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Hot Tearing Evaluation of Al-0.9Mg-0.7Si Aluminium-cast Alloy

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Abstract

This study aimed to evaluate the hot tearing susceptibility (HTS) of the Al-0.9Mg-0.7Si aluminium casting alloy, with a particular focus on how cooling rates and thermal stresses during solidification influence this phenomenon. To capture these parameters, the experiment employed the constrained rod casting (CRC) technique, which facilitated the real-time measurement of both cooling and force curves. Hot tearing was analysed across various casting configurations, incorporating different feeding mechanisms to assess their effect on tear resistance. The fracture surfaces resulting from hot tearing were examined in detail using scanning electron microscopy (SEM), providing insight into the microstructural characteristics at the tear sites. The results revealed that the Al-0.9Mg-0.7Si alloy exhibits an HTS value of 12, indicating moderate susceptibility under the tested conditions. Furthermore, the alloy displayed an average cooling rate of 7.95 °C/s and an average maximum load of 233.01 N, underscoring the significant impact of thermal gradients and induced stress on crack formation. These findings enhance the understanding of the factors governing hot tearing in aluminium alloys, with potential implications for alloy design and process optimisation aimed at reducing defects in cast aluminium products.

Keywords: Hot tear, Al-0.9Mg-0.7Si cast alloy, Solidification rate, Thermal contraction, Constrained rod casting

1. Introduction

Hot tearing is a common defect in metal casting processes, including those involving aluminium alloys. This defect occurs during the solidification phase, particularly in the semi-solid state, when the metal is subjected to excessive thermal stress. The impact of hot tearing is significant for the quality of cast components, making a thorough understanding of this defect essential for various industrial applications. In the automotive industry, for instance, hot tearing can manifest as cracks in components such as engine blocks, cylinder heads, and transmission parts, compromising the strength and reliability of the final product. Therefore, careful control of the casting process and precise adjustment of the casting temperature are fundamental to minimising hot tearing in mass production [1]. In the aerospace sector, where aluminium alloys are preferred for their high strength-to-weight ratio, hot tearing in components like wings, fuselages, and internal structures can result in structural failure, necessitating strictly controlled casting conditions [2]. In electronic device casings, the quality of the structural surface is critical, as hot tearing can introduce surface defects that affect both thermal efficiency and the aesthetic appeal of the product, requiring rigorous control of casting parameters [3]. Heat-treated (T4 and T6) alloys exhibit enhanced tensile strength and impact energy due to improved precipitate distribution, although hardness and tensile properties vary with pouring temperature, displaying non-linear trends [4]. In the construction industry, aluminium alloys are used in both structural and decorative components, and hot tearing can impact both structural integrity and visual quality.

Consequently, a comprehensive understanding of casting conditions is crucial to mitigate this risk [5].

Given this background, there is a need for a detailed experimental investigation into the hot tearing phenomenon in the Al-0.9Mg-0.7Si aluminium cast alloy. Previous studies have explored the effects of different pouring temperatures (680 and 750 °C) and pouring speeds (2 and 16 cm/s) on the mechanical properties of Al-Mg cast alloys [6]. The impact of a pouring temperature of 700 °C and a pressure of 140 MPa on the microstructure, porosity, hardness, and yield stress of AA2024 aluminium alloy has also been analysed [7]. Furthermore, the effect of pouring temperatures of 690, 680, and 670 °C on the microstructure of primary solidification, secondary solidification, eutectic Si, and mechanical properties during the high-pressure die casting (HPDC) process of A356 aluminium alloy has been investigated. The A356 aluminium alloy diecastings were produced using rheo-diecasting (RDC) and high-pressure die casting (HPDC), with microstructural and mechanical properties assessed at different pouring temperatures. The results show that RDC, employing a self-inoculation method (SIM), yields smaller and rounder primary α-Al grains compared to the dendritic structure observed in HPDC. Furthermore, improved mechanical properties were achieved at a melt treatment temperature of 600°C [8]. The mechanism underlying hot tearing in Al-Mg-Si alloys is influenced by a combination of factors, including thermal contraction, cooling rate, and the material's ability to resist deformation during solidification. This complex phenomenon arises when the stresses induced by thermal contraction exceed the material's capacity to accommodate them, resulting in crack formation. Slow cooling rates and optimized alloy compositions can reduce the likelihood of hot tearing by promoting more uniform solidification, minimising thermal gradients, and refining the grain structure. Furthermore, improving the feeding system is crucial for preventing defects caused by inadequate material flow. Previous studies have highlighted the critical importance of controlling cooling rates and thermal stresses to enhance the overall quality of Al-Mg-Si castings. The present study aims to assess hot tearing susceptibility by analysing the decrease in solidification temperature, solidification rate, and load during the solidification of the Al-0.9Mg-0.7Si alloy. The cooling curve was recorded throughout the solidification process to capture temperature variations over time, as well as the cooling rate and associated phase changes. Additionally, measurements of the loads experienced by the alloy during solidification were taken to assess the thermal stress resulting from thermal contraction.

