Influence of mould design and hydrogen content on the tensile properties of Al-Mg cast alloys

Mahmoud Ahmed El-Sayed

Department of Industrial and Management Engineering, Arab Academy for Science and Technology and Maritime Transport, PO Box 1029, Abu Qir, Alexandria 21599, Egypt

Abstract: Double oxide films are significant defects in the casting of light alloys, and have been shown to be detrimental to the mechanical properties. In this work the effect of three casting process parameters (the runner height, filtration and H content) were investigated using a two-level full factorial design of experiments. Four responses; the Weibull modulus and position parameter of both the ultimate tensile strength (UTS) and % elongation were assessed. The results suggested that adopting a 10 mm-thick runner along with the use of 10 PPI filters resulted in a substantial enhancement of the Weibull moduli of the UTS and % elongation, perhaps due to the improved mould filling conditions that eliminated the chance of oxide film entrainment. In addition, it was shown that when the H content of the castings was reduced from 1.31 to 0.48 cm³/100g there was a noticeable decrease in the size of bifilm defects with a corresponding improvement in the mechanical properties. Such significant effect of the process parameters studied on the casting properties suggests that the more careful and quiescent mould filling practice and the lower the H content of the casting, the higher the quality and reliability of the castings produced.

Keywords: Al castings, Oxide film defect, Hydrogen, Mechanical properties

Introduction

The use of aluminium alloys in the automotive and aerospace industries has grown dramatically in recent years. This is due to their distinctive properties, mainly the high strength to weight ratio [1]. Such characteristics made it the ideal nominee to replace heavier materials (steel or copper) to respond to the weight reduction demand within the automotive industry. However, the presence of structural defects, mainly double oxide film defects (or bifilms), results in a high level of variability in mechanical properties of cast Al.

Bifilms are created due to surface turbulence of the liquid Al, which is a common foundry practice during the metal pouring. If liquid aluminium entered a mould cavity with a velocity greater than a critical value, the surface oxide film of the liquid metal would fold over onto itself and be submerged into the bulk liquid with a volume of air entrapped within it [2]. This typically constituted a crack in the solidified casting. Results from earlier studies suggested that oxide bifilms play a major role in the reduction of the quality and reliability of aluminum casting alloys [3]. They cause mechanical weakness and form leak paths through the walls of castings [4]. In addition, it was shown that soluble hydrogen within the melt might diffuse into the bifilms, expanding them to form hydrogen porosity. Therefore, A general acceptance was gradually growing among
researchers that bifilms, either acting as cracks or helping in the nucleation of porosity, are strongly promoting the failure of Al cast alloys [2].

Previous studies have shown that if the ingate velocity (the flow velocity of the melt at the mould entrance) could be kept below a certain value (called the critical velocity), formation of such defects could be avoided. This could be achieved by the study of the running system design to improve mould filling and avoid entrainment of oxide films in the bulk liquid [5,6]. Campbell stated that the entrainment of bifilms during melt pouring depends upon two important terms; the Weber number and the critical velocity. The Weber number (We) is defined as the ratio of the inertial pressure in the melt (that acts to disturb the surface) to the pressure due to surface tension (that tends to keep the surface flat) [1]. The critical velocity (Vc) is the flow velocity at the mould entrance (the ingate) above which entrainment of surface oxide films would occur [1]. If the inertial forces in the liquid exceed the surface tension forces (i.e. Weber number >1), the surface would suffer a significant turbulence which is sufficient to make it enfolding. This situation is equivalent to when the mould-entry velocity exceeds the critical velocity which forces the surface to be propelled upwards, achieving a height sufficient that it may enfold its oxide surface as it falls back under gravity [1,2].

Halvaei and Campbell [7] investigated the critical mould entry velocity for different aluminium bronze alloys. During the casting experiments, the metal was introduced into the mould cavity at different mould entry velocities. The filling process of the mould was recorded using a video camera to monitor the flow behavior of the liquid metal. Also the defects in the finished casting were assessed using x-ray radiography and SEM. The critical velocity was found to be about 0.4±0.08 m s\(^{-1}\). Similar results were obtained by many researchers such as Runyoro and co-authors [6] and Bahreinian et al. [8] for different Al and Mg alloys which suggested that the critical velocity would be around 0.5 m/s.

