Characterization of Superalloy Fabricated by Directed Energy Deposition to Repair Turbine Blade Fins

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Gas turbine engines serve an important purpose in aeronautical applications as they convert between forms of energy and create thrust. Turbine blades–a critical component of a turbine engine–are used to regulate and accelerate gas flow. The end of the turbine blades, or fins, are kept in close contact with the inside of the engine. Because of this, the fins wear down over time, decreasing the fuel efficiency of the engine. Rolls-Royce is exploring the additive manufacturing technique Directed Energy Deposition (DED) to repair worn blade fins. Our team used the optimized laser speed and power parameters recommended from the last senior design group. Using these previously selected process parameters, mechanical tests were performed using ASTM standards to obtain data for hardness, wear, and creep.

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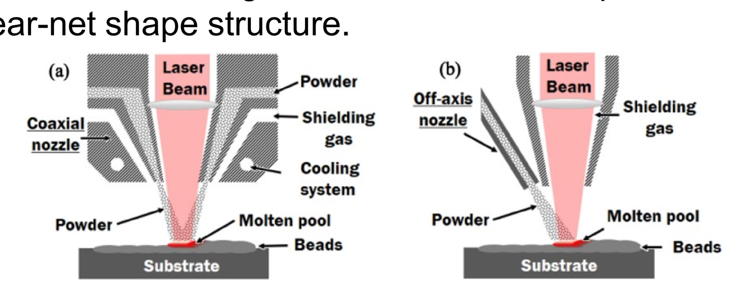
Background

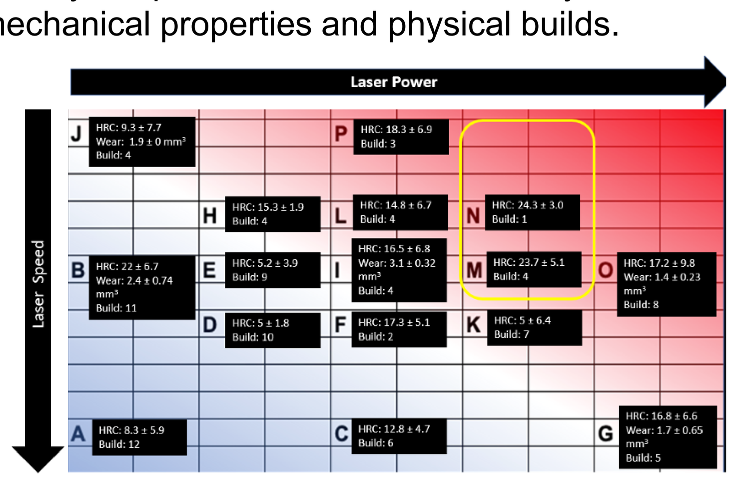
Motivation: Rolls-Royce uses CMSX-4, a single-crystal Ni-based superalloy, as the base material for the turbine blades of their gas turbine engines. The turbine blades operate under high temperatures and pressures. The blade fins will wear down with use of the engine, leading to a decrease in efficiency. It is difficult to replace one entire turbine blade given that blades are often on sections of a disk with several blades on each section. Because of this, DED has been explored as a solution.

Solution: Rolls-Royce has looked into using IN718-RAM3 (a Ni-based superalloy and proprietary composite additive) with 3% reinforcement material as the deposit material for Directed Energy Deposition (DED). DED is an additive manufacturing process in which an existing part can be repaired. Through this process, powder is applied to the substrate, the powder is heated through the laser, and the deposit then cools to create a near-net shape structure.



[1].

Previous teams have looked at printing parameters and focused on pinpointing the optimal laser power and laser speed. They did this by analyzing hardness, wear, and microstructure at varying parameters. Their results can be seen in the figure below. Both parameters N and M were selected by the previous team because they had the most desirable mechanical properties and physical builds.



Project Goal: The goal of this project is to use perform microscopy and mechanical tests to characterize the material produced by the M and N parameters. Optical microscopy, hardness, wear, and creep were used to characterize the material.