2. Experimental Procedures

The chemical composition of the aluminium alloy was determined using standard metal analyser spectroscopy, as presented in Table 1. Aluminium rods measuring 25 x 25 x 1500 mm were cut into smaller pieces using a saw before being melted in a furnace. Once fully molten in the crucible, the liquid metal was poured into a permanent mould at a casting temperature of 850 °C (superheat + 250 °C). For this experiment, a CRC steel mould was specifically designed and utilised to observe hot tearing susceptibility, as shown in Figure 1. The molten metal was poured through a sprue into a rod mould divided into two sections. One section featured a ball end to facilitate the observation of hot tearing defects, with a thermocouple positioned at the ball end to monitor temperature changes over time. Additionally, the other rod was equipped with an S-beam load cell to measure the stress generated during the solidification process (from liquid to solid state). A K-type thermocouple was inserted into both the melt and the mould to monitor the casting temperature and record the solidification temperature of the alloy throughout the experiment. Furthermore, the solidification rate was derived from the solidification curve, which was recorded using a data acquisition system (DAQ).

Table 1.
Chemical composition

Element	Wt.%
Mg	0.90
Si	0.70
Fe	0.60
Cu	0.30
Cr	0.25
Zn	0.20
Ti	0.10
Mn	0.05
Al	Bal.

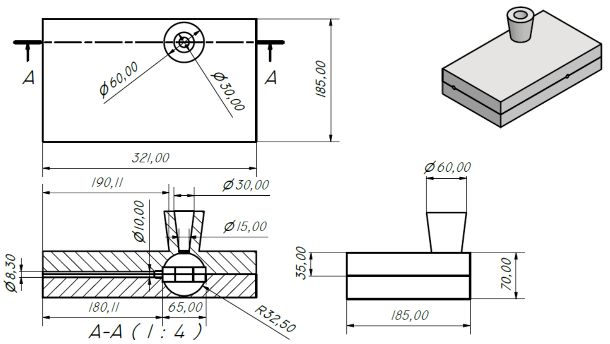


Fig. 1. The CRC metal mold

The extent of hot tearing in the metal alloy was evaluated using the HTS equation, which considered two parameters: tear severity and tear location within the casting. In this study, tear severity was categorised into five levels: no tear, hairline, light, severe, and complete tear. The tear surface was formed by stress distributed along the rod, from the sprue end to the ball end. Hot tearing was predominantly observed at the sprue end of the rod, although tears also occurred at the ball end and the centre of the rod. Cracks were less frequent in the middle of the rod, suggesting a high susceptibility to hot tearing. The HTS calculation is provided in Formula 1 and Table 2 [9].

