Journal of Materials and Environmental Sciences
ISSN : 2028-2508

JMES, 2017 Volume 8, Issue 9, Page 3099-3105

http://www.jmaterenvironsci.com/

Study of hot tear of AlCu5MgTi by restraining casting shrinkage in green-sand mold

A. Hamadellah[1], A. Bouayad[2]

1. Laboratoire des Sciences et Métiers de l'Ingénieur, Ecole Nationale Supérieure d'Arts et Métiers (ENSAM), Moulay Ismaïl University(UMI), BP 15290 El Mansour, Meknès, Maroc
2.Laboratoire des Sciences et Métiers de l'Ingénieur, Ecole Nationale Supérieure d'Arts et Métiers (ENSAM), Moulay Ismaïl University(UMI), BP 15290 El Mansour, Meknès, Maroc

Received 25 Oct2016,
Revised 30 Jan2017,
Accepted 03 Feb 2017

Keywords
- ✓ Aluminum alloys;
- ✓ Hot tear initiation;
- ✓ Cooling curve;
- ✓ Dendrite coherency point (DCP);
- ✓ Rigidity point;
- ✓ Constrained rod casting mold (ICR);
- ✓ Green-sand;

A.Hamadellah
hamadellah@hotmail.com
+212650750270

Abstract

The aim of this paper is to study hot tearing in aluminum alloy casting by impeding the solidification shrinkage in a sand mold. The instrumented constrained rod apparatus (ICR) enables giving real-time measurements of the contraction load developed and temperature variations during solidification. Two important parameters were extracted from plotted curves; dendrite coherency point (DCP) and rigidity temperature (T_R). On the contrary, when the alloy was cast in the sand mold no cracks were observed because the casting is not hindered during solidification. With a fixed bolt, solidification shrinkage is upset and causes the hot tearing that is visually detected. Thermal analysis and force developed curves allowed to elucidate crack initiation mechanism. The experiments clearly show that the rigidity temperature is a crucial parameter in hot tear initiation.

1. Introduction

AlCu5MgTi is a commonly used alloy in applications where superior mechanical properties and lightweight are needed. These conditions refer to this alloy for use in industry of automotive and aerospace. Despite those advantages, AlCu5MgTi is one of the most susceptible aluminum alloys to hot tearing, [1]. This defect occurs within the mushy zone of some castings at high solid fractions during the solidification, [2]. The formation of an irreversible failure in the semisolid casting explains this phenomenon. The characteristics of the hot tearing are known thanks to several studies and metallurgical researches done since the 1940s.It was obviously shown that the hot tearing occurs in a temperature range just above the solidus temperature of the alloy where the solid grains are surrounded by a thin film of low melting point liquid, if the solidification contraction is not done loosely, [3-4]. These include the part geometry, the mold itself, internal cores, centrifugal forces applied in an opposite direction to contraction, etc. Different researches [5–8] have showed that during solidification of metallic alloys, two critical temperatures are responsible of development of strength in the castings, coherency and rigidity temperatures. The "coherency point" corresponds to a temperature in the semisolid temperature range where an extensive skeleton of solid particles has been formed, but the permeability of the mush is still large enough to allow any potential opening in the mush to be healed by mass and interdendritic feeding of the remaining liquid. At this stage, solid particles interaction develops significant shear strength but its tensile strength is still very low. Cooling the melt down, solid particles start to coalesce. The solid fraction increases and dendrite network is getting stronger. At this coalescence solid fraction (rigidity temperature), some solid bridges start to form between the solid particles and the mush starts to acquire significant tensile strength [5–8]. The strength disappears, as soon as the solid bridges fracture under the developing tensile strains. To determine coherency and rigidity temperature Backerud et al. [9, 10] have developed the two-thermocouple technique using thermal analysis method. One thermocouple is located at a nearby inner wall (Tw) of a test crucible, and the other at the center (Tc). The dendrite coherency point DCP is determined by identifying the local minimum on the delta versus time curve (Delta = Tw - Tc) [11]. DCP occurs at this minimum delta versus time curve. This is explained by the fact that heat dissipation from the solid is faster than from the liquid phase. This happens because of the high thermal conductivity of solid dendrites (forming the network) in comparison to the surrounding liquid metal, [12].

