ORNL/TM-2017/733
CRADA/NFE-15-05760

RESIDUAL STRESS DETERMINATION OF DIRECT METAL LASER SINTERED (DMLS) INCONEL SPECIMENS AND PARTS

CRADA FINAL REPORT
NFE-15-05760

Approved for Public Release.
Distribution is Unlimited.

Thomas R. Watkins
Kinga A. Unocic
Philip J. Maziasz
Jeffrey R Bunn
Christopher M. Fancher
Alonso Peralta
Suresh Sundarraj
James F. Neumann
December 10, 2017

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE US DEPARTMENT OF ENERGY

ORNL/TM-2017/733
CRADA/NFE-15-05760

Materials Science and Technology Division
Advanced Manufacturing Office

RESIDUAL STRESS DETERMINATION OF DIRECT METAL LASER SINTERED (DMLS) INCONEL SPECIMENS AND PARTS

Authors
Thomas R. Watkins[1], Kinga A. Unocic[1], Philip J. Maziasz[1], Jeffrey R Bunn[2], Christopher M. Fancher[2], Alonso Peralta[3], Suresh Sundarraj[3], James Neumann[3]

[1] Materials Science and Technology Division, Oak Ridge National Laboratory
Oak Ridge, TN 37831

[2] Chemical and Engineering Materials Division, Oak Ridge National Laboratory
Oak Ridge, TN 37831

[3] Honeywell Aerospace, Phoenix, AZ 85034-218

Date Published:
December 10, 2017

Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831-6283
managed by
UT-BATTELLE, LLC
for the
US DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

CONTENTS

Page

LIST OF FIGURES

ACKNOWLEDGEMENTS

This CRADA NFE-15-05760 was conducted as a Technical Collaboration project within the Oak Ridge National Laboratory (ORNL) Manufacturing Demonstration Facility (MDF) sponsored by the US Department of Energy Advanced Manufacturing Office (CPS Agreement Number 24761). Opportunities for MDF technical collaborations are listed in the announcement “Manufacturing Demonstration Facility Technology Collaborations for US Manufacturers in Advanced Manufacturing and Materials Technologies” posted at http://web.ornl.gov/sci/manufacturing/docs/FBO-ORNL-MDF-2013-2.pdf. The goal of technical collaborations is to engage industry partners to participate in short-term, collaborative projects within the Manufacturing Demonstration Facility (MDF) to assess applicability and of new energy efficient manufacturing technologies. Research sponsored by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Advanced Manufacturing Office, under contract DE-AC05-00OR22725 with UT-Battelle, LLC.

Research at the 2nd Generation Neutron Residual Stress Mapping Facility at the High Flux Isotope Reactor was partially sponsored by the Scientific User Facilities Division, Office of Basic Energy Sciences, U.S. Department of Energy. At ORNL, D.W. Coffey, T.M. Lowe, T.S. Geer, L.N. Donovan assisted with the experimental work.

ABSTRACT

Residual stress determinations and microstructural studies were performed on a series of Inconel 718Plus prisms built using Direct Metal Laser Sintering (DMLS) at Honeywell Aerospace (hereafter also referred to as Honeywell). The results are being used to validate and improve existing models at Honeywell, and ultimately will expedite the implementation of DMLS throughout various industrial sectors (automotive, biomedical, etc.).

1. RESIDUAL STRESS DETERMINATION OF DIRECT METAL LASER SINTERED (DMLS) INCONEL SPECIMENS AND PARTS

This phase 2 technical collaboration project (MDF-TC-2012-003) was begun on December 10, 2015 and was completed on December 10, 2017. The collaboration partner, Honeywell Aerospace is a large business. Residual stress determinations and microstructural studies were performed on a series of Inconel 718Plus prisms, built using DMLS at Honeywell, to validate and improve existing models at Honeywell.

1.1 BACKGROUND

Honeywell Aerospace is a large company (>45,000 employees), sees a future in additive manufacturing and has invested in DMLS. In the phase 1 of a Manufacturing Demonstration Facility (MDF) Technical Collaboration Project,[1] ORNL collaborated with Honeywell Aerospace to determine the residual stresses within two complex parts manufactured by Honeywell as well as some small, simple shapes made of Inconel 718. The project demonstrated the feasibility of neutron residual stress measurements in complex parts providing one method of feedback to modify Honeywell's DMLS process. The improved understanding of residual stress related to the DMLS process has helped the implementation of DMLS at Honeywell.