$$HTS = \sum C_i \times P_i \quad (1)$$

Table 2.
Classification of hot tearing severity and its position in cast alloys

Hot tearing category	*Ci*	Hot tearing position	*Pi*
No tear	0	Sprue end	1
Hairline	1	Middle rod	2
Light	2	Ball end	3
Medium	3		
Complete	4		

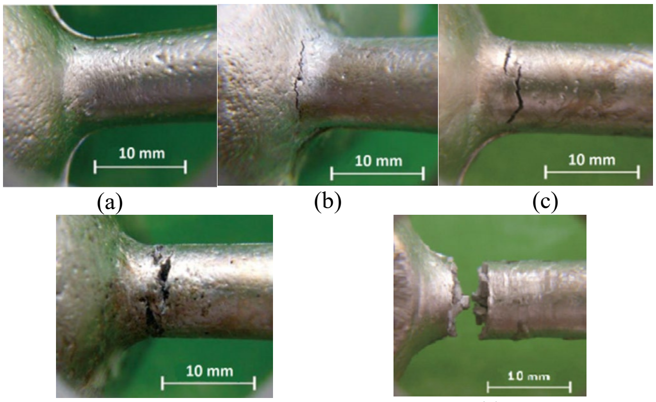


Fig. 2. Typical hot tearing on the surface of cast product [9]

Figure 2 illustrates the hot tear categories along with their indices, calculated using Formula 1. The hot tear categories are defined as follows: No tear (index 0), Hairline (index 1), Light (index 2), Medium (index 3), and Complete (index 4). Furthermore, the position of the tear is assigned an index based on its location, as follows: 1 for the sprue end, 2 for the middle of the rod, and 3 for the ball end.

3. Results and Discussion

Figure 3 presents the cooling curves and their first derivatives recorded during the casting process for the three samples. For sample 1, the data indicated a liquidus temperature of 558 °C, a solidus temperature of 492 °C, and a cooling rate of 9.43 °C/s (Figure 3a). In sample 2 (Figure 3b), the liquidus temperature was found to be 590 °C, the solidus temperature 506 °C, and the cooling rate 14.12 °C/s. For sample 3 (Figure 3c), the recorded liquidus temperature was 576 °C, the solidus temperature 503 °C, and the cooling rate 8.17 °C/s.

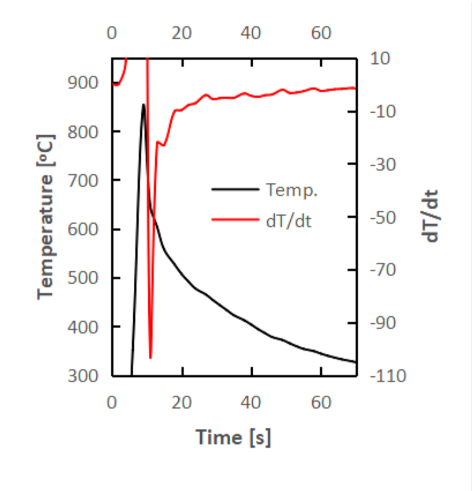
Figure 4 shows that the peak loads achieved were 243.79 N for sample 1, 267.33 N for sample 2, and 187.90 N for sample 3, with a casting temperature of 850 °C (superheat + 250 °C). The load curve was analysed to assess the magnitude of the stresses that developed and to understand their impact on the final cast alloy product. Uneven thermal contraction led to defects in the solidified metal, including tears and deformations. Additionally, the load curve was used to monitor load variations that indicated tearing or volume changes. This curve proved valuable for investigating the thermomechanical properties of metals during solidification, providing results into the material's response to cooling and the liquid-to-solid phase transition. These results are beneficial for enhancing predictive models and optimising casting process designs. In the solidification of the Al-0.9Mg-0.7Si cast alloy, measured over three repetitions, the load began to develop after the liquid metal reached its liquidus temperature.