The rigidity temperature is determined as a second delta minimum identified in the region of solidus, immediately before the solidus temperature [13]. The main reason for the occurrence of this second point is the difference of the thermal conductivity in the solid and liquid phases. At this solid fraction, some solid bridges begin to form between the solid particles and therefore, the slurry begins to acquire a significant tensile strength [7,8]. Therefore, the solid particles begin to move pass each other due to the lubricating effects of the liquid film between them and hot tears start to set in the casting.

For a given alloy composition, the occurrence of hot tearing strongly depends upon process parameters such as mold type, part geometry, melt superheat, cooling rate, and inoculation, [14,15]. The economic impact of this defect is often significant and results in a loss of production. Therefore, it is interesting for casting industries to be able to predict the sensitivity of different alloys to hot tearing under different molding conditions and for specified part geometries.

Hot tearing often occurs at the inside corners of casting geometries, where casting shrinkage is constrained by the relatively rigid mold cavity. Unlike the permanent mold, the green sand mold is less sensitive to the crack thanks to the plasticity of clay. This property promotes the deformability of the mold cavities and hence doesn't impede solidification shrinkage.

A number of experimental methods have been developed over past years to determine the hot tearing susceptibility of metallic alloys, most of which aim to create the defect by limiting the contraction of the solidification of the casting and then quantifying the severity of the tearing [16,17].

In some of these methods, hot tearing susceptibility is controlled by visual inspection of the solidified castings at room temperature [18-20].

Among the quantitative methods, we can find the study of Cao and Kou [21] who investigated the hot tearing susceptibility of magnesium alloy using a permanent mold. Besides, M.R.N. Esfahani et al. [15] studied the hot tearing tendency of A206 alloy using sand-mold T-shaped castings and measured the stress and strain exerted on two bolts clamped to extremities of the castings during solidification. The mold is equipped with a thermocouple and a load cell to record the instantaneous values of temperature and load developed in the castings.

In comparison with previous works, this paper analyses the hot cracking of AlCu5MgTi alloy with a different geometry of the specimen (dog bones) in the sand mold. This is done in presence or absence of discomfort shrinkage during solidification using an instrumented constrained rod casting (ICR) method designed for quantitative determination of hot tearing susceptibility of cast alloys. The method is based on simultaneous real-time measurement and monitoring of the contraction load and temperature during solidification. The first test consists of taking measurements without fixing the end of the specimen during solidification. In the second test the extremity of casting is anchored to a fixed bolt. In both tests, the second end of the casting is connected to the load cell by a rod bolt which transmits the strengths arising in the casting during solidification. The green-sand mold is equipped by two thermocouples and load cell in order to provide cooling and load curves data. These data will be used to demonstrate the relevance of coherency and rigidity temperature as significant parameters of hot crack apparition and to characterize hot tearing and forces developed during solidification.

2. Experimental details

2.1. *Tested alloy*

Aluminum casting alloy AlCu5MgTi was selected because it is characterized by excellent mechanical properties and high temperature strength. This alloy is used for a variety of applications in both automotive and aerospace industries but it is particularly recognized as being difficult to cast, mainly because of its sensitivity to hot tears. The chemical composition of the AlCu5MgTi alloy was measured using a spark emission spectrometer and is given in Table 1.

Table 1: Chemical compositions (wt%) of the AlCu5MgTi alloy

AlCu5MgTi [EN AC-21000]							
Element	Cu	Mn	Mg	Ti	Si	Fe	Al
standard	4.2–5.0	0.2–0.5	0.15–0.35	0.15–0.30	<0.05	<0.10	bal
measured	4.5	0.24	0.27	0.23	0.05	0.1	bal

2.2. *Hot tearing apparatus*

Similar to the setup of M.R.N. Esfahani et al. [15], an instrumented green-sand mold with a new geometric shape was developed. The schematic representation of the ICR apparatus used in this work for hot tearing tests is illustrated in Fig. 1.

