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Research Article

Effect of Casting Conditions on the Fracture Strength of Al-5 Mg Alloy Castings

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During the transient phase of filling a casting running system, surface turbulence can cause the entrainment of oxide films into the bulk liquid. Previous research has suggested that the entrained oxide film would have a deleterious effect on the reproducibility of the mechanical properties of Al cast alloys. In this work, the Weibull moduli for the ultimate tensile strength (UTS) and % elongation of sand cast bars produced under different casting conditions were compared as indicators of casting reliability which was expected to be a function of the oxide film content. The results showed that the use of a thin runner along with the use of filters can significantly eliminate the surface turbulence of the melt during mould filling which would lead to the avoidance of the generation and entrainment of surface oxide films and in turn produce castings with more reliable and reproducible mechanical properties compared to the castings produced using conventional running systems.

1. Introduction

Due to their unique properties, the usage of aluminium alloys in different industrial sectors has grown dramatically in the last decades. Their high elasticity, high electrical and thermal conductivity, and high strength-to-weight ratio allowed them to be widely adopted in the automotive and aerospace industries [1, 2]. However, the mechanical properties of Al castings were found to be greatly affected by the presence of double oxide film defects (or bifilms) which were reported to not only reduce the tensile strength and fatigue limit of the castings but also increase their variability [3–6].

Bifilms were suggested to result from the surface disturbance during metal flow which causes the surface of the liquid metal to fold over onto itself. This causes the upper and lower oxidized surfaces of the folded-over metal to come together and trap a layer of the mould atmosphere between them, creating a double oxide film defect [7–12]. This defect is then incorporated into the bulk liquid in an entrainment action, which typically constitutes a crack in the solidified casting, as shown in Figure 1 [4]. Oxide films were also shown to act as nucleation sites for hydrogen porosity and iron intermetallics [13, 14]. Such consequences were found to have detrimental effects on the mechanical properties of the castings produced [15]. Results of research performed by Green and Campbell [16] and Nyahumwa et al. [17] suggested that aluminium alloys usually achieve just a small fraction of their intended properties while these defects are present.

Several researchers had explained the mechanism responsible for the entrainment of bifilms in Al castings that usually occurs during pouring of the metal into the mould by introducing the concept of the critical velocity. The critical velocity (V_c) is the flow velocity at the mould entrance (the ingate) above which entrainment of surface oxide films would occur [18] and is commonly written as the following:

$$V_c = 2\left(\frac{\gamma g}{\rho}\right)^{1/4}, \quad (1)$$

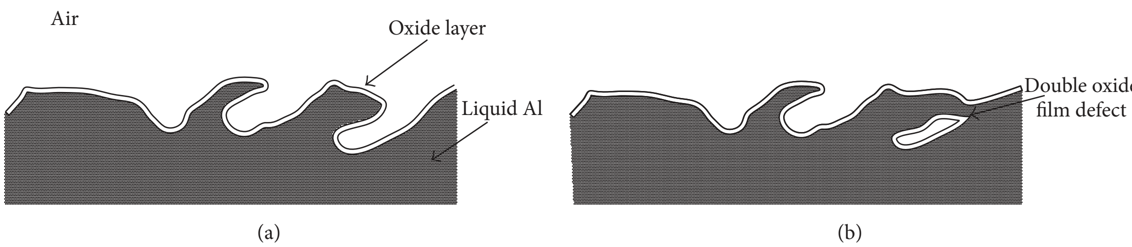


Figure 1: The formation of a double oxide film defect. (a) Surface turbulence leads to a breaking wave on the metal surface, and (b) the two unwetted sides of the oxide films come into contact with each other as the bifilm is entrained into the bulk liquid metal [4].

Table 1: Chemical composition of the alloy used.

Element	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Pb	Sn	Ti	Al
%	0.11	0.10	0.01	0.01	5.00	0.01	0.01	0.01	0.01	0.01	0.02	Bal

where ρ is the density of the melt in kg/m^3, γ is the surface tension in N/m, and g is the gravity acceleration in m/s^2. For liquid aluminium, $\gamma = 1\,Nm^{-1}$ and $\rho = 2400\,kgm^{-3}$; hence, the critical velocity can be estimated to be about $0.5\,ms^{-1}$. If the mould-entry velocity exceeds the critical velocity, the surface of the melt would be forced to propel upwards, achieving a height sufficient to enfold its oxide surface as it falls back under gravity [13, 18]. Results of the experiments by Runyoro and coauthors [19], Halvaee and Campbell [20], and Bahreinian et al. [21] for different Al and Mg alloys suggested that the critical velocity would be between 0.4 and $0.6\,ms^{-1}$.