In this MDF Collaboration phase 2 project, we sought to complete this effort as a CRADA. Here ORNL and Honeywell continued to collaborate by making (Honeywell) prismatic Inconel 718+ bars. After builds at Honeywell, the residual stresses were characterized for a set of prismatic bars using ORNL's High Flux Isotope Reactor. The measured and predicted residual stresses were then compared, and the models refined with the correlated processing parameters. Honeywell's modeling is in its initial stages with respect to residual stress and benefited from further experimental validation. The comparison to measurements and refinement of Honeywell's models defined success. Additionally, microstructural characterization using the Material Science and Technology Division's microscopes and characterization facilities provided guidance for future Additive Manufacturing (AM) builds.

1.2 TECHNICAL RESULTS

A sampling of the results are presented here; an in depth discussion of same will be presented in a future publication.[2]

1.2.1 Samples and microstructure

The samples (Fig. 1) were built using an EOS M280 DMLS system with the salient build parameters listed in Table I. The bars were nominally 75 x 5 x 20 mm (L x W x H). The bars examined in this study were not stress relieved nor heat treated in any way, and were examined in the as built condition.

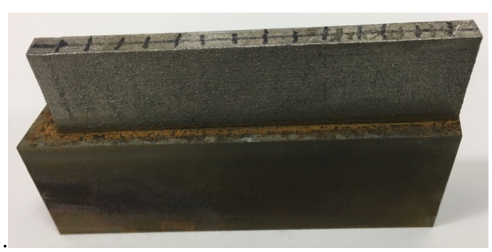
Table 1. Two of five DMLS parameters examined in this study.

Specimen	Laser Power (watts)	Bed Drop Thickness (mm)	Calculated Laser Speed (mm/sec)	Power Density (watts/mm^3/sec)¢
20-B46	370	0.020	1000	185
20-C76	370	0.020	2000	92.5

The hatch spacing was 0.1 mm for all.

¢ Laser power normalized by the interaction volume defined by the distance the laser traveled in 1 second, by the bed drop thickness, by the laser width (0.1 mm assumed).

A. 

B. 

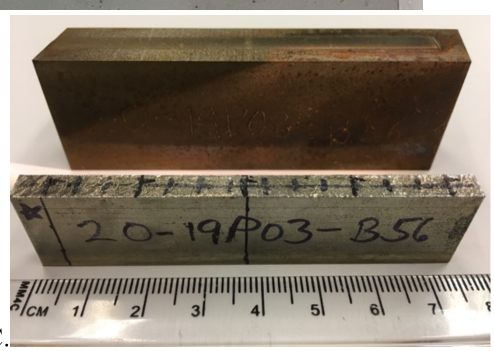
C. 

Fig. 1. A. The as-built samples "all on one base plate". B. Base plate attached. Each sample was EDM sectioned with its own base-plate still attached. C. Base plate removed. Each bar (75mm X 20mm X 5 mm) was EDM cut from its base plate.

As mentioned above, two conditions were selected for detailed microstructural examination: 20-B6 and 20-C76. Fig. 2 shows a low magnification map of the microstructures obtained from the center region of these two samples using electron backscattered diffraction (EBSD) inverse pole figure analysis. Both have elongated/columnar grains parallel to the build direction (A3) and, although the pole figures are not shown, are preferentially oriented with the [100] parallel to the build direction (viz., (100) fiber texture). The grains in the 20-B46 sample are wider and longer (average

50 X 440 μm, respectively) relative to that of 20-C76 (average 30 X 150 μm, respectively) likely reflecting the doubled power density (see Table 1).