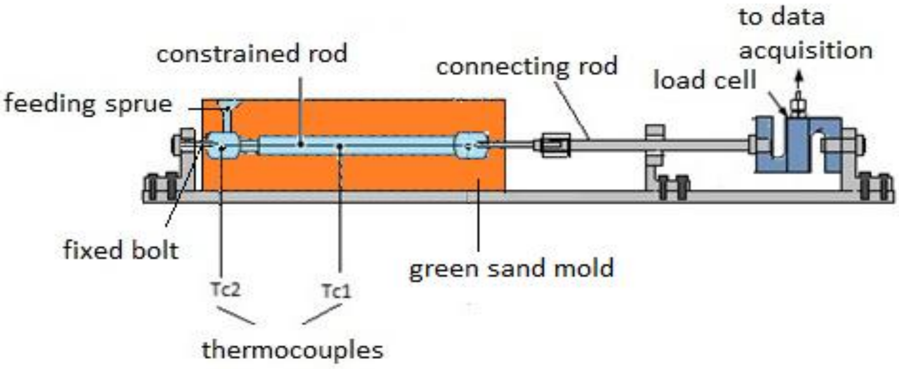

Figure 1: A schematic illustration of the experimental constrained rod dog-bone shape sand mold ICR.

The design concept of the apparatus was based on eliminating the effects of mold constraints on tensions and strains developed in the casting during solidification. As a result, a rod dog-bone shaped mold cavity was selected as shown in Fig. 2a, and necessary constraints to solidification shrinkage were provided by two bolts inserted within two sides of the mold cavity. Indeed, a steel rod was anchored to the near parallelepiped zone of the constrained rod. This rod is connected to a load cell that measured shrinkage induced forces (see figure 1). The mold was equipped with two K-type thermocouples and load cell to simultaneously measure the load/time/temperature developed during solidification and determines the onset of hot tearing. The thermocouple Tc_1 is located in the thin cylindrical part of the rod measuring low temperature similar to wall temperature; whereas Tc_2 is located in the parallelepiped (hot spot) measuring center temperature as shown in Fig. 1 and Fig. 2b. The maximum error on temperature acquisition is 0.5 °C.

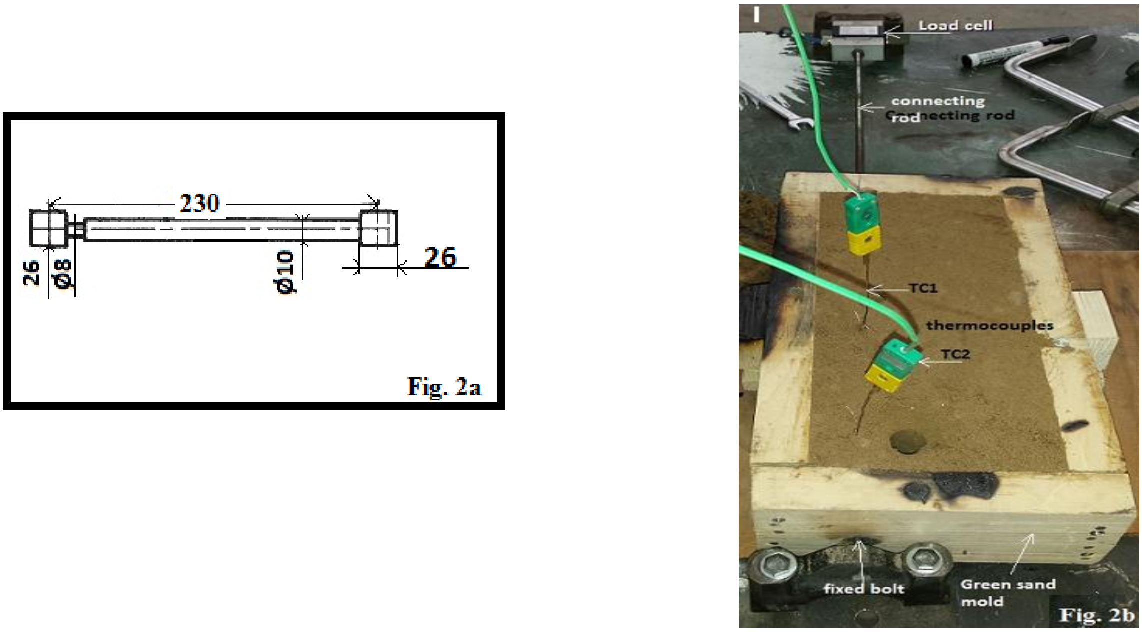

Figure 2: (a) The geometry of constrained rod dog-bone shape (b) Photograph of experimental apparatus.