It was suggested that only bottom-gated filling systems can produce reliable castings if the ingate velocities are to be kept below the critical velocity which might prevent the surface turbulence of the molten metal during pouring and reduce the possibility of entraining the oxidized surface inside the bulk liquid [22]. In this work, two different parameters were considered: the height of the runner and the use of filter. The effect of these parameters on the creation of oxide films in Al castings and by implication on the tensile properties of the resulting castings was determined. Understanding these issues could lead to the development of techniques by which oxide film defects might be reduced or eliminated in aluminum castings.

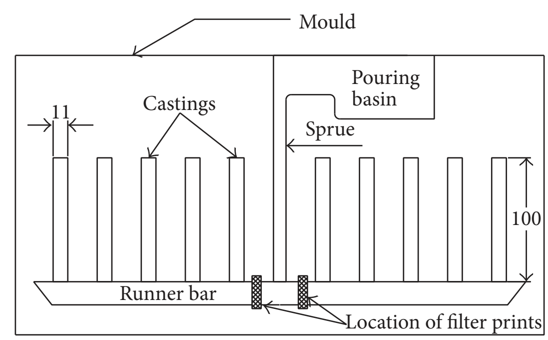


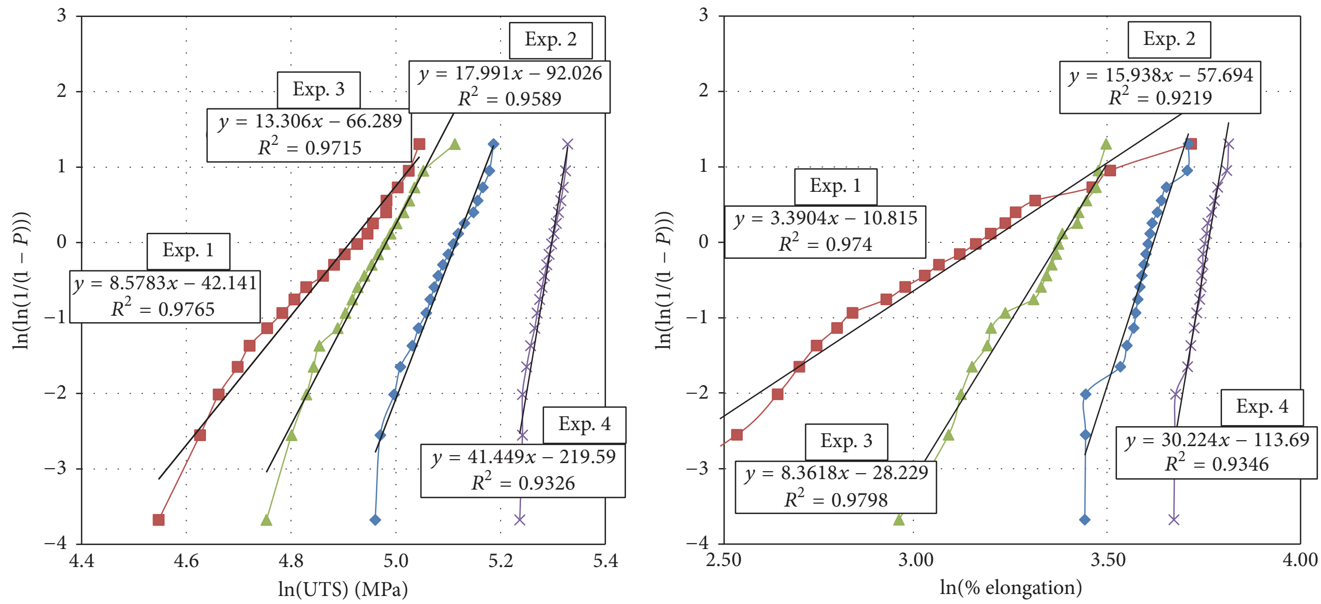
Figure 2: Shape and dimensions of the sand mould used in the experiment (dimensions are in mm).