Dispinar and Campbell argued that double oxide films would work as initiators for the gas porosity in Al castings while the hydrogen acts as a contributor to the porosity formation process [9]. Their results suggested that during solidification the hydrogen, in excess of the solubility limit, comes out of solution and diffuses into the bifilm gap, expanding it into a pore. Evidence for the role of bifilms in the formation of porosity in Al castings was recently presented by El-Sayed et.al [10] who introduced oxide films to a 2L99 alloy melt via stirring, before allowing the melt to solidify under a reduced pressure. SEM investigation of the pores in the solidified ingot showed many MgAl\(_2\)O\(_4\) fragments inside pores suggesting that the observed pores were initially double oxide film defects that expanded due to the application of a vacuum and the decreased melt pressure around them. This might result in tearing the films apart leaving only oxide fragments inside the pores. In other studies by El-Sayed et al. [11] and El-Sayed and Griffiths [12] it was concluded that reducing the H content of an Al casting would cause a significant reduction of the size of bifilms and in turn increase the Weibull moduli of both the UTS and %elongation.

Design of experiments (DoE) is a systematic method to determine the relationship between factors affecting a process and the output of that process. In other words, it is used to find cause-and-effect relationships. This information is needed to manage process inputs in order to optimize the output. A common experimental design is one with all input factors set at two levels each. These levels are called ‘high’ and ‘low’, ‘Good’ and ‘Bad’ or ‘+1’ and ‘-1’, respectively. A design with all possible +1/-1 combinations of all the input factors is called a full factorial design in two levels. If there are k factors, each at 2 levels, a full factorial design has \(2^k\) runs [13].

One of the early trials to utilize DoE in studying the effect of casting parameters on the quality of the castings was that performed by Tiryakioglu et al. [14] who applied Response Surface Method for the optimization of casting parameters for the production of sound Al castings. In this work the effect of different casting parameters such as pouring temperature, shape and volume of the casting on the filling time and
casting density of A56 Al casting was studied. In addition, the casting conditions were optimized to obtain castings with best possible quality. DoE techniques were also applied by other researchers to identify of the critical factors affecting shrinkage porosity in permanent mould casting [15].

The purpose of current study is to explore how different casting conditions, such as the mould design, the use of filters and the H content of the casting, can affect the amount and morphology of bifilm defects, and by implication the tensile properties of the resulting castings. However, the studying of each of these conditions (factors) independently is quite tedious and time consuming. Thus, a factorial design can minimize this difficulty by studying all the affecting parameters collectively at a time. The design determines the effect of each factor (main effect) on responses (the tensile properties of the castings in this study) as well as how the effect of each factor varies with the change in the level of the other factors (interaction effect). Interaction effects of different factors could be attained using design of experiments only [16]. In the present study, three-factor two-level full factorial design ($2^3$ runs) was used for the modeling of casting process. The results of this investigation could lead to the development of techniques by which oxide film defects might be reduced or eliminated in aluminum castings.

Experimental

This study was aimed at investigating the effect of three important parameters in the sand casting process, namely; the runner height, filtration and H content of the casting, on oxide film content and consequently on the tensile properties of Al castings. Castings from Al-5 wt.% Mg alloy were produced via gravity casting. To perform the design of the experiment, Design-Expert Software Version 7.0.0 (Stat-Ease Inc., Minneapolis, USA) was used and the two-level full factorial design was adopted to analyze the effects of the three selected parameters and their interactions.

The two-level full factorial design was selected because the parameters could be easily varied at two discrete levels and statistically analyzed using only eight total experiments, making the DoE easy to regulate and execute due to the low complexity. In this study each parameter was varied at a "-1" and "1" value and its effect on the UTS and % elongation was evaluated. The experiment, therefore, contained 8 combinations of significant factors and the full-factorial experiment (experimental plan) is shown in Table 1.

