PROCESS SIMULATION OF MICROSTRUCTURE AND RELATIONSHIP WITH MECHANICAL PROPERTIES IN DIECASTINGS

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Abstract

A review study is presented on microstructural and mechanical properties of Aluminium and Magnesium diecasting parts. Particular emphasis was given to the effects of typical diecasting defects (shrinkage porosity and gas porosity), their possibility of prediction by numerical process simulation and their relation to resulting diecast properties. The data available clearly show that a large improvement on overall casting properties is achievable by reducing the defect content of the microstructure either by a more strict control of conventional processes or by the adoption of innovative techniques such as vacuum assisted high pressure diecasting.

Riassunto

Il presente lavoro costituisce una sintesi delle principali tematiche di ricerca sulle proprietà microstrutturali e meccaniche dei getti pressocolati in alluminio e magnesio. In particolare viene focalizzata l'attenzione sui tipici difetti dei prodotti pressocolati (porosità di ritiro e da gas), sulle loro possibilità di previsione mediante processi di simulazione numerica e sulle risultanti caratteristiche dei getti. Dalle osservazioni esposte appare chiaramente l'ampio margine di miglioramento delle proprietà generali dei getti pressocolati ottenibile sia riducendo il contenuto dei difetti nella microstruttura con un più stretto controllo dei processi convenzionali, sia con l'adozione di processi più innovativi quali la pressocolata in vuoto.

INTRODUCTION

High pressure die casting (HPDC) is a well known near-net shape casting process in which the molten metal is injected into a permanent mould at high speed and it is allowed to solidify under high pressure. Intrinsic defects related to air and gas entrapment are produced in the castings owing to the high injection speed and to the turbulent flow of the molten metal into the die cavity. The so formed gas porosity adversely affects mechanical properties and pressure tightness of castings [1-4].

In recent years, several investigations aimed at decreasing the castings porosity have been carried out and, as a result of these studies, some process improvements have been proposed [5,7-11]. Foundry techniques similar to pressure die casting like rheocasting, tixocasting, squeeze casting and squeeze forming were developed. These fabrication processes are suitable for obtaining high quality castings but, owing to their high production cost, until now they have not had a widespread application.

In order to overcome the above drawbacks, vacuum die casting processes have been proposed. By creating a low pressure environment in the injection chamber and in the die cavity, the relative absence of air results in a lower back pressure encountered by the metal during die filling and in a marked reduction of gas porosity in castings. A simplification of the above mentioned complete vacuum process consists in the vacuum assistance system whereby only the die cavity is evacuated of the entrapped air. The adoption of this technique requires only simple and relatively cheap modifications of traditional diecasting systems leaving the peculiar productivity of the process substantially unaffected [1,6-13]. Vacuum diecasting can thus be considered as a process "similar" to the conventional die casting that, by means of limited additional efforts (both in terms of costs and of know-how), potentially allows a significant improvement of the final quality of castings to be achieved.

MICROSTRUCTURE AND DEFECTS

When considering typical defects found in diecasting parts, gas porosity represents undoubtedly the defect of greater concern. The main cause of its formation is the entrapped air in the injection chamber and in the die cavity. Gases generated from combustion/volatilisation of plunger lubricant and released hydrogen, originally dissolved in the liquid aluminium, are further mechanisms of influence [1,14-17].

