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INFLUENCE OF PROCESS PARAMETERS ON BLISTERING DURING T6 HEAT TREATMENT OF SEMI-SOLID CASTINGS

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Abstract

High pressures applied to the castings during solidification mean that semi-solid castings tend to be prone to surface blistering during subsequent T6 heat treatment. It is believed that the blistering originates from subsurface defects present in the semi-solid castings, which expand when exposed to high temperatures during the solution heat treatment. Despite the significance of blistering to the commercial development of the semi-solid casting process, there have only been limited quantitative studies of the impact of process parameters on blistering. This paper, therefore, will report on a study to examine the impact of a number of process parameters including intensification pressure, plunger velocity and solid fraction of the feed material on the blistering of semi-solid castings during T6 heat treatment. The location and average size of blisters formed at each condition have been measured and related to the casting conditions.

Introduction

Unlike all other casting processes, semi-solid casting utilizes a feed material that is about 50% solid and 50% liquid. This highly viscous feed material provides a greater level of control during die filling, which, together with the extremely high intensification (feeding) pressures applied as the casting solidifies, provide many benefits compared with fully liquid casting processes such as sand, permanent mold and die casting. These benefits include lower residual porosity levels, improved surface appearance, improved net-shape capability, faster cycle rates, and the ability to generate improved mechanical properties.

To maximize mechanical properties, however, it is necessary to T6 heat treat the semi-solid castings, but surface blistering can be a problem when the castings are exposed to high temperatures during solution heat treatment. So, semi-solid castings are often used in the T5 temper rather than T6 temper in order to avoid significant blistering on the surfaces of the castings, which limits one of the major advantages of the semi-solid casting process - the ability to generate better mechanical properties than competing casting processes.

It is believed that there are several possible causes for the formation of the blisters, including excessive die and plunger lubricants, and turbulent die filling. Midson [1] proposed a mechanism for blister formation in semi-solid castings. He noted that surface blistering is generally not a problem for components produced by gravity casting processes such as sand or permanent mold casting, as these castings are poured and solidify close to atmospheric pressure. Semi-solid castings, however, are produced using pressures close to 1000 bar. Midson suggested that during casting it is possible to trap defects (entrapped air or lubricants) below the casting's surface, and any gas entrapped in the casting will also be pressurized close to 1000 bar. During subsequent solution heat treatment, these gases will expand (while the strength of the aluminum weakens), and blisters can form at the surface of the castings. According to the combined gas law (see Equation1), p_1 is the pressure of the gas or air trapped in a defect, V_1 is its volume and T_1 is its temperature. Semi-solid castings are typically produced in a die preheated to a temperature of about 250°C at an intensification pressure of 1000 bar. During subsequent solution heat treatment, the casting is heated to a higher temperature, resulted in the increasing pressure of gas or air trapped within the defect. At high temperature, the gas or air pressure within a defect close to the surface of the casting will exceed the strength of the aluminum and the defect will expand, forming a blister.

$$\frac{p_1 V_1}{T_1} = \frac{p_2 V_2}{T_2} \qquad \text{Equation 1}$$

Despite the importance of minimizing blistering for the commercial development of semi-solid castings, there have only been a few published reports discussing the impact of process conditions on blistering. Kopper [2] reviewed the impact of different types of plunger lubricants on the blistering of semi-solid castings during T6 heat treatment, while He et al. [3] evaluated the impact of both plunger lubricants and die lubricants on blister formation, and also provided quantitative measurements of the size of the blisters.

The goal of this project was to examine the influence of several semi-solid process parameters on the propensity for blistering, including intensification pressure, plunger velocity and solid fraction of the feed material. Both the size and position of blisters formed on the surfaces of semi-solid castings after solution heat treatment were analyzed using quantitative measurements. In addition, a more detailed examination of the inside surfaces of the blisters was performed using SEM and EDS, with the objective of identifying the source of the blisters.

Experimental Procedures

The trials described in this study were performed on the step casting shown in Figure.1a. The step castings were produced using the thixocasting semi-solid (billet) process, and were cast using the 340-ton Buhler horizontal cold chamber die casting machine with a large-diameter shot cylinder modified for semi-solid casting described in previous papers [4,5]. The 319S alloy (Al-6%Si-3%Cu-0.35%Mg) feed material was produced using a commercial continuous casting process, with electromagnetic stirring used to generate the globular semi-solid structure. Slugs cut from this pre-cast feed material were reheated to the semi-solid temperature range using a 10-coil carousel-style induction heater (operating at about 1,000 Hz). The configuration of the runner and gating system used to produce the step castings is shown schematically in Figure1b.