2. Experimental Work

In this study, castings of Al-5 wt.% Mg alloy were produced via gravity casting. Chemical composition of the alloy used is given in Table 1. Four different casting experiments were carried out. In each experiment, two resin-bonded sand moulds were prepared, with the shape and dimensions shown in Figure 2, each producing 10 test bars. The moulds were then held under partial vacuum of about 0.5 bar for 2 weeks before casting, which was suggested in an earlier work to remove the solvent of the resin binder from the moulds and in turn minimize the hydrogen pick-up by the liquid metal from the mould during casting [23]. Two different heights of the runner (thin (10 mm) and thick (25 mm)) were considered. For each runner height, castings were produced with and without the use of filters. The experimental plan is shown in Table 2.

In each experiment, about 6 kg of the aluminium alloy was melted in an induction furnace. Once the temperature of the melt reached 850°C, the crucible containing the liquid metal was placed in a vacuum chamber, where the melt was held at about 800°C, under vacuum of about 0.2 bar for two hours, a procedure intended to remove previously introduced bifilms from the melt [24, 25]. The melt was then argon-degassed using a lance for 1 h before pouring from a height of about 1 meter into the sand moulds. In Experiments 2 and 4, two 10 PPI (pores per linear inch) ceramic filters, of dimensions 50 × 50 × 20 mm, were placed in the filter prints at the locations shown in Figure 2. The adopting of thin runner along with the use of filters during pouring was intended to reduce the melt velocity at the ingate which might minimize the possibility of having surface turbulence of the molten metal during mould filling with the corresponding entrainment of the surface oxide films. The filters were expected to play an additional role which was the removal of inclusions from the melt.

After solidification, the castings were machined into tensile test bars of a cylindrical cross section of 10 mm diameter with a gauge length of 100 mm, which were pulled to fracture with a strain rate of 1 mm/min. The fracture



(a) (b)

Figure 3: Weibull distribution of (a) ultimate tensile strength and (b) % elongation of Al-5 Mg alloy specimens from different experiments listed in Table 1.

Table 2: Experimental plan.

Experiment number	Runner height (mm)	Filters used
1	25	No
2	25	Yes
3	10	No
4	10	Yes

surfaces of the samples were subsequently examined using scanning electron microscopy (SEM), equipped with energy dispersive X-ray (EDX) analysis, for the evidence of oxide film. The tensile results were evaluated using a Weibull statistical analysis approach to assess the influence of different casting parameters, typically the runner height and the use of filters, on the variability of the mechanical properties of the castings.

It should be emphasized that, in this work, the melt was kept under partial vacuum for two hours before pouring to remove most, or perhaps all, previously existing oxide films. In addition, the amount of hydrogen in the final casting was minimized by keeping the sand moulds under partial vacuum for two weeks before being used which would allow them to lose most of the solvent and therefore minimize the amount of hydrogen picked up by the melt from the mould. Finally, the melt was degassed before pouring to reduce its hydrogen content. These arrangements were considered to eliminate the effect of any other parameter rather than the casting conditions on the mechanical properties of the resulting casting.

3. Results

The two-parameter Weibull distribution was used to analyze the scatter in the mechanical properties of the Al-5 Mg alloy castings produced under different casting conditions, as it was suggested to be more appropriate than a normal distribution [26, 27]. The Weibull modulus (the slope of the line fitted to the log-log Weibull cumulative distribution data) is a single value that shows the spread of properties; a higher Weibull modulus reveals less variability among the studied properties.

