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Rapid Solidification and Phase Transformations in Additive Manufactured Materials

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In recent years, additive manufacturing (AM) has emerged as a promising manufacturing technique to enable the production of complex engineering structures with high efficiency and accuracy. Among the important factors establishing AM as a sustainable manufacturing process is the ability to control the microstructures and properties of AM products. In most AM processes, such as laser sintering (LS), laser melting (LM), and laser metal deposition (LMD), rapid solidification and high-temperature phase transformations play primary roles in determining nano- and microstructures, and consequently the mechanical and other properties of AM products.[1] This topic of *JOM* is dedicated to summarizing the current research efforts in the area of rapid solidification and phase transformations in additively manufactured materials. A brief summary follows below of 10 journal articles in this topic.

AM results in microstructures that typically differ from those produced by more conventional processing. Cheruvathur et al. explore the phases and microstructures of laser powder-bed fusion additively manufactured 17-4 precipitation hardenable (PH) stainless steel, including the role of post-build thermal processing. They determined that homogenization effectively eliminates the as-built solidification structure, resulting in 90% martensite and 10% austenite that exhibits similar microhardness values to conventionally wrought-processed 17-4 PH.

The thermal profiles experienced by various age-hardenable alloys produced by selective laser melting (SLM) and LMD were studied by Jägle et al. They utilized different experimental techniques, such as scanning electron microscopy and atom probe tomography, to study desired and undesired precipitation reactions before, during, and after SLM and LMD. They concluded that laser AM can be used to produce supersaturated alloys that show precipitation during age hardening annealing.

Idell et al. utilized different characterization techniques to study and understand the microstructural differences between samples produced by direct metal LS and wrought-processed samples of Ni-based super alloy. They showed that, as a result of rapid solidification, a dendritic microstructure was created. As the part was built, the underlying layers experienced a variety of heating and cooling cycles. These events produced significant microsegregation of niobium that allowed the formation of a deleterious δ-phase.

Rapid solidification in SLM of AlSi10Mg was studied by Tang et al. They found that the solidification structure was the expected cellular combination of silicon with α-aluminum and suggested that cell spacing can be manipulated by changing the heat input.

A finite element model for simulating the fabrication of Inconel 718 using LM processes was presented by Romano et al. They determined the laser melt pool geometry and temperature distribution and validated their predications by experiments. They introduced two correction correlations to transform their modeling results into meaningful predictions of actual LM melt pool geometries in Inconel 718.

Advanced characterization of materials during processing provides new insights into phase transformations and microstructural evolution. Kenel et al. used synchrotron micro-x-ray diffraction to study Ti-48Al solidification and phase transformation sequences for AM-like processing conditions.

Mohsen Asle Zaeem is the *JOM* advisor for the Solidification Committee and Amy J. Clarke is the *JOM* advisor for the Phase Transformations Committee of the TMS Materials Processing & Manufacturing Division (MPMD), and are the guest editors for the topic Rapid Solidification and Phase Transformation in Additive Manufactured Materials in this issue.

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They also used small-angle x-ray scattering to study precipitation evolution and characteristics in an Al-Cu-Mg alloy.

McKeown et al. performed dynamic transmission electron microscopy to monitor pulsed-laser-induced rapid solidification across microsecond timescales. This in situ investigation of rapid alloy solidification provides unique experimental insight into microstructure evolution and kinetics relevant to AM processing. In particular, they studied two alloy systems: an Al-Si alloy that showed columnar growth of a supersaturated, primary α-Al phase, which persisted until the end of the rapid solidification, and an Al-Cu alloy, in which the columnar growth of a non-equilibrium eutectic solidification product proceeded to the point of absolute stability at the solid–liquid interface.

Holesinger et al. used microscopy and laboratory x-ray tomography to study global and location-specific microstructures and characteristics at a variety of length scales, along with build quality, of an Al-Si-Mg alloy hemispherical shell produced by powder bed AM. This work highlights the complex microstructures frequently observed after AM processing.

The qualification of AM parts remains challenging and requires fundamental understanding of processing–microstructure–property linkages. Kirka et al. examined microstructural and mechanical property variations produced by electron beam melting, solidification, and building of Inconel 718 powder. Three microstructural zones were observed and characterized as a function of build height and are discussed in the context of location-specific mechanical properties.

Welk et al. produced compositionally graded specimens using the LENS^{TM} AM technique to study the glass-forming ability of bulk metallic glass and high entropy alloy composite systems. Their specimens showed an almost fully amorphous region in the first gradient and an amorphous matrix/crystalline dendrite composite structure in the second gradient.

This set of "Rapid Solidification and Phase Transformations in Additive Manufactured Materials" articles highlights the potential of AM to produce a wealth of interesting microstructures and properties by various phase transformation pathways, as revealed by experimental and computational techniques. To download any of these papers follow the URL http://link.springer.com/journal/11837/68/3/page/1 to the table of contents page for the March 2016 issue (vol. 68, no. 3).

- "Additive Manufacturing of 17-4-PH Stainless Steel: Post Processing Heat Treatment to Achieve Uniform Reproducible Microstructure" S. Cheruvathur, E.A. Lass, and C.E. Campbell
- "Precipitation Reactions in Age-Hardenable Alloys During Laser Additive Manufacturing" E.A. Jägle, Z. Sheng, L. Wu, L. Lu, J. Risse, A. Weisheit, and D. Raabe
- "Unexpected δ-Phase Formation in Additive-Manufactured Ni-based Super Alloy" Y. Idell, L.E. Levine, A.J. Allen, F. Zhang, C.E. Campbell, G.B. Olson, J. Gong, D.R. Snyder, H. Z. Deutchman
- "Rapid Solidification: Selective Laser Melting of AlSi10 Mg" M. Tang, P.C. Pistorius, S. Narra, and J. Beuth
- "Laser Additive Melting and Solidification of Inconel 718: Finite Element Simulation and Experiment" J. Romano, L. Ladani, and M. Sadowski
- "In-Situ Synchrotron X-ray Diffraction and Small-Angle X-ray Scattering Studies on Rapidly Heated and Cooled Ti-Al and Al-Cu-Mg Alloys Using Laser-Cased Heating" C. Kenel, P. Schloth, S. Van Petegem, J.L. Fife, D. Grolimund, A. Menzel, H. Van Swygenhoven, and C. Leinenbach
- "Time-Resolved In Situ Measurements During Rapid Alloy Solidification: Experimental Insight for Additive Manufacturing" J.T. McKeown, K. Zweiacker, C. Liu, D.R. Coughlin, A.J. Clarke, J.K. Baldwin, J.W. Gibbs, J.D. Roehling, S.D. Imhoff, P.J. Gibbs, D. Tourret, J.M.K. Wiezorek, and G.H. Campbell
- "Characterization of an Aluminum Alloy Hemispherical Shell Fabricated via Direct Metal Laser Melting" T.G. Holesinger, J.S. Carpenter, T.J. Lienert, B.M. Patterson, P.A. Papin, H. Swenson, and N.L. Cordes
- "Microstructure Development in Electron Beam Melted Inconel 718 and Associated Tensile Properties" M.M. Kirka, K.A. Unocic, N. Raghavan, F. Medina, R.R. Dehoff, and S.S. Babu
- "A Combinatorial Approach to the Investigation of Metal Systems That Form Both Bulk Metallic Glasses and High Entropy Alloys" B.A. Welk, M.A. Gibson, and H.L. Fraser

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1. D.D. Gu, W. Meiners, K. Wissenbach, and R. Poprawe, *Int. Mater. Rev.* 57, 133 (2012).