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Design of A New Hot Tearing Test Apparatus and Modification of Its Operation

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This study introduces a new apparatus for quantitative assessment of hot tearing tendency in casting alloys. In this method, molten metal is cast in a T-shaped mold cavity. Each arm of the T-shaped casting is hooked onto a rigid flask which restrains its free contraction during solidification. One of the hooks connects to a load cell which enables the real-time measurement of the contraction load during the solidification process as well as the load-time curve of each experiment. Temperature-time curves are also plotted using K-type thermocouples placed in the casting hot spot and connected to a data-acquisition system. Through the use of this set up, it is possible to estimate the solid fraction at which hot tearing occurs. Experiments were conducted with Al-9 %Si alloy to investigate the accuracy of the apparatus and modify its operation. The influence of the mold thermal gradient on the load-time curve and the hot tearing severity were investigated. Microscopic study of the observed hot tear regions was also performed to characterize the hot tearing characteristics.

Keywords: alloys, casting, defects, optical microscopy, hot tearing

1. INTRODUCTION

Formation of microscopic tears within the semisolid temperature range during casting has been the subject of metallurgical research since the 1940s, as hot tearing is a major defect in various cast alloys with large mushy zones. Hot tearing refers to formation of tears that occur at high fraction solids within the mushy zone during solidification of shaped castings and ingots. This defect can occur in both ferrous and non ferrous alloys [1-3].

It is an inter dendritic defect with a major band and some branches. The paths of tears propagate through the rough surfaces, and the dendritic morphology can be seen on the torn surface [4]. Hot tearing occurs in the mushy zone near the solidus temperature where solidification is nearly complete and only a thin film of liquid remained around the grains [5].

Due to the nature of this defect, the economic impact is often significant and can lead to immediate productivity loss. It is important for casting industries to be able to predict precisely the susceptibility of various alloys, casting geometries and /or process conditions as they pertain to hot tearing. A number of experimental methods have been devised over the years to determine the hot tearing susceptibility of cast alloys, the majority of which aim to create the defect by constraining the contraction of the casting as it solidifies and then quantifying the severity of the tearing [4,5]. In most of these methods, the susceptibility to hot tearing is examined by visual inspection of the solidified castings at room temperature and quantification of the number and severity of the open fissures observed on the surface of the castings. Experimental designs have generally been of ring type casting, restrained bar type casting, or variations thereof. The principle of the ring casting method involves a central core that acts to resist thermal contraction during the solidification and cooling process, thereby causing tensile stresses to develop in the semisolid regions. Consequently, in the past, the cumulative tear length or number of tears have been linked to the alloys hot tearing susceptibility [3,6]. The dog bone or black bone method is based on preventing free contraction during solidification of a casting bar. Both ends of the casting bar are restrained by the mold; thus, hot tearing occurs at the center of the bar [4]. Hot tensile test is another type of hot tearing test. In this method, the casting sample is heated to the semisolid temperature range and a tensile test machine is used to determine the mechanical properties of the semisolid sample [7]. The mechanical properties in the semisolid state can be discussed in terms of the hot tearing susceptibility. This method enables quantitative data to be obtained.

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Recently, Monroe and Beckermann [8] studied the hot tearing tendency of steel using T-shaped castings and measured the stress and strain that is exerted on two bolts fixed at two ends of the castings during solidification. Due to their use of complicated instruments, however, their method is very complex and analysis of the data is difficult. Moreover, preparation for each test is lengthy and requires specialized experience.

The present study introduces a new apparatus that permits a quantitative determination of the hot tearing tendency of cast alloys. The proposed method, which is a modification of the method used by Monroe and Beckermann [8], is based on simultaneous real-time measurement and monitoring of the contraction load and the temperature during the solidification process. In order to investigate the accuracy of this apparatus and modify its operation, several experiments were performed with Al-9 %Si alloy.

2. DESIGN AND MANUFACTURE

A schematic of the hot tearing test apparatus designed and used in this work is shown in Fig. 1. Its design concept is based on eliminating the mould constraining effects, and thus the mould type, on the tension and strain that develop as the casting solidifies. The mould geometry was therefore required to allow for free contraction of the casting during solidification. As a result, a T-shaped mould cavity was selected and the constraints necessary for contraction were provided by two bolts inserted into two sides of the mould cavity, as shown in Fig. 1 [9,10].

The apparatus consists of a sodium silicate bonded silica sand mould with a T-shaped cavity, two steel bolts (hooks) to restrain the casting contraction, a 50 KN load cell which enables real-time measurement of the contraction load during solidification, a PC system and data converter, two K-type thermocouples inserted into the mould cavity, and a rigid framework in which the flasks are secured with two thick steel plates at both ends [9,11].

The bolts set in the T-shaped cavity transfer the contraction force to the load cell and the rigid framework and therefore restrain the free contraction of the arms of the T-shaped casting. Load cell readings are fed to a special software which provides a real-time load-time curve for each experiment. The real-time temperature-time variations in the hot spot of the castings are also recorded by the K-type thermocouples positioned in the T-junction of the casting [9,11].