Hot tearing susceptibility was calculated using the HTS formula, with parameters based on the typical category of hot tearing and the location of the tear. Figure 5 illustrates the hot tear defects observed in the three cast products. The appearance of hot tearing on the cast samples was evaluated in the CRC mould with a pouring temperature of 850 °C (superheat + 250 °C). At this temperature, all three samples exhibited complete fractures in the middle of the rod.

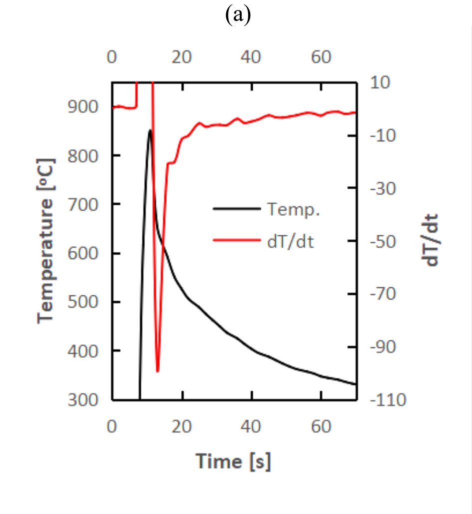
Figure 6 illustrates the SEM morphology of the fracture surface, highlighting the shape and orientation of the cracks, which frequently display hot tearing characteristics, including elongated and irregular formations. The EDS elemental mapping in Figure 6b, corresponding to the entire SEM surface shown in Figure 6a of the cast Al-0.9Mg-0.7Si alloy sample, clearly reveals the quantities of magnesium (Mg), silicon (Si), and iron (Fe), with aluminium being the dominant element in this cast metal alloy. An elevated Si content in metal alloys enhances fluidity and narrows the solidification range, thereby reducing the time the alloy is susceptible to hot tearing. A shorter solidification interval improves the effectiveness of feeding channels, playing a crucial role in preventing cracks during the solidification of AZ91 alloys [8]. However, excessive Si can result in the formation of brittle phases in iron aluminide, increasing material brittleness, causing machining difficulties, and heightening the alloy's vulnerability to hot tearing [9]. If the Si content exceeds an optimal range, it exacerbates brittleness and promotes additional hot tears during solidification [10]. Within a specific range, Si additions facilitate eutectic solidification, forming a eutectic phase network that mitigates stress in semisolid regions and reduces hot tearing [11].

The Fe impurities adversely affect aluminium alloys by forming complex intermetallic compounds that degrade casting performance and reduce hot tear resistance [12-14]. Elevated Fe levels encourage the precipitation of intermetallic compounds, which obstruct liquid feeding during solidification, stiffen the alloy structure, and increase the risk of hot tearing [15]. Thus, while higher Si content improves fluidity and shortens the solidification range, excessive levels increase brittleness and hot tear susceptibility. Moreover, Fe impurities worsen hot tear formation by impairing liquid feeding through intermetallic precipitation. Controlling Si and Fe content is therefore critical to optimising solidification behaviour and minimising hot tearing in aluminium alloys.

Hot tearing susceptibility was determined using the HTS formula, incorporating parameters related to the typical categories of hot tearing and the tear locations [16]. The occurrence of hot tearing in the cast samples was assessed within the CRC mould. At a temperature of 850 °C (superheat + 250 °C), all three samples exhibited complete fractures in the middle of the rod, yielding an average HTS value of 12 (quantitative evaluation).



(a)



