Available online at www.sciencedirect.com

ScienceDirect

Procedia Manufacturing 34 (2019) 678–682

Procedia MANUFACTURING

www.elsevier.com/locate/procedia

47th SME North American Manufacturing Research Conference, Penn State Behrend Erie, Pennsylvania, 2019

In-process Microstructure Tuning in Solid-State Ambient Condition Metal Direct Manufacturing

Anagh Deshpande, Alireza Tofangchi, Keng Hsu*

J. B. Speed School of Engineering. University of Louisville, Louisville, USA

* Corresponding author. Tel.: 502-852-8616; fax: 502-852-8616. *E-mail address:* Keng.Hsu@louisville.edu

Abstract

Acoustoplastic Metal Direct-write (AMD), a recently demonstrated metal direct manufacturing technique, uses acoustic energy to enable deformation and deposition of voxels of fully dense material from metal filaments. Voxel by voxel, this technique is capable of creating high density (> 99.5%) metal parts at room temperature and in ambient conditions without post-processes. To understand the microstructure evolution of the component during the fabrication process, Electron Backscatter Diffraction (EBSD) analysis was performed on three successive layers in a built part. No significant effect of the deposition of additional material was observed on the lower layers. Hence, by manipulating the microstructure of each voxel during deposition process, the microstructure of the bulk of the component can be potentially controlled.

Keywords: Acoustic energy; Additive manufacturing; 3d printing; aluminium; acoustic energy; ultrasonic energy; microstructure; EBSD

1. Introduction

Acoustoplastic Metal Direct-write (AMD), is a novel process of additively manufacturing dense metal components in ambient conditions and at room temperature [1]. So far, a proof of concept of the process has been demonstrated by fabricating millimeter scale pure aluminum components. The process uses acoustic energy to shape fine metal filaments and simultaneously achieve metallurgical bonding. Since the process uses fine filaments as starting material, one advantage of the process is that, it eliminates handling hazards typically associated with Powder Bed Fusion (PBF) processes because of the use of metal powder as starting material. Another advantage of using fine filaments as starting material is that, AMD can produce near net-shape components without the use of a post-processing machining operation. This, and several other aspects like the deformation mechanics and ambient-temperature operation, distinguish AMD from Ultrasonic Consolidation (UC), which is an additive-subtractive hybrid process [2] [3]. Temperature evolution during the AMD process, underlying mechanics and the differences of the process with ultrasonic consolidation have been described in detail in [1]. Being a solid state and ambient condition process, AMD also eliminates the need of a high-power energy source to melt and fuse material, thus making it more energy efficient than commercial PBF processes.

In current melt-fusion based metal additive manufacturing processes like Selective Laser Melting (SLM), the top layer of the component is repeatedly heated during the fabrication process. This causes a temperature gradient in the build direction. One of the consequences of this is the epitaxial grain growth in the build direction resulting in formation of elongated grains. This anisotropic microstructure further results in part property anisotropy [4] [5]. Typically, post-processing heat-treatment is performed

2351-9789 © 2019 The Authors. Published by Elsevier B.V.

