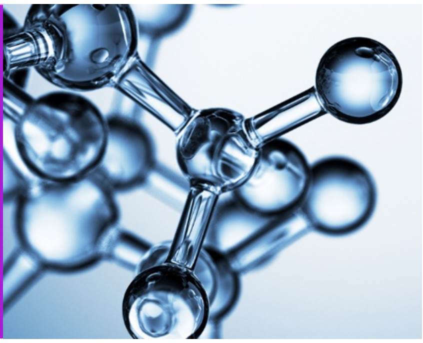
Application Note



Hardness Mapping of 3D Printed Aluminum

Introduction

3D printing, also known as additive manufacturing, is the disruptive manufacturing technique of the 21st century. This compelling technique combines speed and portability with the capability to generate parts with complex and intricate features. However, the significant drawback as compared to traditional methods of casting and machining is that material microstructure and defects of manufactured parts are neither well understood nor well controlled. High-speed nanoindentation is a critical tool for characterizing the links between microstructure, strength, and elasticity in 3D printed materials, with analysis data leading to better printing and processing methods for reliability and safety. In this work, high-speed nanoindentation is used to map the hardness of a 3D-printed sample of Scalmalloy, a commercial aluminum alloy specifically designed for laser-powder-bed additive manufacturing.

Experimental Method

The Scalmalloy was printed and then metallographically mounted, where the part was set in epoxy and then polished to expose a flat surface for nanoindentation. An iNano fitted with a Berkovich indenter was used with the proprietary KLA NanoBlitz 3D option to rapidly generate an array of indentations on the surface. The 200µm x 200µm test area contained an array of 60 x 60 indentations, for a total of 3600 indentations (spacing between individual indents was approximately 3.3µm). The peak load for each indentation was 4mN, which caused an indentation depth of approximately 325nm. Because NanoBlitz 3D completes one indent per second, all 3600 indents were completed in about one hour.

Results and Discussion

The NanoBlitz 3D hardness maps for the Scalmalloy are shown in Figure 1. The top image displays the original hardness map, The bottom image shows the same information, but further processed using the iNano InView software to sort the data into two groups using a method called K-means clustering. K-means clustering assigns each individual hardness measurement to the cluster with the nearest mean value, which minimizes the

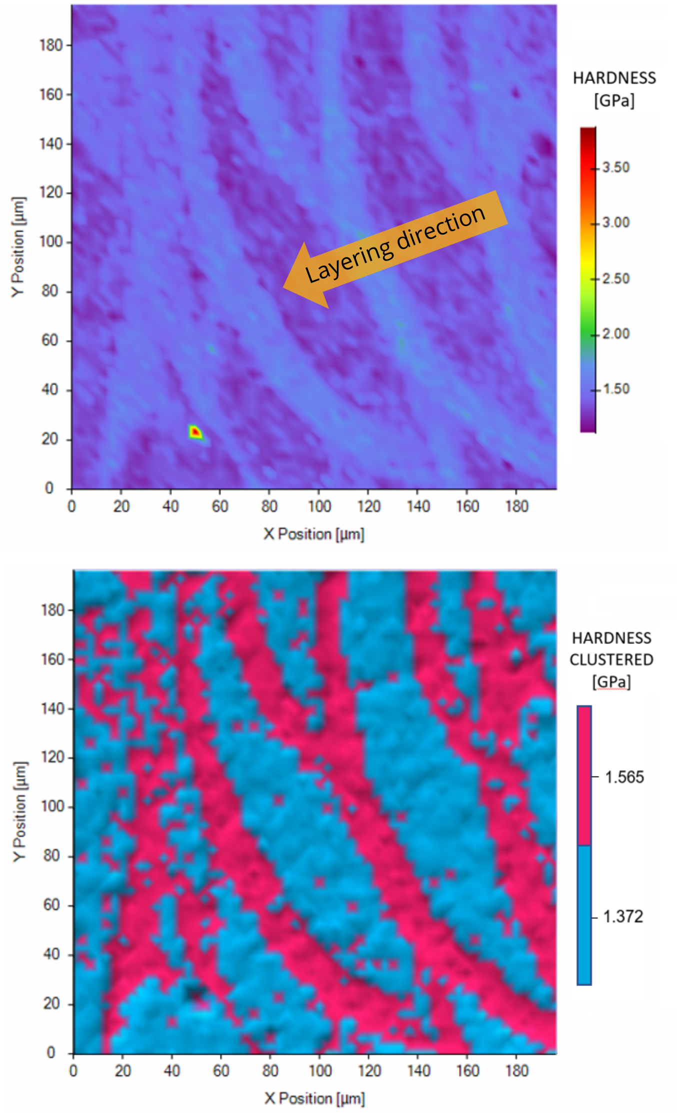


Figure 1. Standard (top) and clustered (bottom) hardness maps of 3D printed Scalmalloy cross section generated from an array of 3600 nanoindentations; each indentation represents one pixel in the image. The 3D printing process deposited droplets onto the surface, creating rounded hillocks which cooled at different rates for the top of the hillock (higher hardness) and the softer core (lower hardness). As each layer of hillocks hardened, more were deposited with each successive layer.