Shrinkage porosity, cold fills, dross inclusions, oxide films and coarse intermetallic particles are additional common diecasting defects related to improper die filling conditions and alloy melting practice. Their mechanisms of generation are well established and documented in the literature [16-20]. A short collection of diecasting defects found in Magnesium alloys is given in Figure 1 for example purposes [21].
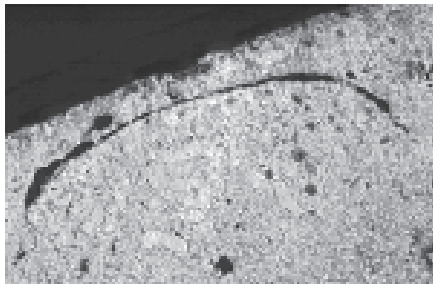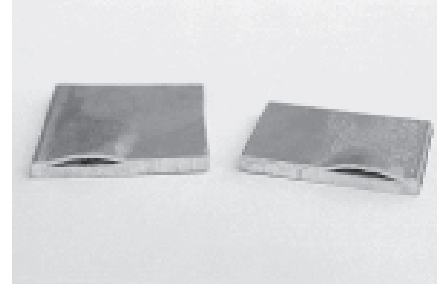
Porosity is, actually, one of the biggest problems
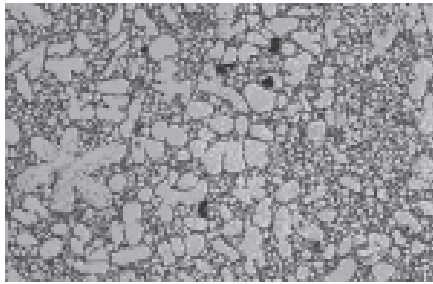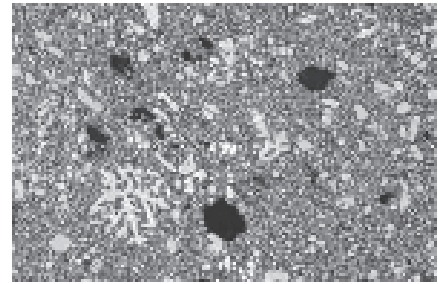
Fig. 1: Typical diecasting defects found in magnesium alloys. (a) shrinkage microporosity; (b) gas porosity; (c) cold fills; (d) blisters

in diecasting components. It produces, not only a strong reduction of the piece mechanical properties, but also other problems as the impossibility to perform thermal treatments and welding.

Castings porosity is indeed promoted by the combination of solidification shrinkage and gas segregation phenomena. In diecasting, shrinkage cavities are largely (but not completely) compensated by the pressure applied in the third phase of the injection cycle. On the contrary, more problematic is the elimination of the hydrogen porosity due to the differences in solubility of this gas in the liquid and solid metal. One of the most common phenomena in aluminium diecastings is the evolution of hydrogen dissolved in the liquid. Figure 2 depicts the equilibrium solubility limit of the hydrogen with temperature.

During alloy solidification, the above variation of solubility with temperature produces the rejection of the atomic hydrogen at the liquid-solid interface where its concentration can exceed the solubility limit. The hydrogen, rejected from
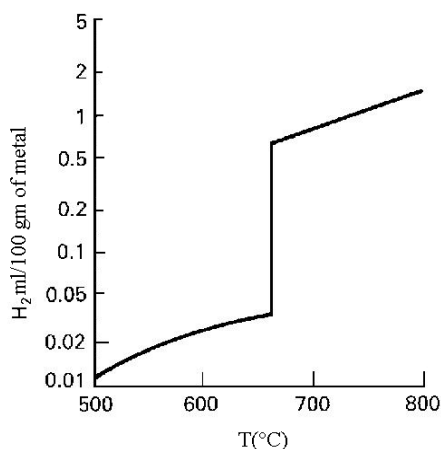

Fig. 2: Hydrogen solubility as a function of temperature for aluminium

the liquid and entrapped between the secondary dendrites arms becomes molecular and precipitates in small bubbles with a size ranging from 10 to 100 mm.

Although microporosity is a term strictly used to define the gas porosity, it often generates with the contribution of shrinkage, as shown in the schematic of Figure 3. The liquid, often of eutectic or near eutectic composition, remaining in the interdendritic regions during casting solidifies by a high degree of dimensional shrinkage. In these zones a proper liquid flow through the dendrite arms cannot be established to compensate for shrinkage, so that cavities easily originate. It is reported that their size is limited by the arm spacing between the dendrites.

It is worth emphasizing that castings having thin sections are particularly vulnerable to the effects of porosity since a few relatively large pores can reduce by a significant fraction the resisting cross-sectional area of the part. Non destructive testing consisting of X-ray examinations, density measurements, ultrasonic testing are therefore routinely applied for structural parts.

Gas porosity is associated both to injection parameters and to hydrogen supersaturation in the molten alloy [22-25]. The actual hydrogen concentration depends on several factors, the most important being the use of wet or dirty charge materials, melt superheating, and not optimised lubrication [26-28]. Further, proper die design is of great concern for the die-casting process optimisation and it strongly affects also the final porosity detected in a die casting part.

