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Hot tearing of aluminum–copper B206 alloys with iron and silicon additions

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ABSTRACT

Hot tearing of B206 aluminum alloys with additions of iron and silicon was studied with constrained mould casting (CRC) to investigate the combined effect of these additions on hot tear resistance. Susceptibility to hot tearing was found to increase gradually with iron content when the conditions were favorable to the formation of the β(FeCu) phase. Additions of silicon with a Fe/Si mass ratio ≤ 1 and high cooling rates, which together promote the α(MnFe) phase at the expense of the β(FeCu) phase, were found beneficial to the hot tearing resistance. Hot tearing sensitivity (*HTS*) of the alloys was evaluated with a new index defined to reflect the compliance of the torn specimens. This index showed a very good correlation with the Katgerman's hot tearing index (*HCS*), providing that one defines the temperature where inadequate feeding starts to be the temperature where 2% of the interdendritic volume is occupied by intermetallic phases. Examinations of the tear surfaces and profiles revealed that a premature crack opening created by insufficient healing correlates well the explanations based on the theoretical hot tearing index. The deleterious effect of iron on hot tearing was demonstrated on alloys having a coarse grain microstructure having Ti contents below or equal to 0.01 wt%. Above this limit, fine grain microstructures were obtained and the influence of iron was not strong enough to have a significant impact on the castings produced.

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1. Introduction

Hot tearing is an inherent defect in 206 type aluminum alloys which is generally attributed to their long freezing range [1]. This defect essentially involves the formation of a macroscopic tear as a result of strain localization in the solidifying metal above the non-equilibrium solidus temperature of the alloy. Hot tearing requires both a susceptible microstructure and a mechanical constraint, the later being most of the time imposed by the mold. Under these circumstances, the total strain is fixed to zero and the irreversible strain increases to compensate the solidification shrinkage and the thermal contraction strain. The mechanisms allowing the irreversible strain to increase depend on the fraction liquid involved. Above the dendrite coherency temperature, the distance between the grains can increase in the directions of tensile stresses, providing that the state of stress allows the conjugated flow of the liquid phase. Below the dendrite coherency temperature, grain boundary sliding will be activated and the stress will rise according to the level of lubrication of the grains [2]. As long as the liquid films lubricating the grains are connected, the inflow of metal from regions where the hydrostatic pressure is high to regions where the hydrostatic pressure is low will prevent the formation of a cavity [3]. When the flow of liquid becomes difficult, the system enters into the vulnerable time period for hot tearing [4,5]. For a given cooling rate, the temperature range covered in this period is critical for hot tearing since the longer will be that range and the larger will be the irreversible strain necessary to accommodate the solidification shrinkage. Clyne and Davies [5] were the first to propose a hot tearing index based on the concept of the vulnerable time period versus the time allowed for accommodation. Their index called the cracking susceptibility coefficient (*CSC*) was defined as:

$$CSC = \frac{\Delta t_v}{\Delta t_r} \quad (1)$$

where Δt_v represents the vulnerable time period and Δt_r represents the time period available for stress relief processes. These two time periods are contiguous at the critical point (t_{cr}) where, according to Katgerman [6], the system transits from a regime where liquid feeding is adequate to a regime where liquid feeding is inadequate. Katgerman also makes the point clear that the time period for stress relief starts when dendrite coherency is attained, since the latter is by definition the point where the stress sustained by the solid phase becomes different from those in the liquid phase [7]. Therefore, the total time period circumscribed between the time where the system reaches dendrite coherency (t_{coh}) and the time

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where the system becomes rigid ($t_{0.99}$) is divided in two contiguous segments: $\Delta t_v = t_{0.99} - t_{cr}$ and $\Delta t_r = t_{cr} - t_{coh}$ so that Eq. (1) can be written as:

