Oxide Inclusions, Mould Design and Mechanical Properties of Aluminium Castings

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Abstract

The variability in the mechanical properties of aluminum castings has been attributed to entrained double oxide films, commonly referred to as bifilms. These bifilms form as a result of the folding of oxide films during the handling and pouring of molten metal, causing the atmosphere to be trapped within the folded-over film. Additionally, the presence of dissolved hydrogen in the aluminum melt can exacerbate these defects, as it is expected to diffuse into the bifilm, leading to hydrogen porosity, further compromising material properties. In this study, we conducted a comparative analysis of ultimate tensile strength (UTS) and elongation percentage in sand-cast bars produced under various casting conditions. Our aim was to assess casting reliability, with a focus on the impact of oxide film content. Our findings underscore the significant improvement in tensile strength and elongation achieved by incorporating filters into the gating system and reducing the runner height. This enhancement is attributed to the improved mold filling conditions, which reduce the likelihood of oxide film entrapment. This research contributes to a deeper understanding of the factors influencing the properties of lightweight metal alloy castings and offers insights into developing practices for producing healthier castings with enhanced properties.

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

Introduction

In recent years, the utilization of aluminum and its alloys has experienced significant growth, particularly in the automotive and aerospace sectors. This surge in usage can be attributed to the remarkable blend of qualities that aluminum offers, including its lightweight nature, high strength, exceptional corrosion resistance, and cost-effectiveness. These attributes have firmly established aluminum and its alloys as one of the most widely employed metal groups in various applications [1-5]. As the demand for cast aluminum components has increased, especially in applications where mechanical properties must be consistently reliable, it has become imperative to delve into the study of inclusions—such as their types, origins, and the detrimental effects they exert on castings [6-10].

Among the most critical casting defects that undermine the reproducibility of mechanical properties of aluminum castings is the double oxide film defect [11-13]. This defect arises due to the surface turbulence of liquid metal, with a common occurrence during the transfer and pouring of molten metal in shape casting processes. When the surface of liquid metal comes into contact with air, it rapidly forms an oxide film [14-16]. Subsequent surface disturbances can lead to the folding over of the liquid metal surface onto itself, resulting in the oxidized surfaces of the folded-over metal coming into proximity without fusing. This action traps a layer of the local atmosphere between them, creating a double oxide film defect, often referred to as a "bifilm." These bifilms can then become entrained into the bulk metal [17, 18] (see Figure 1).
These entrained double oxide film defects represent one of the easiest initiators for cracks, as their unbonded inner surfaces can be separated with minimal force. Furthermore, gas dissolved in the liquid metal can precipitate within these bifilms, initiating porosity [19, 20]. Additionally, double oxide films provide favorable sites for the nucleation and growth of intermetallic compounds. Consequently, these effects not only diminish the elongation, tensile strength, and fatigue properties of aluminum alloy castings but also introduce greater variability into their performance [21-24].

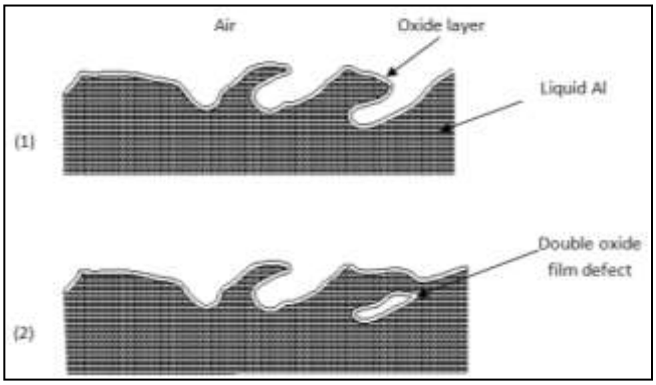


Fig. 1. The formation of a double oxide film defect. (1) Surface turbulence leads to a breaking wave on the metal surface, and (2) the two unwetted sides of the oxide films contact each other as the bifilm is entrained into the bulk liquid metal [17].

