve bridge area that was most sensitive to thermo-mechanical fatigue cracking. The extracted material was machined according to the ASTM test standard recommendations to the geometry as shown in Figure 4. While it is possible to cast test specimens, it often is difficult to replicate the complex microstructural variations often found in the cylinder heads produced by industrial manufacturing processes [66] and hence, the cast cylinders heads were used to extract the test specimens.

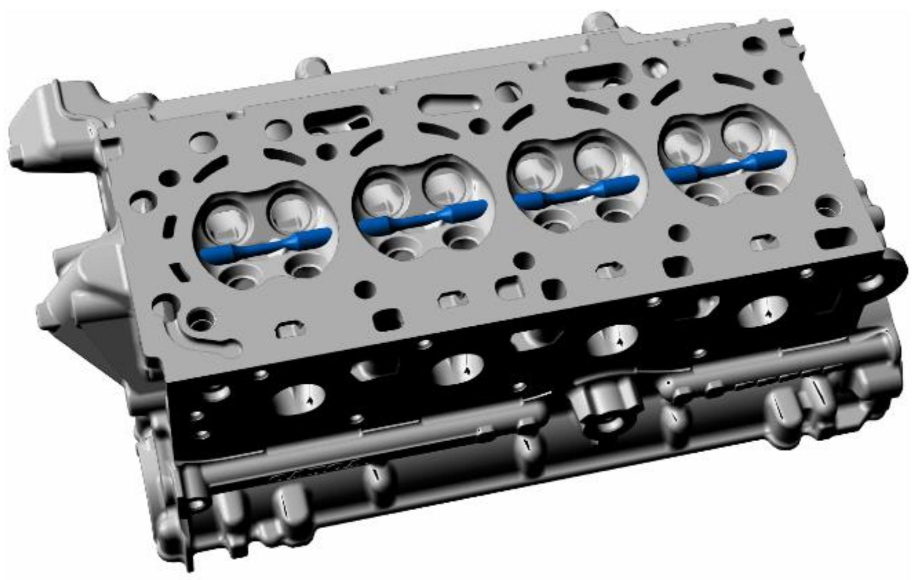


Figure 3: 3D CAD rendering indicating the specimen extraction zones.

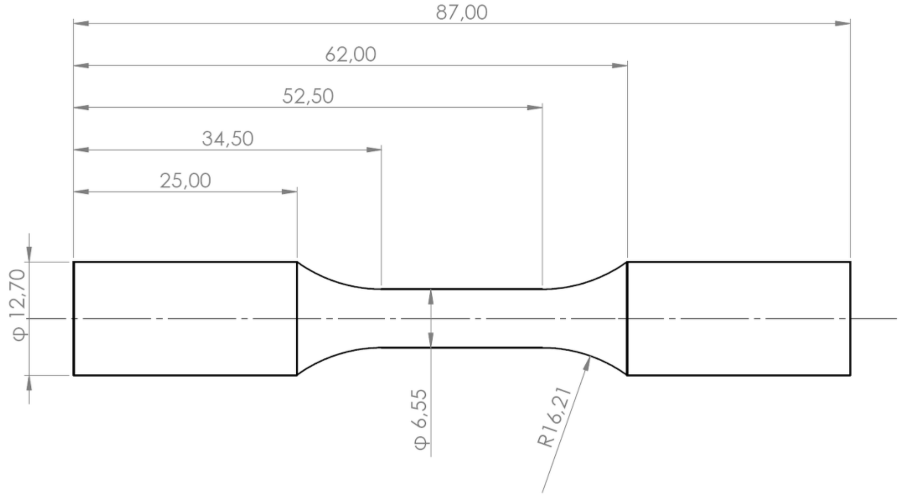


Figure 4: Test bar geometry machined in accordance with ASTM standards.