within-cluster variance. These maps of the 3D printed material cross section reveal a unique microstructure of interlocking “hillocks” which manifest a higher hardness on the surface of the hillock and a softer core. The clustered map clarifies that the higher-hardness surfaces have a consistent thickness of about 15μm.

The variation in hardness arises from the laser-rastering process used to fuse the powder bed of each layer, though the exact mechanism is not fully understood. The upper surface of each formed hillock may be harder because it cools more rapidly, leading to a quenched microstructure. Materials may also segregate within the melt pool based on cooling rates. Further investigations of material composition and crystallinity are needed to explain the underlying cause of the hardness distribution. Whatever the cause, the observed hardness variation has very little effect on the distribution of Young’s modulus. Figure 2 shows the histograms for all 3600 measurements of hardness and Young’s modulus. The hardness histogram (top) is broad with a binomial distribution, while the Young’s modulus (bottom) is Gaussian.

Conclusions

The microstructure generated by the 3D metal printing process is unique, such that mechanical properties cannot be assumed to be the same as those of parts traditionally manufactured from the same metal. For 3D printed Scalmalloy, high-speed nanoindentation reveals a surprising distribution in the hardness but also shows a uniform modulus. Material property maps achieved by high-speed nanoindentation are key to discovering and quantifying the unique microstructural properties of 3D printed metals. This new nanomechanical information will contribute to improved design and control for optimized performance of 3D printed metal parts.

Acknowledgements

KLA gratefully acknowledges Dr. Shinya Sasaki of the Tokyo University of Science for providing the sample and the inspiration for testing. Scalmalloy® is a registered trademark of APWORKS, GmbH.

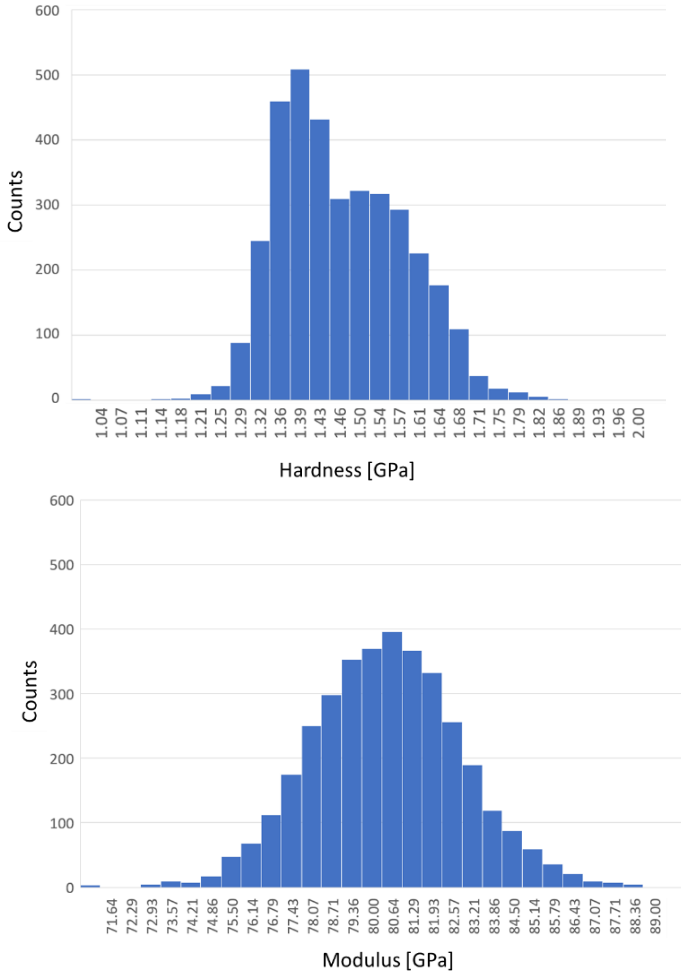


Figure 2. Histograms of hardness (top) and modulus (bottom) from 3600 nanoindentations on 3D printed Scalmalloy. The hardness histogram shows two peaks for the surface and internal hardness of each hillock, while the modulus distribution is Gaussian.