10.1016/j.promfg.2019.06.196

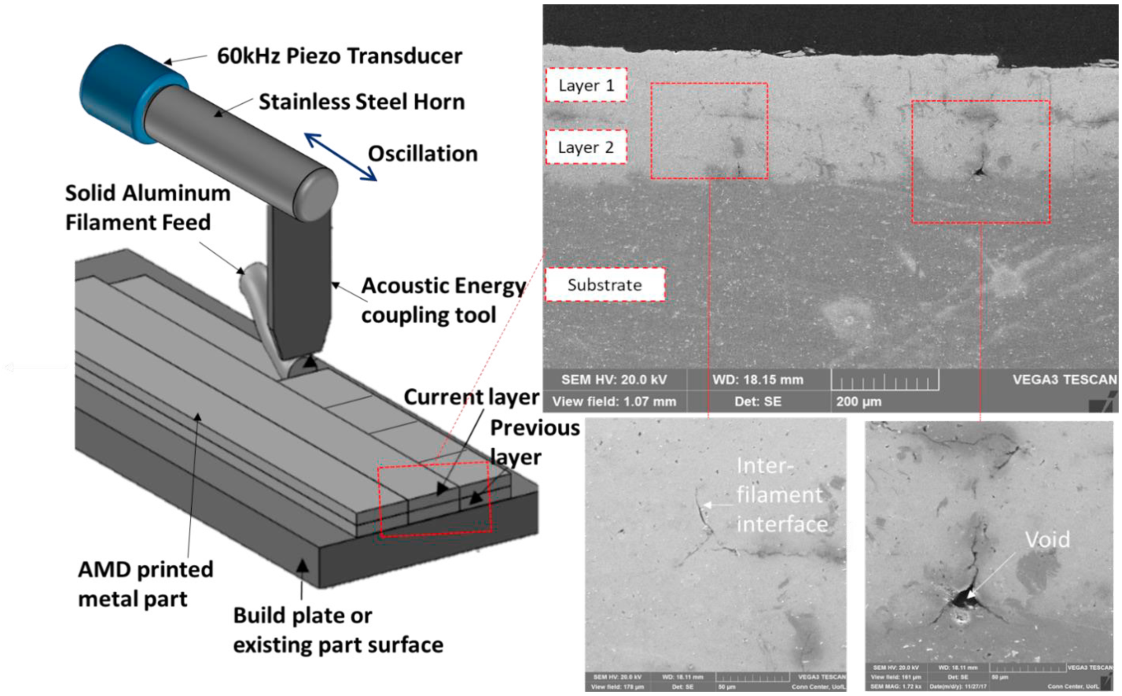

Figure 1. Schematic showing the experimental setup of AMD process (left). A SEM image of 2-layer aluminium sample and magnified images of the inter-filament interface have been shown in the insets (right).

on the components to alter the microstructure. There have been some efforts to achieve in-process microstructure control during melt-fusion based processes by monitoring the melt pool size, and then adaptively controlling process parameters such as laser power and scan speed [6]. However, actual in-process monitoring and microstructure control is still a distant goal for melt-fusion based processes. This manuscript aims to demonstrate that, unlike melt-fusion based processes, the deposition of subsequent layers does not affect the microstructure of the lower layers in AMD process. Hence, by manipulating the microstructure in each voxel during the deposition process, the microstructure of the bulk component can be potentially controlled, which is expected to enable fabrication of functionally graded materials in the future.

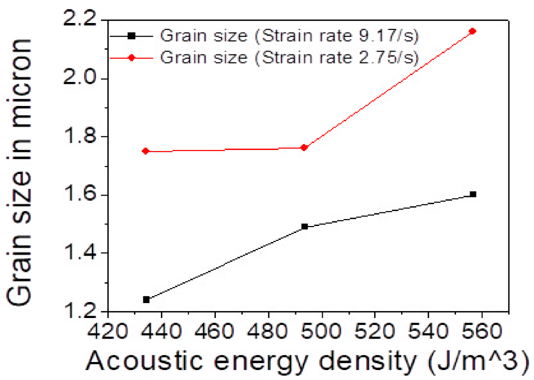

Figure 2. The effect of acoustic energy density and strain rate on the grain size of the deposited voxels [11].

In AMD, an acoustic energy coupling tool vibrates at 60 kHz frequency, simultaneously compressing a voxel of fine filament as shown in Figure 1. The interaction of acoustic energy with the material results in two effects: 1) reduction in material yield and flow stresses proportional to the acoustic energy input (commonly referred to as acoustic softening) which enables forming of the voxel, and (2) large amounts of mass transfer across the interface of the filament and the lower layer (or substrate) which enables bonding of the voxel. This process is repeated to additively fabricate a 3-dimensional object voxel-by-voxel in a direct write fashion. The phenomenon of kilo hertz range acoustic energy causing reduction of yield and flow stresses in metals, now referred to as acoustic or ultrasonic softening, was discovered in 1960s [7]. Since then, this phenomenon has been used in several manufacturing operations such as metal drawing and forming, to reduce the deformation stresses and therefore mechanical energy inputs [8] [9] [10]. In the authors' previous work, it was demonstrated that increase in acoustic energy or a decrease in strain rate during voxel shaping results in an increase in the grain size in the voxel, as shown in Figure 2 [11]. Hence, by modulating the acoustic energy density input and the strain rate during voxel deposition, the microstructure of each voxel can be controlled in-process. It is the purpose of this manuscript to show that, because the microstructure of deposited voxels remains unaffected throughout the component fabrication process, controlling the microstructure of the bulk component can be achieved by adjusting the microstructure at voxel level.