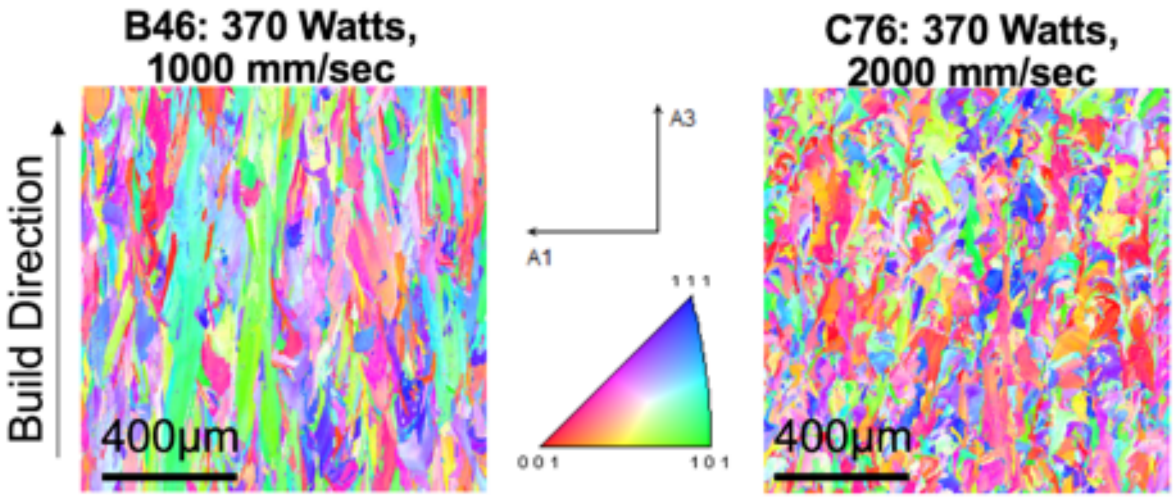


Fig. 2. (a-b) Inverse pole figure maps showing microstructures and grains orientations along the build direction generated from the center locations within the 20-B46 (a) and 20-C76 (b) samples.

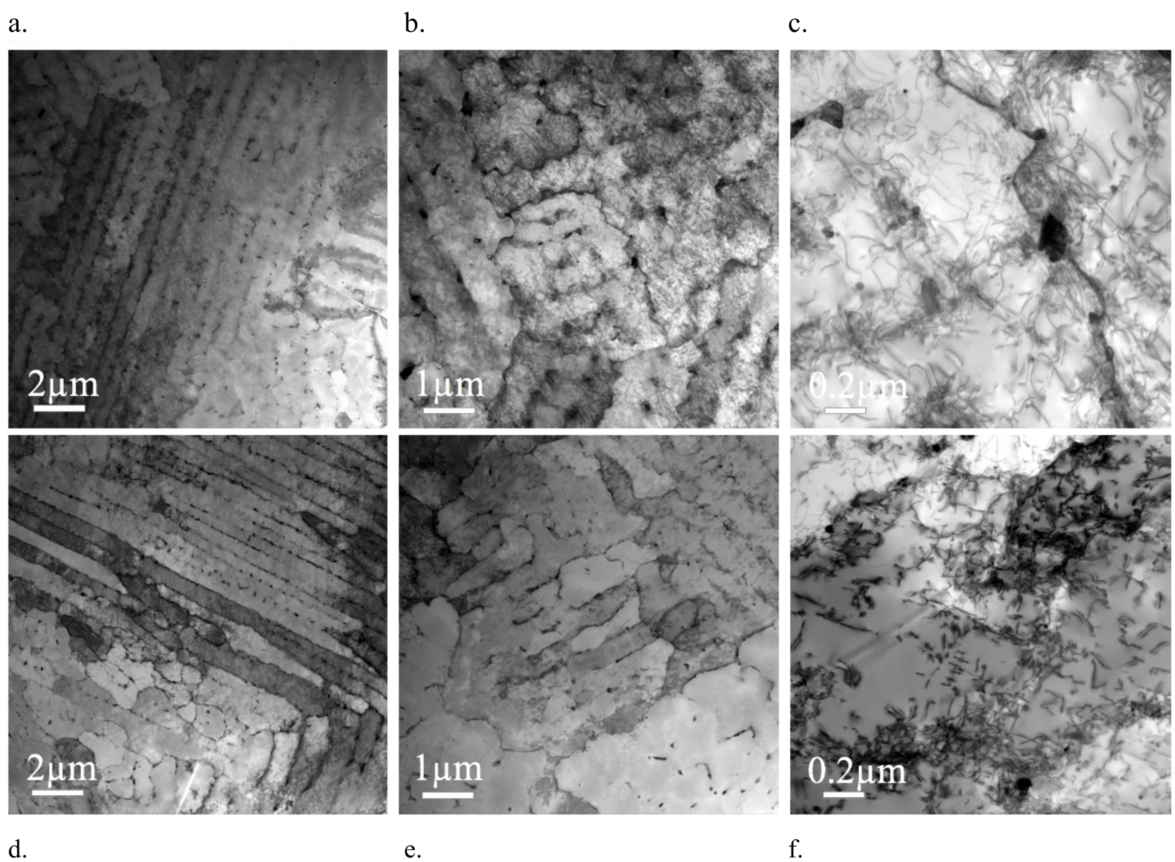


Fig. 3. BF-STEM images acquired from the 20-B46 (a, b, c) and 20-C76 (d, e, f) samples from the center region. The build direction is perpendicular to the plane of the page (out of plane).