Table 1. Experimental plan

<table>
<thead>
<tr>
<th>Factor</th>
<th>Coded symbol</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Runner Height</td>
<td>A</td>
<td>-1</td>
<td>1</td>
<td>-1</td>
<td>1</td>
<td>-1</td>
<td>1</td>
<td>-1</td>
<td>1</td>
</tr>
<tr>
<td>Filtration</td>
<td>B</td>
<td>-1</td>
<td>1</td>
<td>-1</td>
<td>1</td>
<td>-1</td>
<td>1</td>
<td>-1</td>
<td>1</td>
</tr>
<tr>
<td>Hydrogen content of the casting</td>
<td>C</td>
<td>-1</td>
<td>1</td>
<td>-1</td>
<td>1</td>
<td>-1</td>
<td>1</td>
<td>-1</td>
<td>1</td>
</tr>
</tbody>
</table>

In each experiment two resin-bonded sand moulds were prepared, each producing 10 test bars. The pattern used for this experiment was the tensile test bar mould shown in Figure 1 (a). Each mould contained 10 test
bars, each with a diameter of 10 mm and length of 110 mm. For each of the eight experiments, about 6 kg of the aluminium alloy were melted and held at about 1073 K (800°C) under a reduced pressure of about 200 mbar for two hours, in an attempt to remove previously-introduced bifilms from the melt, by expansion and flotation to the surface [16]. The melt was then poured into the sand moulds in a way that might cause the creation and entrainment of fresh double oxide film defects.

To investigate the effect of the H content of the casting, the experiments were divided into two types; the first type (the high H content (experiments 1-4)), in which the molten metal was poured into sand moulds that had been prepared one day before the experiment. For the second type (the low H content (experiments 5-8)), additional procedures were applied in order to obtain castings with low H content. In these experiments and after the vacuum treatment the melt was kept at 750°C and argon-degassed using a lance for 1 hour. Also, for this set of experiments the sand moulds had been being held under a partial vacuum of about 500 mbar for two weeks before carrying out the experiment. This was expected to remove the solvent from the resin binder from the moulds, and in turn minimise the H pick-up by the casting from the mould during solidification [12]. In addition, for experiments 3, 4, 7 and 8 two 10 PPI (Pores Per linear Inch) ceramic filters, of dimensions 50x50x20 mm, were placed in the filter prints at the locations shown in Figure 1. The ceramic filters would play a role in removing any remaining inclusions and oxide bifilms, and also reduce the flow speed of the molten alloy filling the mould which might prevent any further oxide film from being entrained. Finally, the heights of the thin and thick runners were 10 and 25 mm respectively. The appropriate selection of the runner height would prevent the melt issuing from the filter from jetting into the air with the associated risk of the recreation of oxide bifilm defects.

During the experiments, the hydrogen content of the melt (in cm³/100g) was evaluated after melting, after the vacuum treatment and after degassing (whenever applicable) using a Severn Science HYSCAN machine. Also, for each of the eight experiments, a Leco sample for solid state H determination was cut out from the running bars of the solidified castings from each experiment. The samples were machined to the dimensions of standard Leco samples (8 mm diameter and 49 mm length) and analyzed to determine the hydrogen content of the castings from different experiments.

After solidification, the castings were machined into tensile samples of the shape and dimensions shown in Figure 1 (b). 20 test bars were produced from each experiment. The tensile tests were conducted using a WDW-100E universal testing machine using a constant loading speed of 1 mm/min. Tensile results were evaluated using the Weibull statistical analysis approach to assess the influence of different casting parameters on the variability of the mechanical properties of the castings. Finally, Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray (EDX) studies were carried out on the fracture surfaces of the tensile test specimens using a Philips XL-30 SEM with Oxford Inca EDS, for the evidence of bifilm.

![Figure 1](https://example.com/figure1.png)

**Figure 1.** (a) Schematic sketch of the pattern used in this research, (b) Dimensions (in mm) of the test bars machined from the castings.
Results and Discussion

Holding an Al melt under vacuum would be expected to cause the expansion of any atmosphere within the entrained double oxide films and increase their buoyancy. This would allow the bifilm defects to float to the surface of the melt, and therefore reduce their harmful effects on the mechanical properties of the casting. In the current work, an Al-5Mg melt was first held under vacuum to eliminate the effect of previously-introduced oxides in the raw and ensure that the variability among the castings produced is mainly due to the changing casting conditions under which they were produced. These conditions (factors) involved the design of the running system (mainly the runner height and the use of filters) and the H content of the solidified casting. The results of different experiments were interpreted to allow a better understanding of the behaviour of bifilms in Al alloy castings.

