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ORNL Manufacturing Demonstration Facility
Technical Collaboration **Final Report**

Residual Stress Determination of Direct Metal Laser Sintered (DMLS) Inconel Specimens and Parts[1]

Honeywell Aerospace, Honeywell International, Phoenix, AZ

Project ID:	MDF-UP-2012-003
Start Date:	02/08/2013
Completion Date:	05/31/2014
Company Size:	Large business, 45,000 employees

Summary

ORNL collaborated with Honeywell Aerospace to determine the residual stresses within parts manufactured by Honeywell. The project demonstrated the feasibility of neutron residual stress measurements in complex parts providing one method of feedback to change Honeywell's direct metal laser sintering (DMLS) process. The improved understanding of residual stress related to the DLMS process will expedite the implementation of DLMS at Honeywell Aerospace.

Background

Honeywell Aerospace is creating components using DMLS, an additive manufacturing process, because of the savings in time and cost relative to casting processes. Because the process is relatively new, testing, modeling and validation are required to assure this process can produce components that meet the design specifications.

One of the manufacturing challenges that Honeywell faces is the presence of residual stresses in DMLS components. Residual stresses can cause part distortion and/or cracking and as such need to be measured, understood and accounted for in part design. The team proposed to address this challenge by examining simple shapes and complex components manufactured by DMLS using neutron diffraction. Although there are limitations, the neutron diffraction technique is uniquely qualified to measure residual stresses within the bulk of a sample, non-destructively.

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The metric that defined success in this project is the ability to measure the residual stress in parts of interest, ultimately to improve Honeywell's additive manufacturing processes. Experimental residual stress determinations are crucial to advancing additive manufacturing processes. These experiments will have a significant impact on all future engine development programs at Honeywell.

Technical Results

The residual stresses were entirely mapped in a simple shaped rectangular prism made by Directed Manufacturing for Honeywell and in portions of two complex parts, an engine mount and a turbine nozzle vane. The complex samples were made using DMLS at Honeywell from Inconel alloy starting powders. The neutron measurements were performed at the Neutron Residual Stress Facility 2 (HB-2B beamline) at the High Flux Isotope Reactor (HFIR) at ORNL. Briefly, the wavelength of the neutron beam was 1.537Å; further experimental details can be found in reference [1].

The chosen IN718 rectangular prism was 5 x 10 x 15 mm with the build direction parallel to the 15 mm dimension and was removed from the 304 base plate by EDM (see Figure 1). Typical build parameters were investigated: average beam speed=1200 mm/sec, average melt power=185W, layer thickness=0.02 mm, hatch spacing=0.1 mm. The interplanar spacings of the (311) reflection were measured throughout the volume of this rectangular prism sample in the as-built condition. The results of the HIPed samples are not reported due to the very large grain size (~1 mm) yielding non-representative results. Using standard methods,[2] the interplanar spacings were measured using a 2 mm^3 gauge volume within the sample and stress-free sample assembly; the residual stress distribution was determined.[1] The calculations show that the residual stress values are very sensitive to the stress-free interplanar spacing (d_0). Where possible, we recommend that for additively manufactured components, measurement of the interplanar spacing throughout the entire sample volume, with a spatial resolution that is as small as possible. Then, the balancing the forces and moments can be applied as a method for defining d_0(s). In Figure 2, the residual stress distribution within a representative volumetric slice of the 5 x 10 x 15 mm sample is shown. For brevity, the other slices are not shown. Also, Figure 2 compares the residual stress distributions with force- and moment balance corrected stress-free interplanar spacings (d_0's) to those with measured d_0's from a sister sample that was mechanically relieved of stress by EDM sectioning. Figure 2 shows that the range of stresses amongst the different directions is significantly reduced with the force- and moment correction relative to the measured. That is, without force- and moment balance, the stresses in the Y and Z directions are more tensile and compressive, respectively, although the trends are the same. As an aside, the residual stresses in DMLS samples are also much larger than those from electron beam melting because the powder bed in DMLS is not pre-heated.[1] The above recommendation for comprehensive volumetric measurements is typically not feasible for most samples due to the limited availability of neutrons and large sample thicknesses. Future studies may include recommendations regarding imposing a force- and moment balance correction when only portions of a sample are measurable.