Of particular importance is the interrelation existing between melt cleanliness, as ruled for instance by hydrogen content and microstructural refinement practice, and porosity/microporosity formation [18, 29-31]. A recent work by Tian et al. [31] clearly demonstrated that inclusions in the melt (typically Fe-bearing intermetallics in die cast Al alloys) would act as nucleation sites for dissolved hydrogen, thus promoting porosity generation. Inclusions in the melt would also impair fluidity of the alloy thus hindering die feeding and further promoting microshrinkage formation.
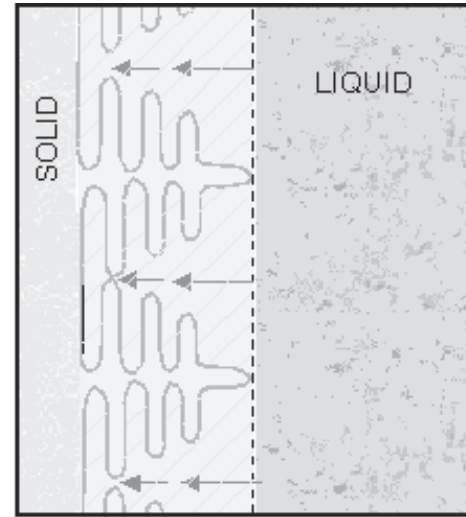

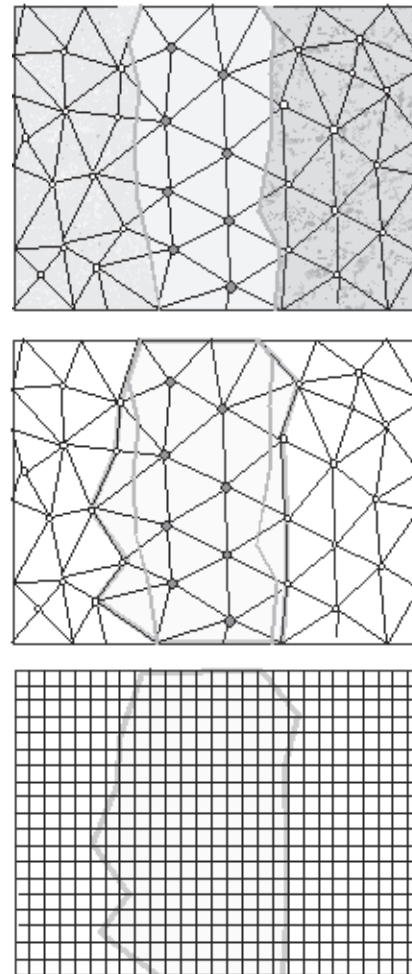Fig. 3: Liquid metal flow in the mushy zone, during solidification

Fig. 4: Schematic plot describing the adaptive and evolving mesh concept. (a) only few points fall into the mesh describing the mushy zone; (b) coloured finite elements considered as belonging to the mushy regions; (c) superimposed finer mesh which better describes the coloured elements of the mushy zone [35]

BACKGROUND OF NUMERICAL MODELLING

The design of the casting geometry can nowadays be supported by reliable tools such as finite element modelling of filling and solidification stages, allowing to optimise runner and gating systems as well as process parameters [6,32-33]. In addition, the most developed thermo and fluid-dynamic calculation codes allow prediction of shrinkage and gas porosity formation as well as evaluation of solidification residual stresses. A short background of the physical phenomena involved in pore nucleation and of the related fundamental equations to be solved for numerical process modelling is given below.

Microporosity is a casting defect formed during alloy solidification within the mushy zone, that is the transition or biphasic region in which solid and liquid metal co-exist (see Figure 3). The microscopic model used in computer simulation, which allows to evaluate the possibility of gas porosity generation is based on the formulation of liquid pressure drop due to shrinkage and gas segregation [34-35].

