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HAADF and Analytical TEM of The Metastable α-Al and θ'-Al_2Cu Phases in a Rapidly Solidified Hypo-Eutectic Al-Cu Alloy

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Laser based additive manufacturing produces unusual microstructures due to rapid solidification (RS) and subsequent non-equilibrium thermal transients [1,2]. To control and improve the properties of the additively manufactured materials understanding of the microstructure formation provides foundational knowledge. The present work is focused on the atomic-scale characterization of the rapidly solidified multi-phase microstructure in hypo-eutectic Al-11Cu alloy. Previous *in-situ* TEM studies of laser melting induced RS of electron transparent Al-Cu alloy films have enabled quantitative measurements of the solidification interface velocity for the different crystal growth modes responsible for the formation of morphologically distinct microstructural regions [2, 3]. RS microstructures in hypo-eutectic Al-Cu exhibit characteristically four morphologically distinct regions that evolve behind an accelerating solidification interface: 1. heat affected zone (HAZ); 2. transition zone; 3. columnar growth zone; 4. banded region (Fig. 1 (a)). Conventional transmission electron microscopy (TEM) showed presence of α- Al and θ-Al_2Cu phase in the HAZ, and α-Al and θ'-Al_2Cu phase in the remaining three regions. Scanning transmission electron microscopy (STEM) was performed using a Titan Themis G2 200 instrument to determine the structure and composition of the supersaturated Al-phase, the Al_2Cu-phases, and the interfaces between them, for the columnar growth zone and the banded region (see Fig. 1(a)). These microstructures formed at the highest solidification rates where significant to complete solute trapping occurred under conditions deviating from local equilibrium at the transformation interface [3].

High resolution high angle annular dark field (HAADF) images of the Al matrix and θ'-phase acquired along [1-10] (e.g. Fig.1(b)) for the partitioned two-phase region of the banded microstructure zone revealed the presence of coherent interface structure for (002)-θ'-sections and incoherent interface structure for the perpendicular (110)–θ'-sections. The corresponding FFT (inset Fig.1(b)) shows that the (200) planes of α-Al and (002) planes of θ'-phase are unexpectedly misoriented by ~ 3˚. Such misorientations are not observed for solid state phase transformation based (α/θ')-interfaces. The differences of the morphology and the interfacial structure of the θ'-phase formed during RS relative to that formed by solid-state transformation are likely related to the required nucleation process at the rapidly migrating solid-liquid interface and details of the growth into the deeply undercooled alloy liquid. The EDXS mapping (Fig.1(c)) shows a constant composition inside the θ'-phase, whereas the α-Al matrix exhibits characteristic nm-scale spatial Cu concentration fluctuations. The highly supersaturated Al matrix showed signs of Cu clustering. HAADF imaging (Fig.1(d)) clearly revealed the presence of Cu rich GP zones along (002), a more diffuse background intensity variation implying Cu concentration modulation, and in [001]-HAADF images the presence of embryonic θ'-phase for the Al matrix. These results show that θ' phase formed during RS is different from the θ' phase formed during solid state phase transformation in terms of morphology, interface structure and composition.

Implications for the details of the mechanisms of multiphase crystal growth into the alloy liquid at the extreme interfacial migration rates during RS of the Al-11Cu alloy will be discussed.

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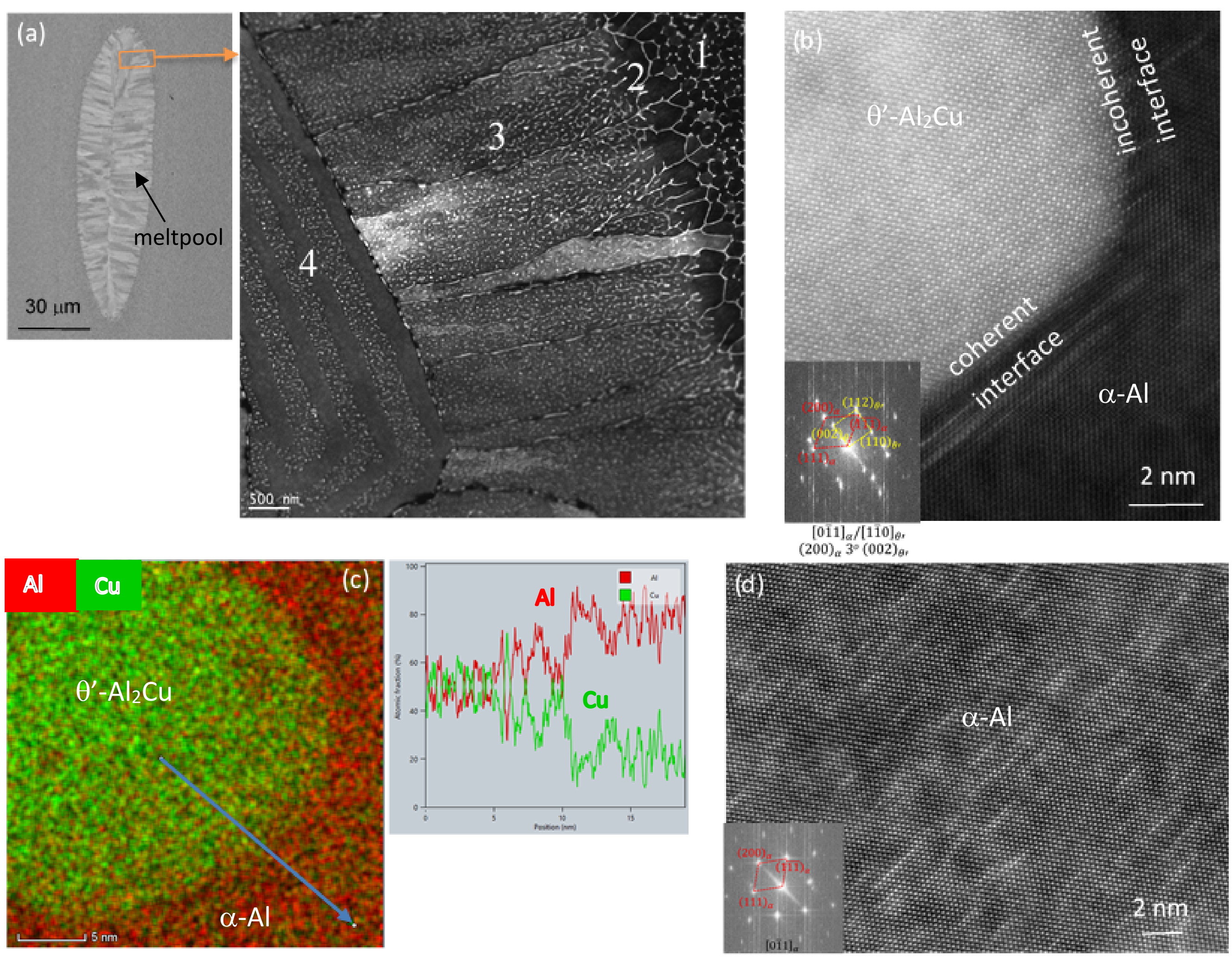

Figure 1. (a) Overview and detailed (from red rectangle) STEM images of the laser melted region in the hypo-eutectic Al-11Cu alloy showing (1) HAZ, (2) transition, (3) cellular and (4) banded regions, (b) High resolution HAADF image of θ' and α-Al phases showing the presence of coherent and incoherent phase boundaries, (c) EDXS phase map and line scan showing the presence of composition fluctuations in the matrix region and (d) HAADF image of the α-Al matrix showing the presence of GP zones along (200) planes.

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