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Hot-tearing of multicomponent Al-Cu alloys based on casting load measurements in a constrained permanent mold

Adrian S. Sabau[1], Seyed Mirmiran[2], Christopher Glaspie[2], Shimin Li[3], Diran Apelian[3], Amit Shyam[1], J. Allen Haynes[1], and Andres F. Rodriguez[4]
[1]Oak Ridge National Laboratory, Oak Ridge, Tennessee, 37831
[2]Fiat Chrysler Automobiles North America, LLC., Auburn Hills, MI 48326
[3]Worcester Polytechnic Institute, Worcester, MA 01609
[4]Nemak Monterrey, Garcia 66000, Mexico

ABSTRACT

Hot-tearing is a major casting defect that is often difficult to characterize, especially for multicomponent Al alloys used for cylinder head castings. The susceptibility of multicomponent Al-Cu alloys to hot-tearing during permanent mold casting was investigated using a constrained permanent mold in which the load and displacement were measured. The experimental results for hot tearing susceptibility are compared with those obtained from a hot-tearing criterion based temperature range evaluated at fraction solids of 0.87 and 0.94. The Cu composition was varied from approximately 5 to 8 pct. (weight). Casting experiments were conducted without grain refining. The measured load during casting can be used to indicate the severity of hot tearing. However, when small hot-tears are present, the load variation cannot be used to detect and assess hot-tearing susceptibility.

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INTRODUCTION

One of the challenges for the high-volume production of automotive cast metal parts is the reduction of casting defects. Hot tearing is one of the most detrimental solidification casting defects [1]. The appearance of hot-tear defects depends on both

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the local state of stress and interdendritic feeding. When the interdendritic liquid flow can feed local deformation regions, in which dendrite arms are pulled apart over a significant distance, the space between displaced dendrite arms is filled, and the hot tears are “healed”. As the solidification proceeds, the solid fraction increases, area open to interdendritic fluid flow decreases, and liquid feeding of solidification shrinkage and hot tears becomes more difficult. Thus, at high volume fraction of solid, when an opening of the dendritic network by tensile deformation remains unfilled, as liquid feeding is difficult, cracks nucleate and grow, causing a “hot tear” defect [2]. Identifying criteria for hot-tear formation has been the subject of numerous studies [3, 4]. For Al-Cu alloys, Campbell and Clyne [5] found that the peak of the lambda curve for hot tearing susceptibility correlated with the non-equilibrium freezing range. Other criteria are based on the critical values for the strain, accumulated plastic strain, or strain rate [2]. One of the most recent criteria that was developed for solidification cracking in welding was also applied for estimating hot tearing during casting [6]. Most of the studies on hot-tearing of Al alloys were mainly dedicated to the DC casting [7]. Li et al. [8] reviewed hot tearing molds for permanent mold castings.

In this study, Al-Cu multicomponent alloys are considered [9]. The Cu composition was varied from approximately 5 to 8 pct. (weight). The susceptibility of four multicomponent Al-Cu alloys to hot-tearing during permanent mold casting was investigated using a constrained permanent mold in which the load and displacement were measured. The experimental results for hot tearing susceptibilities were compared with those obtained from the hot-tearing criterion presented by [6]. This criterion was based temperature range evaluated at fraction solids of 0.87 and 0.94.

SOLIDIFICATION CHARACTERISTICS FOR HOT TEARING CRITERIA

The Cu content of the four alloys (DA1, DA2, DA6, and DA7), whose hot-tearing resistance was characterized in this study, was 4.95, 6.6, 7.3, and 8 wt%, respectively [9]. The microstructure model in ProCAST was used to conduct thermodynamic simulations for the four alloys considered based on the Scheil model. The variation of the fraction solid (f_s) as a function of temperature (T) is shown in Figure 1. This fraction solid data can be used in different hot-tearing criteria [2, 6]. For reference, the f_s data on 206 and A356 aluminum alloys was also presented. The solidification characteristics can be used as a first-order estimate of hot-tear resistance. For example, alloys that freeze over a larger temperature range with only a small amount of final eutectic liquid are expected to be less hot tear resistant [5, 10]. The freezing range is almost the same for all DA# considered (from a minimum of 108 ^oC for DA7 to 116 ^oC for DA6). Thus, based on freezing range alone, one would expect that DA# family would not be hot tear resistant.