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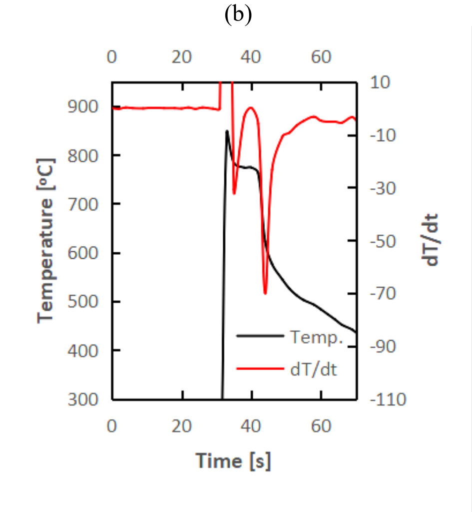
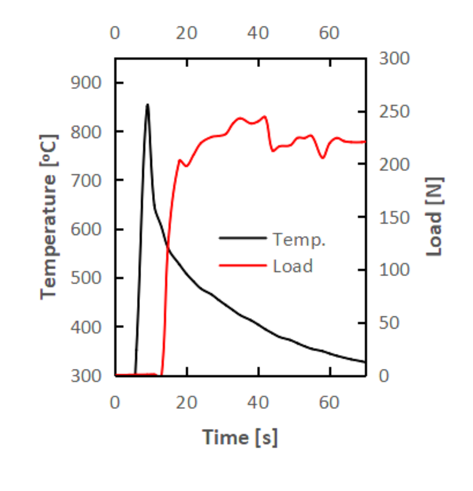
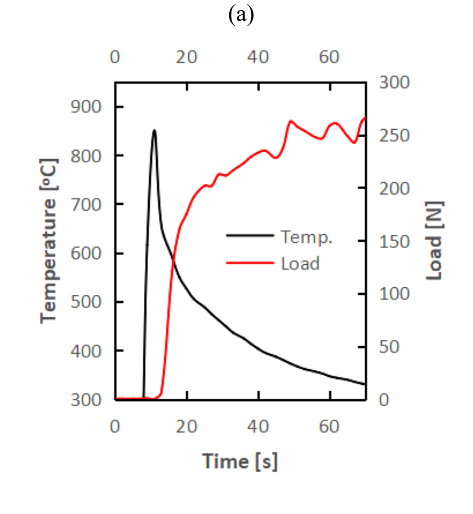


(c)

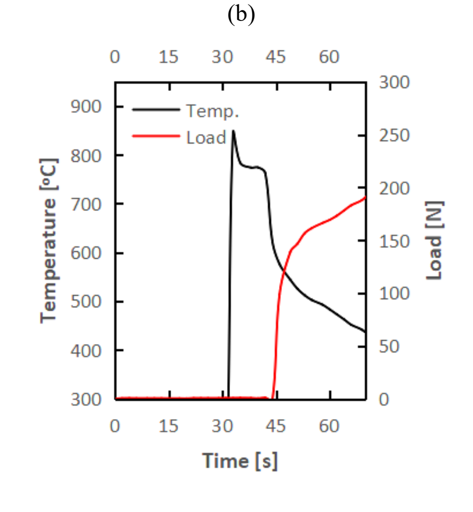
Fig. 3. Thermal analysis of Al-0.9Mg-0.7Si cast alloy: (a) sample-1, (b) Sample-2, and (c) sample-3



(a)