In this manuscript, the microstructure evolution of each successive layer after deposition has been described to understand the microstructure evolution during AMD process in its entirety. Aluminum samples with three layers were fabricated using AMD. Electron Backscatter Diffraction (EBSD) analysis on each layer of the sample was conducted. Microhardness measurements were also performed on each layer of the sample to analyze the mechanical property evolution during the material deposition process.

2. Experimental methods:

The experimental setup for AMD is shown in Figure 1. A piezo-electric crystal vibrates at 60 kHz frequency. Acoustic energy coupling tool is connected to the piezo-electric crystal through a stainless-steel horn. An aluminum filament with a diameter of 300 µm is fed under the tool. As the tool vibrates, it moves down at a rate-controlled, to compress the filament and deform it from a circular cross-section into a rectangular cross-section. At the same time, bonding of the compressed filament to the aluminum substrate occurs, which essentially results in deposition of one voxel on the substrate. This process is repeated several times to deposit a layer of material on the substrate as shown in Figure 1. Ultimately, by successively depositing such layers of materials, a 3D metal part can be printed.

2.1 Sample preparation for EBSD-

To study the microstructure evolution during the fabrication of a component, samples with three layers were fabricated as shown in Figure 3. The foot print of the component was 6 mm x 3 mm and the thickness was 200 µm. Then, the samples were sectioned and polished. The initial coarse polishing was performed by successively polishing the sample with 240 grit, 400 grit, 600 grit, 800 grit and 1200 grit SiC carbide papers respectively. This was followed by polishing the samples with 1 µm diamond slurry and 0.02 µm colloidal silica. Polishing time for each step was approximately 1-2 minute. As a final polishing step, the samples were polished in a vibratory polisher with 0.02 µm colloidal silica for 2 hours.