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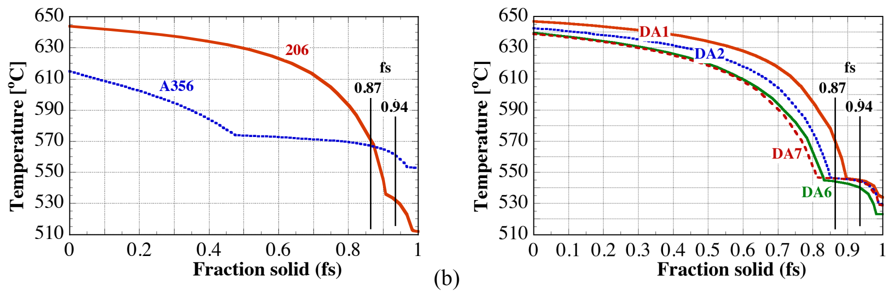
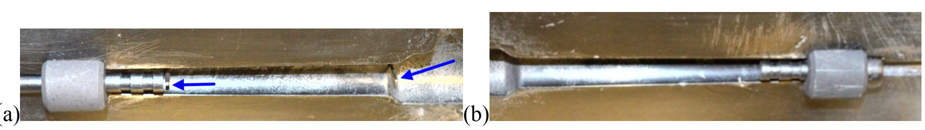


(a) (b)

Figure 1. Calculated solid fraction using the Al material database Computherm and microstructure module in ProCAST for: (a) 206 and A356, and (b) four new alloys considered.

ASSESSMENT OF HOT-TEARING RESISTANCE BASED ON VISUAL INSPECTION OF CASTINGS

The casting experiments to assess the hot-tear resistance were conducted using an instrumented constrained rod mold, which was developed by WPI and CANMET [8] to measure the load and/or temperature during solidification for a restrained casting. The casting consists of two tapered arms that emerge from the bottom of the riser. Three types of castings were made for each alloy, temperature measurement (TM), load measurement (LM), displacement measurement (DM). In the TM castings, the temperature was measured with two thermocouples, whose tips are indicated by arrows in Figure 2. If the front view of the casting is considered to be on the vertical casting surface in which the thermocouples are placed, then the LHS (left-hand-side) arm will have its end fixed for all casting types and most measurements will be taken from the right-hand-side (RHS) arm. In this section, pictures taken of the casting surface in each arm-riser joint region, where hot tearing is expected to occur, were presented to assess the level of hot tearing resistance.



(a) (b)

Figure 2. Picture of mold setup for load measurement type castings showing: (a) mold cavity for the RHS arm with the location of two thermocouples. The thermocouples were intentionally inserted in the mold cavity to their location for the temperature measurement castings, and (b) mold cavity for the LHS arm with the bushing used to fix the arm end.

The pictures of the RHS arm can always be identified by the thermocouple indent mark near the joint transition. Due to the fact that the end of the LHS arm is always fixed, while the RHS arm has a more relaxed geometric constraint at its end, hot tearing defects are expected to appear more pronounced on the LHS arm than on the

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RHS arm. The castings were visually inspected and the severity of cracking was ranked according to the classifications considered in Table 1. For reference, Kamga et al., [11] used four hot tear classifications, which correspond to SH, LH, S, and C in Table 1. For the sake of simplicity, images for representative LM castings are presented in Figures 3, 4, 5, and 6 for the DA1, DA2, DA6, and DA7 alloys. The figures 3 and 4 indicate that severe hot tearing is seen for DA1 and DA2 castings. The hot-tearing defects were found to be limited to very thin hairline cracks for the DA6 and DA7 castings. The summary of the visual inspection ranking of hot-tearing severity is shown in Table 2.

Table 1. Assigned Visual Hot-Tearing Indicator (VHTI) for different types of hot-tears.

VHTI	Label	Description
0	None	No hot tearing
1	Very short hairline tear (VSH)	hairline tear near the surface; length less than 1/4 the circumference of the arm
2	Short hairline tear (SH)	hairline tear near the surface; length less than 1/2 the circumference of the arm
3	Long hairline tear (LH)	hairline tear near the surface; length approx. the entire circumference of the arm
5	Medium tear (M)	deep tear that extends over the entire circumference of the arm
8	Severe tear (S)	wider tear than medium tear that extends over the entire circumference of the arm
10	Complete tear (C)	partial or complete separation of the arm

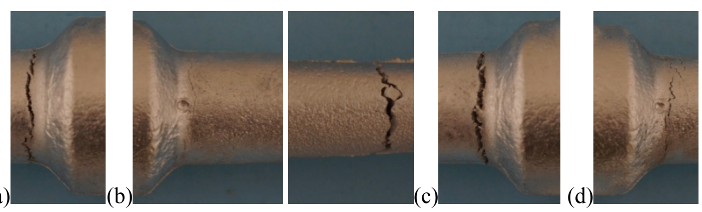
(a) (b) (c) (d)

Figure 3. Pictures of the DA1 alloy load measurement castings, showing hot tearing in: (a) L4 left arm, (b) L4 right arm, (c) L5 left arm, and (d) L5 right arm.

