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Characterisation and investigation of local variations in mechanical behaviour in cast aluminium using gradient solidification, Digital Image Correlation and finite element simulation

Jakob Olofsson [a,*], Ingvar L. Svensson [a], Pascal Lava [b], Dimitri Debruyne [b]

[a] Materials and Manufacturing – Casting, Department of Mechanical Engineering, School of Engineering, Jönköping University, P.O. Box 1026, Jönköping SE-551 11, Sweden
[b] Department MTM, KU Leuven, Kasteelpark Arenberg 44, Leuven B-3001, Belgium

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A B S T R A C T

Due to design and process-related factors, there are local variations in the microstructure and mechanical behaviour of cast components. This work establishes a Digital Image Correlation (DIC) based method for characterisation and investigation of the effects of such local variations on the behaviour of a high pressure, die cast (HPDC) aluminium alloy. Plastic behaviour is studied using gradient solidified samples and characterisation models for the parameters of the Hollomon equation are developed, based on microstructural refinement. Samples with controlled microstructural variations are produced and the observed DIC strain field is compared with Finite Element Method (FEM) simulation results. The results show that the DIC based method can be applied to characterise local mechanical behaviour with high accuracy. The microstructural variations are observed to cause a redistribution of strain during tensile loading. This redistribution of strain can be predicted in the FEM simulation by incorporating local mechanical behaviour using the developed characterisation model. A homogeneous FEM simulation is unable to predict the observed behaviour. The results motivate the application of a previously proposed simulation strategy, which is able to predict and incorporate local variations in mechanical behaviour into FEM simulations already in the design process for cast components.

1. Introduction

Casting is a powerful manufacturing method that enables the design and manufacturing of products and components with several desirable properties, e.g. complex geometries, near net shape and cost efficiency. Although casting has been known and used for thousands of years, the last few years has seen it evolve into a highly advanced and modern production method which is highly utilised in e.g. the automotive and transportation sectors [1]. As demands for reduced emission levels and fuel consumption increases, it becomes important to achieve full utilisation of all features of the casting process in order to enable design and production of optimised and robust components.

The solidification of cast components involves several complex phenomena, where factors such as component geometry, chemical composition, heat transfer and solidification kinetics affect the extraction of heat during solidification. This leads to local variations in solidification conditions, microstructure and material behaviour of the solidified casting and results in cast components which display local variations in mechanical behaviour rather than homogeneous material behaviour [2,3]. In cast aluminium components, local mechanical behaviour is highly related to local cooling rates during solidification. A high local cooling rate yields a highly refined microstructure, typically measured by determining Secondary Dendrite Arm Spacing (SDAS). A high cooling rate yields a low SDAS-value while a lower cooling rate yields a higher SDAS-value [4,5]. High microstructural refinement is generally associated with high strength, whereas decreasing the SDAS-value causes a general increase in yield strength, ultimate tensile strength and ductility for as-cast materials [4–9]. However, there may be complex variations of these trends because the cooling rate also affects the solidification conditions of other microstructural features [9,10]. For example, an increased cooling rate refines the eutectic silicon particles [11], strengthens the dendrites due to silicon enrichment [12] and affects the segregation profiles within the different phases [13].

In recent years, extensive research has been conducted in the field of modelling and simulation of solidification in cast aluminium components. Solidification models have been developed which calculates the phase diagram, cooling curves and solidification behaviour to predict microstructural features locally throughout the component based on the chemical composition of the alloy [14]. By implementing these models into casting simulation software, it is possible to determine the local variations in microstructural features throughout cast components with high

* Corresponding author. Tel.: +46 36 10 16 59.
E-mail address: jakob.olofsson@jth.hj.se (J. Olofsson).

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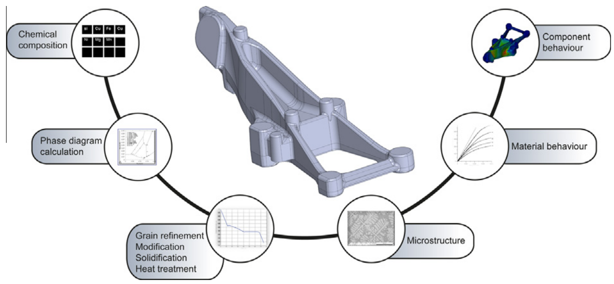

Fig. 1. Schematic illustration of the closed chain of simulations for cast components [16]. Figure reprinted with permission from Elsevier.

accuracy [3,14,15]. By relating microstructure and mechanical behaviour using material characterisation models, local mechanical behaviour can be predicted [3]. These simulation tools provide the basis for a simulation strategy denoted *the closed chain of simulations for cast components* which has recently been presented by two of the authors of this work [16]. The strategy, schematically illustrated in Fig. 1, connects and utilises numerical solidification models and casting process simulations to predict local variations in microstructure and mechanical behaviour and then incorporates this data in a Finite Element Method (FEM) simulation of the behaviour of the cast component [16]. The simulation strategy includes characterisation models developed for cast iron [17] and sand cast aluminium alloys [2,3], whereas models for High Pressure Die Cast (HPDC) aluminium alloys have not been previously established.

