Entrained Defects and Mechanical Properties of Aluminium Castings

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Abstract — **Entrained double oxide films (bifilms) have been held responsible for the variability in mechanical properties of aluminium castings. A bifilm consists of doubled-over oxide films containing a gas-filled crevice and is formed due to surface turbulence of the liquid metal during handling and/or pouring. In addition, hydrogen dissolved in the aluminium melt was suggested to pass into the defects to expand them and cause hydrogen porosity which in turn increasing their detrimental effect on the properties. In this work 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 suggested that adopting filters in the gating system and reducing the runner height had resulted in a noticeable increase of the tensile strength and elongation due to the enhanced mould filling conditions that minimised the possibility of oxide film entrainment. The results of this study would allow a better understanding of factors influencing the properties of light metal alloy castings which will lead to the development of improved practices by which healthier castings with enhanced properties could be obtained.**

Keywords: **oxide film; aluminium casting; mould design, mechanical properties.**

I. INTRODUCTION

The use of aluminum and aluminum alloys has increased in recent years specially in automobiles and aerospace industries due to the excellent combination of light weight, high strength, great corrosion resistance, and reasonable cost which had made aluminum and its alloys one of the most commonly used metal groups [1-4]. As the use of cast aluminum has increased, where their mechanical properties must be reliable and reproducible, and since the mechanical properties of Al castings were greatly affected by their inclusion contents, it was important to study these inclusions, their types, causes and harmful influences on castings [5, 6].

One of the most important casting defects affecting the reproducibility of mechanical properties of aluminium castings is the double oxide film defect[7, 8], created due to surface turbulence of the liquid metal, a common feature during metal transfer and pouring in the shape casting process. When the liquid metal surface is exposed to air, a surface oxide film forms [9-11]. As a result of surface disturbance, the liquid metal surface can be folded over onto itself, causing the oxidised surfaces of the folded-over metal to come together but not to fuse, trapping a layer of the local atmosphere between them, and creating a double oxide film defect or "bifilm" which can be entrained into the bulk metal [12]. See Figure 1.

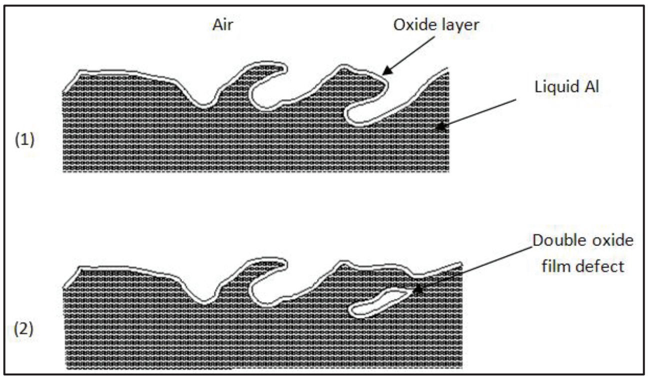

Figure 1. The formation of a double oxide film defect. (1) Surface turbulence leads to a breaking wave on the metal surface, and (2) the two unwetted sides of the oxide films contact each other as the bifilm is entrained into the bulk liquid metal [11].

Such entrained double oxide film defects represent one of the easiest possible initiating features for cracks, since their unbonded inner surfaces can be separated with little force. Also, gas dissolved in the liquid metal can precipitate inside the bifilm initiating porosity [13]. In addition, double oxide films are favourable sites for the nucleation and growth of intermetallic compounds. These effects not only reduce the elongation, tensile strength and fatigue properties of aluminium alloy castings, but also increase their variability [12, 14, 15].

Earlier research has demonstrated that the the entrainment of oxide films during the pouring of the melt could be explained through the critical ingate velocity concept. As the melt enters the mould cavity with a speed more than a critical value (about 0.5 m/s for most aluminium alloys), the flow front becomes unstable and allows the creation of surface oxide foldable layers[7, 11, 16-18].

Literature has also confirmed the impossibility of top-pouring methods to produce reliable castings. They advocated that only bottom-pouring gating techniques can avoid melt quality retrogradation during mold filling if the design of the gating system would take place in such a way that satisfies critical ingate-velocity requirements for sound castings [19-26].