Chapter 5

Test Methods and Apparatus

5.1 Test Apparatus

All tests were performed using an Instron 8501 servo-hydraulic testing machine equipped with a fast-electronic control system and 1 kHz data logging system. All the elevated temperature mechanical tests were performed using the Instron 3119-407 series temperature chamber and a summary of the test set-up is presented in Table 2. The temperatures were monitored and controlled using the built-in K-type thermocouple and a Eurotherm 2408 controller. Two types of extensometers were used for measuring the strain, the tests at and below 150 ˚C were performed using the Instron 2620-603 axial clip on dynamic extensometer [71] and the tests above 150 ˚C were performed using the Epsilon 3555-010M-020 high temperature axial capacitive extensometer and the specifications are summarized in Table 3.

Table 2: Summary of Test Set-up

Figure 5: Instron 8501 Servo-hydraulic testing machine.

Test Equipment:
Instron 8501 Servo-Hydraulic Testing Machine

Specifications:

Max load: 100 kN

Feedback: LVDT, Load Cell or Additional extensometer

Instron 3119-407 Series Temperature Chamber for elevated isothermal mechanical tests

Grips: Instron fatigue rated mechanical grips

Temperature Chamber:
Instron 3119-407-222 Environmental Chamber

Specifications:

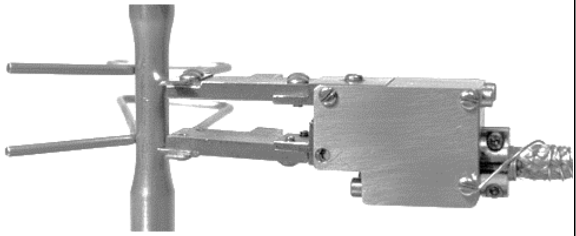
Temperature Range: -150 ˚C to 350 ˚C

Heating: Forced convection using air

Eurotherm 2408 controller with K-type thermocouples in the temperature Chamber

Overall System Accuracy in the temperature range RT-300 ˚C: ±3.5 ˚C

Table 3: Specifications of Extensometers Used

Instron dynamic extensometer 2620-603	**Epsilon high temp. axial extensometer Model: 3555-010M-020 (Capacitive)**
	
Type: Axial clip on dynamic extensometer with T1351-1007 knife edge	**Type**: Axial clip on capacitive extensometer with hardened tool steel knife edges
Model: 2620-603 | Dynamic Extensometer	**Model**: 3555-010M-020 | High Temperature Axial Capacitive Extensometer.
Dynamic Extensometer for direct strain measurement and closed loop strain control. Suitable for tensile, compressive & fatigue testing, the extensometer has a 10 mm gauge length with a travel of ±1 mm giving ±10 % strain.	Dynamic Extensometer for direct strain measurement and closed loop strain control. Suitable for tensile, compressive & fatigue testing, the extensometer has a 10 mm gauge length with a travel of + 2 mm and - 1 mm giving a + 20 % and - 10 % strain range.
Frequency Response: 100 Hz	**Frequency Response**: Not Specified
Temperature range: - 80 ˚C to + 200 ˚C	**Temperature range**: Ambient to 540 ˚C

5.2 Heatup and Temperature Stabilization

The heat up procedure is carried out under load control with no force exerted on the sample as the specimen and the equipment expanded with increasing temperatures. The overall measured system temperature accuracy for the temperature range tested is ± 5 °C. The total heat up time and the time to reach the stable temperature condition accounting for equipment and sample expansion is about 3 h. Figure 6 below shows the thermal expansion of the equipment (displacement) with time as the force on the sample is held at zero.