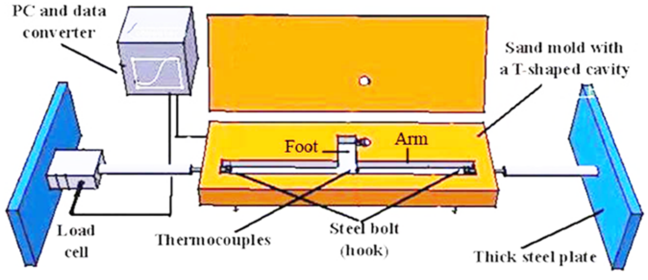

Fig. 1. Schematic plane of hot tearing test apparatus.

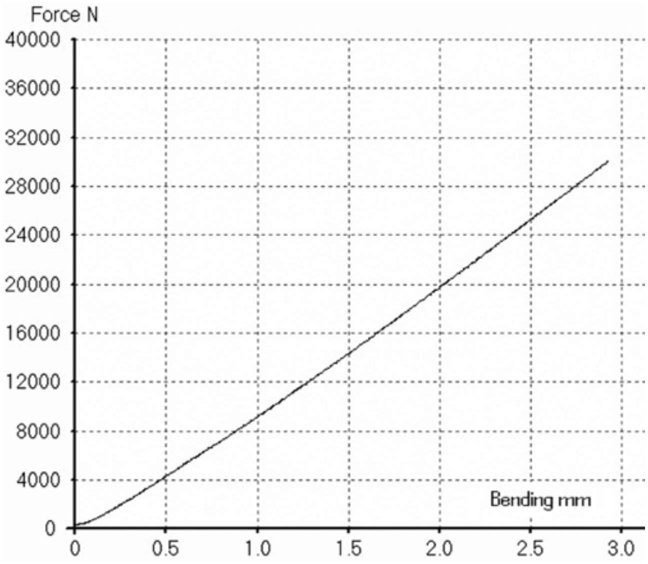

Fig. 2. Bending test curve of rigid plates.

To estimate the rigidity of the steel plates upon which the load cell is positioned, the steel plates were tested in a condition close to that of the actual condition (the casting condition). The plates were tested in a bending test machine, leading to a stress-strain curve similar to that shown in Fig. 2. The curve shows that for bending loads up to 30 KN, the plates show elastic deformation and a linear deflection. Under a bending load of 30 KN, approximately 2.9 mm of bending occurs.

Preliminary studies showed that the hot tearing occurred under much lighter loads where the deflection of the plates were negligible. Therefore, it was recognized that the effects due to bending of the plates on the load cell measurements were very small and could be overlooked.

The bending of each plate was also measured in an actual condition by setting a micrometer on the back of each plate and the maximum deflection of each 27 mm thick steel plate under a 30 KN bending load was found to be 1.5 mm. This confirmed the accuracy of the test condition.

The plates were connected using four pipes and other pieces of equipment were set in this rigid flask as shown in Fig. 1.

When melt is poured in the T-shaped cavity, rapid solidification around the bolts fixes the bolts. At this stage, the bolts can transfer the solidification load to the load cell. The prevention of the free contraction of the casting will concentrate the strain in the mushy zone of the casting, and hot tearing will occur. The tearing is presented as a peak or change in the slope in the load-time curve. The temperature-time curve (cooling curve) is used for determining the solid fraction and temperature at which hot tearing occurs.

3. OBSERVATIONS

Figure 3 shows the load-time curve and the cooling curve of the Al-9%Si alloy. At the beginning of the solidification, when the solid fraction of the melt is small, the contraction forces of the melt and the casting cannot be transferred efficiently to the load cell. Therefore, the expansion-induced compressive force due to heating of the bolts will be dominant. After a while, when a strong solid shell is formed on the surface of the mould, the contraction force overcomes the expansion force and the load curve starts to move to the positive region of the curve.

Based on the experiences gained during the design and manufacturing stage, hot tearing occurs at very small loads. However, the compressive force developed as a result of the initial expansion of the bolts, can offset the slope changes in the curves. Therefore, the effects of this compressive force must be reduced. This is a phenomenon that has also been observed in other studies but often neglected [12].

In order to minimize this compressive force, an original method was used. The method minimizes the heating of the bolts during the casting process by use of a cooling medium at the end of each bolt. Figure 4 shows the load-time curve and the cooling curve of the Al-9 %Si alloy at an experiment where the temperature of the bolts and their expansion were minimized. This ensured that the compressive force was very small.

4. DISCUSSION

In the first test (Fig. 3), at the beginning of the solidification, the expansion-induced compressive force will be dominant and therefore, the contraction forces of the casting cannot be transferred efficiently to the load cell. With continuation of the solidification, the solid fraction increases and a strong solid shell is formed on the bolts as well as on the mould surface. Thus, the contraction force overcomes the expansion force and the load curve begins to move to the positive region.