In the current research, the effect of the runner thickness and the use of filters on the bifilm content and, subsequently the properties of 2L99 (Al–7Si–0.4Mg) alloy castings was investigated. Understanding these issues could lead to the development of techniques by which oxide film defects might be reduced or eliminated in aluminum castings.

II. EXPERIMENTAL

The two-parameter Weibull distribution is an empirical distribution [27] introduced by Weibull in 1951, and the distribution function is expressed as

$$P = 1 - \exp\{-[x/x_0]^m\} \quad (1)$$

where:

P = the cumulative fraction of failures in the mechanical property, e.g., a tensile test;

x = variable being measured, e.g., tensile strength;

x_0 = position parameter or characteristic value at which 63% of the samples failed;

m = Weibull modulus.

Taking the logarithm of Equation (1) twice yields a linear equation:

$$\ln[-\ln(1 - P)] = m \ln(x) - m \ln(x_0) \quad (2)$$

with a slope of "m" and an intercept of "$-m \ln(x_0)$". When "$\ln[-\ln(1-P)]$" is plotted versus "ln(x)", Weibull probability plot is obtained and therefore the values of "m" and "x_0" could be determined [11].

Literature suggests that Weibull distribution could better explain the failure of materials under a mechanical loading than a normal distribution [27-29]. A greater Weibull modulus and position parameters mean that the samples have fewer defects, which indicate higher and more reproducible properties. This study employed a two-parameter Weibull distribution to quantify the variability of the ultimate tensile strength and the % elongation of Al-Si-Mg cast alloys. Chemical composition of the alloy is given Table 1.

Table 1. Chemical composition of the 2L99 alloy used

Element	Si	Fe	Cu	Mn	Mg	Al
%	7.1	0.07	0.15	0.4	5.00	Bal

In this study 2L99 alloy castings were produced via gravity casting. 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. 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.

Table 2. Experimental plan

	Experiment			
Factor	1	2	3	4
Runner thickness (mm)	25	10	25	10
Filtration	Unfiltered		Filtered	

After solidification the castings were machined into tensile test bars of a cylindrical cross-section with a gauge length of 100 mm and diameter in the gauge length of 7 mm, which were pulled to fracture with a strain rate of 1 mm/min. Their fracture surfaces were subsequently examined using scanning electron microscopy (SEM), equipped with energy dispersive x-ray (EDX) analysis, for the evidence of oxide film.

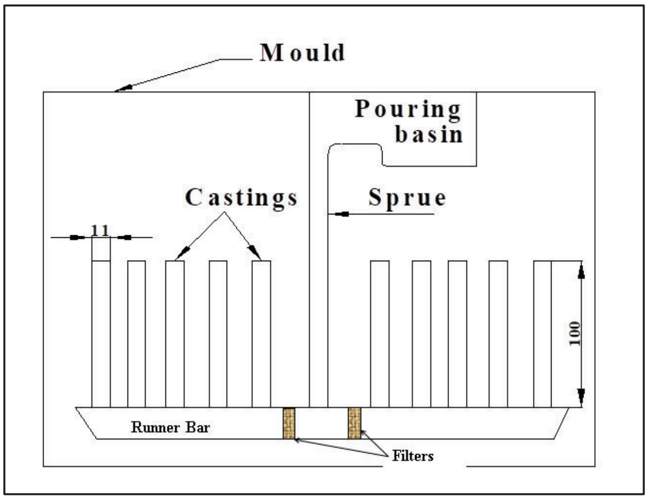

Figure 2. Shape and dimensions of the sand mould used in the experiment (dimensions are in mm).

III. RESULTS AND DISCUSSION

In this study the 2L99 alloy melt was held under vacuum to eliminate the effect of previously introduced oxides in the raw material and ensure that the castings' variability is only due to the changed casting conditions; i.e. the runner thickness and the filtration [30, 31]. Table 3 lists the casting conditions of the experiments performed and the corresponding Weibull analysis results for different properties. It was noted that for both the UTS and % elongation, the Weibull moduli and position parameters of the castings from experiment 4, where filters along with the thin runner were used, were higher than those produced using thick runner and/or without filters.