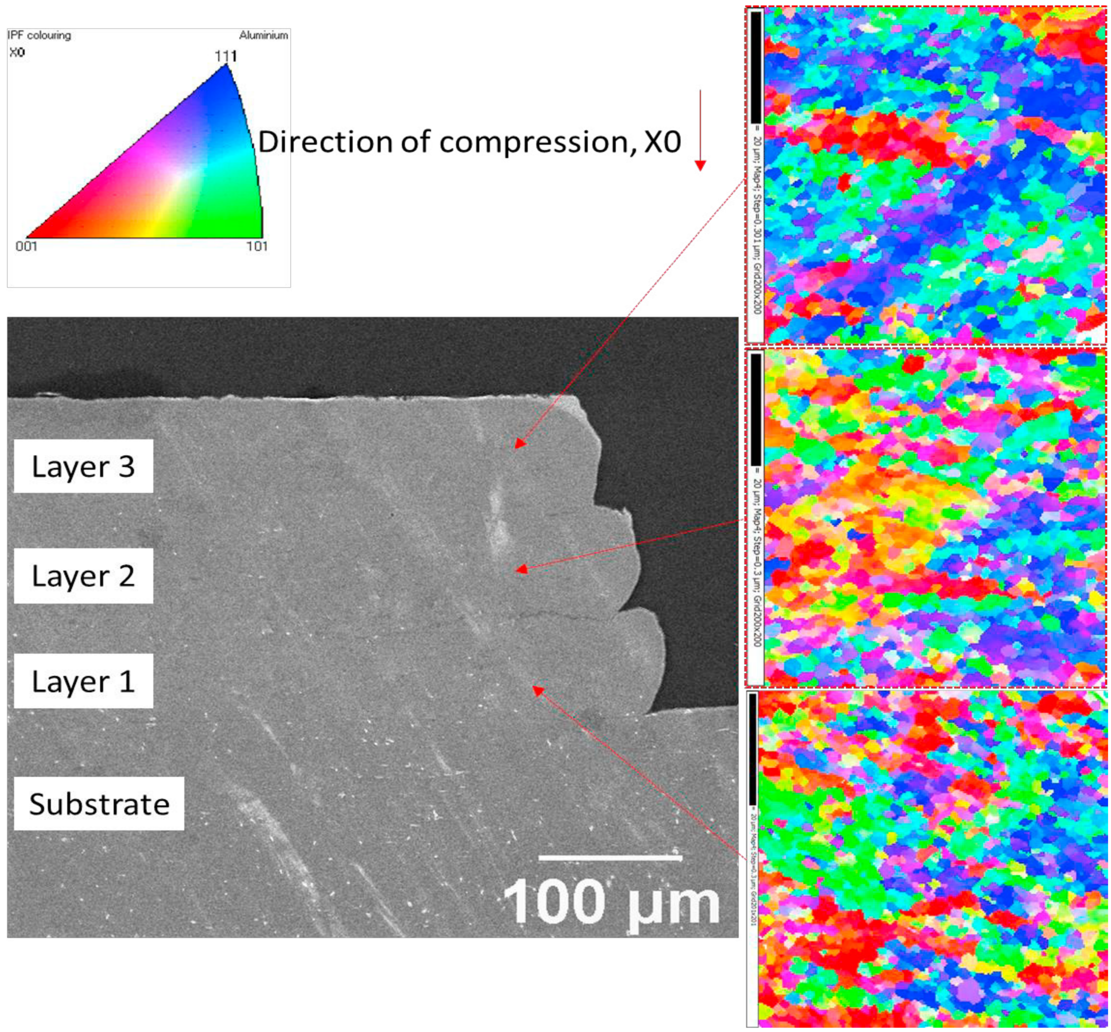

Figure 3. Image of a 3-layer sample fabricated using AMD (left), and EBSD micrographs for each of the three layers (right).

After the samples were polished, Electron Backscatter Diffraction (EBSD) analysis was performed on each layer of the samples to obtain the average grain size and misorientation data in each sample.

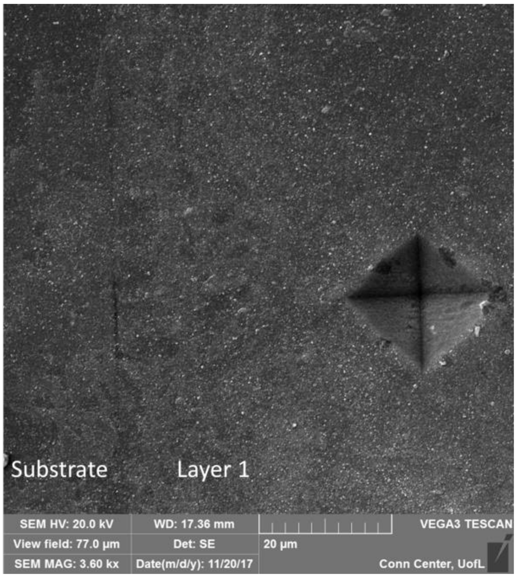

Figure 4. SEM image showing an example of indentation created during the Vickers microhardness test.

2.2 Microhardness measurement-

Vickers microhardness test was performed on each layer of the polished samples according to the ASTM E384 standard. 10 micro-indents were made at the center of each layer using a force of 98.07 mN and a dwell time of 15 seconds. Figure 4 shows an example of an indentation created during the tests. The mean of the length of two diagonals of the indents was calculated to obtain the hardness values using the formula, $HV = \frac{2F\sin\left(\frac{136}{2}\right)}{d^2}$, where F is the force (measured in kilogram-force or kgf) and d is the mean value of two diagonals of the indents.