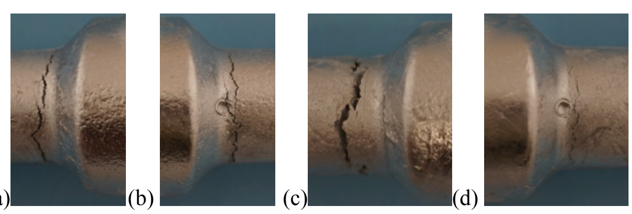
(a) (b) (c) (d)

Figure 4. Pictures of the DA2 alloy load measurement castings, showing hot tearing in: (a) L3 left arm, (b) L3 right arm, (c) L4 left arm, and (d) L4 right arm.

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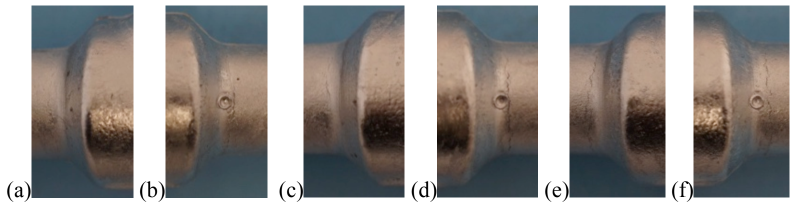

Figure 5. Pictures of the DA6 alloy load measurement castings, showing: (a) L1 left arm, (b) L1 right arm, (c) L2 left arm, (d) L2 right arm, (c) L3 left arm, (d) L3 right arm.

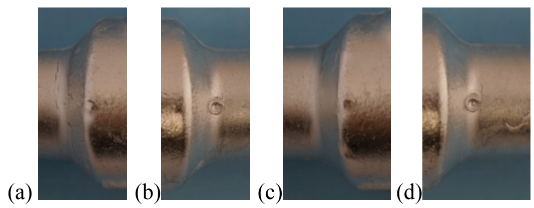

Figure 6. Pictures of the DA7 alloy load measurement castings, showing: (a) L1 left arm, (b) L1 right arm, (c) L2 left arm, and (d) L2 right arm.

Table 2. Summary of hot-tearing defects in LM castings based on visual inspection.

Alloy	**No.**	**LHS arm**	VHTI LHS arm	**RHS arm**	VHTI RHS arm
DA1	L4	S/C (9)	9.5	C (10) arm SH (2)	6.5
	L5	C (10)		LH (3)	
DA2	L3	M (5)	7.5	LH (3)	2.5
	L4	C (10)		SH (2)	
DA6	L1	None (0)	1	VSH (1)	2
	L2	None (0)		SH (2)	
	L3	LH (3)		LH (3)	
DA7	L2	VSH (1)	0.5	None (0)	0.5
	L3	None (0)		VSH (1)	

LOAD MEASUREMENT DURING CASTING SOLIDIFICATION

The load measurements during casting in the WPI mold can be used to obtain quantitative data on the hot-tearing defects, as it was shown for A356 and 206 alloys [8] by correlating the load variation with the solidification behavior. Specifically, Li et al. [8] correlated sudden changes in the load rate with onset of hot-tearing and crack propagation. The "zero" time origin was selected for both the TM and LM castings to be that instant at which molten metal enters the right casting arm, i.e., as evidenced by the initial rise in the measured temperature on the riser side. The raw data for measured load, i.e., unsmoothed by any data post processing algorithm, is shown in Figure 7 as a function of time during casting solidification for the four new alloys considered. For each LM case, the load onset time (i.e., cross-over from the initial

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negative values to positive values) is marked on each figure. As shown in Figure 7, the lowest and highest load levels were measured for DA1 and DA7, respectively. DA1, DA2, and DA6 were found to exhibit a wide range load variation while the load measurement for DA7 showed very good reproducibility.