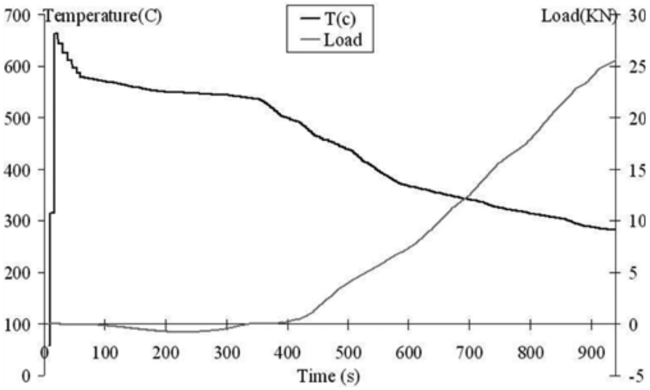

Fig. 3. Load-time and temperature-time curves for the first test.

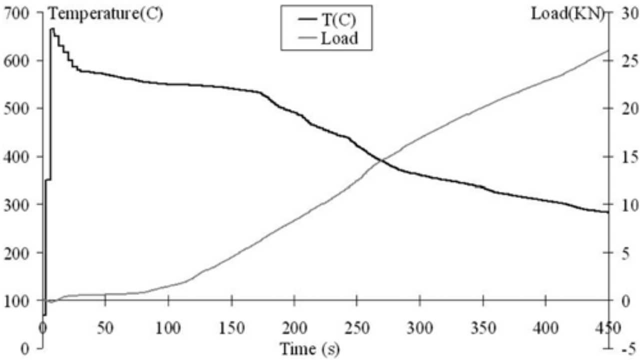

Fig. 4. load-time and temperature-time curves for the second test.

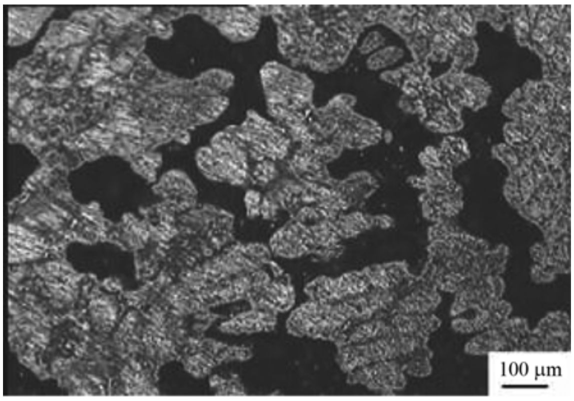

Fig. 5. Optical micrograph of surface crack, first test.

In the first test, the load cell shows compressive force due to the expansion of the bolts and the instruments. The maximum compressive force developed during this test is (–784 N) and the corresponding temperature is 548 °C. At 536 °C, the solid fraction begins to increase and the contraction force appears. The contraction force on the hot spot can lead to a condition in which hot tearing occurs. At the end of the solidification and after the knock-out of the mold, a visible tear was observed on the surface of the casting.

The T-junction of each casting was cut, ground, polished and etched according to standard metallographic techniques. Figure 5 shows an optical micrograph of a casting which confirms the presence of interdendritic tearing. Microscopic study of the observed torn regions was performed to characterize the hot tearing.

In Fig. 3, no peak appears. The expected peaks of the hot tearing were possibly eliminated by the compressive load. Therefore, a second test was designed to investigate this possibility.

In the second test, two copper blocks were joined to the bolts to reduce their temperature. This led to a reduction in the amount of expansion of the bolts. Thus, the compressive force in this test was smaller than that of the first test. The compressive force in this test was nearly (−178 N) (Fig. 4). Through the use of two copper chills at the end of the casting arms, an increase in the heat transfer from the mold was attempted. This should cause an increase in the rate of strain on the hot spot. Reduction of the compressive force in the second test increased the accuracy of the apparatus. It appears that by using the chills on the arms of the casting, a directional solidification condition is set. Thus, solidification proceeds rapidly from the arms to the center of the casting. Therefore, the hot spot is transferred to the foot of the casting (Fig. 1) and the contraction force cannot open the dendritic network. Therefore, hot tearing does not occur in the previous region. Other experiments with other alloys upheld the accuracy of the apparatus.

5. CONCLUSIONS

In this study a new apparatus that facilitates the quantitative investigation of hot tearing was introduced. The apparatus can estimate the susceptibility of cast alloys to hot tearing without the need for visible tearing and allows the comparison of the hot tearing susceptibility of different cast alloys. Susceptibility to hot tearing can be determined by quantifying the strain rate in the mushy zone. Using this method, it becomes possible to determine the temperature and the solid fraction at which hot tearing occurs in the hot spot. The accuracy of this apparatus can be compared to other methods that uses a load cell. Application of the apparatus is very simple and does not require specialized experience.

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