Weibull plots of the UTS and % elongation of the test bars cut from all castings (see Table 2) are represented in Figures 3(a) and 3(b), respectively. The values of the correlation coefficients (R^2) suggested that the data points expressing both the UTS and % elongation values were linearly distributed. It was noted that, for both the UTS and % elongation, the Weibull moduli (the slope of the trend line) of the castings from Experiment 4, where filters and the thin runner were used, were the highest among all castings. Figures 4(a) and 4(b) show plots of the Weibull moduli of the UTS and % elongation of the Al alloy versus the height of the runner with and without the use of filters. Weibull modulus of the UTS, when the runner height was 25 mm and without the use of filters, was 8.58. Decreasing the runner height to 10 mm increased the modulus to 13.41, while the use of filters increases the modulus to 17.99. Nevertheless, the use of 10 mm thick runner accompanied by the use of 10 PPI filters caused the Weibull modulus to increase to 41.45. Also, an elongation modulus of 3.39 was obtained for the casting produced using a runner height of 25 mm and without the use of filters. Castings with Weibull moduli of 8.36, 15.94, or

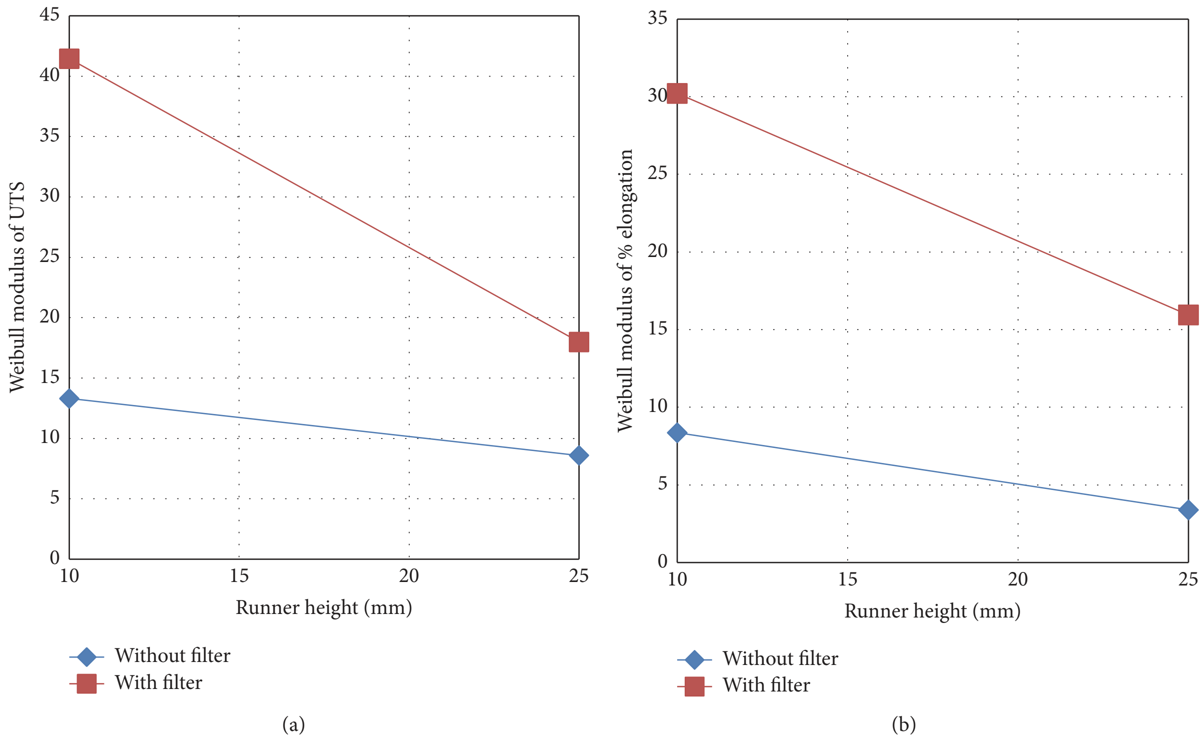


Figure 4: Plot of runner height versus (a) Weibull modulus of UTS and (b) Weibull modulus of % elongation.

30.22 were obtained when a 10 mm thick runner was used, when filters were implemented, or when both the thin runner and the filters were adopted.

Plots of the position parameter (the characteristic stress at which 1/*e* of the samples survived) [26] of both the UTS and % elongation of the Al alloy versus the height of the runner with and without the use of filters are represented in Figures 5(a) and 5(b), respectively. The position parameter showed a similar behavior to that of the Weibull moduli of both the UTS and % elongation. 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% to 43%, respectively.