Earlier research has shed light on the entrainment of oxide films during the pouring of molten metal through the concept of critical ingate velocity. When the melt enters the mold cavity at a speed surpassing a critical value (approximately 0.5 m/s for most aluminum alloys), the flow front becomes unstable, enabling the creation of surface oxide layers that can fold over [25-27]. Existing literature has also underscored the impracticality of employing top-pouring methods to produce reliable castings. Instead, it has been recommended that only bottom-pouring gating techniques can effectively prevent the retrogression of melt quality during mold filling, provided that the design of the gating system adheres to the prerequisites of critical ingate velocity for the production of sound castings [28-32].
In the present research, we conducted a comprehensive investigation into the impact of runner thickness and the application of filters on bifilm content and, consequently, on the properties of 2L99 (Al–7Si–0.4Mg) alloy castings. The insights derived from this study have the potential to pave the way for the development of techniques aimed at mitigating or completely eliminating oxide film defects in aluminum castings.

Experimental

The two-parameter Weibull distribution is an empirical distribution introduced by Weibull in 1951 [33], and the distribution function is expressed as

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

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 (1) twice yields a linear equation:

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

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 [17].

Current literature highlights the superiority of the Weibull distribution in explaining material failure under mechanical loads, in contrast to the normal distribution [34, 35]. A higher Weibull modulus and position parameters signify that the specimens possess fewer defects, indicating better and more consistent properties. In this particular study, we employed a two-parameter Weibull distribution to assess the variation in both ultimate tensile strength and the percentage elongation for Al-Si-Mg cast alloys. The chemical composition of the alloy can be found in Table 1.

Table I. 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 our research, we manufactured 2L99 alloy castings using the gravity casting method. We conducted four distinct casting experiments, each involving the preparation of two resin-bonded sand molds. The molds' shapes and dimensions are illustrated in Figure 2, where each mold yielded 10 test bars. We considered two different runner heights: thin (10 mm) and thick (25 mm). For each runner height, we produced castings both with and without the application of filters. A detailed breakdown of the experimental plan is provided in Table 2.

Table II. Experimental plan

	Experiment			
Factor	1	2	3	4
Runner	25	10	25	10

thickness (mm)				
Filtration	Unfiltered		Filtered	

After the solidification, we subjected the castings to machining, transforming them into tensile test bars with a cylindrical cross-section. These bars featured a gauge length of 100 mm and a diameter of 7 mm within the gauge length. We conducted mechanical testing by pulling the bars (using a strain rate of 1 mm/min) until they fractured. Subsequently, we examined their fracture surfaces using scanning electron microscopy (SEM) equipped with energy-dispersive X-ray (EDX) analysis to identify any evidence of oxide film presence.

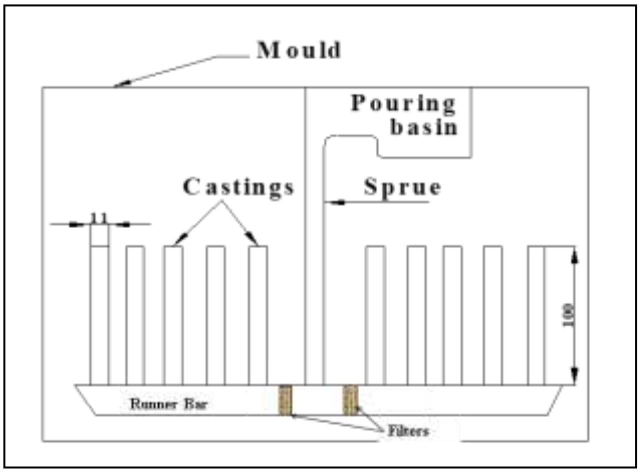


Fig. 2. Shape and dimensions of the sand mould used in the experiment (dimensions are in mm).