The process parameters evaluated in this study included intensification pressure, plunger velocity and solid fraction of the feed material and the detailed testing parameters are listed in Table 1.

Table 1 Detailed testing parameters

Intensification pressure (bar)	415, 900, 1120
Plunger velocity (m/s)	0.12, 0.25, 0.50
Slug temperature (°C)	580, 590

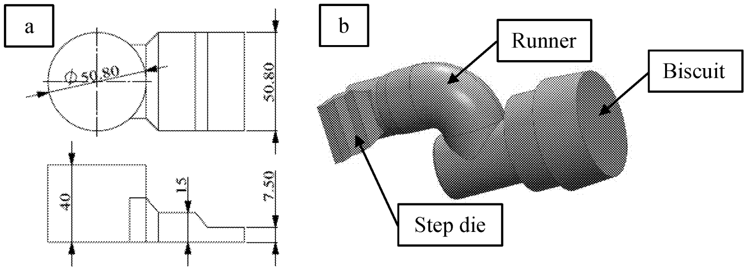

Figure 1 Semi-solid step casting using thixo casting process
a) The dimension of step casting; b) Schematic drawing of runner and gating system

All the castings were solution heat treated at 500°C for two hours and water quenched. Note that <u>all</u> the blisters generated in this study were produced during the solution heat treatment – no blisters were observed on the castings in the as-cast condition.

To provide a quantitative estimate of the impact of process parameters on the level of blistering, the size of the largest blister in each of five separate areas of the step casting was measured as shown in Figure 2, and the scoring system shown in Table 2 was used. The score from each of the five separate areas was averaged, providing an overall score for each processing condition evaluated. The morphology and chemical composition of the inner surfaces of blisters were analyzed by SEM and EDS.

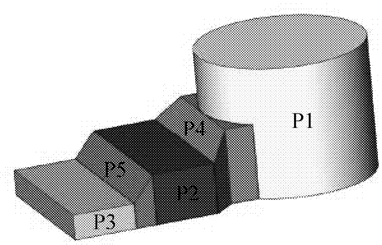

Figure 2 Five separate areas of step casting used to measure the blisters

Table 2 Method used to characterize the size of blisters

Blister Size	Score
< 0.1 mm	0
0.1 to 0.5 mm	1
0.5 to 1.0 mm	2
>1.0 mm	3

Results and Discussion

The first item to mention is that there was a large variation in the level of observed blistering, even for a series of castings produced under the same condition. For example, for castings produced using the same processing parameters, some castings had large (>1 mm) blisters after heat treatment, while other castings had only small blisters (<0.5 mm). Therefore, the results discussed in this paper are the average values for a number of castings produced under the same conditions (generally the results for between 5 and 10 separate castings have been averaged).

Table 3 summarizes the impact upon blistering of changing the intensification pressure for castings produced using a slug temperature of 580°C and plunger velocity of 0.50 m/s. The observation that the average size of the blisters became larger with increasing intensification pressure suggests that high intensification pressure is indeed causing the blisters. However, high intensification pressure maximizes the quality of the castings by helping to minimize shrinkage porosity, and it is normal to use an intensification pressure of close to 1000 bar for the production of high integrity semi-solid castings.

Table 3 Impact of the intensification pressure on the average blister size

Intensification Pressure (bar)	Plunger velocity (m/s)	Slug temperature (°C)	Blister score
413	0.50	580	0.20
900	0.50	580	1.13
1120	0.50	580	1.15

As the high intensification pressure of 1120 bar can improve the quality of the semi-solid castings, this pressure was used for the remainder of castings produced in this study. Table 4 shows the impact of plunger velocity on the average size of blisters for castings produced using a slug temperature of 580°C (which corresponds to a liquid fraction of about 46% [6]). The data in Table 4 indicates that the average blister size increased considerably with higher plunger velocities. Comparable data is shown in Table 5 for castings produced with a higher slug temperature of 590°C (about 58% liquid [6]), and in this case the blisters are smaller and show no relation to plunger velocity. This result is surprising, as it was expected that the die filling behavior would be more turbulent with the lower viscosity semi-solid metal produced at the higher slug temperature, resulting in a higher level of entrapped air and larger blisters. The reason for the larger blisters formed on the castings with the lower slug temperature is not fully understood at this stage.