Scanning transmission electron microscopy (STEM) was carried out on the bottom, center, and top areas of the selected builds. Fig. 3 shows the bright field (BF) STEM images of the microstructures from the center region which were representative for the three regions for both samples. The ~0.7 µm thick lamella in 20-B46 were almost twice the thickness of those found in 20-C76 (Fig. 3a and d, respectively). Although with similar sizes, the subgrain structure in 20-B46 appeared to be more defined with prismatic boundaries relative to the less distinct ones in 20-C76 (Fig. 3.b and e, respectively). A close up view of the sub-structure shows a lot of dislocations in both conditions but 20-B46 has relatively very sharp boundaries compared to 20-C76 (Fig. 3.c and f, respectively). These differences are again likely due to the larger power density of the 20-B46 condition.

1.2.2 Residual Stress and Modelling

The strains in each sample were measured with x-rays (not shown here) serially in each of three nominal conditions: "all on one base plate", sectioned with a base plate attached and base plate removed (Fig. 1). With neutrons and modelling, only the latter two, serially, were measured due to multiple experimental difficulties associated with the closeness of the bars when located in the "all on one base plate" condition. Sample sectioning was accomplished using electrical discharge machining (EDM) so as to eliminate the introduction of any plastic deformation that accompanies sawing.

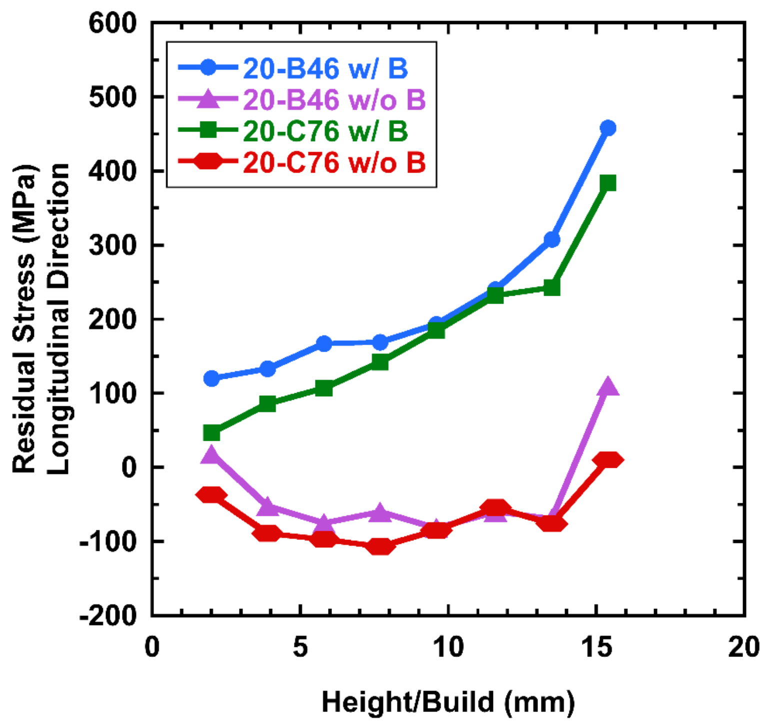


Fig. 4. The longitudinal residual stresses as a function of location in the build direction in 20-B46 and 20-C76 samples with (w/ ; estimated standard deviation ±28 MPa) and without (w/o ; estimated standard deviation ±39 MPa) a baseplate as measured using neutron diffraction. Midsection X= 37.5 mm.

