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X-ray micro-tomographic observations of hot tear damage in an Al–Mg commercial alloy

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X-ray micro-tomography and three-dimensional image analysis were used to characterize hot tearing. The formation and interconnectivity of deformation induced damage during hot tearing was quantified in specimens of DC cast aluminum alloy AA5182 (of composition Al–4.63%Mg–0.49%Mn–0.17%Fe–0.04%Cu) subjected to tensile load at a temperature of 528 °C (fraction solid ~0.98) over a range of strains varying from 0 to 0.20 (failure). This technique also allowed for quantification of the porosity formed during DC casting.

Keywords: X-ray computed tomography; Hot tearing; High temperature deformation; Aluminum alloys; Tension test

The direct chill (DC) casting process [1] is commonly used to solidify non-ferrous alloys into primary ingots (rectangular cross-section) and billets (circular cross-section). Although this process has been used successfully by industry for many years, certain defects remain technically challenging, such as cold cracks, ingot distortion, and hot tears. Hot tears are commonly encountered during the start-up phase of the casting process and are most prevalent in long freezing range alloys [2]. It appears that these defects both initiate and propagate in regions of the casting that are at temperatures just above the solidus [3] and that are subjected to thermally or mechanically induced stresses acting on material with limited ductility [3,4].

A number of criteria have been developed to predict the occurrence of hot tears (see review by Eskin et al. [5]). These approaches can be divided into two classifications: those relating to the mechanical aspects of the problem, such as total strain [6]; and those relating to solidification aspects, such as freezing time [7]. Recently, Suyitno et al. [8] evaluated a number of these criteria by implementing them into a FE simulation of the DC billet casting process, and concluded that their predictive ability was qualitative at best. The lack of quantitative correlation suggests that our understanding of the mechanisms of hot tearing is insufficient, and that there is a need for more fundamental experimental studies. While most prior experiments have focused on quantifying the macroscopic aspects of hot tearing behavior (e.g. load as a function of fraction solid [9,10]), only a few studies have examined hot tearing in situ. For example, one study focused on an Al–0.5%Cu alloy in which surface cracking was observed in a partially solidified alloy subject to tensile loading [11]. A second study, using a transparent organic analogue [12], identified three different hot tearing initiation mechanisms – directly as elongated tears in the intergranular region, on pores caused by solidification shrinkage, and as a restarted hot tear in the region that was earlier considered to be a healed hot tear – illustrating the benefits of in situ observation. This study examines the applicability of X-ray micro-tomography (XMT) for the 3D quantification of damage formed during hot tearing.

In the current study, four tensile specimens of commercially DC cast AA5182 were heated to 528 °C, corresponding to a fraction solid (f_s) of approximately 0.98 [13]. Subsequent to reaching the test temperature, each specimen was loaded in tension to different values of strain as shown in Table 1, using a Mushy Zone Tensile Tester. The cross-head displacement rate was 0.085 mm/s. Full details of the apparatus are provided in [14]. The key feature of the apparatus is that a parabolic temperature gradient prevails along the specimen, promoting strain localization near the center of the gauge length.

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Table 1. Summary of analysis of XMT data

Test no.	$D_{initial}$ (mm)	D_{final} (mm)	ε_{XMT}	$\varepsilon_{dimetral}$
1	7.98	7.91	0.02	0.018
2	7.99	7.77	0.06	0.054
3	7.99	7.53	0.16	0.118
4	8.00	~7.35	~0.20	0.169
5[a]	8.00	8.00	$\%P = 0.32\%$	

[a] Undeformed specimen.

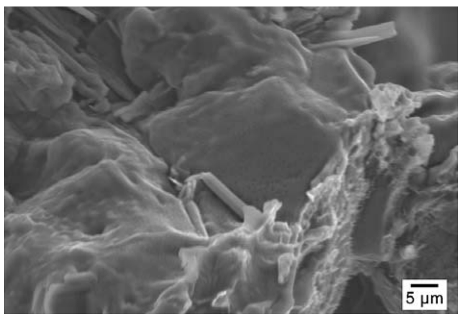

Figure 1. SEM image of specimen 4, showing the presence of liquid at the crack interface.