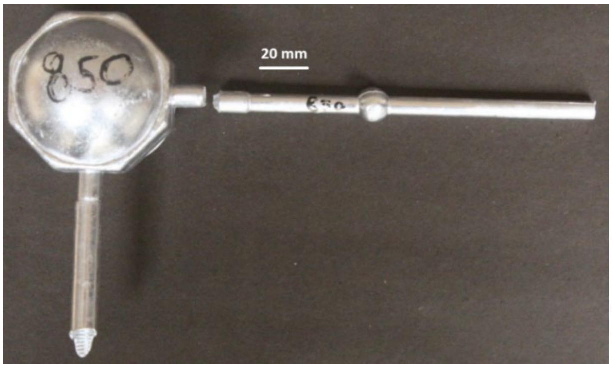


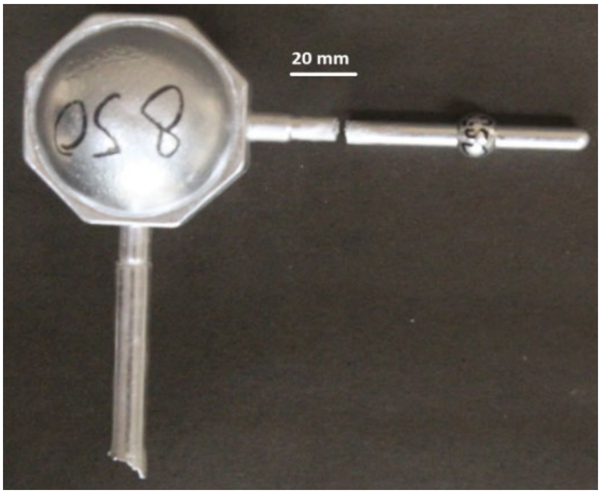
(b)



(c)

Fig. 4. Thermal load curves related to solidification: (a) sample-1, (b) sample-2, and (c) sample-3

a) 

b) 

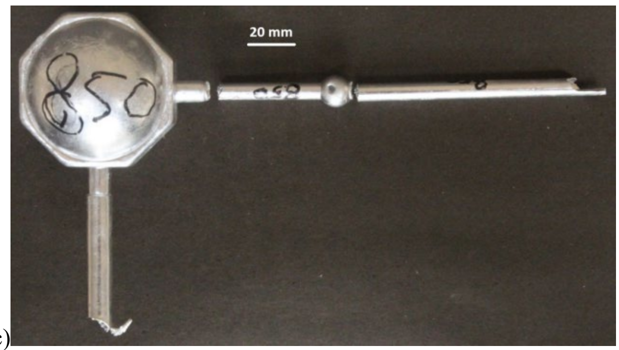
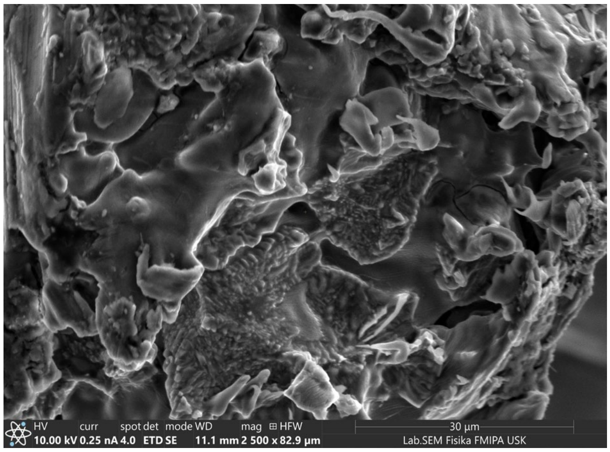
c) 

Fig. 5. Cast products: (a) sample 1, (b) sample 2, and (c) sample 3

The SEM surface revealed two fracture mechanisms: closed micro-tears with transcrystalline and intercrystalline characteristics. These are small or micro-cracks that do not fully open and, therefore, do not appear as large fractures, often occurring beneath the surface. The cracks develop through the crystal structure or individual grains within the material, while others occur along the boundaries between the grains. Transcrystalline fractures typically indicate greater deformation within the grains due to high stress/load caused by non-uniform solidification, as observed in casting processes. The dendritic structure observed on the fracture surface indicated that hot tearing occurred during the semi-solid phase, when the metal experienced thermal contraction and elevated thermal stress [17]. Furthermore, the dendritic pattern represented the solidification process of the metal, with cracks forming in areas where thermal stress exceeded the material's strength [18]. By reducing the temperature gradient between the liquid metal and the mould, the solidification process was slowed, thereby broadening the liquid-solid phase range (mushy zone). This increased susceptibility to hot tearing was attributed to prolonged thermal stress accumulation, greater thermal contraction, and alterations in microstructure [19]. The controlled hot-tear formation, influenced by cooling and displacement rates, was quantified using X-ray microtomography for validating cold-cracking models [20].