Table 3. Weibull modulus and Position parameter of the UTS and %Elongation of cast specimens produced under different

Exp. No.	Runner Thickness (mm)	Filtered applied	UTS (MPa)		% Elongation	
			Weibull Modulus	Position Parameter	Weibull Modulus	Position Parameter
1	25	No	4.15	81	2.17	4.08
2	10	No	6.7	95	4	4.7
3	25	Yes	7.78	105	4.88	4.72
4	10	Yes	18.35	133	8.3	6.78

Figures 3 (a) and (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. It was indicated that both moduli had increased consistently with reducing the runner thickness and/or the application of filters. At a runner thickness of 25 and without using filters the Weibull moduli of the UTS and % elongation were 4.15 and 2.17, respectively. Lessening the thickness to 10 mm raised the moduli to 6.7 and 4, respectively, implementing filters in the running system elevated the moduli to 7.78 and 4.88, respectively. However, the simultaneous adopting of thinner runner and filtration resulted in a significant improvement of the moduli to reach 18.35 for the UTS and 8.3 for the % elongation.

The influence of the two casting conditions on the position parameters of both tensile properties is shown in Figures 4 (a) and (b). Position parameters were shown to exhibit similar trends to those of the Weibull moduli. The parameters were enhanced 81 to 133 MPa for the UTS, and from 4.08 to 6.78 for the % elongation upon reducing the runner thickness and application of filters.

Generally, it was obvious that the use of thin runners as well as the application filters in the runner system had a significant effect on the enhancement of the Weibull moduli and position parameters of both tensile properties. As could be inferred from Figures 3 and 4 the properties of the castings produced in experiment 4, where filtered castings were produced using thin runners, were the highest among all castings. This indicates that the casting properties have been improved, and the variability among them has been reduced.

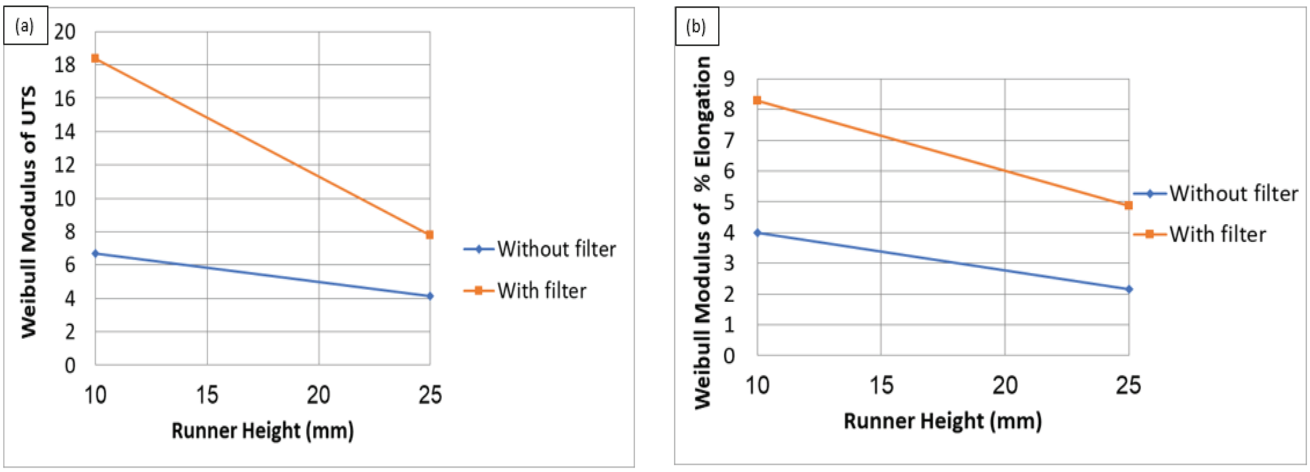

Figure 3. Plot of runner height versus (a) Weibull modulus of UTS and (b) Weibull modulus of % elongation.