2.3. *Melting and process parameters*

Melting was conducted in an electric furnace, and the melt was well degassed before pouring. The pouring temperature is about 760°C. No grain refinement was used in these tests. The castings were then extracted from the mold and examined for cracks. Subsequently, the cooling curve, load versus time curve were processed to obtain critical information about the solidification process and hot tearing formation.

3. Results and Discussion

Hot tearing occurs in the hot spots of castings where the strain resulting from the solidification contraction is concentrated and when the contraction of a solidifying casting is excessively restrained by the bolt and the connecting rod during solidification. Fig. 3 (a) zoomed in Fig. 3 (b) shows examples of section where hot tear is observed in the restrained rod castings. It is noticed that hot tearing is usually formed closer to the in-gates. In the case of molding without setting the bolt, we note that the casting part has no defects (see Fig. 4). We also notice a difference in the sizes of castings obtained with and without constraining. The casting with the fixed bolt is 1.1 mm longer than the casting without bolt as seen in Fig. 3 (c) and Fig. 4.

Figure 3: a) Shape of casting part, b) Hot tearing in the rod, c) Size of the casting

Fig. 5(a) shows the evolution of temperature versus time and delta= Tc1-Tc2 versus time curves for AlCu5MgTi alloy. The first minimum on the delta−T curve indicates the DCP temperature. We found for this parameter the value of 632°C. The second minimum denotes the rigidity temperature close to the solidus temperature, which is about 530°C. For the same alloy, M.R.N. Esfahani et al. [15] found in sand mold the value of 640 °C for DCP point and 569 °C for rigidity temperature. These values are not far from those obtained in the present study since the experimental conditions are not exactly identical (not the same sand and not the same geometry). Fig. 5(b) indicates the variation of the load induced with fixed bolt and temperature as a function of time. We studied also the variation of the load and delta as a function of temperature instead of time (Fig. 6), which give probative results.

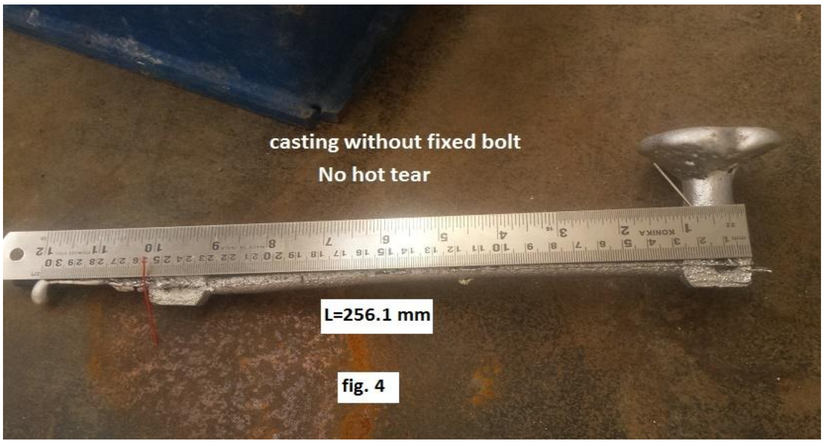

Figure 4: The size of the casting poured without fixed bolt.

