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Predictive equations of the tensile properties based on alloy hardness and microstructure for an A356 gravity die cast cylinder head

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ABSTRACT

One of the main problems in the design of complex Al–Si cast components is the wide variety of mechanical properties in different regions of the castings which is due to the wide range of solidification microstructures, related to the local solidification conditions. There are many papers available on the widely used A356/A357 Al–Si–Mg alloys, however, most experimental data on their tensile or fatigue properties are generally obtained from specimens cast separately or produced under controlled laboratory conditions, that are extremely different from those of industrially cast components. Moreover, most of these data often relate the mechanical properties to only one microstructural parameter, such as solidification defects or secondary dendrite arm spacing, and do not take their simultaneous effect into consideration. For all these reasons, the main problem, in the design phase, is the lack of knowledge of the true local mechanical properties in complex-shaped castings, which often means a conservative approach is necessary, with a consequent increase in thickness and therefore in weight. The aim of this research was to study a complex A356 gravity die cast cylinder head, in order to verify the range of variability of the main microstructural parameters and tensile properties, using specimens directly machined from the casting. The component was heat treated at the T6 condition, and the effect of the delay between quenching and aging on the alloy hardness was also evaluated. Simple experimental equations have been proposed, able to successfully predict the local tensile properties in the casting, when only the most important microstructural parameters and alloy hardness are known. These equations allow the designer to predict the local tensile behaviour without any tensile tests; moreover they can also link the post-processing results of the casting simulation software to the pre-processing phase of the structural ones, with an approach of co-engineered design.

1. Introduction

Excellent castability, corrosion resistance and high strength-to-weight ratio, which increase performance and fuel economy, make Al–Si–Mg casting alloys suitable materials for various applications in the automotive industry, such as engine blocks, pistons, cylinder heads, and crankcases. These alloys (typically A356 and A357) offer the ability to cast complex, thin-walled components, by sand and permanent mould casting, with tensile strengths up to 350 MPa. This high strength level is achieved by the T6 heat treatment, where Mg–Si precipitates provide strengthening through age hardening.

The mechanical properties of a casting are greatly influenced by the size, volume, and morphology of microstructural constituents, which depend on composition, solidification conditions and heat treatment [1–11].

The microstructure of A356 and A357 casting alloys consists of primary aluminium dendrites, eutectic Si, intermetallic compounds and solidifications defects, such as gas and shrinkage porosity and oxides. The volume fraction of dendrites and eutectic particles is determined by chemistry, whereas the size, morphology and distribution of the dendrites, eutectic particles and intermetallics also depend on the local solidification conditions.

Several works [4–11] report that the ultimate tensile strength (UTS) and the elongation to failure (E%) are strongly affected by the primary and secondary dendrite arm spacing (DAS and SDAS). Moreover, they are also affected by the size and morphology of the eutectic Si, and by the presence of casting defects, while the yield strength (YS) is mainly controlled by age hardening induced by heat treatment. The general results show that UTS and E% increase when SDAS decreases and that small globular Si structures, induced for example by chemical modification, mainly enhance E%.

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The reasons for the relation between DAS/SDAS and mechanical properties are certainly found in the direct control that a dendritic structure has on the distribution and size of eutectic particles and intermetallic compounds, as well as on solidification defects. The eutectic structure, for example, in more rapidly solidified alloys is very fine and uniform. By contrast, in slowly solidified structures, the eutectic is more segregated and thus the size and quantity of large particles are higher. In the presence of eutectic modifiers such as Na or Sr, however, the effects of the cooling rate on the particle size and aspect ratio become negligible.

Moreover, fine dendritic structure has an indirect effect on the heat treatment response, because the dissolution of smaller second phases during solutionizing is easier and consequently the higher solute concentration allows a more effective age hardening. However, it has been reported by Wang [6] that the relation between UTS, E% and SDAS is not linear for A356/ heat-treatable age-hardening alloys and, in particular, ductility does not always decrease as the dendrite cell size increases.

The influence of eutectic Si and Fe-based intermetallics on the tensile properties of Al–Si–Mg alloys was highlighted in several works [5–10]. If solidification defects are negligible, fracture occurs when the damage reaches a critical level and the failure follows three stages [6–8]: (1) cracking of the eutectic Si particles, at low plastic strains (1–2%); (2) generation of localized shear bands, with microcracks forming by joining adjacent cracked particles; (3) microcracks coalescence, followed by propagation, leading to the final fracture. Increasing Si particle size and their aspect ratio, increases the probability of their fracture, while clusters of particles favour both a high particle cracking rate and the linkage of microcracks during the damage process. Fe-based intermetallics, especially π-$Al_8Mg_3FeSi_6$, have a similar behaviour and play an important role in the fracture of the alloys, if present in large volumes.