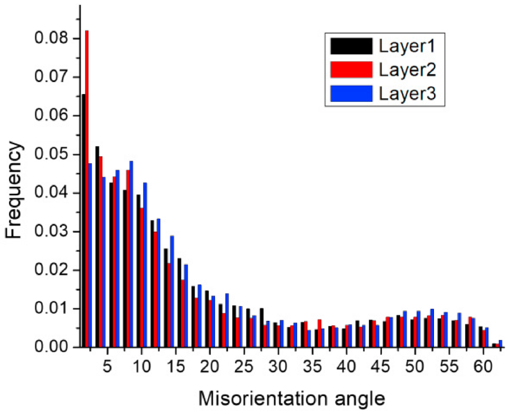

Figure 5. Misorientation data for 3 layers of a sample fabricated using AMD.

3. Results and Discussion:

Figure shows experimental setup of the process and the Scanning Electron Microscope images of the cross-section of two layers of pure aluminum (99.99%) deposited on Al 1100 substrate using AMD process. In AMD, large amounts of plastic deformation in the filament during voxel formation results in a flow of the material in the lateral directions. This flow of material helps to achieve inter-filament diffusion as shown in Figure 1. In some cases, due to the inaccuracy of the filament positioning mechanism in the current experimental setup, a void is formed in the region of the inter-filament interface. Efforts are being made by the authors to improve the current experimental setup in order to eliminate this inconsistency. Nevertheless, in the X-ray tomography scans of millimeter scale specimens fabricated with AMD, over 99% density was observed [1].

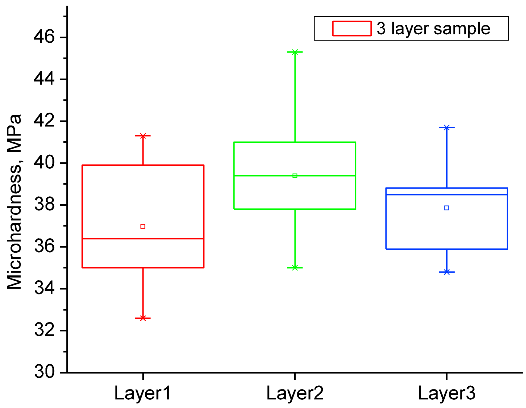

Figure 6. The graph depicts the microhardness variation across 3 layers in a sample fabricated using AMD.

Figure 3 shows a three-layer sample fabricated using AMD. The microstructure from EBSD scans shows formation of subgrain boundaries (or low angle grain boundaries), which are nothing but networks of entangled dislocations. This is also corroborated by the histogram in Figure 5 which shows Frequency versus Misorientation angle. Across all 3 layers of the component, a large fraction of the grain boundaries are subgrain boundaries (or low angle grain boundaries) depicted by first 7 columns of the histogram. Such subgrain formation during acoustic energy assisted deformation was also observed in acoustic energy assisted indentation experiments [12]. Simultaneous application of acoustic energy during voxel deposition process results in a reduction in the yield stress of the voxel being deformed. Hence, the plastic deformation of the voxel requires significantly low compressive forces. During the deformation, acoustic energy assists in dislocation annihilation which results in coarsening of the subgrain network. Hence, by increasing the amount of acoustic energy density (or decreasing strain rate which provides more time for dislocation annihilation) during deposition, the subgrain size can be increased as shown in Figure 2. For a more detailed analysis and explanation, readers are referred to authors' previous work [11].

By using acoustic energy density of 560 J/m^3 and a strain rate of 2.56/s, an average subgrain size of 2.2 micron was obtained across all 3 layers of the component through the EBSD microstructure analysis shown in Figure 3. This analysis further revealed that all the layers have a similar average grain size and grain misorientation spread. Figure 6 shows the Vickers microhardness variation in the 3 layers of the sample. It is evident from the graph that there is no significant variation in the microhardness in all the 3 layers, indicating similar mechanical properties across the whole sample. Such similar microstructure and microhardness distribution across all layers strongly suggests that effect of addition of more material on altering the microstructure of the lower layers is negligible; unlike the melt-fusion based processes in which addition of more material results in epitaxial grain growth along the build direction [4] [12]. Since AMD process uses athermal phenomenon during deformation and metallurgical bonding cycles, it thus eliminates the inherent complications which typically occur in melt-fusion based processes due to repeated thermal cycling in the components. Our results indicate the microstructure of a voxel once deposited majorly remains unaffected throughout the component fabrication process. This allows the control over the microstructure of a voxel, by manipulating the input process parameters of acoustic energy density and strain rate, to be extended to control over the microstructure of the bulk of the component in AMD process.