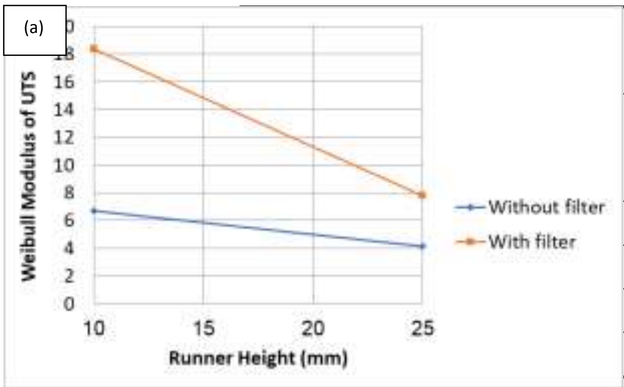
Results and Discussion

In this study, we subjected the 2L99 alloy melt to a vacuum environment to eliminate any potential impact of previously introduced oxides in the raw material. This step was crucial to ensure that any variations in the properties of the castings could be attributed solely to the altered casting conditions, specifically the runner thickness and filtration [36, 37]. Detailed casting conditions for the experiments and the corresponding results from Weibull analysis for various properties can be found in Table 3. It is noteworthy that, in both the UTS and % elongation, the Weibull moduli and position parameters of the castings from experiment 4, which involved the use of filters in combination with the thin runner, surpassed those of castings with thick runners and those without filters.

Figures 3 (a) and (b) provide graphical representations of the Weibull moduli for the UTS and % elongation in the Al alloy concerning runner height, both with and without the application of filters. These graphs reveal a consistent increase in both moduli as the runner thickness decreased and filters were incorporated. For example, when using a 25 mm thick runner without filters, the Weibull moduli for UTS and % elongation were 4.15 and 2.17, respectively. Reducing the thickness to 10 mm raised the moduli to 6.7 and 4, respectively, and the introduction of filters elevated the moduli to 7.78 and 4.88, respectively. Remarkably, the simultaneous adoption of a thinner runner and filtration resulted in a substantial improvement in the moduli, reaching 18.35 for UTS and 8.3 for % elongation. The influence of these two casting conditions on the position parameters of both tensile properties is depicted in Figures 4 (a) and (b). These parameters exhibited similar trends to the Weibull moduli, with enhancements observed, such as an increase from 81 to 133 MPa for UTS and from 4.08 to 6.78 for % elongation upon reducing the runner thickness and implementing filters.

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

UTS (MPa)		% Elongation	
m	x_0	m	x_0
4.15	81	2.17	4.08
6.7	95	4	4.7
7.78	105	4.88	4.72
18.35	133	8.3	6.78



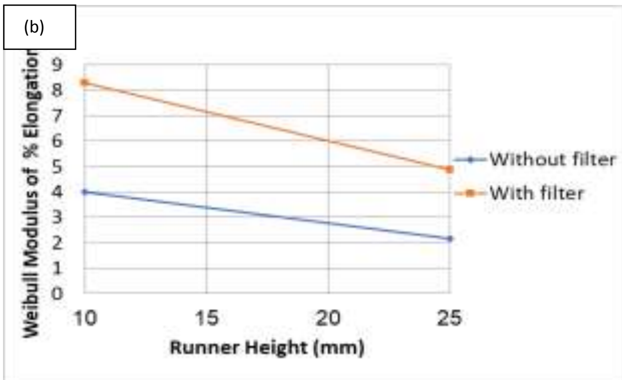
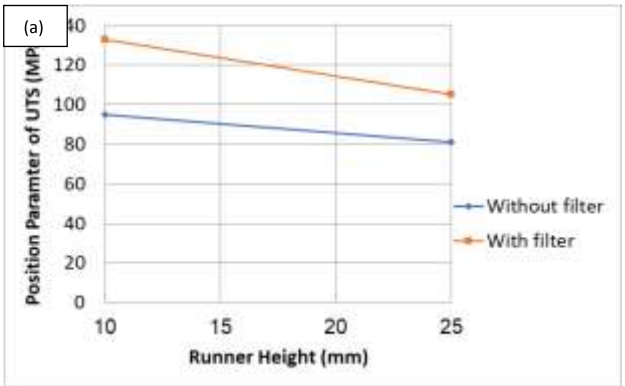


Fig. 3. Plots of runner height versus (a) Weibull modulus of UTS and (b) Weibull modulus of % elongation.

In summary, it is evident that employing thinner runners and incorporating filters into the runner system significantly enhanced the Weibull moduli and position parameters for both tensile properties. As indicated by Figures 3 and 4, the castings produced in experiment 4, featuring filtered castings with thin runners, exhibited the highest properties among all experiments. This suggests a substantial improvement in casting properties along with a reduced variability among them.