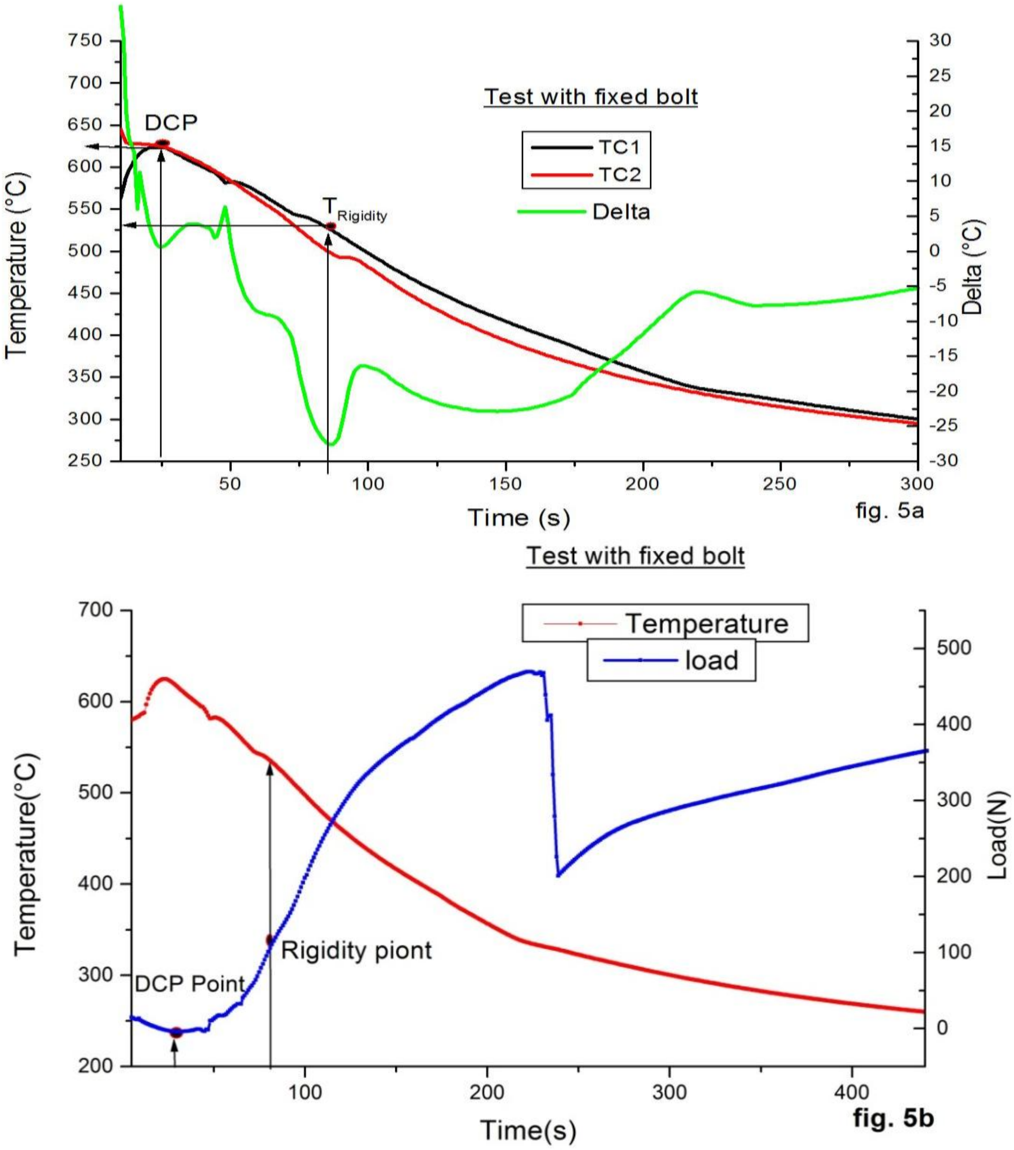

Figure 5: a) Cooling curves at the side and the centre of the hot spot region of the casting and their difference (delta= Tc1-Tc2), b) load and temperature vs time curves for AlCu5MgTi casting with fixed bolt.