The neutron stress maps for the bars with a drop bed thickness of 0.02 mm were all remarkably similar with only small differences. In Fig. 4, the residual stresses for both 20-B46 and 20-C76 bars as a function of length (Build Height) or distance above the baseplate are shown. Each line or curve is taken at the midsection of the bars (X=37.5 mm) where the residual stresses are most constrained (as opposed to the ends). Surprisingly, the longitudinal residual stresses are least tensile adjacent to the baseplate where the thermal expansion mismatch is greatest, but increase with build height. Extrapolating, the heat from the subsequent laser overpasses continuously flows out and into the baseplate during the build, providing a thermal anneal to the bottom regions of the bar. When the bars are EDM cut from the baseplate (Fig. 4), the curves as a whole redistribute to become uniformly compressive, while the upper and lower surface stay relatively tensile to the stresses at the intermediate heights (3.9 > H > 13.5 mm). These are clustered together at the same ~ -100 MPa residual stress in the longitudinal direction.

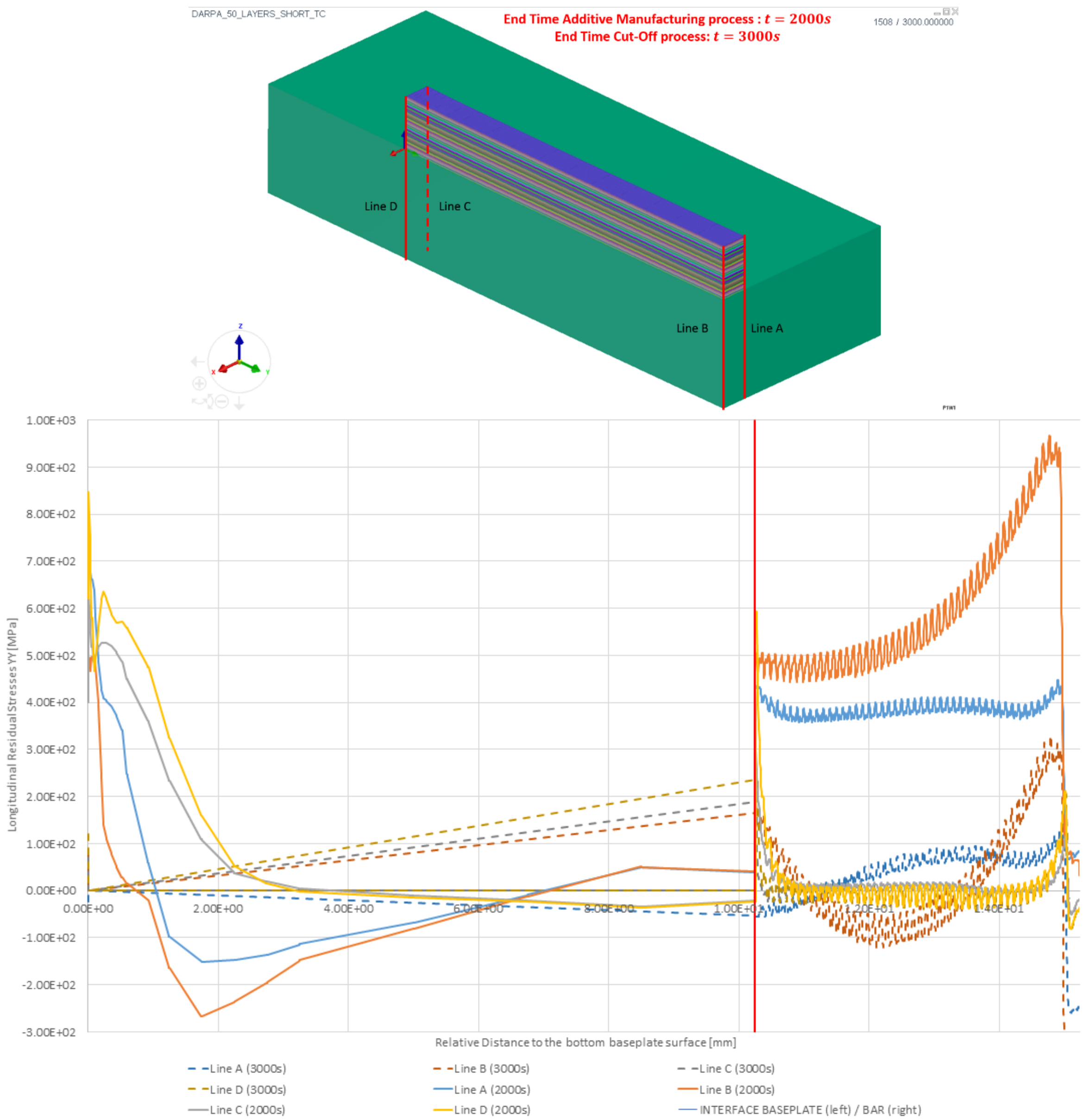


Fig. 5. Honeywell modeling result. Top: Axisymmetric section-Build and baseplate quartered, planes DB and BA bisect the length and width of the build bar-baseplate assembly, respectively. Bottom: residual stress as a function of height. (left is the residual stress through the height of the baseplate and right through the height of the build). The solid and dotted lines represent the stress state when the build and baseplate are attached and separated, respectively. (Laser power 200 W, Calculated laser speed 1000 mm/s, hatch 0.10 mm, bed drop thickness 0.02 mm).

Fig. 5 shows a Honeywell modelling result for comparable parameters. Therein the axisymmetric section is shown and the residual stresses as a function of height starting at the bottom of the baseplate to the top of the build. Of the lines/curves shown, only the dark orange curves for line B are relevant as it is the only one within the bulk/interior of the build prism. Prior to baseplate removal (solid dark orange line), the residual stresses rise from +500 at the baseplate to +900 at the top surface of the build, a change of ~ 400 MPa. In Fig. 4, a similar measured change is shown increasing by ~450 MPa. After baseplate removal, the model shows a huge relaxation of at least 500 MPa, which exceed the measured change by >1.5X. Interesting that the absolute relaxed residual stress values are close.

1.3 IMPACT

The residual stresses developed during the Additive Manufacturing process leads to component deformation that could lead to separation of the component from the built plate and/or to excessive deformation that could lead to the building of a component that is dimensionally out of specification. The work performed during this project has provided insight into the full field stresses that develop during the AM process. Such stress distributions could have only been determined using X Ray and Neutron Diffraction