The results show that the H content of the molten Al alloy before and after the vacuum treatment were 1.75 and 0.94 cm$^3$/100g Al, respectively (Experiments 1-8). For experiments 1-4, the vacuum-treated melt was poured into sand moulds made one day before the experiment. The average H content of the solidified castings from these experiments was determined to be 1.31 cm$^3$/100g Al, a bit close to the untreated casting. This is probably due to the evaporation of the solvent (of the resin bonding the sand grains) during pouring and the consequent release of hydrogen which might have been absorbed by the liquid metal.

In contrast, for experiments 5-8, degassing of the melt for 1 hour after the vacuum treatment has significantly decreased the H content of the melt from 0.94 to 0.37 cm$^3$/100g Al. The average H content of the solidified castings from these experiments was 0.48 cm$^3$/100g Al, about one third the H content of the castings in experiments 1-4. This is suggested to be due to the moulds being held under vacuum before casting which seems to cause the moulds to lose most of the solvent and therefore minimized the amount of H picked up by the melt from the mould [17,12], hence the relatively low H content of the castings of 0.48 cm$^3$/100g Al was obtained.

EasyFit (MathWave Technologies) [18] software was used to obtain the probability distribution for each of the UTS and % elongation for test bars cut from the castings from different experiments. Figure 2 shows the distribution of the UTS values of samples from experiment 7. It was evident that the distribution had a good fit with the Weibull distribution, rather than normal or exponential distributions, suggesting that the characterization of the results using a Weibull Modulus approach was appropriate. In this way EasyFit was utilized to confirm the fitting of the Weibull distribution [19] to the data obtained for each property from different experiments. Weibull distribution was also suggested in previous studies to be the best distribution to describe the variability in the properties of Al castings [3,20].

Therefore, in this study the two-parameter Weibull distribution was used to analyse the scatter in the mechanical properties of the castings from different experiments. The Weibull modulus is a single value that shows the spread of properties; a higher Weibull modulus is indicative of a narrower spread of properties. In addition, the position parameter is the characteristic stress at which 1/e of the samples survived [19]. EasyFit was also used to determine the Weibull modulus and position parameter for the UTS and % elongation of the test bars from different experiments. The results of the Weibull analysis of both of the UTS and percentage elongation values obtained from the different experiments are given in Table 2.

Figures 3 (a) and (b) show 3D surface plots of the interaction between the runner height and filtration for the Weibull moduli of the UTS, at high and low H content, respectively. The corresponding plots for the Weibull moduli of the % elongation are shown in Figures 3 (c) and (d) respectively. For the castings with high H content (experiments 1-4), the Weibull modulus of the UTS, when the runner height was 25 mm and without the use of filters, was 4.5. Decreasing the runner height to 10 mm increased the modulus to 7, while the use of filters increases the modulus to 9.8. Nevertheless, the use of 10 mm-thick runners accompanied by
the use of 10 PPI filters caused the Weibull modulus to increase to 25.2. Also, for these experiments an elongation modulus of 2.9 was obtained for the casting produced using a runner height of 25 mm and without the use of filters. Castings with Weibull moduli of 4.9, 7.6 and 14.3 were obtained when a 10 mm-thick runner was used, filters were implemented and when both the thin runner and filters were adopted. For the castings with low H content (experiments 5-8), the Weibull modulus of the UTS increased from 8.6 (when a thick runner was used without filtration) to 41.5 (for the filtered casting produced using a thin runner). The Weibull modulus of the % elongation followed similar behaviour as the simultaneous use of a thin runner and filters caused the modulus to increase from 3.4 to 30.2.

**Figure 2.** Distribution of the UTS values for the test bars from experiment 7 as compared to the calculated frequency of different distributions emphasizing the adequacy of the Weibull distribution.