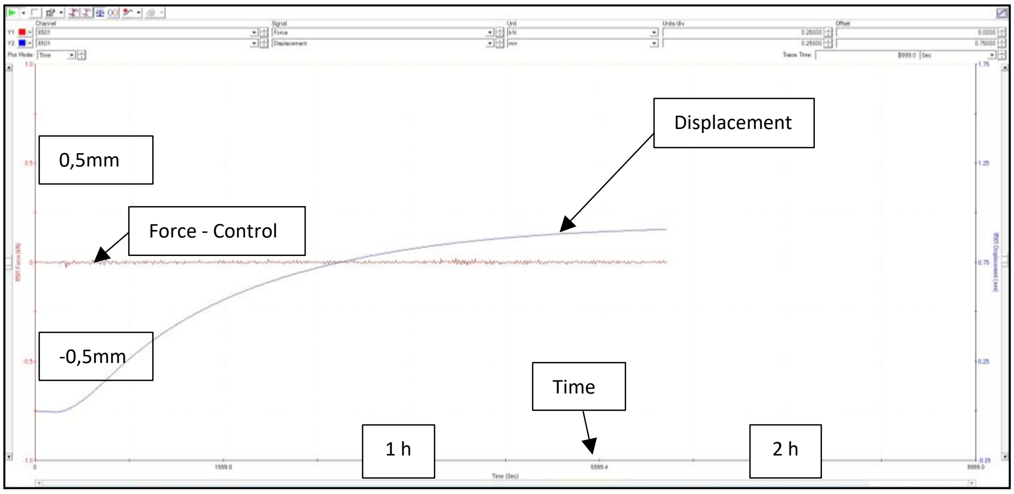


Figure 6: Temperature stabilization of the equipment.

With equipment and sample expansion being significant, it is imperative that the heat up and stabilization procedures are followed rigorously to avoid interference from the equipment expansion on the measured sample deformation during the tests. The material ages when subjected to the elevated temperatures during the equipment stabilization before the high temperature tests commence. Internal studies [32] on the material ageing characteristics of the A356 + 0.5 % Cu - T7 heat treated material is summarized in Figure 7 for the tested ageing temperature-time combinations. The material exhibits decreasing strength with increasing heat treatment temperatures and times at temperatures above 150 °C.

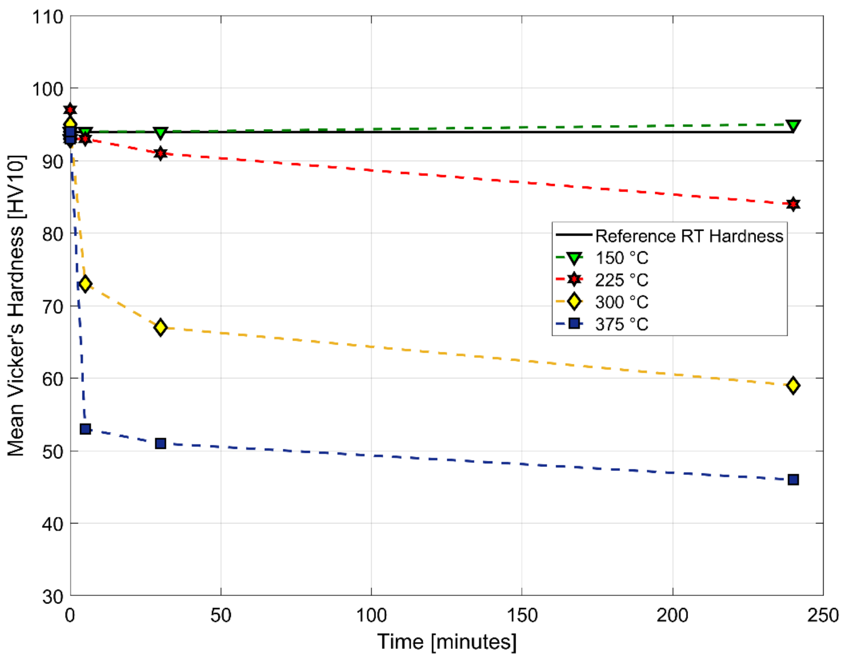


Figure 7: Ageing curves developed using Vickers hardness test (HV10).

The rate of material softening is higher for higher temperatures. With the above phenomenon in mind, the effect of the 3-hour hold time for the equipment temperature stabilization can be summarized as in Figure 8 and Figure 9. The samples subjected to the 3 h hold time at temperatures above 150 °C are expected to develop a lower stress response for the applied loads as against the ideal test condition in which the samples are loaded without the need for a high temperature hold for equipment stabilization. Higher the test (and consequently, the stabilization) temperature, greater is the expected material softening before the tests commence. All the test results (deformation and lives) presented in subsequent sections are of specimens that have been aged for 3 h at the stated isothermal temperatures prior to testing.