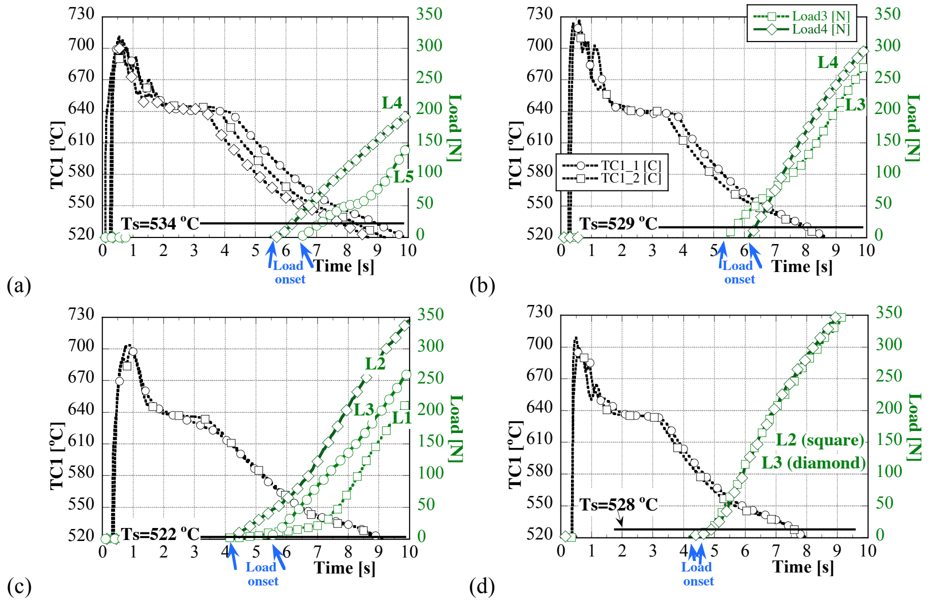

Figure 7. Measured load during casting for alloys: (a) DA1, (b) DA2, (c) DA6, and (d) DA7.

The variation in the load rate was found to be very important by Li et al. (2011) for the WPI castings. The 7-point moving-average data for load rate is shown in Figure 8 as a function of time during casting solidification for the four new alloys considered. Li et al. (2011) indicated that a "V" like signature of the load rate variation was found to occur for hot-tearing, the left-top point on the "V" indicating the "crack onset" and the end of the "V" indicating the end of the "crack propagation". This "V" signature was identified for each of the LM data presented in Figure 8. The typical "V" signature for hot-tearing can be easily observed for DA1 castings (Figure 8a). For DA2, only the L3 casting shows the hot-tearing signature (Figure 8b). The L4-DA2 casting does not exhibit the "V" hot-tearing signature, indicating that for the short hairline tear (SH) (Figure 4d for the right arm), the load measurement is not sensitive enough to identify this type of very small hot-tearing. This is also evidenced for the L1-DA6 and L2-DA6 load data, i.e., a "V" shape in the load variation could not be noticed to characterize the Very short hairline tear (VSH) and Short hairline tear (SH) seen in Figure 5b and 5d, respectively. On other hand, the Long hairline tear (LH) seen in Figure 5f, which is actually extended over the entire arm circumference unlike the SH tear seen in Figures 5b and 5d, exhibits the typical "V" shape signature in the

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load variation (Figure 8c). The load rate exhibited the most consistent variation for the DA7 castings (Figure 8d).