Examinations of test bars fracture surfaces from experiments 1, 2, and 3 revealed intriguing findings, as shown in SEM images presented in Figures 5 (a), (b) and (c). Analysis by EDX conducted at the marked 'X' locations suggested the presence of $MgAl_2O_4$ spinel on the surfaces. Notably, the areas of oxide fragments detected on the fracture surfaces of specimens from experiment 1 were considerably larger than those observed in experiments 2 and 3. This discrepancy is attributed to the gating system design, which appeared to minimize oxide film entrainment during mold filling.

Previous research works have established that the utilization of a poorly designed gating system, as depicted in Figure 1 and characterized by a 25 mm thick runner and the absence of filters, was associated with the formation and entrainment of a significant number of bifilm defects [38]. In our current study, deliberately employing an inappropriate mold design in experiment 1 was anticipated to violate the critical ingate velocity, resulting in substantial entrainment of oxide films.



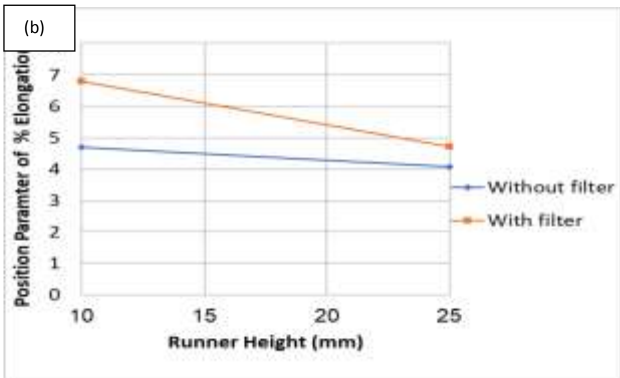


Fig. 4. Plots of runner height versus (a) position parameter of UTS and (b) position parameter of % elongation.

This was subsequently confirmed by the SEM examination of the fracture surfaces (see Figure 5 (a)). This condition led to a notable reduction in UTS and % elongation in the castings produced in experiment 1, with position parameters of 81 MPa and 4.08%, respectively, and increased variability (Weibull moduli of 4.15 and 2.17, respectively), as shown in Table 3. In an effort to mitigate ingate velocity, we considered two distinct methodologies in this study: reducing the runner height and implementing filters (experiments 2 and 3, respectively). Each of these approaches resulted in a noticeable reduction in the presence of oxide films on the fracture surfaces of the specimens from the corresponding castings, as illustrated in Figures 5 (b) and (c). This reduction corresponded with a perceptible increase in both Weibull moduli and position parameters for UTS and % elongation, as depicted in Figures 3 and 4.

Combining both methodologies proved to be highly effective in enhancing mechanical properties. The Weibull moduli for UTS and % elongation experienced a remarkable boost of approximately 340% and 280%, respectively. Similarly, the position parameters for both UTS and % elongation increased by roughly two-thirds. It can be inferred that the use of thin runners may eliminate the occurrence of molten metal jetting during its passage through the runner. Additionally, the application of filters appeared to reduce the acceleration of the incoming flow of liquid metal inside the runner before it entered the mold cavity [39, 40]. This facilitated a more controlled filling regime for the mold cavity, resulting in a reduced ingate velocity to below 0.5 m/s, minimizing the entrainment of oxide films and consequently enhancing mechanical properties. These findings align with results obtained by other researchers, validating the substantial improvement in Weibull moduli of tensile properties in Al–7Si–Mg castings when employing a turbulence-free filling system to prevent oxide film entrainment [41-43].

In essence, these findings suggest that optimizing the design of the runner system can lead to a more controlled mold filling regime, significantly reducing the production of bifilm defects. These considerations hold the potential to enable casting producers to reduce the presence of bifilms in the melt, ultimately resulting in aluminum cast alloys with improved mechanical properties.