**Table 2.** Results of the Weibull analysis for the test bars of the castings from different experiments.

<table>
<thead>
<tr>
<th>Exp. No.</th>
<th>Runner Height</th>
<th>Use of Filters</th>
<th>H Content</th>
<th>UTS (MPa)</th>
<th>% Elongation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Thick</td>
<td>Unfiltered</td>
<td>High</td>
<td>4.50</td>
<td>98.60</td>
</tr>
<tr>
<td>2</td>
<td>Thin</td>
<td>Unfiltered</td>
<td>High</td>
<td>7.00</td>
<td>105.14</td>
</tr>
<tr>
<td>3</td>
<td>Thick</td>
<td>Filtered</td>
<td>High</td>
<td>9.83</td>
<td>122.58</td>
</tr>
<tr>
<td>4</td>
<td>Thin</td>
<td>Filtered</td>
<td>High</td>
<td>25.24</td>
<td>140.18</td>
</tr>
<tr>
<td>5</td>
<td>Thick</td>
<td>Unfiltered</td>
<td>Low</td>
<td>8.58</td>
<td>135.83</td>
</tr>
<tr>
<td>6</td>
<td>Thin</td>
<td>Unfiltered</td>
<td>Low</td>
<td>17.99</td>
<td>166.60</td>
</tr>
<tr>
<td>7</td>
<td>Thick</td>
<td>Filtered</td>
<td>Low</td>
<td>13.31</td>
<td>145.54</td>
</tr>
<tr>
<td>8</td>
<td>Thin</td>
<td>Filtered</td>
<td>Low</td>
<td>41.45</td>
<td>199.88</td>
</tr>
</tbody>
</table>

3D surface plots of the position parameters of the UTS of the Al alloy against both the runner height and filtration, at high and low H contents, are presented in Figures 4 (a) and (b), respectively, while those for the position parameters of the % elongation are shown in Figures 4 (c) and (d) respectively. The position parameters showed a similar behavior to that of the Weibull moduli of both the UTS and % elongation. For example, and for the castings with low H content the use of thin runner together with the utilization of filters caused the position parameter of both the UTS and % Elongation to increase from 134 to 200 MPa, and from 24.2 to 43, respectively.
Generally, it was obvious that the use of thin runners and filters, as well as the application of casting procedures that tended to minimize the H content of the casting produced, had a significant effect on the increase of both the Weibull moduli and position parameters of both the UTS and % elongation. As could be inferred from Figures 3 and 4, the properties of the castings produced in experiment 8, where low H content castings were produced using filters and thin runners, were the highest among all castings. This indicates that the casting properties have been improved and the variability among them had been reduced.

Using the experimental data, a factorial analysis was performed and Analysis of Variance (ANOVA) statistical approach was performed to determine the standardized effects of different parameters (the runner height, filtration and H content of the casting) and their interactions on the Weibull modulus and position parameter of both the UTS and % elongation. Table 3 summarizes the list of factors and their interactions as well as the effect of each factor and/or interaction. The effect is the change in the response as the factor changes from the "-1" level to the "+1" level. In other words, the effect of a given factor A is the difference between the average response at the "+1" level of A and the average response at the "-1" level of A. A positive value of the effect indicates a synergistic effect that favors optimization, while a negative sign represents an antagonistic or inverse effect of the factor on the selected response [21].

![3D surface plots showing the effect of the interaction between the runner height and filtration on: (a) and (b) Weibull modulus of the UTS at high and low H content respectively, (c) and (d) Weibull modulus of the % Elongation at high and low H content respectively.](image-url)
Table 3. Factorial analysis of the castings properties.

<table>
<thead>
<tr>
<th>Term</th>
<th>Weibull modulus of UTS (MPa)</th>
<th>Position Parameter of UTS (MPa)</th>
<th>Weibull modulus of % Elongation (%)</th>
<th>Position Parameter of % Elongation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-Runner Height</td>
<td>11.0</td>
<td>16.8</td>
<td>6.8</td>
<td>6.8</td>
</tr>
<tr>
<td>B-Filtration</td>
<td>15.0</td>
<td>36.3</td>
<td>12.3</td>
<td>11.3</td>
</tr>
<tr>
<td>C-Hydrogen Level</td>
<td>8.5</td>
<td>45.8</td>
<td>6.8</td>
<td>20.8</td>
</tr>
<tr>
<td>AB</td>
<td>8.0</td>
<td>8.3</td>
<td>3.3</td>
<td>2.3</td>
</tr>
<tr>
<td>AC</td>
<td>2.5</td>
<td>4.8</td>
<td>2.8</td>
<td>-1.3</td>
</tr>
<tr>
<td>BC</td>
<td>3.5</td>
<td>6.3</td>
<td>5.3</td>
<td>2.3</td>
</tr>
<tr>
<td>ABC</td>
<td>1.5</td>
<td>3.3</td>
<td>1.3</td>
<td>-1.8</td>
</tr>
</tbody>
</table>