Oxide film defects were found on all the fracture surfaces of test bars investigated from Experiments 1, 2, and 3. Only the fracture surfaces of the specimens from Experiment 4 were found to be free of oxide films. Figures 6–8 show SEM images of bifilm defects found on the fracture surfaces of test bars from Experiments 1–3, respectively, while an SEM micrograph of the fracture surface of a specimen from Experiment 4 is presented in Figure 9. The fracture surfaces were always selected from test bars that showed the lowest tensile strengths. Analysis by EDX was carried out at locations marked with “X” where it is suggested that MgO existed on the surfaces.

4. Discussion

In earlier studies of the effect of oxide films on the mechanical properties of different Al castings, the mould design shown in Figure 2 (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 [23]. In the present work, the poor mould design, shown in Figure 2, was deliberately used in Experiment 1. This was expected to cause the velocity of the molten metal at mould entrance (the ingate velocity) to firmly exceed the critical velocity. This would lead to oxide film entrainment, which was subsequently confirmed by the SEM examination of the fracture surfaces (see Figure 6). This caused a significant reduction in the UTS and % elongation of the casting produced in Experiment 1 (position parameters of 134 MPa and 24%, resp.) and also increased the scatter of both properties (Weibull moduli of 8.6 and 3.4, resp.), as shown in Figures 4 and 5.

In an attempt to reduce the ingate velocity, two different methodologies were considered in this study: the use of filters and decreasing the runner height (Experiments 2 and 3, resp.). Each of the two approaches showed a noticeable reduction of the amount of oxide films on the fracture surfaces of the specimens from castings in these experiments, as shown in Figures 7 and 8, respectively. This resulted also in a perceptible improvement of both the Weibull moduli and position parameters of the UTS and % elongation, as shown in Figures 4 and 5.

However, the use of 10 PPI filters seems to have a stronger effect on enhancing the mechanical properties than the effect of reducing the runner height, especially for the Weibull moduli. This could be due to their secondary role in the removal of inclusions out from the melt. For instance, the reduction of runner height from 25 to 10 mm without the use of filters (Experiment 3) increased the Weibull modulus of

