Using EBSD to Improve the Material Properties of Additive Manufactured Metals

Materials Challenge

Additive manufacturing (AM), also known as 3-D printing, is a manufacturing process where solid objects are built layer by layer from a digital model. This process offers cost, material, and time savings over conventional manufacturing, and shows potential in the aerospace, automotive, and medical device markets to produce near-net-shape metallic components. In these demanding applications it is not enough that the final 3-D printed output have the same shape as a conventionally fabricated product. It must also have material properties that meet or exceed their conventionally processed counterparts. The optimization of both the AM deposition parameters and any subsequent thermal processing is important for obtaining the material properties needed.

Comparison with Existing Solutions

AM processing parameters and any subsequent thermal processes are adjusted to change the microstructure and obtain the desired properties to meet the demands of high performance applications. Characterization of the microstructure can be achieved through a variety of techniques:

- Light Optical Microscopy (LOM). LOM images provide qualitative information on grain size and shape through grain boundary contrast imaging. Due to the rapid cooling during AM, however, the grain size is often too small to accurately resolve with LOM.

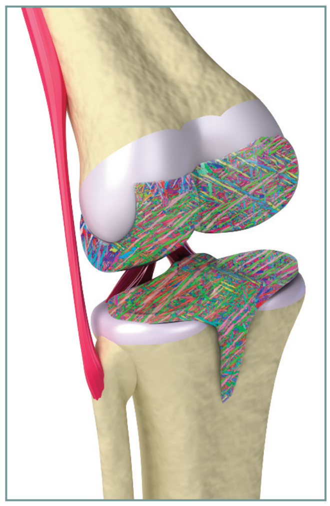
- Scanning Electron Microscopy (SEM). SEM images also provide information on grain size with improved spatial resolution. This technique, however, provides limited information on the phase distribution present within the AM microstructure, particularly for polymorph phases where the chemistry remains constant and only the crystallographic structure changes (HCP-Ti vs BCC-Ti for example).

- Transmission Electron Microscopy (TEM). TEM analysis provides information on the local phase distribution as well as for the orientation relationships that develop during phase transformations. The analysis area is limited with TEM and determination of phase and orientation relationships is often done manually which limits the number of quantitative measurements.

- X-Ray Diffraction (XRD). XRD provides information on the phase fraction present as well as the preferred orientation that can develop during AM. However, XRD is a bulk-measurement technique and does not provide information on the spatial distribution of the data. With layer by layer manufacturing, spatial information can be important for understanding any variations that develop during manufacturing.

Electron Backscattered Diffraction (EBSD) is an alternative characterization technique that provides comprehensive characterization of AM materials. The advantages of EBSD include:

- Direct measurement of grain size and grain shape through discrete crystallographic orientation measurements with nanometer-scale spatial resolution. By measuring the grain size directly, grain boundary contrast errors are eliminated. Grain size and shape can be measured after solidification and after any subsequent thermal processing.



- Direct phase identification and spatial mapping of phase distributions. During AM, metal is heated, melted and rapidly solidified. This thermal processing can cause phase transformations and control of these transformations is important for obtaining the desired material properties.

- Automated rapid characterization of AM materials. This allows for large area data collection, fine spatial resolution, and good, statistically accurate analysis, which in turn make local variations more meaningful and relevant.

- Direct measurement of crystallographic orientation coupled with the spatial distribution of these orientations. This allows for direct correlation of local orientations and microstructure with the actual stresses within the material.

Microanalysis Results

There are a number of additive manufacturing approaches for metallic alloys that are classified by the starting material used. Powder-based approaches include Electron Beam Melting (EBM) and Selective Laser Sintering (SLM), while rod-based approaches include Fused Deposition Modeling (FDM) and Shaped Metal Deposition (SMD). Each of these methods heats the starting material to allow controlled deposition followed by cooling to solidify the structure in the desired shape. The heating and cooling profiles determine the microstructure and mechanical properties.

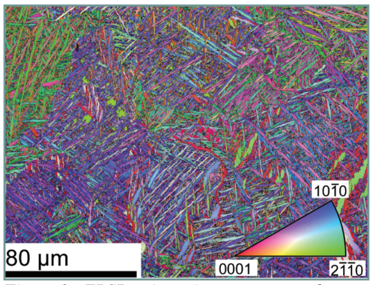


Figure 1 - EBSD orientation map across the cross-section of selective laser melting (SLM) deposited titanium showing lath and packet microstructure with no significant preferred orientation.

