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Nano-Scale Spatio-Temporal Resolution *in situ* TEM and Numerical Modeling of Rapid Solidification Microstructure Evolution in Al Alloys After Laser Melting

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Additive manufacturing (AM) is potentially a pervasive technology, offering capabilities for preparation of complex components. However, its broader adoption requires development of an ideally physical evidence–based and quantitative understanding of processing-microstructure-property-performance relationships [1-3]. During selective laser melting (SLM)–based AM, surface melting and re-solidification produce microstructural modifications under far-from-equilibrium conditions. The resultant gradient microstructures develop by rapid solidification (RS) and differ significantly from those of conventionally cast or wrought products [4-6]. Hence, developing experiment-based understanding of microstructure evolution during RS at the appropriate spatio-temporal scales is critical. *In situ* transmission electron microscopy (TEM) of the irreversible reactions can provide important mechanistic understanding and measurements to support model development and validation for SLM AM [4]. Exploiting the unique capabilities of the dynamic transmission microscope (DTEM) and using Al-Cu as a model system, the transformation dynamics and microstructure evolution during pulsed-laser-stimulated RS have been studied here. The TEM experiments revealed crystal growth-mode changes under composition-dependent characteristic conditions and facilitated quantitative measurements of locally resolved instantaneous and average solidification front velocities during the transformations (Fig. 1) [4-6]. *In situ* DTEM studies enabled determination of the critical velocities for the growth-mode transitions as a function of Cu fraction in Al-Cu alloys. Fig. 1D illustrates four morphologically distinct zones established in Al-Cu alloys by an accelerating RS interface [6]. Since temperature measurements are inherently difficult while performing *in situ* DTEM RS experiments, here complementary enthalpy-based numerical modeling has been performed to determine the thermal field evolution during the RS. Calculation results have been benchmarked simultaneously against several transformation-related quantitative metrics provided by *in situ* DTEM experiments. A comparison of low-magnification bright-field DTEM images and matching computer model calculations of the RS sequence of a pulsed-laser-induced melt pool (dark gray in Fig. 1A) in Al shows the entire melt pool. Example temperature profiles calculated at various stages during the RS transformation are depicted in Fig. 1C. Combining post-mortem microanalysis with the *in situ* DTEM experiments and numerical modeling enabled determination of temperature and microstructure evolution maps, as well as discovery of mechanistic details of the melting processes and subsequent RS-based crystallization for Al and several Al-Cu alloys. The direct observation-based metrics offer insight to non-equilibrium processes responsible for microstructure development in materials during transformations under conditions driven far from equilibrium that are typically encountered in SLM-based AM processes. [7]

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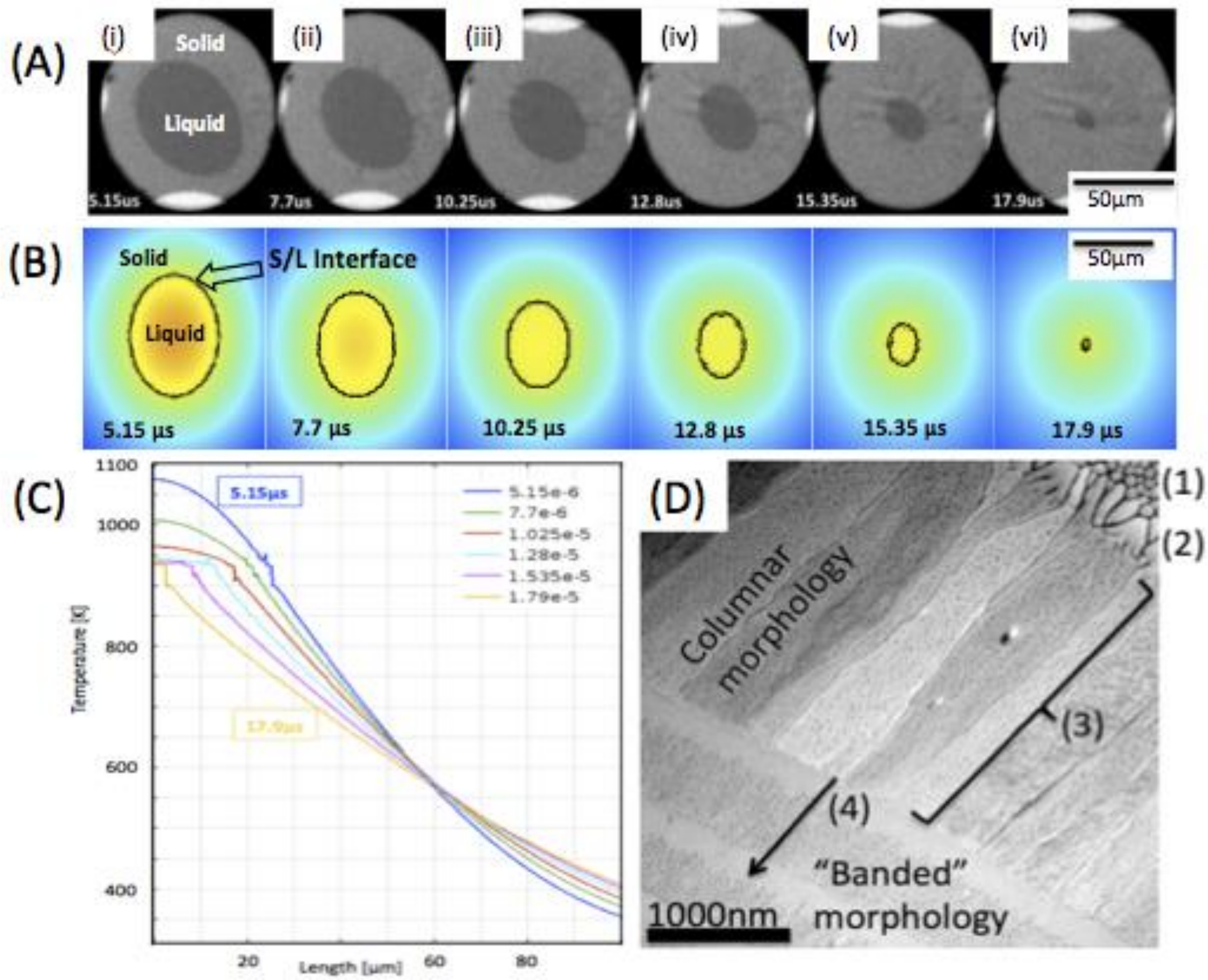

Fig. 1: Examples of (A) DTEM movie-mode sequence of 500-ns exposure bright-field TEM images, documenting the RS dynamics of a melt pool in Al, (B) matching enthalpy-based calculations of temperature (Blue/Orange=Cold/Hot, e.g. for 5.15µs calculation 630K to 1074K) evolution, (C) temperature profiles along major axis of elliptical melt pool, (D) morphologically distinct microstructure zones (1), (2), (3) and (4) established during RS in Al-9at%Cu alloy.

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