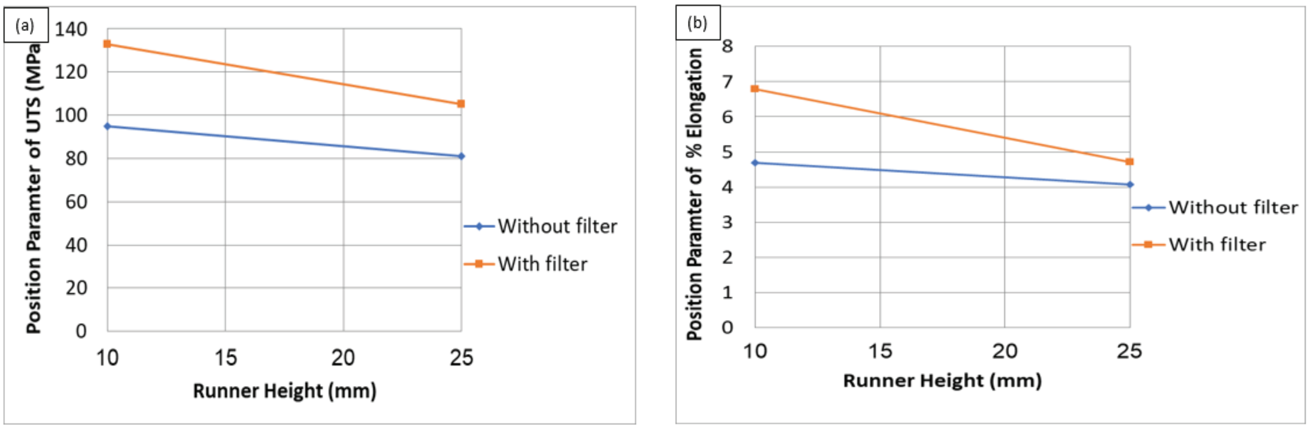

Figure 4. Plot of runner height versus (a) position parameter of UTS and (b) position parameter of % elongation.

Figures 5 (a), (b) and (c) show SEM images of oxide films found on the fracture surfaces of test bars from the experiments 1, 2 and 3 respectively. Analysis by EDX taken at location marked with 'X' suggested the presence of $MgAl_2O_4$ spinel on the surfaces. It was shown that the areas of oxide fragments detected at the fracture surface of specimens from experiment 1 were too much larger than those detected in experiments 2 and 3. This is suggested to be a result of the gating system design that seemed to minimise the oxide film entrainment during mould filling.