A numerical investigation of a ductile iron component using the proposed simulation strategy has shown that the predicted behaviour of the component when subjected to load is significantly affected by local variations in mechanical behaviour, which cause a redistribution of stresses and strains that it is impossible for a model in a homogenous material to predict [18]. However, this effect has only been predicted numerically, not confirmed experimentally.

The mechanical behaviour of a cast alloy is typically characterised by a tensile curve obtained through a tensile test, where the obtained strain is plotted versus applied load. The strain is typically measured using a contact extensometer or a non-contact laser extensometer. However, both these methods measure the average strain over a gauge area and are unable to display the complex variation in the strain field of the specimen [19]. Digital Image Correlation (DIC) is an optical non-contact deformation measurement method that offers the opportunity to study the full displacement and strain field for a specimen. Usually, a speckled pattern is applied to the specimen and by observing the displacement of the pattern when a load is applied, it is possible to calculate the displayed strain field in the specimen using a DIC algorithm. The method can be applied on different scale levels, e.g. on the macroscopic level (entire samples/components) or on the microscopic level (using the natural pattern in micrographs). The accuracy and precision of DIC in elasto-plasticity has been the subject of intensive research and development in recent years [20–22] and has been used in various applications for material characterisation, e.g. inverse methodologies [19,23], internal and external work comparisons [24] and virtual fields methodologies [25]. Regarding cast materials, DIC has e.g. been applied on a microstructural level to study the distribution of strain over different phases during tensile loading of cast irons [26] and on a macroscopic level to study the fracture of a HPDC aluminium alloy [27]. However, the use of DIC to characterise or investigate the macroscopic effects of local variations in microstructure caused by local variations in solidification conditions has not, to the authors' knowledge, been reported in the literature.

In this work, the effects of local variations in microstructure and mechanical behaviour in a HPDC aluminium alloy is characterised and investigated. Two sets of gradient solidified specimens were produced. The first set was produced to obtain specimens of high microstructural homogeneity. This set was used for characterisation of mechanical behaviour at three different solidification conditions. The second set was produced to display a controlled and repeatable variation in microstructure throughout the specimens and was used to study the effects of local variations in microstructure on the strain field observed using DIC. This contribution aims to extend the characterisation models available in *the closed chain of simulations for cast components* to include HPDC alloys and also to experimentally investigate the numerically predicted redistribution of strain. Local variations in mechanical behaviour directly affect both the performance and optimal design of cast components; incorporating these variations into the design process of cast components will improve the design process of optimised and robust cast components. Thus, the results of the current work directly affect not only the work of design and CAE engineers, but also that of metallurgists and foundry engineers.

2. Experimental setup

2.1. Material

The alloy under investigation is a typical alloy used for HPDC components and meets the EN AC 46000 alloy standard. It contains a relatively high iron (Fe) content, 0.6–1.1%, and although this reduces the problem of die soldering in permanent moulds, there is a risk that formation of iron-rich intermetallics will occur during solidification, which is detrimental to the mechanical properties of the material [28]. In the current work, the alloy has been studied using a gradient solidification method, in which cylindrical samples are remelted and solidified using a furnace mounted on an electric lifting device. Setting the velocity at which the furnace is lifted provides control over the cooling rate and, thus, the microstructural refinement obtained in the samples. Except for providing a controlled and repeatable process for producing materials with microstructures which are highly homogeneous, the gradient solidification method also has the advantage of producing materials with low content of oxide films, low porosity and low degree of shrinkage related defects. The layout of the equipment is further described elsewhere [29] and the technique has been extensively applied in investigations and characterisations of the behaviour of cast aluminium alloys [2,6,7,12,29]. As previously pointed out, it is important to stress that the value of SDAS is not the only parameter affected by changes in cooling rates. However, SDAS is an accepted measure of the microstructural refinement in as-cast aluminium.

The base material was taken from a component manufactured in serial production at a HPDC foundry. The material was remelted in an induction furnace and cast into cylindrical samples, each casting producing six samples. A sample for chemical analysis was also made and the chemical composition was measured using a Spectro Spectromax optical emission spectrometer. The average chemical composition obtained from three measurements is shown in Table 1. The cylindrical samples were preheated in a holding furnace at 125 °C for at least 30 min. Three samples were then placed in steel pipes and put into the gradient solidification furnace. The operating temperature of the gradient furnace was 715 °C. The samples were initially heated for 30 min in order to achieve total remelting of the material prior to lifting the furnace at a defined speed. This caused directional solidification of the cast sample from the bottom of the steel pipe upwards.

In this work, two sets of specimens were produced. The first set was produced using constant lifting speed of the furnace, which provided a constant temperature gradient in the sample holder during solidification. This leads to a microstructure with high microstructural homogeneity throughout the sample. The samples