Table 4 Impact of the plunger velocity on the average blister size at slug temperature of 580°C

Intensification Pressure (bar)	Plunger velocity (m/s)	Slug temperature (°C)	Blister score
1120	0.12	580	0.67
1120	0.25	580	0.83
1120	0.50	580	1.15

Table 5 Impact of the plunger velocity on the average blister size at slug temperature of 590^{o}C

Intensification Pressure (bar)	Plunger velocity (m/s)	Slug temperature (^{o}C)	Blister score
1120	0.12	590	0.30
1120	0.25	590	0.28
1120	0.50	590	0.36

Figure 4 shows SEM photographs of the inner surfaces of blisters from castings produced in this study. Visually the inner surfaces of the blisters appeared clean and shiny, and there were local smooth surfaces and dimple fracture morphology, caused by the expansion of air or gas entrapped in the defect during the solution heat treatment.

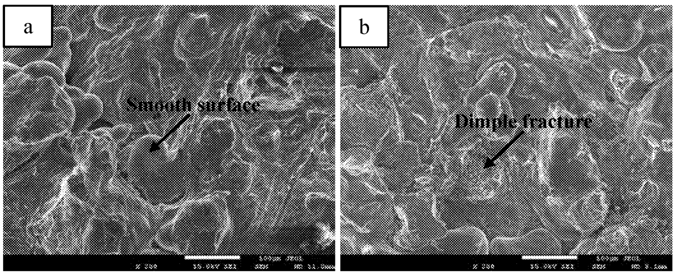

Figure 3 SEM photomicrographs of the inner surfaces of blisters produced using different plunger velocities (slug temperature 580^{o}C and intensification pressure 1120 bar)
a) 0.12m/s; b) 0.25m/s

In comparison, Figure 5 shows an optical photomicrograph of the inner surface of a blister reported in Reference [3], from a casting produced using high levels of plunger lubricant. The inner surface of this blister was very rough and contained a dark-colored material, most likely produced from the plunger lubricant.

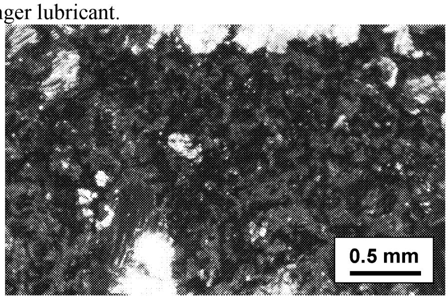

Figure 4 Inner surface of a blister produced using high levels of an oil-based plunger lubricant

Figure 5 shows an EDS analysis of the two types of blisters shown in Figure 3 and Figure 4. The blister produced using the high level of plunger lubricant contained relatively high levels of carbon and oxygen, while the blister produced in this study had essentially no carbon and only a low level of oxygen. This suggests that the blisters in this study were produced by entrapment of air, and not from lubricants applied to the die.

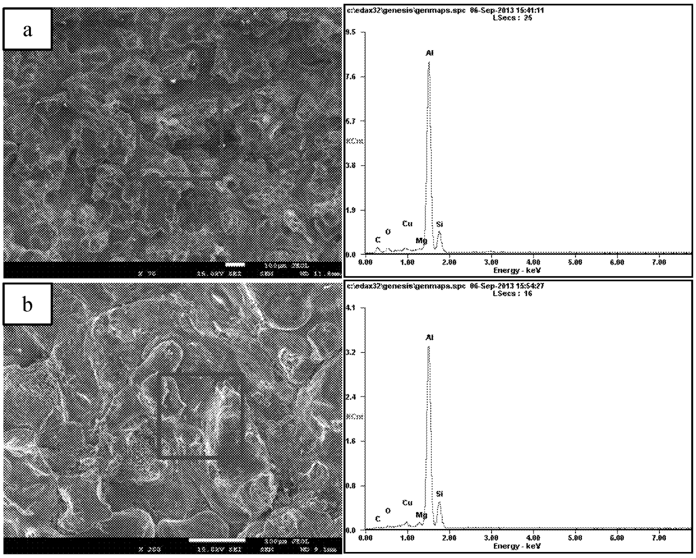

Figure 5 Chemical analysis of inner blister surface by EDS
a) Blister produced by heavy lubricant; b) Blister produced in this study

Conclusion

The results presented here confirm that blistering in semi-solid castings can originate from the entrapment of air, as well as from lubricants applied to the faces of the dies. The results from this study indicated:

1) With increasing of intensification pressure, the average size of the blisters became larger.
2) Plunger velocity has great influence on blister when the slug temperature was 580^{o}C, however, there was little change of blister size when the slug temperature was 590^{o}C

Acknowledgments

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