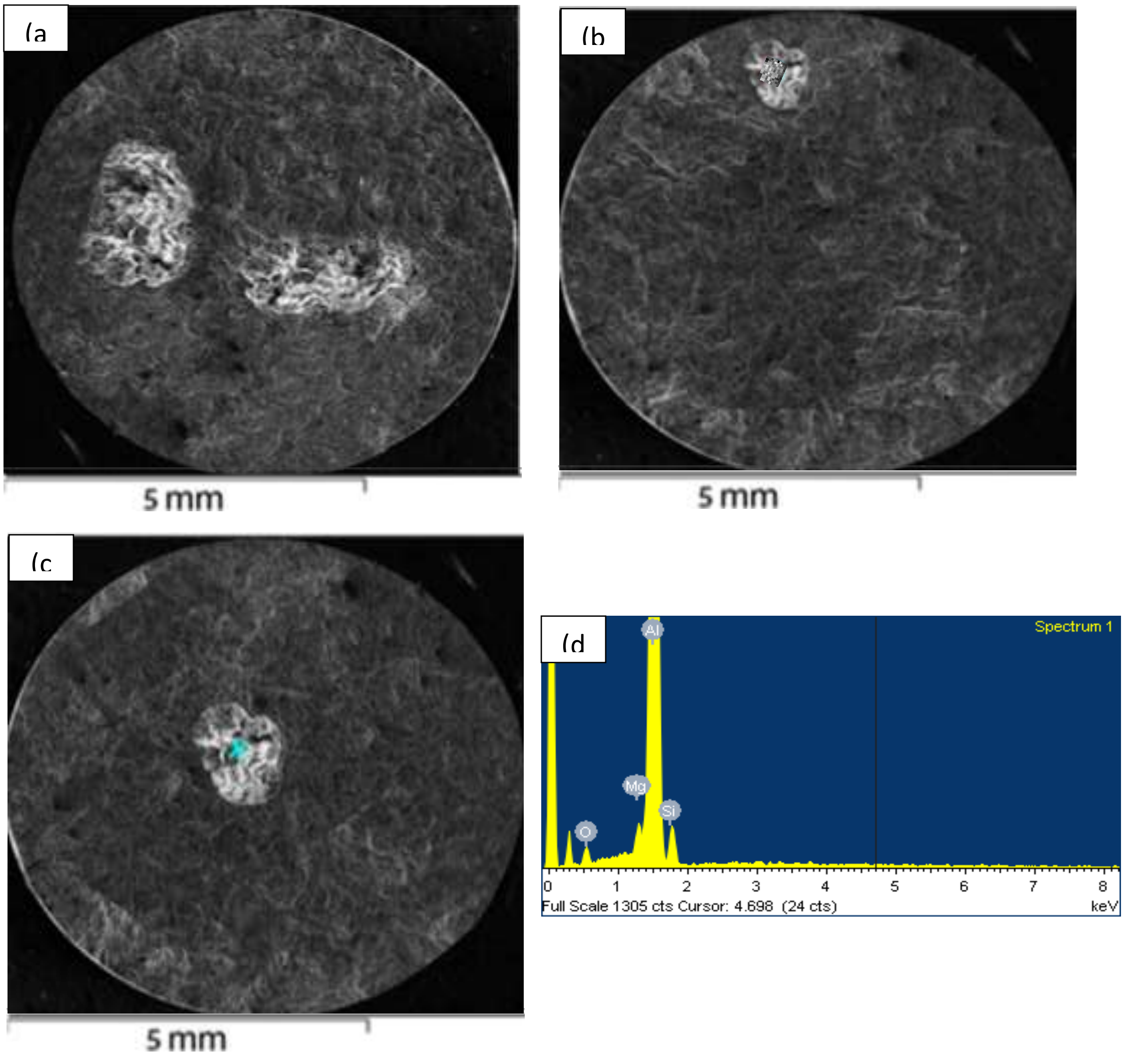


Fig. 5. Images (SEM) of spinel films on fracture surfaces of specimens from; (a) Experiment 1, b) Experiment 2, c) Experiment 3- and (d) EDX analysis at location marked 'X' in (c)

Conclusions

1. The observation of bifilms on the fracture surfaces of the majority of examined tensile samples signifies the detrimental impact of this defect on the properties of 2L99 castings.
2. The utilization of a 10 mm-thick runner led to a significant boost of the Weibull moduli, approximately 60% for the UTS and 85% for % elongation. In contrast, employing filters yielded even more substantial improvements, with moduli increasing by approximately 90% for UTS and 125% for % elongation.
3. The optimization of casting conditions, which involved the implementation of thin runners and filtration, resulted in a remarkable enhancement of the Weibull moduli for UTS and % elongation, with increases of approximately 340% and 280%, respectively. This improvement is likely attributable to the improved mold filling conditions that effectively eliminated the risk of oxide film entrainment.

Adhering to meticulous and tranquil mold filling practices consistently led to higher-quality castings with increased reliability.

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