4. Conclusion:

Acoustoplastic Metal Direct-write (AMD) process, a voxel-by-voxel additive manufacturing approach that uses acoustic energy to deform and metallurgically bond voxels, was used to fabricate a component with 3 layers. Microstructure variation across the 3 layers was investigated using Electron Backscatter Diffraction (EBSD) analysis. No significant microstructure variation was observed in any of the 3 layers of the sample. Hence, by varying the acoustic energy density and strain rate during voxel deformation, microstructure of each voxel can be manipulated thereby enabling the possibility of in-process microstructure control. The athermal process physics enables addition of material during fabrication without affecting the microstructure of the rest of the component, thus eliminating thermal history related complications which result in anisotropic microstructure in other heat energy based additive manufacturing processes.

References

[1] A. Deshpande and K. Hsu, "Acoustoplastic Metal Direct-write: Towards solid aluminum 3D printing in ambient conditions," *Additve Manufacturing,* vol. 19, pp. 73-80, 2018.

[2] S. G. A. J. W. G. J. T. A. B. Gregory S. Kelly, "A model to characterize acoustic softening during ultrasonic consolidation," *Journal of Materials Processing Technology,* vol. 213, pp. 1835-1845, 2013.

[3] J. E. Mueller, J. W. Gillespie Jr. and S. G. Advani, "Effects of interaction volume on X-ray line-scans across an ultrasonically consolidated aluminium/copper interface," *Scanning,* vol. 35, pp. 327-335, 2013.

[4] C. Li, R. White, X. Y. Fang, M. Weaver and Y. B. Gui, "Microstructure evolution characteristics of Inconel 625 alloy from selective laser melting to heat treatment," *Material Science and Engineering A,* vol. 705, pp. 20-31, 2017.

[5] D. Tomus, Y. Tian, P. A. Romtesch, M. Heilmaier and X. Wu, "Influence of post heat treatments on anisotropy of mechanical behavior and microstructure of Hastealloy-X parts produced by selective laser melting," *Material Science and Engineering A,* vol. 667, pp. 42-53, 2016.

[6] J. Gockel and J. Beuth, "Understanding Ti-6Al-4V microstructure control in additive manufacturing via process maps," in *28th Annual International Solid Freeform Fabrication (SFF) Symposium*, Austin, texas, 2017.

[7] B. Langenecker, "Effects of ultrasound on deformation characteristics," *IEEE Transasction of sonics and ultrasonics,* Vols. SU-13, no. 1, March 1966.

[8] A. Abdullah, M. Paknejad, S. Dashti, A. Pak and A. M. Beigi, "Theoretical and experimental analyses of ultrasonic-assisted indentation forming of tube," *Journal of Engineering Manufacture,* vol. 228, no. 3, pp. 388-398, 2014.

[9] S. Amini, A. H. Gollo and H. Paktinat, "An investigation of conventional and ultrasonic-assisted forming of annealed AA1050 sheet," *Internation Journal of Advanced Manufacturing Technology,* 2016.

[10] C. Yang, X. Shan and T. Xie, "Titanium wire drawing with longitudinal-torsional composite ultrasonic vibration," *International Journal of Advanced Manufacturing Technology,* vol. 83, pp. 645-655, 2016.

[11] A. Deshpande and K. Hsu, "Acoustic energy enabled dynamic recovery in aluminium and its effects on stress evolution and post-deformation microstructure," *Material Science and Engineering A,* vol. 711, pp. 62-68, 2018.

[12] S. Raghavan, Z. Baicheng, P. Wang, C.-N. Sun, M. L. Sharon, T. Li and J. Wei, "Effect of different heat treatments on the microstructure and mechanical properties in selective laser melted Inconel 718 alloy," *Materials and Manufacturing Processes,* 2016.

[13] K. W. Siu, A. H. W. Ngan and I. P. Jones, "New insight on acoustoplasticity – Ultrasonic irradiation enhances subgrain formation during deformation," *Internation journal on plasticity,* vol. 27, pp. 788-800, 2011.