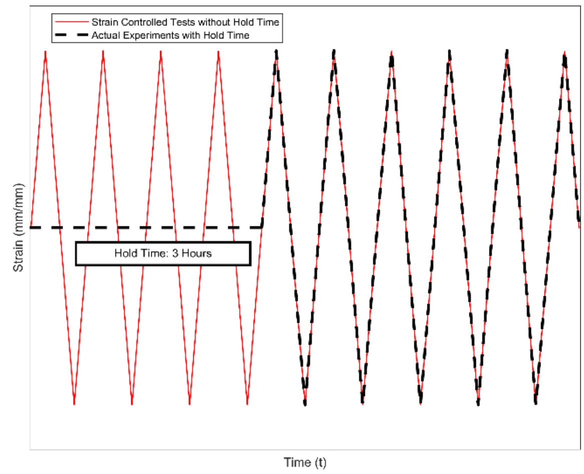


Figure 8: Load application in strain controlled LCF tests with and without hold time.

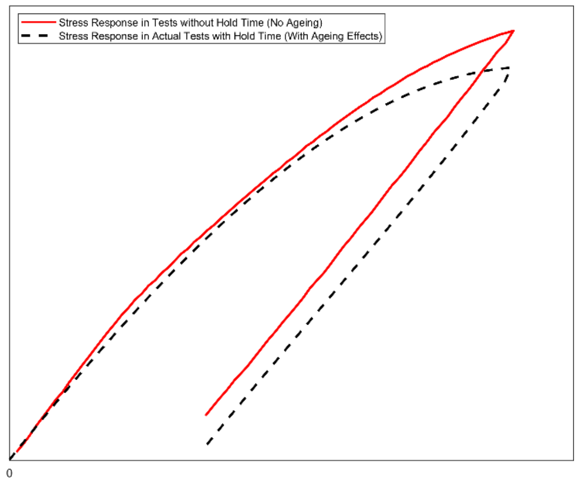


Figure 9: Stress response in strain controlled LCF tests with and without hold time.

Chapter 6

Summary of Appended Papers

6.1 Summary of Paper A [72]

Title: Deformation and Fatigue Behaviour of A356-T7 Cast Aluminium Alloys Used in High Specific Power IC Engines.

Monotonic tensile testing and cyclic stress and strain-controlled testing of A356-T7 + 0.5 wt.% Cu cast aluminium alloys have been performed in this study. The uniaxial tests were performed on polished test bars extracted from highly loaded areas of cast cylinder heads.

- Under monotonic loading, the material yielded on average at 210MPa and exhibited a hardening behaviour with the peak tensile tress reaching values up to 272 MPa on average. A scatter in yield and tensile strength of around 5% was observed between the replicas, while the fracture strains were consistent at 4.7% between the replicas tested.

- Under strain controlled cyclic loading, the material exhibits slight cyclic hardening for all load levels with the stress amplitudes increasing by up to 7–9% from the initial cycle for all tested load levels. As with monotonic loading, the cyclic tests exhibit considerable scatter in the stress response between the replicas.

- Equivalent stress-controlled fatigue in relation to the strain controlled cyclic tests were performed to study the influence of the loading mode on the cyclic deformation and fatigue lives. The two types of tests exhibit similar fatigue lives and stress-strain responses indicating minimal influence of the mode of loading in fatigue testing of A356-T7+0.5% Cu alloys.

- The monotonic and cyclic hardening curves could be modelled accurately with a power law type Ramberg-Osgood deformation models. The continuum deformation behaviour of the material can be modelled using a rate independent nonlinear isotropic-kinematic combined hardening model.

6.2 Summary of Paper B [73]

Title: Effect of Temperature on Deformation and Fatigue Behaviour of A356–T7 Cast Aluminium Alloys Used in High Specific Power IC Engine Cylinder Heads.