The examined IN718 engine mount that was aged, heat treated and HIP'ed is shown in Figure 3 with the schematically (not to scale) indicated measurement locations around the area of interest, the flange. X-ray diffraction revealed the sample was predominantly FCC phase (a=3.59 Å). In this sample, the residual stress distribution was determined twice using two different crystallographic planes, (311) and (220), which showed two different distributions for the same stress state. The (311) and (220) distributions were overall coarsely neutral and compressive, respectively, and this difference could not be accounted for with crystallographic anisotropy, but is likely a combination of grain size and texture effects. That is, there are likely many large grains >0.1 mm which could dominate the signal coming out of a selected gauge volume. Crystallographic texture is also expected in the as-built state and could shift the center of gravity of the gauge volume causing peak shift. This would be erroneously interpreted as a residual stress. Given that the multiplicity of the (311) plane is twice that of the (220) plane (24 vs. 12 for a cubic material), the (311) results were taken as more representative. Here, experimentally determined d_0's from EDM sectioned sister sample were used (i.e., force and moment balance were not applied). In Figure 4, there is a region of high compressive and high tensile stresses in the direction normal to the flange, parallel to the build direction. This compressive region is towards the exterior of the mount while the tensile is in the interior (also see Figure 3C). The stresses are quite low in the direction parallel to the flange radius. Mechanical testing of this part by Honeywell found its performance to be satisfactory.[3]

Finally, a stress-relieved IN738 turbine nozzle was examined with neutron diffraction to determine the residual stresses along the leading edge of a vane. Because the vane wall thickness was only ~1mm, the cross-section was over sampled through thickness to assure at least one fully buried gauge volume. Figure 5 shows the residual stress distribution calculated using force balanced determined and experimentally determined and stress free interplanar spacings. Both plots show similar trends with tensile spikes near the ends of the vane. X-ray diffraction revealed the sample contained 3 phases: Ni_3Al (simple cubic, a=3.57 Å), Ni containing phase (simple cubic, a=2.88 Å) and corundum, Al_2O_3.

Impact

The improved understanding of residual stress related to the DLMS process will expedite the implementation of DLMS at various OEM's and throughout various industrial sectors (automotive, biomedical, etc.). With respect to Honeywell, the direct benefits of the implementation of DLMS supported by this work will be:

- 72% time savings (conventional manufacture: 308 days, DMLS: 84 days)
- $75M cost reduction relative to typical EMD approach
- $0.5M cost reduction by eliminating tooling
- $10M annual savings by allowing refurbishment of turbine blades for a fleet of 5000 engines
- $0.75M cost savings for legacy low volume parts and tooling

Summary and Conclusions

Complex and simple shaped samples were fabricated, and the residual stresses determined using neutron diffraction. Two rectangular prisms, as-built and HIP'ed, were mapped completely. In so doing, the discrepancies between and experimental stress-free interplanar spacings and those calculated based on force and moment balance were described. Although the trends remained the same, the magnitude of the residual stresses decreased overall after applying force and moment balance. The HIPed samples were not reported due to the very large grain size (~1mm) yielding non-representative results.

An engine mount and turbine nozzle were also examined. The residual stresses in the engine mount were measured for two different reflections and showed difference residual stress values for the same state. More work is necessary to reconcile these differences. The residual stresses in the nozzle were measured on the leading vane edge. These values qualitatively agreed with prior observations of the stress state in the vane edge. Based on this successful collaboration, a phase 2 project is envisioned wherein the impact of additional parameters within simple and complex shapes on the residual stress would be measured with both neutron and additional techniques for residual stress measurement for comparison to each other and to modeling.

About the Company [4]
“Honeywell Aerospace is the largest manufacturer of aircraft engines and avionics, as well as a producer of auxiliary power units and other aviation products. Headquartered in Phoenix, Arizona, it is a division of the Honeywell International conglomerate. It generates approximately $10 billion in annual revenue from a 50/50 mix of commercial and defense contracts.”