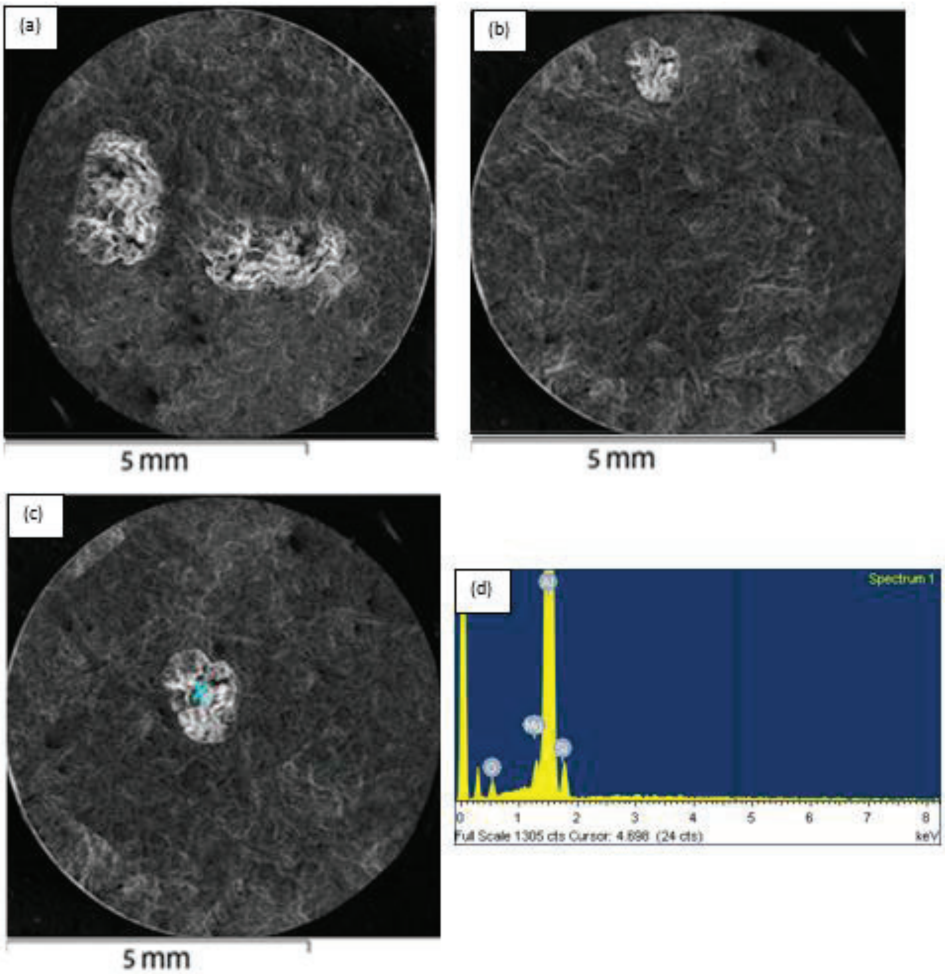

Figure 5. Images (SEM) of spinel films on fracture surfaces of specimens from; (a) Experiment 1, b) Experiment 2, c) Experiment 3- and (d) EDX analysis at location marked 'X' in (c)

Former research works demonstrated that the use of the badly-designed gating system, presented in Figure 1, using a 25 mm thick runner and without the use of filters, was associated with the formation and entrainment of a substantial amount of bifilm defects [32]. In the present work and in experiment 1 the poor mold design was deliberately used. This was anticipated to violate the critical ingate velocity and, accordingly, plenteous entrainment of oxide films which was subsequently confirmed by the SEM examination of the fracture surfaces (see Figure 5 (a)). This caused a significant reduction of the UTS and % elongation of the casting produced in experiment 1 (position parameters of 81 MPa and 4.08%, respectively) and also increased their scatter (Weibull moduli of 4.15 and 2.17, respectively), as shown in Table 3.

In an attempt to reduce the ingate velocity, two different methodologies were considered in this study; decreasing the runner height and the use of filters (experiments 2 and 3 respectively). 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 5 (b) and (c). This was resulted also in a perceptible rise of both the Weibull moduli and position parameters of the UTS and % elongation, as shown in Figures 3 and 4.

Combination of the two methodologies was demonstrated to considerably improve the mechanical properties. The Weibull moduli of the UTS and % elongation experienced a remarkable boost of about 340% and 280%, respectively. Also, the position parameters of both the UTS and % elongation have been increased by about two thirds each. 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 reducing the acceleration of the incoming flow of liquid metal inside the runner before entering the mould cavity [14, 15, 33-35]. This allowed for more quiescent filling regime of the mould cavity and in turn led to a reduction in the ingate velocity to less than 0.5 m/s, which minimized the amount of entrained oxide films and correspondingly enhanced the mechanical properties. These results were in agreement with the results by This confirms the results obtained by Green, Campbell, Basuny and El-Sayed [2, 28, 36-38], who apprised a considerable improvement in the Weibull moduli of the tensile properties of Al–7Si–Mg castings, of about 350%, while applying a turbulent-free filling system that seemed to prevent oxide film entrainment.

The connotation of the current findings would be that the optimization of the runner system design would allow a more quiescent mold filling regime which in turn could significantly reduce the production of bifilm defects. These considerations would allow a casting producer to reduce the amount of bifilms in the melt and consequently obtain an Al cast alloy with improved mechanical properties.

IV. CONCLUSIONS

1. The detection of bifilms at fracture surfaces of the majority of tensile samples examined is an indication of the harmful impact of such defect on the properties of 2L99 castings.
2. The use of a 10 mm-thick runner increased the Weibull moduli of the UTS and % elongation by about 60% and 85%, respectively, while the use of 10 PPI filters increased the moduli by 90% and 125%, respectively.
3. The optimised casting conditions involving the implementation of thin runners and filtration caused a considerable improvement of the Weibull moduli of the UTS and % elongation by about 340% and 280%, respectively, perhaps due to the improved mould filling conditions that eliminated the chance of oxide film entrainment.
4. The more careful and quiescent mould filling practice the higher the quality and reliability of the castings produced.

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