techniques, used in this study, or using the Contour analysis technique. Experimental studies performed at Honeywell had provided insight into the intensity of stress distribution that develops during the build as a function of processing conditions, but it could not determine the full extent of the distribution because the studies were performed on specimens that were removed from the build plate. When the specimens are removed from the build plate the average extensional stress is relaxed and such information is lost. Further, the results of this study have helped Honeywell to understand the stress distribution throughout the build height of the component. This understanding will be used to calibrate the ANY software code used to predict residual stresses. This will in turn allow the whole industry to predict the full effect of the residual stresses on the deformation of components during the build, to predict possible separation of the component from the build plate and to predict possible build crashes.

The improved understanding of residual stress related to the DLMS process will expedite the implementation of DLMS at various original equipment manufacturers and throughout various industrial sectors (automotive, biomedical, etc.). Honeywell is targeting cycle time reduction, cost reductions of manufacturing jet engine components using DMLS technology.

1.4 SUMMARY

Residual stress determinations were performed on a series of Inconel 718Plus prisms built using Direct Metal Laser Sintering considering two variables: laser speed and laser power. The samples were examined before and after base plate removal using a neutron diffraction technique. While there is general agreement between both, the agreement needs to be improved. The residual stress results compared favorably to the modelling with respect to the increased tensile residual stress with increasing distance from the baseplate. The microstructure showed the grain morphology, dislocation networks and precipitation to be essentially the same along the build direction/height from the steel baseplate within a sample, but varied with changes in processing conditions (laser power and speed). These will ultimately expedite the implementation of DMLS throughout various industrial sectors (automotive, biomedical, etc.).

2. HONEYWELL AEROSPACE BACKGROUND

"Honeywell Aerospace is a manufacturer of aircraft engines and avionics,[1] as well as a producer of auxiliary power units (APUs) 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."[3]

3. REFERENCES

1. T.R. Watkins and V. Nangia, ORNL Manufacturing Demonstration Facility, Technical Collaboration Final Report, "Residual Stress Determination of Direct Metal Laser Sintered (DMLS) Inconel Specimens and Parts," Project ID:MDF-UP-2012-003, May 2014.
2. T. R. Watkins, K. A. Unocic, P. J. Maziasz, J. R. Bunn, C. M. Fancher, A. Peralta, S. Sundarraj, J. F. Neumann, "Residual Stresses and Microstructure within Inconel 718Plus Direct Metal Laser Sintered Bars," in preparation.
3. https://en.wikipedia.org/wiki/Honeywell_Aerospace