Points of Contact

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[2] M. T. Hutchings, P. J. Withers, T. M. Holden, T. Lorentzen, Introduction to the characterization of residual stress by neutron diffraction. CRC Press, Boca Raton, FL, USA 2005.
[3] M. Purkhiser, Honeywell internal report, 9NOV2011.
[4] http://en.wikipedia.org/wiki/Honeywell_Aerospace

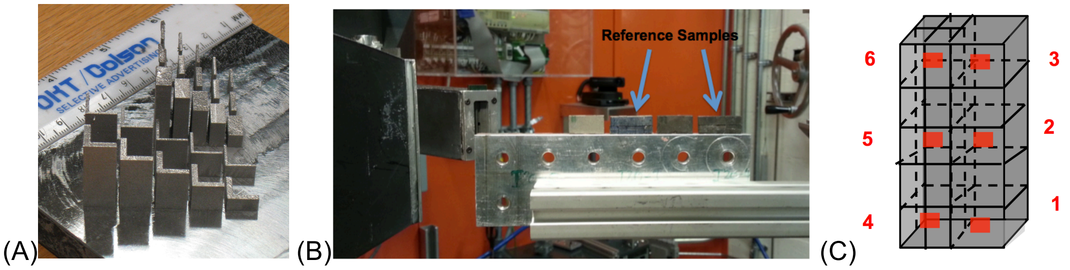


Figure 1 – (A) IN718 simple shape samples still attached to build plate. (B) Samples and stress-free references mounted on neutron goniometer (L to R: DMLS-HIPed stressed, DMLS-HIPed stress-free reference, DMLS stressed, DMLS stress-free reference). The incident and receiving slits are seen mid-left center and left, respectively. (C) Schematic of 5 x 10 x 25 mm reference sample shown in (B) sectioned by EDM to mechanically relieve strain and be the stress-free reference. Cube numbers 1-3 are 5 x 5 x 5mm while parallelepipeds near locations 3-6 are 2 x 2 x 5 mm.