Material for testing was extracted from the highly loaded valve bridge area of specially cast cylinder heads to study the monotonic and cyclic deformation behaviour of the A356-T7 + 0.5% copper alloy at various temperatures. Monotonic tensile tests performed at different temperatures indicate decreasing strength from 211 MPa at room temperature to 73 MPa at 300 °C and a corresponding increase in ductility . Completely reversed, strain controlled, uniaxial fatigue tests were carried out at 150, 200 and 250 °C.

- The material exhibits decreasing strength and increasing ductility with increasing temperatures under monotonic loading. The material exhibits strain hardening at temperatures at and below 150 °C and a strain softening at temperatures above 150 °C under uniaxial tensile loading.

- The material exhibits cyclic softening with strain load cycles at all the tested temperatures of 150, 200 and 250 °C. The tests at elevated temperatures show reduced stress response and following increased plastic strains amplitudes.

- Dilatometry reveals a fairly constant coefficient of thermal expansion measured varying between $25\text{-}26{\cdot}10^{-6}$ $°C^{-1}$ in the temperature range 25 – 250 °C.

- The monotonic and cyclic stress-strain curves, exhibiting no significant yield point, can be modelled accurately with a Ramberg-Osgood type model.

- The cyclic deformation behaviour can be modelled using a temperature dependent non-linear combined kinematic and isotropic model with one linear and one non-linear backstress.

- The scatter in mechanical properties measured is influenced by the test temperature with the difference between replicas decreasing with increasing temperatures.

6.3 Summary of Paper C

Title: Evolution of Yield Surface and Stress Asymmetry in A356–T7 Cast Aluminium Alloy.

This study investigates the effect of temperature on the evolution of yield stress under cyclic loading in A356-T7+0.5% Cu cast aluminium alloy. To study the effect of mean strain on the cyclic mean stress evolution and fatigue behaviour of the alloy, tests with tensile and compressive mean strains of +0.2% and -0.2% are compared against fully reversed strain-controlled tests at test temperatures ranging from RT – 250 °C.

- The material exhibits a non-linear cyclic hardening behaviour at room temperature. At 150 °C, the material hardens initially before quickly saturating and softening with subsequent strain load cycles. At 200 and 250 °C, the material exhibits non-linear isotropic softening.

- The material exhibits yield strength asymmetry, with higher yield strength under compressive loading than under tension. This asymmetry decreases with increase in temperature.

- The material exhibits cyclic stress-strain asymmetry, with the peak stress response under compression higher than in tension for a fully reversed strain controlled cyclic loading.

- The material exhibits mean stress relaxation for strain controlled cyclic loading with tensile and compressive mean strains at all temperatures. The mean stress developed for tests with a compressive mean strain is higher than the corresponding tests with a tensile mean strain at all temperatures.

- Tensile mean strain has a deleterious effect on the fatigue life of the tested A356-T7+0.5% Cu aluminium alloy for lower temperatures up to 150 °C. At elevated temperatures of 200 and 250 °C, however, the material shows no such reduction in the number of cycles to failure.

6.4 Summary of Paper D [74]

Title: Effects of Dwell Time on the Deformation and Fatigue Behaviour of A356-T7 Cast Aluminium Alloys Used in High Specific Power IC Engine Cylinder Heads.

This study seeks to investigate the effect of dwell times on the deformation and fatigue behaviour of the A356-T7 + 0.5 wt.% Cu alloy used to cast cylinder heads. In particular, we study the effect of dwell time duration at various temperatures. A combined fatigue-dwell testing procedure, with the dwell at the maximum compressive strain, replicates the service conditions.

- A356-T7 + 0.5% Cu cast aluminium alloys extracted from specially cast engine cylinder heads are subjected to cyclic strain-controlled fatigue tests with interspersed dwell times at compressive strains at various temperatures and load levels. Dwell times of 600 s and 3600 s were used to study the effect of the length of the dwell times on the fatigue lives.

- The material exhibits a significant stress relaxation at all temperatures and load levels with a rapidly decreasing stress relaxation rate.