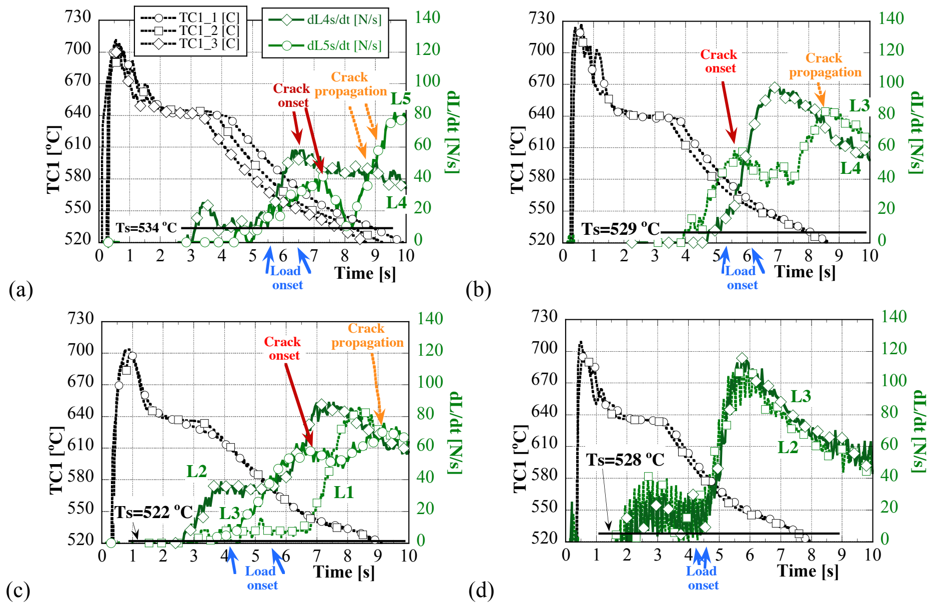

Figure 8. Calculated load rate during casting solidification for alloys: (a) DA1, (b) DA2, (c) DA6, and (d) DA7.

DISCUSSIONS AND CONCLUSIONS

The susceptibility of multicomponent Al-Cu alloys to hot-tearing during permanent mold casting was investigated using the WPI constrained permanent mold in which the load and displacement were measured. First, it has to be mentioned that the alloys with 7.3 and 8 wt. Cu were found to be the most hot-tear resistant. Second, the data for the hot-tearing indicator introduced by Kou [6], which is based on variation of $T\left(\sqrt{f}\right)$ between f_s=0.87 and f_s=0.94, is compared directly with the hot-tearing indicator evaluated from the visual inspection of the WPI castings (Table 2). It has to be noted that it is more convenient to use Kou's hot-tearing indicator (KHTI) rather than conduct casting experiments, as KHTI can be obtained solely from thermodynamic simulations. For the data shown in Table 3, the VHTI was calculated by averaging the VHTI for the left arm and right arm (Table 2). The values of the Kou's hot-tearing indicator (KHTI) based on temperature slope in the $T\left(\sqrt{f}\right)$ curve indicate that DA2, DA6, and DA7 are expected to be hot-tearing resistant alloys while the VHTI data indicate that DA7 and, to some extent DA6, are hot-tear resistant alloys. The ranking of the hot-tear resistance of the least hot-tear resistant alloy, DA1, and the most hot-

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tear resistant alloy, DA7, are in good agreement between the KHTI and the experimental VHTI. However, the DA2 alloy, which experimentally is shown to have a poor hot-tear resistance, the KHTI predicts a very high hot-tear resistance. This comparison between experimental and computational data is very important, as provides more information that can be used to assess the range of applicability of the KHTI criterion to accurately predict hot-tearing resistance of Al alloys.

Table 3. Comparison between hot-tearing indicators based on thermodynamic data and experimental data.

Alloy	DA1	DA2	DA6	DA7
Cu wt. [%]	4.95	6.6	7.3	8
KHTI - $\Delta T/\Delta\sqrt{f}$ between f_s=0.87 and f_s=0.94	620	61	126	66
Expected hot-tear resistance based on KHTI	Very low	High	High	High
VHTI (scale 0-10)	8	5	1.5	0.5
Hot-tear resistance based on VHTI	Very low	Low	Low-High	High

Third, in an attempt to correlate the hot-tearing with the quantitative variables related to load and load rate values, the VHTI for the right casting arm (Table 2) are shown in Table 4 together with load at solidus point and load rate average. It has to be mentioned that when small hot-tears are present, the load variation cannot be used to detect and assess hot-tearing susceptibility. Although it is not a strong correlation, it can be seen from the data shown in Table 4 that the higher the load at solidus temperature, the lower the hot-tearing indicator. Excluding the L1-DA6 data on average of the load rate, it was found that there is a relatively strong correlation in the average of the load rate and the hot-tearing indicator, i.e., the higher the average of the load rate the lower the hot-tearing indicator. The data also show that at higher VHTI values larger crack growth times were observed. Thus, load at solidus point and load rate average over the freezing range, which were obtained from the measured load data, can be used to indicate the hot tearing resistance of the Al-Cu multicomponent alloys.

Table 4. VHTI for the right casting arm (Table 2), load at solidus and load rate average.

Alloy	LM No.	VHTI for RHS arm	Load at solidus [N]	Load rate average [N/s]
DA1	L4	2	141	45.7
	L5	3	63	28.4
DA2	L3	3	166	46
	L4	2	125	75
DA6	L1	1	153	31.5
	L2	2	283	59.6
	L3	3	196	54.7
DA7	L2	0	246	76.6
	L3	1	252	79

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