It should be emphasized that the achieved inferences for the effect of casting conditions on the mechanical properties of Al-5Mg alloy castings are only valid within the investigated range of process parameters. Other situations, such as the exaggerated slow filling practice of the mould associated with the use of very thin runner or filters with tight meshes, might take place outside the examined range which might result in an improper filling of the mould cavity and the creation of other defects such as misrun and/or cold shut.

Figure 4. 3D surface plots showing the effect of the interaction between the runner height and filtration on: (a) and (b) position parameter of the UTS at high and low H content respectively, (c) and (d) position parameter of the % Elongation at high and low H content respectively.
SEM investigation of fracture surfaces of test bars from the different experiments revealed the presence of oxide films in specimens from experiments 1-3 and 5-7. Examples of these surfaces are shown in Figures 5 (a) and (b). Analysis by EDX was carried out at locations marked with “X” where it was suggested that MgO existed on the surfaces. Only the fracture surfaces of the specimens from experiments 4 and 8 were found to be free of oxide films. An example is shown in Figure 5 (c). The fracture surfaces were always selected from test bars that showed the lowest tensile strengths.

As shown in Figure 5 (a), MgO layers were detected at the fracture surface of a specimen from experiments 1. Corresponding oxide fragments were detected at the fracture surface of a specimen from experiment 5 (Figure 5 (b)). However, the sizes of such fragments were relatively smaller than those detected in experiment 1. Generally, it was shown that the areas of oxide films detected on the fracture surfaces of test bars from experiments 5, 6 and 7 were relatively smaller than those associated with castings from experiments 1, 2 and 3. This might be due to the significantly lower H content of former experiments due to the application of degassing.

Finally, and as shown in Figure 5 (c), no oxide films were detected at the fracture surfaces of the test bars from experiment 8. EDX analysis performed at several locations of these surfaces always detected peaks for aluminium and magnesium only indicating the absence of oxide films on these surfaces. This is suggested to be a result of the simultaneous use of filters and thin runners that seemed to prevent the oxide film entrainment during the pouring of the melt.

![Figure 5](image-url)

**Figure 5.** SEM images with the corresponding EDX analysis (at the locations marked "X" of the fracture surface of specimens from Experiments 1, 5 and 8 respectively.

In earlier studies of the effect of oxide films on the mechanical properties of different Al castings, the mould design shown in Figure 1(a) (using a 25 mm thick runner and without the use of filters) was suggested to cause severe surface turbulence of the melt during mould filling which resulted in the creation of a significant amount of oxide films [22]. Previous studies by Dispinar and Campbell [9], Raiszadeh and
Griffiths [23] and recently by El-Sayed et al. [11] also suggested that hydrogen in excess of the solubility limit of the Al melt might diffuse into the bifilm gap to form H porosity in the Al castings.

In the present work and in experiment 1 the poor mould design was deliberately used while casting practices were applied to produce a casting with high H content. This was expected to cause the velocity of the molten metal at mould entrance (the gate velocity) to firmly exceed the critical velocity, resulting in an oxide film entrainment. Also, the relatively high H content of the castings in this experiment (about 1.31 cm$^3$/100g Al) would have allowed more H to diffuse into the bifilms and increase their sizes, which was confirmed by the SEM examination of the fracture surfaces (See Figure 5 (a)). This caused a significant reduction in the UTS and % elongation of the casting produced in experiment 1 (position parameters of 98.6 MPa and 6.1%, respectively) and also increased they scatter (Weibull moduli of 4.5 and 2.9, respectively). This could be easily inferred from the results presented in Table 2 and Figures 3 and 4 which showed that the castings from experiment 1 experienced the worst properties among all experiments.