During state transformation from liquid to solid the metal experiences a density variation and consequently a volume contraction which implies a sort of suction of metal and a pressure drop in the liquid. The equation describing this phenomenon is the Darcy equation, according to which the flow of the liquid inside the dendrite arm spaces in the mushy zone is a linear function of the pressure gradient:

$$v = -\frac{K}{\mu} \cdot \left[grad\ P_l - \rho_l g \right] \qquad [1]$$

where v is the average solidification front growth rate, K is the dendrite solid permeability, m is the dynamic viscosity of the liquid metal, ρ_l is the liquid local pressure, ρ_l is the liquid specific density, and g is the gravity acceleration. The permeability is described by the following equation:

$$K = \frac{(1 - f_s)^3 \cdot d_2^2}{180 \cdot f_s^2} \qquad [2]$$

in which d_2 is the secondary dendrite arm spacing (SDAS) and f_s the solid fraction.

Since equation [1] has two unknowns, pressure and velocity field, a mass balance equation has to be considered:

$$\frac{\partial \rho}{\partial t} + div[\rho v] = \frac{\partial}{\partial t} \left[\rho_l f_l + \rho_s f_s \right] + div\left[\rho_l f_l v_l \right]$$

$$\qquad [3]$$

$$f_l = 1 - f_s - f_p$$

in which r_l, r_s and r are the liquid, the solid and the mushy zone density, respectively, and f_p is the pore volume fraction.

Therefore, combining the mass conservation and Darcy equations, the system can be solved:

$$div\left[-\frac{K}{\mu} \cdot (gradP_l - \rho g) \right] + \frac{\partial f_s}{\partial t} \left[\frac{\rho_s}{\rho_l} - 1 \right] - \frac{\partial f_p}{\partial t} = 0 \qquad [4]$$

Equation [4] is actually valid just in the mushy zone during its evolution and it needs the correct boundary conditions to be solved.

In the theoretical case of total absence of microporosity (f_p=0), the only variable becomes the pressure and the above system can be solved with two different approaches. A first method consists in using a fine adaptive and evolving mesh, schematically depicted in Figure 4, superimposed to the traditional one, and following the transition zone. A second solution can be found by using a coarser mesh as that used for the thermo-fluid dynamic calculations.

As mentioned above, equation [4] completely defines the problem of microporosity only in the case of shrinkage with the assumption of no pore formation (f_p=0). On the contrary, when considering the existence of dissolved gas (always present in traditional diecasting processes), equation [4] contains another unknown parameter: ($\partial f_p / \partial t$). Therefore, the hydrogen distribution has to be determined by the simulation software. If no pores were formed (f_p=0), considering that gases cannot diffuse at a macroscopic scale during solidification, the local mass balance would be calculated by the lever rule:

$$f_s \cdot \rho_s \cdot [H]_S + f_l \cdot \rho_l \cdot [H]_l = \rho_l \cdot [H]_0 \qquad [5]$$

where $[H]_0$ is the initial (uniform) hydrogen concentration, $[H]_S$ is the hydrogen concentration in the solid and $[H]_l$ in the liquid. Considering that $[H]_S = k_H[H]_l$, where k_H is the partition coefficient, the above equation becomes:

$$[H]_l = \frac{[H]_0}{f_s \cdot \dfrac{\rho_S}{\rho_l} \cdot [H]_S + (1 - f_S)} \qquad [6]$$

When hydrogen porosity occurs ($f_p \neq 0$), the gas balance given in equation [5] is modified by adding a porosity term ($\alpha \times f_p \times p_p / T$):

$$f_s \cdot \rho_s \cdot [H]_S + f_l \cdot \rho_l \cdot [H]_l + \alpha \cdot \frac{f_p \cdot p_p}{T} = \rho_l \cdot [H]_0 \qquad [7]$$

in which a is a conversion factor that transforms the actual hydrogen content in the pores to that measured at standard conditions (temperature T_{stp}=273 K, pressure p_{stp}=101 kPa), p_p is the pressure within the pores and T is the actual temperature of the metal where the pores are forming. Assuming that the pores are spheres of radius R, the internal pressure is given by the Laplace equation:

$$p_p = p_l + \Delta p_\sigma = p_l + \frac{2 \cdot \sigma_{g,l}}{R} \qquad [8]$$

in which Δp_σ is the overpressure due to the surface tension, and $\sigma_{g,l}$ is the interfacial tension between gas and liquid.