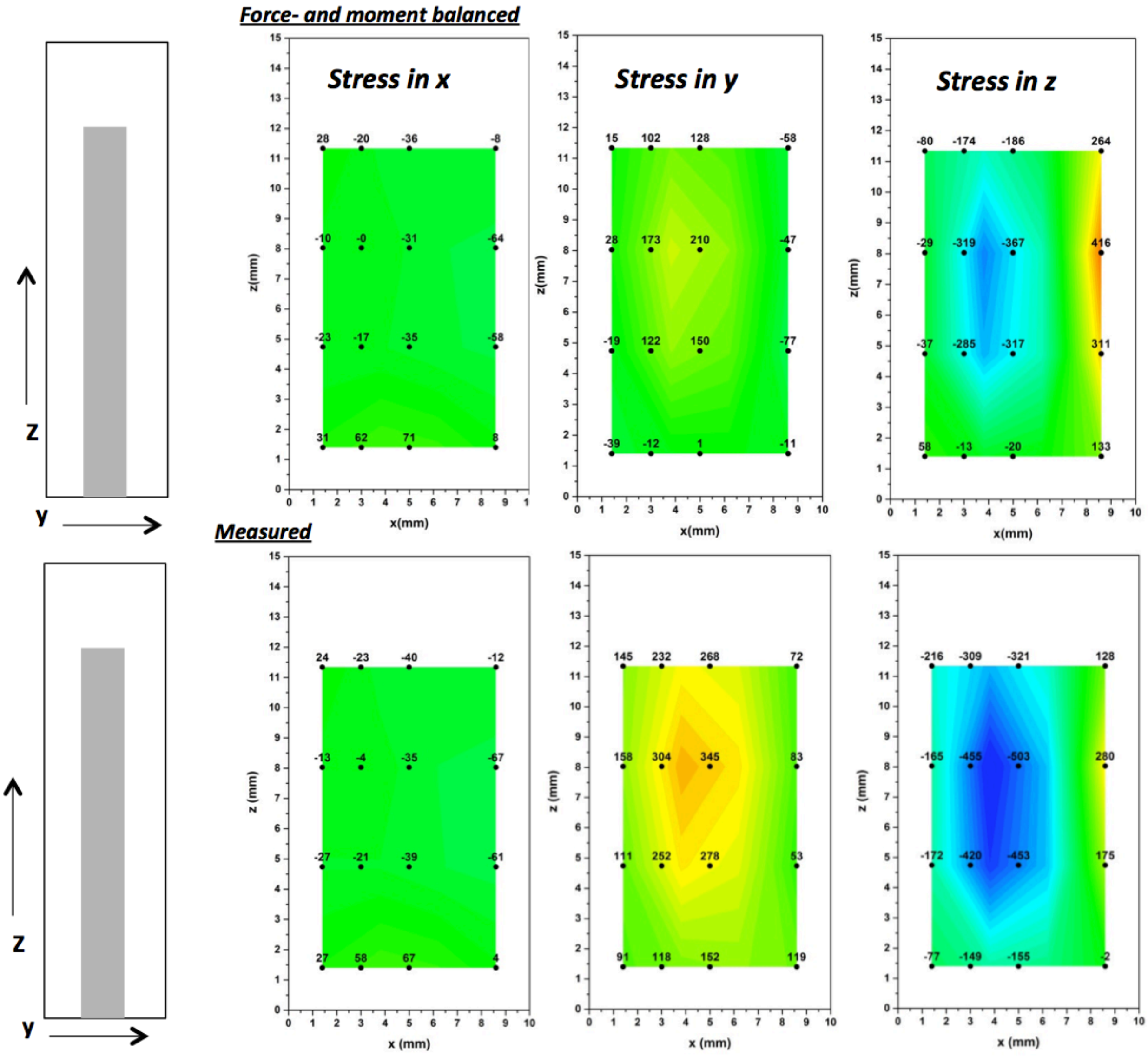
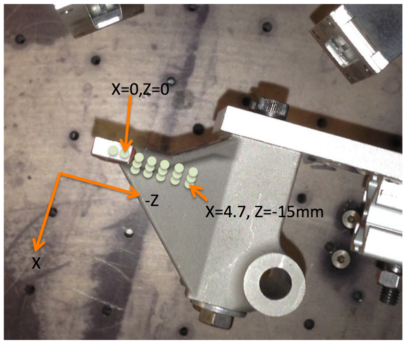
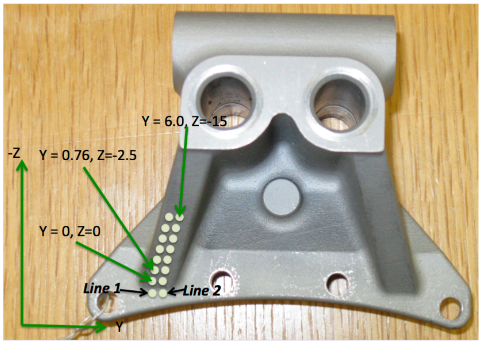


Figure 2 – The calculated residual stress (MPa) distribution in the XZ plane from a slice (grey areas) of the YZ cross-section: (top-row) with force- and momentum balanced and (bottom-row) with measured d_0's value. Blue (compressive); Red (Tensile). For both the corrected (top three maps) and uncorrected stresses (bottom three maps), a separate d_0 was used for each stress direction (x,y and z) to eliminate measurement variabilities from direction to direction.

(A)



(B)



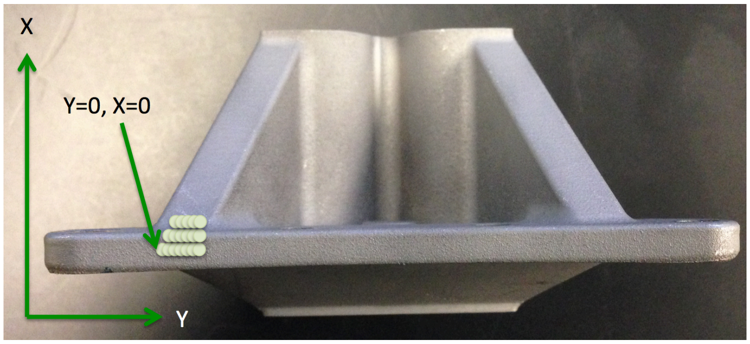
(C) 

Figure 3 – Inconel 718 engine mount with the measurement locations schematically shown. (A) Sample mounted on neutron goniometer. Stress-free cubes affixed to flange tip (0,0) with incident and receiving slits seen in the upper right and left corners, respectively. (B) The -Z Y plane view. Note lines 1 and 2. (C) The X Y plane view, which corresponds to the horizontal plane in Figure 4.