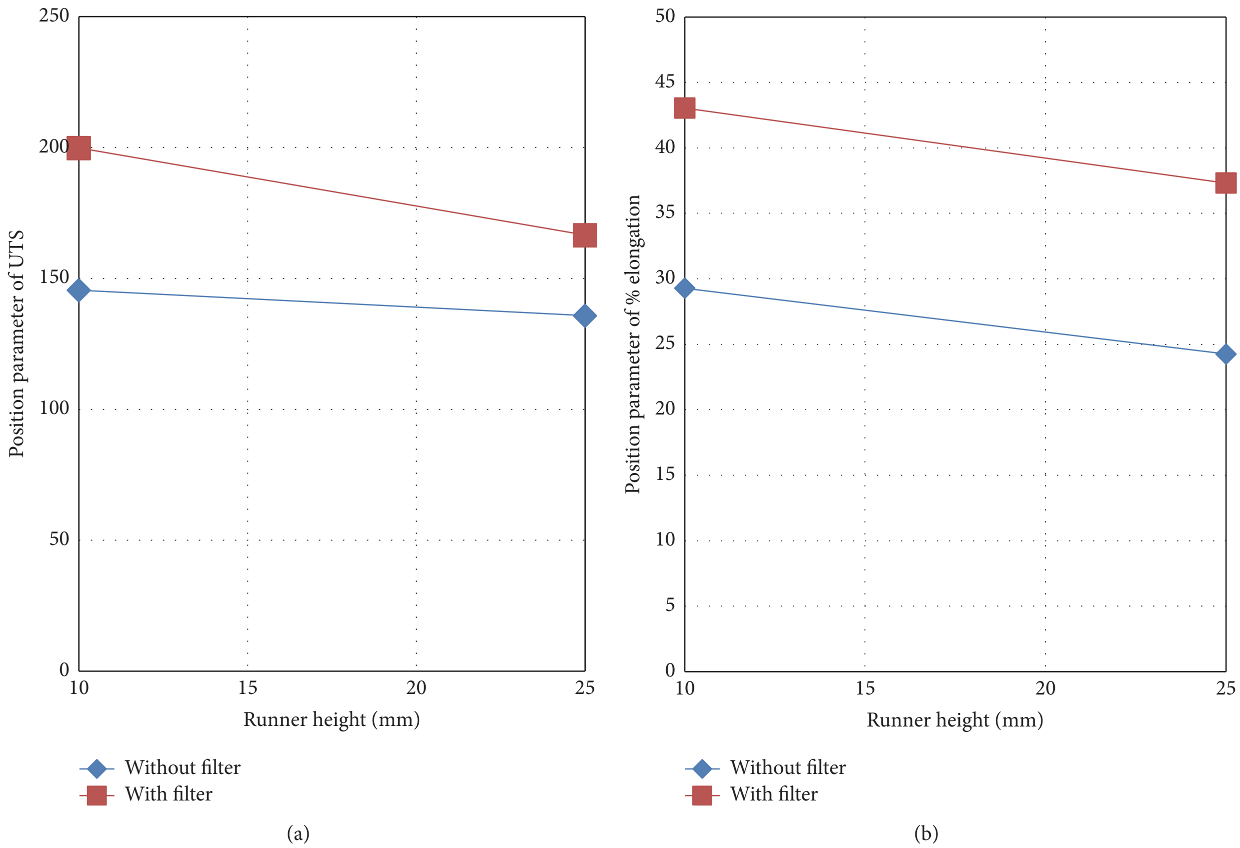


Figure 5: Plot of runner height versus (a) position parameter of UTS and (b) position parameter of % elongation.

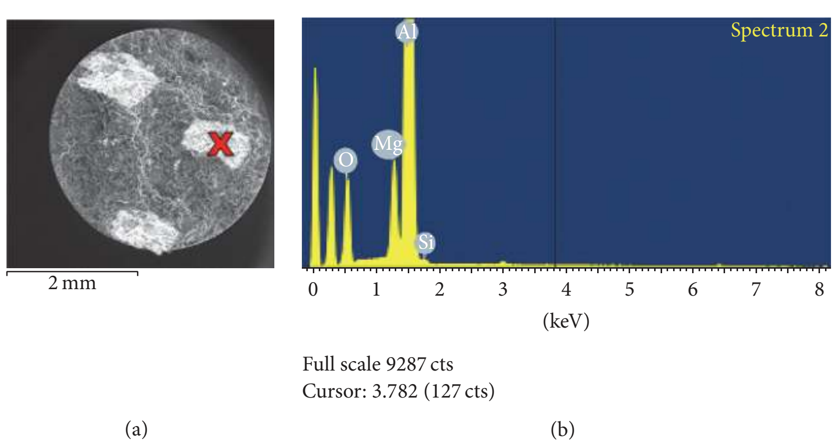
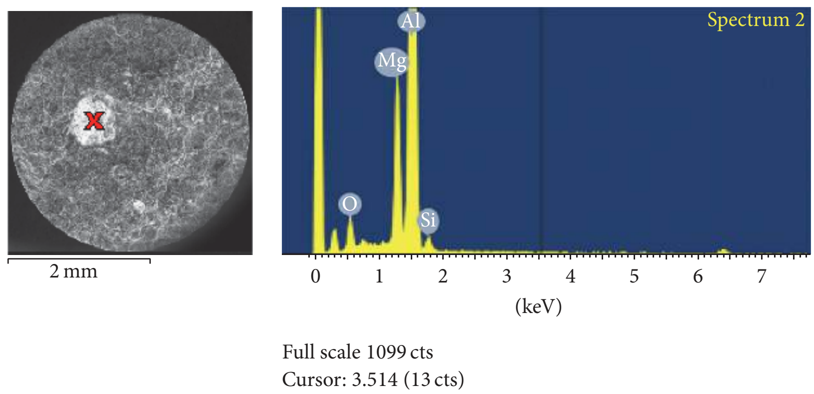


Figure 6: (a) An SEM image of the fracture surface of a specimen from Experiment 1; (b) EDX analysis at the location marked "X" in (a).