The gas concentrations in the liquid and solid phases are given by:

$$[H]_l = A_l(T) \cdot \sqrt{p_p} \quad , \quad [H]_s = A_s(T) \cdot \sqrt{p_p} \qquad [9]$$

where A_l and A_s are temperature and solute-dependent equilibrium constants. According to such hypotheses, microporosity evaluation depends on pore size R and on their internal pressure p_p. A schematic picture of the above mentioned factors of influence is depicted in Figure 5.

For a more detailed simulation, the main difficulty becomes the definition of a pore nucleation mechanism and its numerical treatment. A common method allowing to completely solve the problem of microporosity prediction considers the nucleation of a density of pores (n_c) at a critical overpressure ($\Delta p^C s$). If the concentration of hydrogen in the liquid metal, calculated by equation [9], is higher than that of the equilibrium condition corresponding to a critical pressure ($p_p = p_l + \Delta p^C s$):

$$[H]_l \geq A_l(T) \cdot \sqrt{p + \Delta p_\sigma^c} \qquad [10]$$

then n_c pores per unit of volume will nucleate and grow. Their dimension can be calculated by combining equations [7], [8] and [9], according to:

$$f_S \cdot \rho_S \cdot A_S(T) \cdot \sqrt{p_l + \frac{2 \cdot \sigma_{g,l}}{R}} + (1 - f_S) \cdot \rho_l \cdot A_l(T) \cdot \sqrt{p_l + \frac{2 \cdot \sigma_{g,l}}{R}} +$$

$$+ \alpha \cdot \left(n_c \cdot \frac{4}{3} \pi R^3 \right) \cdot \frac{p_l + \frac{2 \cdot \sigma_{g,l}}{R}}{T} = \rho_l \cdot [H]_0 \qquad [11]$$
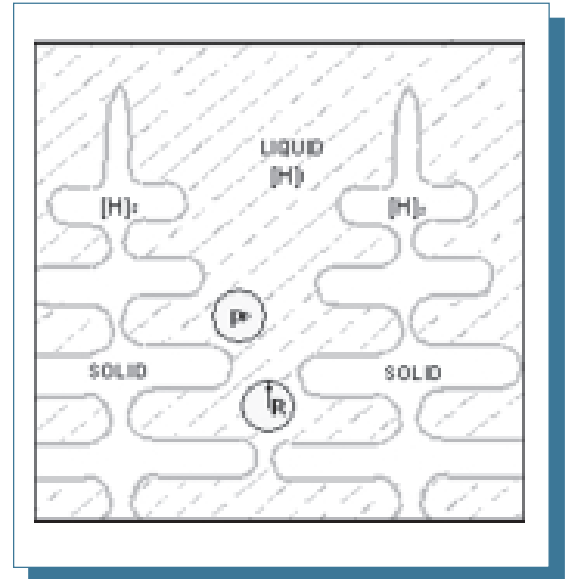

Fig. 5: Schematic of microporosity formation by numerical simulation

The software has now all the necessary equations in order to predict the microporosity distribution as a function of local conditions, either in terms of pores formation and dimension (eq. [11]) and in terms of change in the pressure of the liquid as well.

FABRICATION AND MECHANICAL PROPERTIES OF DIECASTINGS

The presence of gas porosity has the immediate consequence that some fundamental technological high temperature operations are prevented on die castings. As temperature increases the gases entrapped into porosity expands. In particular, when the expansion is not opposed by the surrounding metal (in thin sections), enlargement of the pre-existing porosity occurs and the metal experiences a relevant deformation leading to the so-called "blisters" (see Figure 1(d)) that impair both aesthetics and functionality of the component [1, 36].