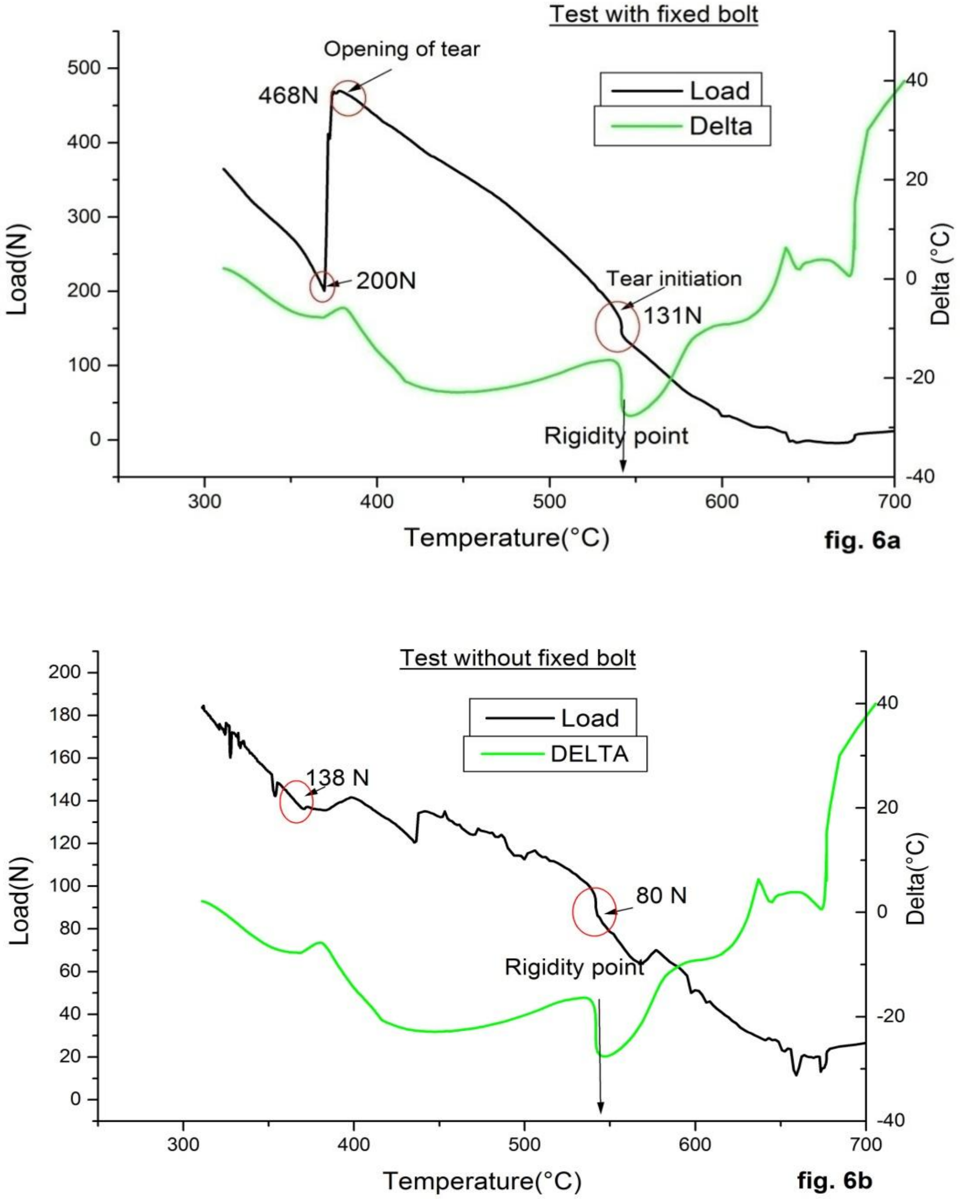

Figure 6: Load vs temperature and Delta vs temperature curves for AlCu5MgTi: a) casting with fixed bolt, b) casting without fixed bolt.

Fig.6 displays load vs temperature and Delta vs temperature. The first graph shows that hot tear initiation coincides with rigidity temperature (determined by the second peak of delta versus time). At this point the big shift in the load causes hot tear initiation. The load continues to increase significantly from 131 N to the maximum value of 468 N as seen in Fig. 6a. This maximum characterizes the opening of the crack. At this point the load drops sharply from 468 N to 200 N, which is explained by crack outbreak that leads to a stress relief. At the opposite, in the second graph Fig. 6b load continues to rise smoothly after rigidity point with decreasing temperature without reaching important values (from 80 N to 138 N).

The difference in part dimensions between the two tests demonstrates that the solidification shrinkage is not blocked in unfixed mold, but when the end of the specimen is fixed by a bolt, solidification is limited and the specimen is subjected to extensive forces (see Fig.3c and Fig. 4) which confirms the results obtained from temperature vs time, delta vs time and load vs time curves Fig. 5 and also from load and delta vs temperature Fig. 6.