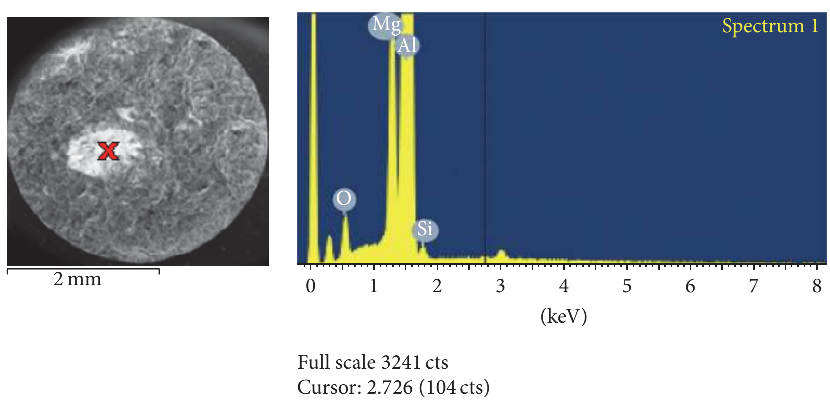
the UTS by about 56%. Conversely, a rise of such modulus of about 109% was achieved through the use of filters while keeping the runner height at 25 mm.

Combination of the two methodologies was found to considerably improve the mechanical properties. The Weibull moduli of the UTS and % elongation experienced a remarkable boost of about 380% and 790%, respectively. Also, the position parameter of the UTS increased by about 50%, while that of the % elongation was almost doubled. It could be suggested that the use of 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 in reducing the acceleration of the incoming flow of liquid metal inside the runner before entering the mould cavity. This allowed for more quiescent filling regime of the mould cavity and in turn led to a reduction of the ingate velocity to less than 0.5 m/s, which minimized the amount of entrained oxide films and correspondingly enhanced the mechanical properties. This



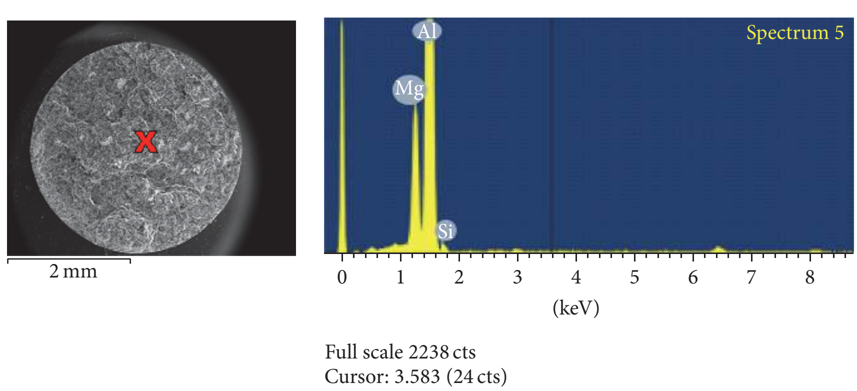
(a) (b)

Figure 7: (a) An SEM image of the fracture surface of a specimen from Experiment 2; (b) EDX analysis at the location marked "X" in (a).



(a) (b)

Figure 8: (a) An SEM image of the fracture surface of a specimen from Experiment 3; (b) EDX analysis at the location marked "X" in (a).



(a) (b)

Figure 9: (a) An SEM image of the fracture surface of a specimen from Experiment 4; (b) EDX analysis at the location marked "X" in (a).

could be demonstrated via the SEM image in Figure 9 that did not show any oxide fragment on the fracture surface, which was also confirmed by the accompanied EDX analysis results. These results were in agreement with the results obtained by Dai et al. [28], Eisaabadi Bozchaloei et al. [29], and Nyahumwa et al. [17], who suggested that optimization of the design of the running system and the use of filters in the running system might help keep the ingate velocity below the critical velocity which could eliminate the possibility of oxide film entrainment. 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 so that the mechanical strength and reliability of aluminium alloy castings can be enhanced.

5. Conclusions

(1) Entrained bifilm defects reduce the mechanical properties of Al-5 Mg alloy castings.

(2) The use of a 10 mm thick runner increased the Weibull moduli of the UTS and % elongation by about 56% and 147%, respectively, while the use of 10 PPI filters increased the moduli by 109% and 368%, respectively.

(3) Adopting the 10 mm thick runner along with the use of 10 PPI filters resulted in a substantial improvement of the Weibull moduli of the UTS and % elongation by about 380% and 790%, respectively, perhaps due to the improved mould filling conditions that eliminated the chance of oxide film entrainment.

(4) The more careful and quiescent the mould filling practice, the higher the quality and reliability of the castings produced.

Competing Interests

The authors declare that they have no competing interests.

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