To demonstrate the characterization capabilities of EBSD, data was collected using TEAM™ EBSD from a titanium sample manufactured by SLM. This process uses a focused laser beam to locally melt and sinter together powdered titanium to build up the 3-D structure. Figure 1 shows an EBSD orientation map where the colors correspond to the crystallographic planes oriented along the deposition axis. The microstructure consists of small needle shaped grains distributed within packets. These packets define the prior beta phase grain size. No beta phase has been retained, and only alpha phase titanium was detected. No significant preferred orientation was observed from this sample, which suggests that no significant solidification textures are developing during manufacturing. In similar materials produced by wire-fed approaches, columnar grains with a stronger texture were observed.

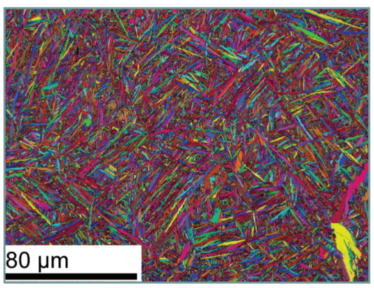


Figure 2 - EBSD grain map from SLM deposited titanium where detected grains are randomly colored to showcase size and morphology.

Figure 2 shows a grain map, where the grains are randomly colored to show size and shape. From this region, over 30,000 grains have been sampled with an average grain size of 740 nm, assuming a circular grain. The grain shape is obviously not circular, however, so a grain area metric is also derived for this microstructure with a value of 0.794 μm^2, which more accurately reflects the true grain structure. A few anomalous larger grains are observed in the lower-right analysis region. Measurements on grain size, grain shape, grain shape aspect ratio, and grain shape orientation are available, as well as crystallographic correlations with these measurements. These can be important when analyzing the solidification microstructures that develop during AM, as well as the changes that can occur during subsequent thermal processing.

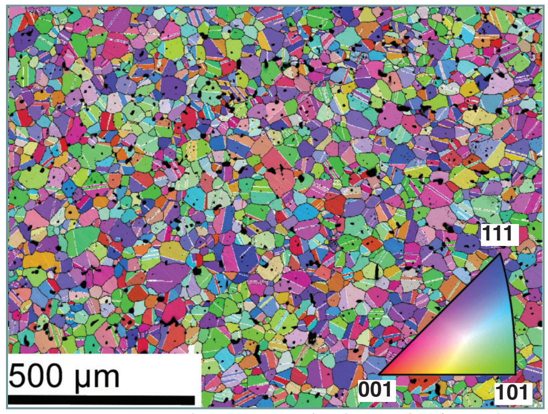


Figure 3 - EBSD orientation map from 3-D printed and sintered 316L stainless steel sample where identified twin boundaries are colored white and random grain boundaries colored black. Local porosity is also identified as larger black regions within the microstructure.

Figure 3 shows an orientation map from a 316L stainless steel sample produced by locally binding metallic powder in three dimensions and sintering this structure at high temperature. The grain size is significantly larger with this material and process (15 μm), and again no significant preferred orientation is observed. In this sample, only FCC austenite was detected. Note that in both cases, the possible phases are both chemically similar and structurally different, making EBSD an ideal tool for phase analysis. In Figure 3, a significant fraction of twin boundaries are observed and shown as white lines. These special boundaries can influence final material properties such as corrosion resistance or yield strength. Porosity is also observed in this image, which can be related back to the deposition parameters used.

Recommended EDAX Solution

TEAM™ Pegasus Analysis Systems are recommended to help develop and optimize additive manufacturing processes that produce consistent, high-performance metallic components for the aerospace, automotive, and medical device markets. TEAM™ Pegasus Analysis Systems offer integrated EDS and EBSD characterization with an easy to use interface for fast and reliable analysis of grain size and shape, grain orientation and preferred orientation, phase distribution, and composition. Hikari XP cameras provide fast, sensitive, and smart EBSD pattern collection with superior indexing rates and orientation precision for analysis of the complex microstructures that develop during additive manufacturing.