The high level of porosity characterising current diecasting parts is thus responsible for the impossibility of performing heat treatments and weldings on diecastings. Therefore, it prevents any significant increase of mechanical properties, potentially achievable by heat treatment, and secondly, it hinders the use of castings within
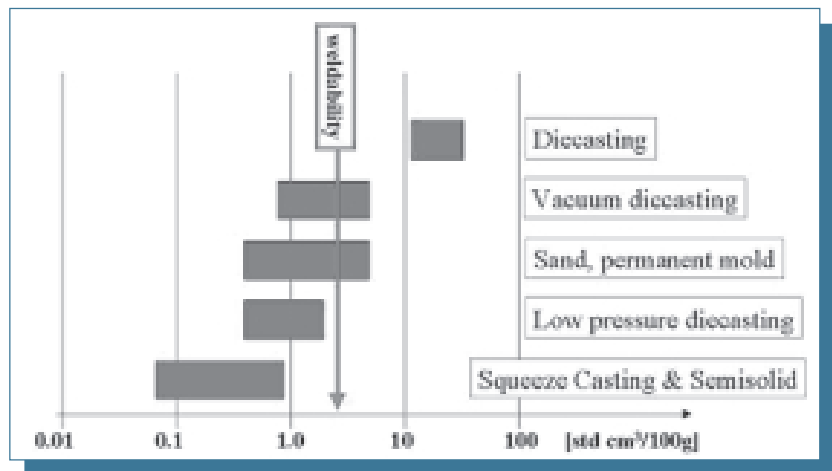

Fig. 6: Typical gas content (overall hydrogen, entrapped air, and other gases developed from lubricants) into castings produced via different processes

complex structures, assembled by welded joints.

The weldability of a diecast component implies an excellent metallurgical quality (absence or minimisation of gaseous defects) as well as a properly designed alloy chemical composition. Investigations on weldability of diecastings produced by means of innovative diecasting processes such as squeeze casting and thixocasting [3,37], characterized by gas porosity

contents significantly lower than conventionally diecast parts, are presented in literature [6, 38-40]. A gas amount of 4 std cc per 100 g of aluminium is usually considered as the upper threshold for achieving sufficient weldability, as shown in Figure 6 [37].

Such value is clearly exceeded in conventional diecastings, for which the gas amount typically ranges between 10 and 50 std cc/100 g), but the limit is potentially achievable in vacuum diecasting process (for which values as low as 1 std cc/100 g can be reached in the most favourable cases) [38]. The above discussed points highlight the need of a more detailed knowledge about causes and mechanisms of porosity formation in diecast components, in order to optimise the different stages of the production cycle, from alloy design to the extraction of the casting from the die. Therefore, every study and technical effort aimed at the comprehension of the causes and at limiting porosity, associated either to shrinkage phenomena during solidification or, more frequently in diecast parts, to gas supersaturation [1, 41-45] is mandatory for a wider extension of die casting technology.
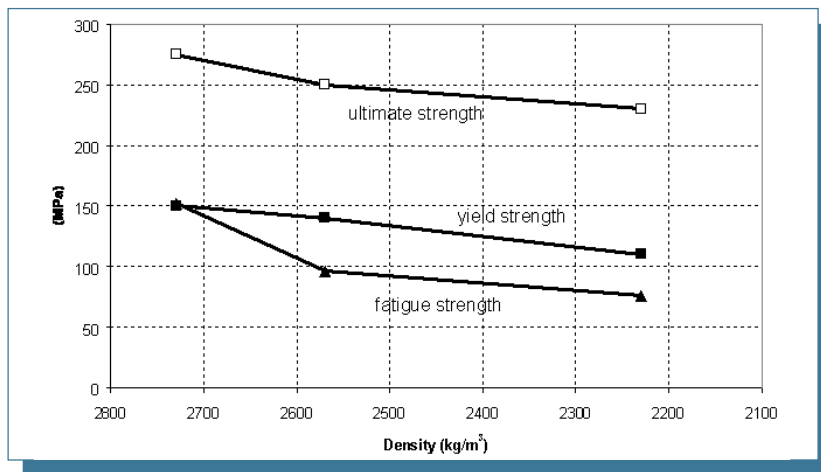

Fig. 7: Decrease of static and fatigue properties in diecast specimens as a function of material density for different sprue-runner design

From published papers on mechanical properties of defect-containing aluminium-alloy castings, it is inferred that also a remarkable improvement in material strength and ductility can be achieved provided a reduction of size and number of defects is obtained [14-15].