$$CSC = \frac{t_{0.99} - t_{cr}}{t_{cr} - t_{coh}} \quad (2)$$

This definition of the cracking susceptibility coefficient is often referred in the literature as the Katgerman's hot tearing index. Indices of this kind are recognized to give a correct picture of the compositional dependence of hot tearing susceptibility [8]. They cannot be used however to predict the occurrence of hot tearing when casting conditions are changing, unless the times appearing in Eq. (2) are associated to the temperature distribution in the metal, as Katgerman did in the case of the direct chill casting [6]. In fact, prediction of hot tearing is only possible if the mechanical aspects of solidification are also taken into account [9]. Several criteria were proposed to predict hot tearing. Most of them have been evaluated in Ref. [10] by using a mathematical modeling of the direct chill casting process. In their paper, the authors concluded that the RDG criterion [3], which calculates the pressure drop associated to the deformation of the microstructure imposed by the solidification shrinkage, shows the greatest potential for hot tearing prediction. The other criteria examined failed to predict hot tearing in particular situations where normally hot tearing is encountered. The RDG criterion is based on the mass conservation equation and the most recent two-phase hot tearing models include such a feeding based criterion [7,11–14]. Although these models include many features helping to capture the essential of the hot tearing phenomena, their major limitation is that they are two-phase models. Commercial alloys always have a certain amount of iron, which combines with the other elements to generate intermetallic phases at elevated temperature. So in general, there are not only two phases in the pre-eutectic portion of the solidification path but three and often more depending on the composition. Contrary to the dendrite arms, which coarsen by a uniform migration of the solid–liquid interface, secondary phases nucleate in the interdendritic space at different locations and grow across the liquid film. Their formation inevitably impedes the flow of liquid by a plugging effect and may induce premature hot tearing. Very few reports in the cited literature have explored the effect of pre-eutectic intermetallics in aluminum alloys. In their review, Eskin et al. [15] wrote that impurities in amounts of tenths of a percent can considerably affect the ductility and the brittle range of alloys. They cited Novikov [16] who mentioned, as translated by Eskin et al., "that impurities or small additions that change the morphology and distribution of intermetallic particles can affect the ductility and the span of the brittle range accordingly". Oya et al. [17] found that additions of Sn, Zn, Fe and Ni in Al–4.5%Cu and Al–4.5%Cu–5%Si alloys have for effect to reduce the hot tearing resistance of the alloy. They pointed out the importance of interdendritic fluid flow in the initiation of hot tears. Chadwick [18] arrived at the opposite conclusion regarding the influence of iron in Al–4.5%Cu. He explained his results by the action of the iron intermetallics filling the gap between the dendrites and forming a framework, "which isolates the eutectic into pockets increasing the ability of the test pieces to resist constraint stresses imposed by the die". Chadwick also reported that the iron intermetallics had a deleterious effect on the tensile strength of the alloy. Novikov and Grushko [19] observed a gradual increase of the hot tearing susceptibility of two Al–Cu–Li alloys with manganese additions. They did not however reported the causes of this deleterious effect. They only mentioned that there was a decrease in the elongation to failure with manganese additions in the solid–liquid condition. In a more recent contribution, Nagaumi et al. [20] found that iron additions increase the hot tearing sensitivity of a 6XXX type alloy due to the formation of the α(MnFe) intermetallics, which crystallizes into grain boundary and make the latter to become fragile. They did not clearly stated whether the tear starts from the decohesion of the α(MnFe)–dendrite interface or from the formation of a cavity in the liquid phase near the intermetallic particle. It is indeed a possibility that hot tearing may be initiated in the solid phases as pointed out recently by Lesoult [21] and before by Guven and Hunt [22]. The latter specified however that hot tear can start in the solid just below the eutectic temperature if the volume fraction of liquid is below 2%.

Table 1
B206 alloy composition.

Cu	Si	Fe	Mn	Mg	Ti	Zn	Ni	Al	Fe/Si
4.60	0.10[a]	0.06	0.40	0.25	<0.01	0.00	<0.01	Balance	0.60

[a] Si was out of specification.

The presence of β(FeCu), Al_7FeCu_2, phase in aluminum–copper alloys is well known to have deleterious effect on the tensile strength [23]. In a recent study on solidification of 206 type alloys [24], the authors showed that the precipitation of the β(FeCu) phase could be partially or completely suppressed depending on the iron to silicon ratio as well as the cooling rate. Under favorable conditions, precipitation of α(MnFe), $Al_{32}(Cu,Fe,Mn)_8(Al,Si)_4Si_2$, phase can bypass the precipitation of the β(FeCu) phase, capturing then almost all the iron available. The porous structure of the α(MnFe) phase is likely to ease the flow of liquid metal, while its cubic structure may show more coherency with the aluminum matrix.

Having the same motivation as expressed by others [25], that it could be acceptable for automotive applications to use naturally aged 206 type alloy castings with higher iron contents, it was decided to investigate the effects of iron and silicon additions on the hot tearing susceptibility of the B206 alloy. The objective of this study was to determine the possibility that higher iron contents could be used while preserving most of the good properties of the B206 aluminum alloy.

2. Experimental procedure

2.1. Materials

The base alloy is a B206 ingot produced by Rio Tinto Alcan and its chemical composition is shown in Table 1. Compositions were modified using aluminum1020 and commercial master alloys (Al–50%Si, Al–25%Fe, Al–25%Mn, Al–50%Mg, and Al–50%Cu). Chemical analyses were carried out with an optical emission spectrometer and the compositions are presented in Table 2.

A Constrained Rod Casting (CRC) mould was used in this study. The design of this mould made of cast iron is presented in Fig. 1. The mould cavity was designed to cast four 12.7 mm diameter cylindrical constrained rods with nominal lengths of 50.8 mm (bar A), 88.9 mm (bar B), 127 mm (bar C), and 165.1 mm (bar D). The bars are constrained at one end by the sprue and at the other end by

Table 2
Alloys designation and composition (wt%).

Alloy[a]	% of Alloying elements						
	Cu	Fe	Si	Mn	Mg	Ti	Fe/Si
B1213	4.68	0.12	0.13	0.24	0.32	0.02	0.92
B2312	4.70	0.23	0.12	0.24	0.30	0.01	1.92
B2121	4.72	0.21	0.21	0.24	0.29	0.02	1.00
B3511	4.54	0.35	0.11	0.25	0.30	0.01	3.18
B3223	4.74	0.32	0.23	0.24	0.29	0.03	1.39
B3134	4.73	0.31	0.34	0.24	0.32	0.04	0.91
B2332	4.95	0.23	0.32	0.27	0.35	0.01	0.72

[a] Bxxxx; the first two digits represent the wt% of Fe and the last two digits represent the wt% of Si.

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