The experiments clearly showed that hot tearing occurs when anchoring a bolt in the end of the casting. This is due to obstructed solidification shrinkage phenomenon. Indeed, the extremities of specimen, which solidify first by thermal conduction with bolts, generate tensile stresses by impeding solidification shrinkage of inner part of casting.

Conclusions

The discomfort effect of green sand mold on the hot tearing susceptibility of AlCu5MgTi aluminum alloy was investigated in this study. The Instrumented Constrained dog bone rod casting apparatus enabled the real-time measurements of the contraction load developed in the casting and the temperature variations during solidification as a function of time with and without fixed bolts. The experiments conducted allowed us to draw the following conclusions:

- Hot tearing is not observed in sand mold without anchoring part. This is due to the free deformation of green sand.
- DCP and rigidity temperatures extracted from cooling curves for this alloy are respectively 632°C and 530°C.
- The contraction load developed at the rigidity point of the castings was identified as a crucial indicator of hot tearing susceptibility of casting alloys. For AlCu5MgTi, and when the bolt was fixed load shifted from 131 N to 468 N leading to crack initiation. On the contrary, in the absence of fixed bolt the load experienced a small increase from 80 N to 138 N not sufficient to cause failure.

References

1. Kamga H. K., Larouche D., Bournane M., Rahem A., *Mat. Sci.Eng. A*. 527.27 (2010) 7413.
2. EskinD. G., *Physical metallurgy of direct chill casting of aluminium alloys, CRC Press*,(2008).
3. Wang, Y., Wang Q., Wu G., Zhu Y., Ding W., *Mater. Lett.* 57.4 (2002) 929.
4. Yu K.O., *Modelling for casting and solidification processing, CRC Press*, (2001).
5. Ludwig O., Drezet J.M., Ménésès P., Martin C.L., SuéryM., *Mat. Sci. Eng. A*.413 (2005) 174.
6. Dahle A.K., StJohn D.H.,*Acta Materialia*.47(1998) 31.
7. Ludwig O., Drezet J.M., Martin C.L., Suéry M., *Metall. Mater. Tans. A*. 36.6 (2005) 1525.
8. Rappaz M., Jacot A., Boettinger W. J., *Metall. Mater. Tans. A* . 34.3 (2003) 467.
9. Backerud L.,Chai G., Tamminen J., *Solidification Characteristics of Aluminium Alloys.Foundry Alloys. AFS, Inc. IL, USA* (1990).
10. Chai G., Backerud L., Rolland T., Arnberg L., *Metall. Mater. Tans. A*. 26.4 (1995) 965.
11. Djurdjevic M. B., Huber G. *J. Alloys Compd*. 590 (2014) 500.
12. Djurdjevic M. B., Sokolowski, J. H., Odanovic, Z., *J.Therm.Anal. Calorim*. 109.2 (2012) 875.
13. Djurdjevic M.B., Manasijević, S., *Metall.Mater. Eng*. 20.4 (2014) 235.
14. Sequeira W., Pikhovich V., Weiss D. *Finding new strength in aluminium. Eng. Cast. Solutions*. 8.1 (2006).
15. Esfahani M.R.N., Niroumand B., *Mater.Charact*. 61.3 (2010) 318.
16. Beeley PR., *Foundry technology, Butterworth-Heinemann*, (2001).
17. Li X., *Study of hot-tearing during solidification of Aluminium alloys via the acoustic emission method, University of Quebec, Chicoutimi* (2000).
18. Eskin D. G., Katgerman L., et al. *Prog. Mater. Sci*. 49.5 (2004) 629.
19. Zhoua Y, Volek A., *Mater.Sci. Eng., A*.479.1 (2008) 324.
20. Zhang J., Singer R. F., *Acta. Mater*. 50.7 (2002) 1869.
21. Cao G., Kou S., *Real-time monitoring of hot tearing in AZ91E magnesium casting. Proceedings of the 111th Metal Casting Congress, Texas* (2007).

(2017) ; http://www.jmaterenvironsci.com