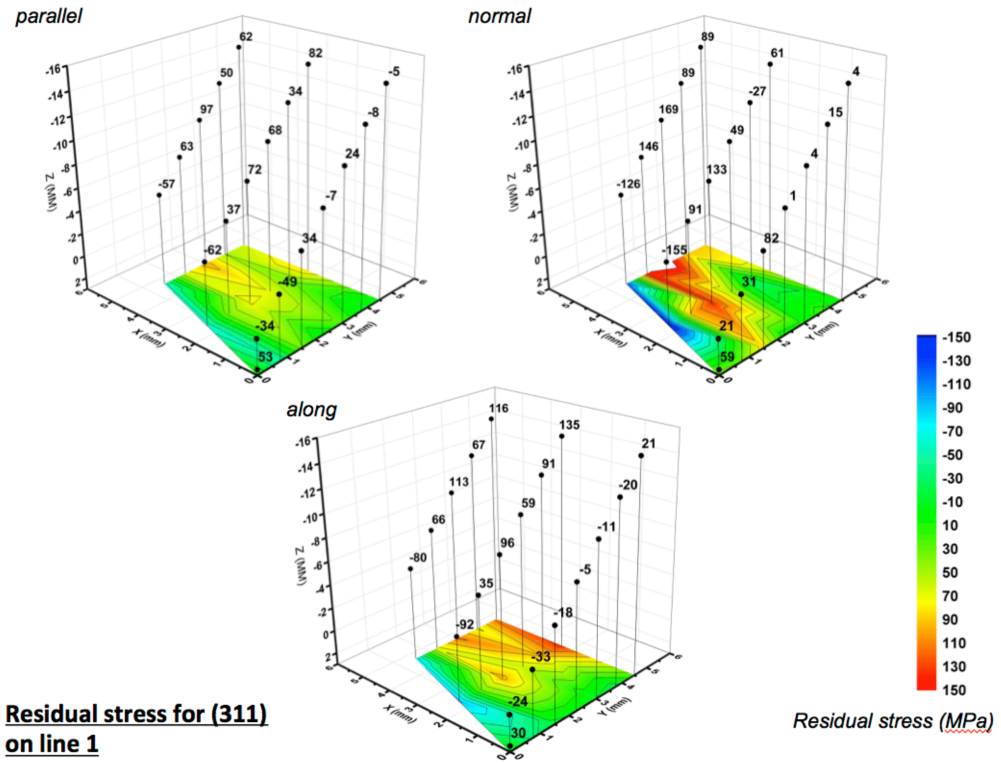
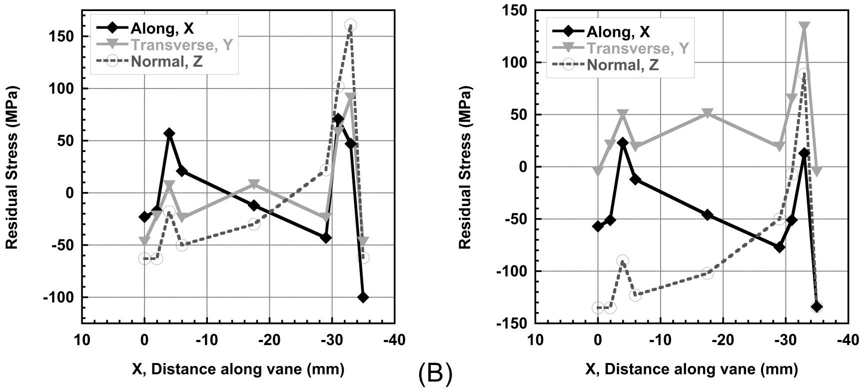


Figure 4 – The residual stress distribution for the (311) plane, line 1 (see Figure 3B). The X = direction normal to the flange, Y = direction along the flange, Z = direction parallel to the flange radius.



(A) (B)

Figure 5 –The residual stress distribution of the (220) plane within the stress-relieved IN738 turbine nozzle along the length of the leading edge of the vane: (A) using force balance to determine the d_0's and (B) using experimentally determined d_0's.