Therefore, DoE was applied to study the effect of different casting conditions, namely the runner height, the filtration and the H content of the casting, on the formation and morphology of double oxide film defects and by implication on the mechanical properties of Al-5Mg cast alloys. Referring to Table 3, reducing the runner height from 25 to 10 mm showed to have a positive effect on the Weibull modulus and position parameter of the UTS of 11 and 16.8 MPa respectively, and on the Weibull modulus and position parameter of the % elongation of 6.8 and 6.8% respectively. The use of 10 PPI filters had also an optimistic effect on both the Weibull moduli and position parameters of the UTS and % elongation. However, the standardized effects of the filtration on the measured responses were about twice those related to the decreased runner height. This could be due to their secondary role in the removal of inclusions out from the melt.

It could be suggested that the use of a thin runner could eliminate the jetting of the molten metal during its journey through the runner. In addition, the use of filters seems to help to reduce the acceleration of the incoming flow of liquid metal inside the runner before entering the mould cavity. Therefore, the adopting of thin runner along with the use of filters (experiments 4 and 8) would allow for more quiescent filling regime of the mould cavity and in turn led to a reduction in the innate velocity to less than 0.5 m/s, which minimized the amount of entrained oxide films and correspondingly enhanced the mechanical properties. This could be demonstrated via the SEM image of the fracture surface of a specimen from experiment 8 (shown in Figure 5 (c)), that did not show any oxide fragments on the surfaces, which was also confirmed by the supplemented EDX analysis spectrum. These results were in agreement with the results obtained by Bozchaloeia et al. during their study of the effect of runner height after filter on oxide film formation and mechanical properties of Al-7Si-Mg castings [4]. In this work the authors reported a considerable improvement in the Weibull moduli of the both the UTS and % elongation of about 350% when reducing the runner height from 24 to 12 mm that seemed to keep the ingate velocity at less than 0.5 m/s.

Finally, the H content of the casting was shown to have a significant effect on the tensile properties. As indicated in Table 3, reducing the H content of an Al-5Mg alloy casting from 1.31 to 0.48 cm$^3$/100g Al had a positive effect on the Weibull modulus and position parameter of the UTS of 8.5 and 45.8 MPa respectively, and on the Weibull modulus and position parameter of the % elongation of 6.8 and 20.8% respectively. This could be demonstrated by comparing the SEM images of the fracture surfaces of specimens from experiments 1 and 5, shown in Figures 5 (a) and (b) respectively. The size of oxide layers detected in the casting from experiment 5 was less than half the size of those in the casting from experiment 1. Accordingly, the castings from experiment 5 showed an increase of the Weibull moduli of the UTS and %elongation by about 91% and 16% respectively. Also, a significant enhancement in the position parameters of both properties by about 38% and 295%, respectively were obtained due to the reduced H content, see Table 2 and Figures 3 and 4. These
results are in agreement by the results by El-Sayed and Griffiths who reported an increase in the Weibull moduli of the UTS and %elongation of the 2L99 alloy by 400% and 200% respectively, when the H content was reduced from 0.18 to 0.08 cm$^3$/100g Al [12].

The implication of these results is that the optimization of the runner system design and improving the flow behavior during mould filling could significantly reduce the production of oxide films. In addition, reducing the H content of the final casting would minimize the amount of the gas diffuses into the bifilms, reducing their sizes and in turn, improve the Weibull moduli of the UTS and the % elongation. Therefore, if the H content of the melt could be decreased (by degassing) prior to pouring into the sand mould, this would allow the production of castings with minimum H content. Also, if a mould with a thin runner was used and filters were adopted, this would allow a more quiescent mould filling regime. These considerations would allow a casting producer to reduce both the amount and the size of the oxide film defects in the Al alloy and in turn lead to castings with higher and more reproducible mechanical properties.

Conclusions

1. Factorial analysis revealed that filtration had the largest effects on the Weibull moduli of both the UTS and % elongation, which were about 15 and 12.3 respectively.
2. DoE results also indicated that H level was the most significant factor influencing the position parameters of both the UTS and % elongation, with effects of 45.8 MPa and 20.8% respectively.
3. Decreasing the H content of an Al-5Mg alloy casting from 1.31 to 0.48 cm$^3$/100g accompanied with the use of 10 mm-thick runner and the use of 10 PPI filters resulted in a substantial improvement of the Weibull moduli of the UTS and % elongation by about 820% and 930% respectively, compared to a casting with a 1.31 cm$^3$/100g H content that was produced using a 25 mm-thick runner and without filtration.

References