- The magnitude of stress relaxation is influenced significantly by the load level. This effect is stronger at the lower test temperatures of 150 °C than at the higher test temperature of 250 °C. This can be attributed to the plastic hardening behaviour of the alloy at lower temperatures, while the material due to excessive stress relaxation shows insignificant hardening at 250 °C.

- The dwell times at constant compressive strains have no discernible influence on the cyclic hardening behaviour or the fatigue life of the material, even at elevated temperatures.

- The visco-plastic deformation behaviour can be modelled with a high degree of accuracy using a combination of the Chaboche combined non-linear kinematic and isotropic mixed hardening model and the rate dependent Cowper-Symonds overstress power law model.

6.5 Summary of Paper E [75]

Title: Effect of Strain Rate on the Deformation Behaviour of A356- T7 Cast Aluminium Alloys at Elevated Temperatures.

This study examines the effect of strain rate on the cyclic deformation behaviour of the A356-T7+0.5% Cu aluminium alloy commonly used in modern internal combustion engine cylinder heads. Samples extracted from the valve bridge areas of the cylinder heads are tested in strain-controlled fatigue tests. Samples are tested at strain rates of 1% s^{-1} and 10% s^{-1} at room temperature, 150 and 200 °C. The role of silicon particles in the fracture mechanism is investigated using electron microscopy techniques.

- The influence of the strain rate on the cyclic peak stress development is minimal and exhibits no specific pattern at the tested temperatures and strain rates.

- Strain rate has a significant influence on the development of cyclic mean stress, especially at room temperature, with the mean stress changing by over 30 MPa, moving from compression initially to tension with subsequent cycling for the tests at 10% s^{-1}.

- The higher strain rate has a similar influence on the yield strength asymmetry, with the yield in tension showing an increase over the yield in compression at room temperature. For all the other tested temperatures, the yield in compression is higher than the yield in tension for both the tested strain rates of 1% s^{-1} and 10% s^{-1}.

- The material exhibits steeper isotropic hardening changes at higher strain rates, with the material hardening at room temperature and softening isotropically at 200 °C. The material exhibits insignificant changes to its yield surface at 150 °C for both the tested strain rates.

- The material exhibits increased number of cycles to failure at higher strain rates, which could be explained partially by the adiabatic nature of the high strain rate tests and the associated higher heat accumulation in the material during deformation.

- Fractographic investigation of the fracture cross-section highlights the role of eutectic silicon and the intermetallics on the crack initiation process. The larger precipitates are preferentially cracked highlighting the importance of refining the silicon particles and minimizing the shrinkage porosity.

6.6 Summary of Paper F

Title: Effect of Natural and Artificial Ageing on the Deformation and Fatigue Behaviour of A356-T7 Cast Aluminium Alloys Used in High Specific Power IC Engine Cylinder Heads.

Material taken from cast cylinder heads of A356-T7+0.5% Cu aluminium alloys were tested in as-received condition, after natural ageing in room temperature for 5 years, and after strong artificial at 375 °C in air for 6 hours. From the studies on the influence of artificial and natural ageing, fatigue presents itself as a transient phenomenon. The conventional modelling assumption that it is stable over time needs careful consideration of the effect of natural and artificial ageing in the material, especially in cases where they have a deleterious effect on the durability of the material and the structures.

- Artificial ageing (375 °C in air for 6 hours) increases the ductility and reduces the strength of the material under monotonic tensile loading. Natural ageing (5 years in room temperature) has the opposite effect of artificial ageing as it decreases the ductility and increases the strength of the material under monotonic tensile loading.

- Artificial ageing of the alloy alters both the yield strength evolution and the cyclic hardening behaviour of the alloy. The material exhibits reduced flow stress after ageing, but hardens cyclically even at elevated temperatures when tested at 200 °C. The cyclic hardening rate is higher at room temperature than at 200 °C.

- Natural ageing increases the peak stress response and exhibits lower plastic strain amplitudes at both room temperature and 200 °C in comparison with the as-received material. Both harden cyclically at room temperature and soften with cyclic loading at 200 °C.