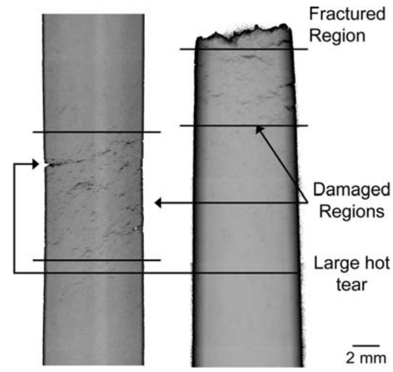

Figure 2. Radiograph images showing the axial extent of damage in specimens 3 and 4, strained to values of: (a) 0.16 and (b) 0.20 (fracture).

X-ray micro-tomographic (XMT) scans using a commercial laboratory scale XMT unit[1] were performed on an undeformed specimen, and four specimens deformed to strains ranging from 0.02 to 0.2 (see Table 1). Reconstructed images consisting of $\sim 800 \times 800 \times 400$ voxels (each ~ 9 μm), were collected from the deformed region of each specimen. A 1.0 mm thick planar sample was then machined for transmission radiography. Image analysis was performed on the tomographs using VGStudioMax.[2]

Figure 1 shows a scanning electron microscopy (SEM) image of the fracture surface of specimen 4 ($\varepsilon \cong 0.20$). The surface has a smooth, glassy-like morphology, which is indicative of some liquid being present during deformation and failure and confirms that the specimen was semi-solid during testing.

Transmission radiographs of specimens 3 and 4 (Fig. 2) show that the damaged region of each specimen contains a significant void fraction, which was not present in the undeformed specimen. The strain is accumulated both by dimetral reduction and also internal void growth. Previous studies have used the dimetral strain to characterize semi-solid properties [14]. However, the assumption of a fully dense structure during mushy zone testing ignores the internal accumulation of strain. Strain can be more accurately estimated by calculating the logarithm of the ratio of the initial cross-sectional area to the number of metal voxels in each slice of the reconstructed volumes. Therefore, in this study both the internal and dimetral strains in each of the four tensile specimens were measured (Table 1). At low strains, the dimetral and XMT measurements are similar, with an increasing divergence at high strains due to increased internal damage.

The initial void content prior to tensile deformation was $\sim 0.32\% \pm 0.05$, as quantified from the XMT data of the undeformed specimen. This corroborates earlier findings, where DC as-cast Al–Mg alloys were found to contain 0.4–0.7% voids [15] arising from a combination of gas, shrinkage and/or thermo-mechanical loading during cooling. Since it is not possible to differentiate in a single XMT scan between the as-cast void population, and voids formed during subsequent application of strain, the term porosity will be used to refer to the voids that formed during DC casting, and the term damage will refer to voids visible after tensile testing.

Further examining the transmission radiograph of specimen 3 ($\varepsilon = 0.16$) in Figure 2(a), the central region is highly necked and heavily internally damaged, containing both many small hot tears and a few large ones. These hot tears are oriented normal to the axial (loading) direction, as would be expected in a tensile test. One of the hot tears extends through a large portion of the cross-section of the specimen and it is probable that only a small increment in the strain would have caused this specimen to fracture. It should also be noted that the damage is fully constrained to the center (~5 mm) portion of the radiograph. The damage is localized to this region because of the temperature profile that exists along the length of the specimen during testing – i.e. during testing the damaged region is above the solidus temperature ($T_{solidus}$), while the remainder of the sample is below $T_{solidus}$.

The tomographs of all five specimens are shown in Figure 3(a)–(e). Figure 3(d) shows the 3D reconstruction of the damaged area of the sample strained to 0.16. The same area was previously presented in cross-section in the low magnification radiograph shown in Figure 2(a). In this image, two cross-sectional slices, one parallel to the loading direction, and a second, perpendicular to the loading direction, are displayed behind the isosurfaces. The voids intersecting the surfaces of the planes have been colored black, while in front of these planes the solid AA5182 has been removed. Thus, only the isosurface of the voids appear in the foreground. The loading direction is vertically oriented. This tomograph

[1] Phoenix|X-ray Systems and Services GmbH.
[2] Volume Graphics GmbH.