All these issues have to be considered during the design of a complex Al–Si–Mg casting, because a variety of local microstructures, produced by different solidification conditions, can lead to a range of mechanical properties. For this reason, one of the goals of researchers over the last 40 years has been to relate the properties of Al alloy castings to their microstructure, in order to develop non-destructive test techniques that can predict the tensile properties of a casting from its microstructural characterization.

McLellan [11], using multiple correlation analysis, developed empirical relations among microstructural parameters (such as aluminium cell size, silicon average particle area, average number of particles per unit area, aspect ratio, spacing between particles) and tensile properties UTS and E%. The statistical analysis was carried out to define a microstructural function which does not directly represent tensile property, but is related to the quality index established by Drouzy [12]. According to McLellan, the analytical expressions of this function should contain a material constant and three variables, which represent solidification rate, solution treatment and the effect of solidification conditions on eutectic Si.

Meyers [10], by means of regression analyses, using UTS and E% as the dependent variables and various functions of solutionizing time as the independent variables, pointed out the combined effect of chemical modification and grain refinement on the geometric characteristics of Si particles, which control the tensile properties of the A357 alloy. Using relationships between solutionizing time and eutectic Si, he developed empirical equations that predict the mechanical properties of the A357 alloy, as a function of both solutionizing time and morphology, size and distribution of Si particles. According to these equations, the numerical densities of the eutectic Si, such as areal and bulk lineal density, define UTS and uniform elongation in A357 alloys that have been modified and grain refined, while the Si size parameters, such as average area, mean diameter, and mean spacing of Si particles, influence the tensile behaviour of unrefined and unmodified A357 alloys.

Oswald and Misra [13], assuming that the UTS and E% of Al–Si–Mg castings of similar composition, melt quality, soundness and heat treatment depend on DAS, obtained experimental relationships between DAS and mechanical properties of simple test bars, able to predict the properties in complex castings.

In the last two papers, hardness and yield strength of A357/A356 alloys were considered essentially unaffected by the microstructure and only related to the heat treatment parameters.

Caceres and Griffith [9] developed a model for the Al–Si–Mg alloys relating the dendrite cell size, and the size and shape of the Si particles, with the ductility of the material. This model is based on the assumption that fracture occurs when a critical level of damage of the Si particles is attained. The level of damage was described in terms of Weibull statistics, while the theory of dispersion hardening was applied to calculate the stresses that lead to particle cracking. According to this model, the morphology and size of Si particles influence the ductility of the alloys in coarse structures, while the dendrite cell size also plays an important role in fine structures.

The influence of solidifications defects on tensile properties was not considered in the aforementioned papers. This assumption can be only true for the yield stress in the case of sound castings, because no substantial deformation occurs and the reduction of the loading area due to defects is negligible. On the contrary, UTS and E% are clearly affected by solidification defects, because the tensile failure propagates by plastic bridges between different defects, clearly reducing the amount of plastic deformation [4].

Another weak point of some of the previously reported relations refers to the measurement of the microstructural parameters linked to the Si particles. This requires a high quantity of data to be processed, mainly in the coarser structures for which the Si particles are not equiaxed and the particle parameters in the plane of polishing do not represent the three-dimensional parameter. This microstructural analysis and data processing is very time-consuming, which is critical for industrial application.

Oswald and Misra [13], instead, evaluated UTS using DAS as the main microstructural parameter. However, according to their model, in order to predict the local UTS in a cast component it is necessary to know the UTS for a test bar of similar composition, melt quality, soundness and heat treatment. Additionally, as reported by the authors, a small difference in the heat treatment procedures can significantly enhance the scatter between measured and calculated UTS. This greatly limits its industrial application, because in complex castings the heating or cooling rate are not uniform during the heat treatment.

The aim of this work is therefore to develop simple experimental equations that can successfully predict the local tensile properties in complex Al–Si–Mg castings on the basis of three simple parameters: SDAS, percentage of defects and hardness.

The main advantage of this approach is that the previously mentioned parameters can be obtained by simulation in the preprocessing phase design. Moreover, they can also be easily measured on metallographic specimens, even in zones of the casting from which tensile specimens cannot be taken.

2. Experimental

A primary A356 aluminium alloy (EN AC 42100) was used to fabricate cylinder heads (Fig. 1a) and engine blocks by permanent mould casting. Chemical composition of the alloy, obtained by spectrometric analyses, is listed in Table 1.

The A356 ingots were first remelted in a gas furnace. The melt was then poured into a crucible to control the hydrogen level in