- Samples subjected to the artificial ageing show improved number of cycles to failure under strain-controlled loading at both room temperature and at 200 °C. Natural ageing has the opposite effect with a significant reduction in the number of cycles to failure at both the tested temperatures.

- Hence, the transient nature of the fatigue life curves, and continuum deformation behaviour needs to be taken in to account for a reliable computation prediction of the thermo-mechanical fatigue life of structures subjected to cyclic thermal loads.

Chapter 7

Conclusions

- The material exhibits decreasing strength and increasing ductility with increasing temperatures under monotonic loading. The material exhibits strain hardening at temperatures at and below 150 °C and a strain softening at temperatures above 150 °C under uniaxial tensile loading.
- The material exhibits cyclic hardening at room temperature and cyclic softening at elevated test temperatures of 150, 200 and 250 °C for strain load cycling at all load levels. The tests at elevated temperatures show reduced stress response and increased plastic strains amplitudes. The scatter in mechanical properties measured is influenced by the test temperature with the difference between replicas decreasing with increasing temperatures.
- Dilatometry reveals a fairly constant coefficient of thermal expansion measured varying between 25-26·10^{-6} °C^{-1} in the temperature range 25 – 250 °C.
- The material exhibits cyclic yield and peak stress asymmetry, with the stress response in the material higher under compression than in tension for strain controlled fully reversed cyclic loading at all tested load levels.
- Compressive strain with dwell times of 600 s and 3600 s were used to study the effect of the length of the dwell times on the fatigue lives. The material exhibits a significant stress relaxation at all temperatures and load levels with a rapidly decreasing stress relaxation rate. The magnitude of stress relaxation is influenced significantly by the load level. The dwell times at constant compressive strains have no discernible influence on the cyclic hardening behaviour or the fatigue life of the material, even at elevated temperatures. The visco-plastic deformation behaviour can be modelled with a high degree of accuracy using a combination of the Chaboche combined non-linear kinematic and isotropic mixed hardening model and the rate dependent Cowper-Symonds overstress power law model.
- Time and temperature induced changes in the microstructure result in transient continuum deformation and fatigue behaviour of the A356-T7+0.5% Cu alloy.
- The influence of the strain rate on the cyclic peak stress development is minimal. Strain rate has a significant influence on the development of cyclic mean stress, especially at room temperature.

Chapter 8

Recommendations for Future Work

1. As a vital cog in the thermo-mechanical fatigue life prediction process, TMF testing to study the influence of simultaneous thermal and mechanical loadings on the deformation and durability of the alloy is needed. Such TMF tests will also enable the verification of the calibrated material models. Interpretation of isothermal fatigue life curves developed at various temperatures within the expected operating temperature range for thermo-mechanical fatigue life prediction is a challenging topic. Although various methods have been proposed in literature, with energy based methods in particular gaining traction in recent years [21], [23], [29], [36], [76], availability of thermo-mechanical fatigue life data will enable us to evaluate the suitability of such methods to predict the thermo-mechanical fatigue life of the material.

2. Ageing has a profound impact on the deformation and fatigue behaviour of the A356-T7+0.5% Cu alloy. The constitutive models need to be updated to account for this ageing induced changes in the cyclic hardening characteristics of the alloy. This is essential to better predict the durability of the alloy with respect to the thermal loadings in the cylinder head [77].

3. Cast iron plasticity models account for the difference in tensile and compressive yield behaviour in cyclic loading. The use of cast-iron plasticity models could be explored to examine if we get a better prediction of the stress-stress response of the tested A356-T7+0.5% Cu cast aluminium alloy.

4. Further research using TMF testing is strongly recommended along the lines of the work by Beck et al. [78]. A detailed study of the combined effect of stress relaxation associated with the low frequency thermal start-stop cycle and superimposed high frequency loads associated with the combustion cycles is needed to get a more complete picture of the effect of these loads on the durability of cylinder heads.

5. A statistical study of the different in-service loading scenarios and the scatter in the fatigue strength of the material, considering the cylinder head production process, can be used for developing a provisional reliability approach for the cylinder head design, durability testing and manufacturing process cycles.

Chapter 9

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Chapter 10

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