Of particular importance is the speculation made in [15] suggesting that the tensile behaviour poorly correlates with average bulk porosity. Instead, a reasonably good agreement exists between mechanical behaviour and the maximum amount and size of defects in the most critically stressed region of the casting. These correlations typically stem from laboratory analyses on "post-mortem" specimens aimed at evaluating the projected area of pores on fracture surfaces. A notable research work concerned with the effects of thermal treatments was published by Niu and co-workers [1]. A promising picture of data were given by a comparison of mechanical and microstructural properties of several Al-Si alloys produced by conventional and vacuum assisted diecasting. The Authors showed that a significant improvement in mechanical properties was achievable on the

as cast vacuum diecast alloys with respect to conventionally processed castings due to reduction of gas porosity. In addition, an even increased performance was attained with the solution treated and aged (T6 temper) vacuum diecast alloys. The improvement was also related to spheroidisation of the silicon particles in the structure, leading to reduction of brittleness when compared to as cast needle-like silicon.

The influence of porosity on fatigue strength was studied under constant-amplitude, variable-amplitude and simulated in-service conditions. It is generally acknowledged that the fatigue strength of materials containing defects is lower than that of a defect free material.

It is also generally accepted that fatigue life is affected not only by the average size of the cavities but also by the distance of the defect from a free surface. Recent data also showed the importance of the distribution and morphology of phases in the microstructure. Fatigue strength was reported [46] to vary with solidification parameters and, hence, with the location of the samples cut from the casting. In particular, it has been observed that the decrease of static and fatigue strength for specimen batches where the porosity level had been changed by variations in the sprue-runner design was significantly higher (even for the same porosity levels) than the decrease of static and fatigue strength obtained for specimen batches where the porosity level was changed by means of hydrogen addition fig. 7.

A non-optimised filling channel is likely to increase the number of gas cavities as well as the number of shrinkage cavities. These latter, having an irregular shape, cause higher stress concentrations when compared to gas cavities that have a regular circular shape. In addition, a non-optimised filling channel may introduce other casting defects such as oxide layers and cold fills which drastically lower the material fatigue strength. Another interesting feature about the fatigue behaviour of diecast parts is the opportunity to compare standard specimens and production components. In particular, it has been reported in the literature [14] that the rotating bending fatigue tests run on standard specimens may be significant for predicting the component fatigue behaviour.

CONCLUSIONS

In this paper, issues related to recent advances in Al and Mg diecasting technology and metallurgy were discussed. An analysis of typical casting defects was performed showing that gas and shrinkage porosity undoubtedly represent the aspects of greater concern. The main cause of gas porosity formation is the entrapped air in the injection chamber and in the die cavity. Gases generated from combustion/volatilisation of plunger lubricant and released hydrogen, originally dissolved in the liquid aluminium, are further mechanisms of influence.

It was speculated that fabrication processes relying on reduction of the entrapped gases within the die by vacuum assistance represent the most immediate way for a significant quality improvement in diecasting. In addition, wide margin of improvement are related to possible process optimisation achievable by more accurate design of cavity geometry and by numerical simulation of filling and solidification stages.

The presence of shrinkage and gas porosity is responsible for the impossibility of performing heat treatments on diecastings. Therefore, it prevents any significant increase of mechanical properties, potentially achievable by heat treatment. Further, it hinders the use of castings within complex structures, assembled by welding. From existing studies, it was shown that a maximum amount of 4 std cc/100 g of cast metal is considered as the upper limit for achieving a sufficient weldability. Such value is clearly exceeded in conventional diecastings but it is potentially achievable in vacuum diecasting processes.

From published papers on mechanical properties of defect-containing aluminium-alloy castings, it was demonstrated that also a remarkable improvement in material strength and ductility can be achieved, provided a reduction of size and number of defects is obtained. The distribution and morphology of defects as well as their location within the casting (especially the distance from free surfaces) are of particular importance for fatigue properties.

Fatigue strength was reported to vary with solidification parameters and hence with the location of the samples cut from the castings. In particular, it was observed that the decrease of static and fatigue strength for specimens where the porosity level had been changed by modification of filling and solidification conditions was significantly higher than the decrease of static and fatigue strength obtained for specimen where the porosity was varied by changing the intrinsic gas level before casting.

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