The use of the instrumented CRC technique in this study provided critical insights into the cooling and force curves of aluminium alloys during solidification. This technique, which involves real-time measurements, enabled precise tracking of the thermal and mechanical responses of the alloy under varying casting conditions [21]. Such measurements are vital for understanding the dynamic processes occurring during solidification, as they allow for a detailed analysis of temperature gradients, cooling rates, and the forces that act on the material during the casting process [22].

a) 

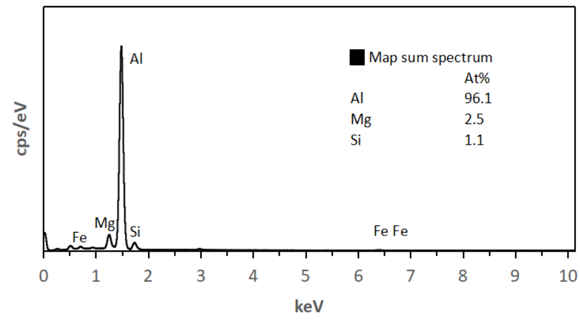
b) 

Fig. 6. Hot tear morphology: (a) the microstructure, and (b) typical energy dispersive X-ray spectroscopy (EDS) elemental mapping images

The complex interplay between thermal gradients, alloy composition, and casting parameters highlights the importance of fine-tuning casting conditions to minimise the risk of defects, such as hot tearing, which can severely impact the integrity of the final cast product [23]. Hot tearing, often caused by rapid cooling and inadequate feeding of the molten metal, can lead to cracks that reduce the mechanical strength and durability of cast components [24]. Optimising casting parameters, such as mould temperature, cooling rates, and alloy composition, is crucial to minimising defects and ensuring the reliability of cast products [25]. The notion that careful control of these variables can significantly improve the quality and performance of aluminium castings in industrial applications is well supported [26]. Manufacturers can better predict and mitigate defects, ultimately resulting in components with improved mechanical properties and enhanced service life.

The use of instrumented constrained rod casting has provided valuable data that not only enriches our understanding of the solidification process in aluminium alloys but also offers practical implications for the optimisation of casting parameters. These advancements contribute to the ongoing effort to improve the efficiency, quality, and performance of cast components, particularly in industries where material reliability is principal.

4. Conclusions

In conclusion, this study successfully investigated the hot tearing susceptibility of the Al-0.9Mg-0.7Si aluminium cast alloy, emphasising the critical roles of cooling rate and thermal stresses during the solidification process. The use of the instrumented CRC technique enabled precise measurements of cooling and force curves, providing valuable insights into the alloy's behaviour under various casting conditions. The analysis revealed that the alloy had an HTS value of 12, with an average cooling rate of 7.95 °C/s and an average load of 233.01 N, indicating a significant response to the thermal conditions imposed during casting. Furthermore, the examination of fracture surfaces using SEM confirmed the presence of hot tearing defects, which are crucial for understanding the material's integrity. These findings contribute to the body of knowledge regarding the solidification behaviour of aluminium alloys and highlight the importance of optimising casting parameters to minimise defects such as hot tearing, ultimately enhancing the quality and performance of cast components in industrial applications.

Hot tearing occurs when the stresses induced by thermal contraction during the solidification of an alloy exceed the material's capacity to accommodate them. This phenomenon often arises when the metal solidifies unevenly, leading to internal stresses and cracks, particularly during the transition from liquid to solid phases. Factors such as rapid cooling rates, high thermal gradients, and the inability of the alloy to adequately feed the solidifying regions contribute to the formation of tears. To minimise the HTS value, it is essential to slow the cooling rate, thereby promoting more uniform solidification, reducing thermal gradients, and optimising the alloy composition. Enhancing the feeding system and refining the mould design can also help mitigate thermal stress accumulation, thus lowering the likelihood of hot tearing. Based on the findings, defects can be minimised by controlling the cooling rate and optimising casting process parameters. Specifically, slower cooling rates facilitate better solidification, reduce thermal gradients, and decrease the likelihood of hot tearing.

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