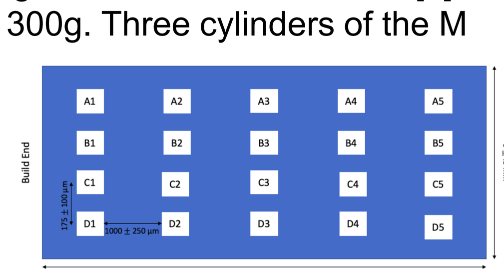
Experimental Procedure

Optical Microscopy

Cylindrical samples of 5 +/- 1mm height with a diameter of 3+/- 0.5mm were mounted in Bakelite and polished to a 3μm surface finish using a series of grit papers and diamond paste. The samples were then etched using Kallings 2 (waterless) etchant. Analysis on dendrite arm spacing and grain size was performed.

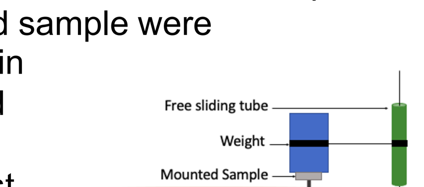
Hardness

Cylindrical samples that were used for optical microscopy were also used for Vickers Hardness tests according to ASTM standard E384 [2]. The load used to create the indents was 300g. Three cylinders of the M parameter were tested, and 4 cylinders of the N parameter were tested. For each cylinder, twenty measurements were taken. The layout can be seen in figure to the right. Care was taken to not get within 200μm of the edge so the bakelite was not indented.



Wear

Wear tests were conducted using a polishing wheel following Standard Test Method for Wear Testing with a Pin-on-Disk Apparatus (ASTM G99-17). The setup can be seen below. Before each test, the wear pin was weighed and then applied to the bottom of a 500g (4.91N) weight using crystal bond. Each test was conducted for 30 seconds, with a sliding speed of approximately 4.3 m/s. Water was continuously sprayed onto the abrasive disk to mitigate any temperature rise of the sample. Once each test was complete, the weight and sample were separated, and the sample was weighed again to find total mass loss. The test was repeated 3 more times for each sample, resulting in a total wear time of 120 seconds. The mass lost per slide distance was calculated for each 30 second interval.

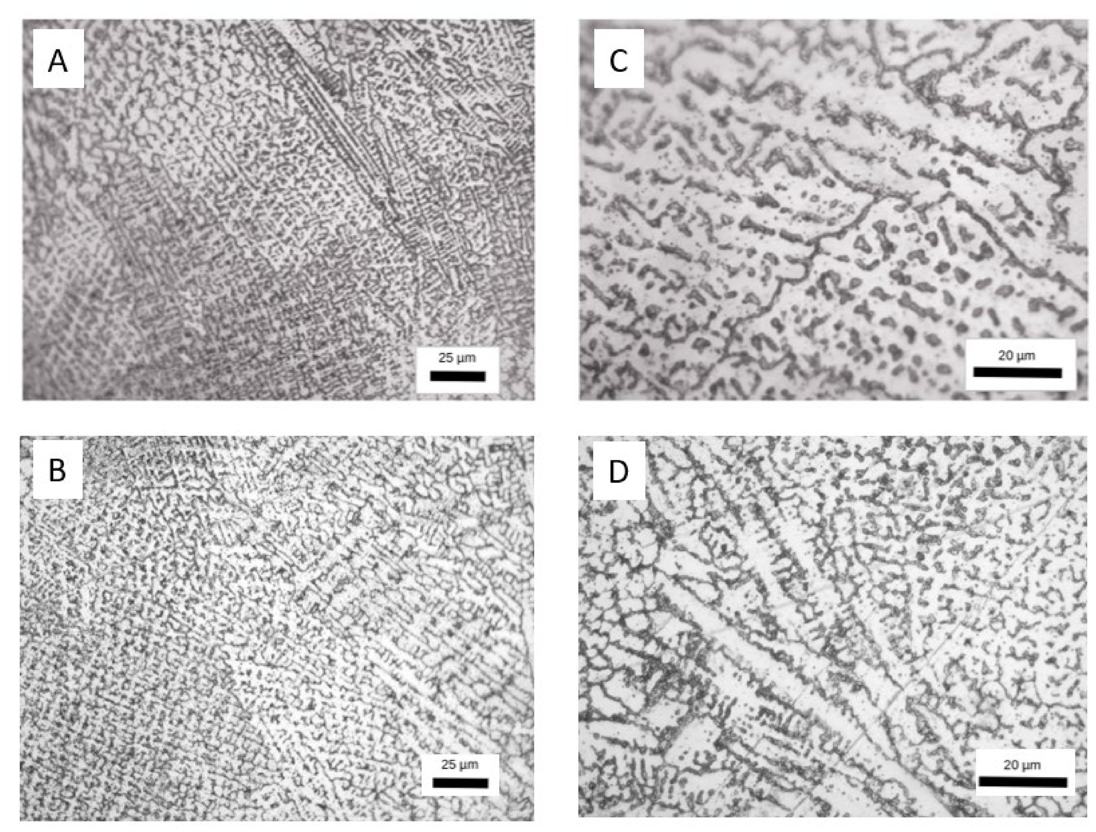


Creep

Once built using DED, cylindrical samples were machined using EDM to be 7.12mm and 7.05mm tall respectively, with diameters of 2.95mm each. The samples were compressively tested at 735ºC at a stress of 550 MPa for approximately 50 hours to obtain steady-state creep data. The samples were not tested to rupture.

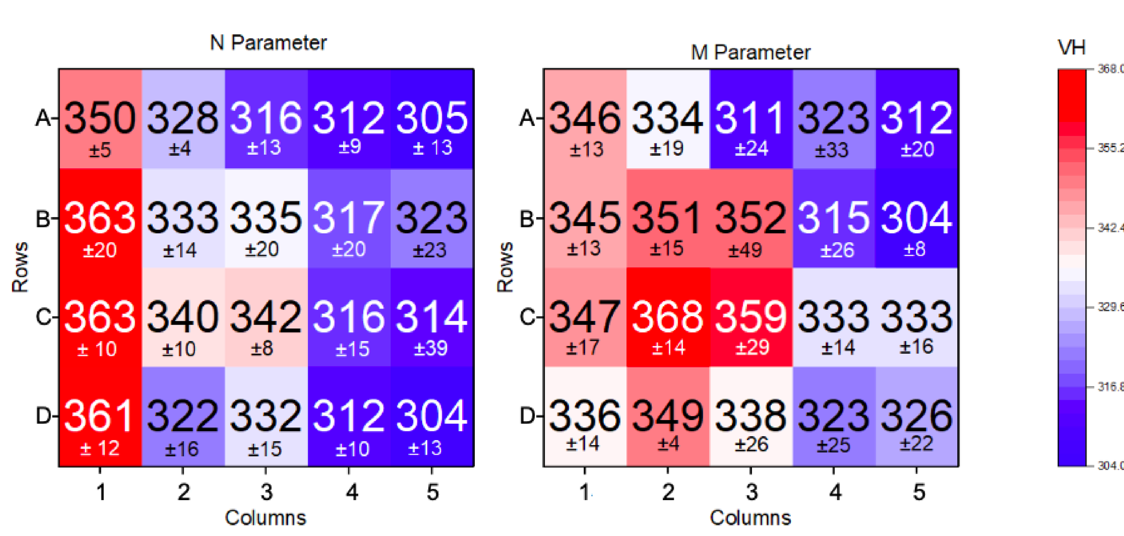
Results

Optical Microscopy



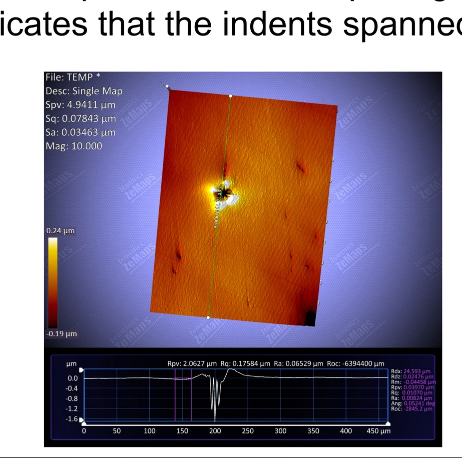
Microscopy images A and C were taken from samples built using laser parameter set N. Images B and D were taken using laser parameter set M. The average primary dendrite arm spacing (DAS) was found to be 5.2μm for parameter set N, and 6.3μm for parameter set M. The larger DAS may be due to a slower cooling rate of the M parameter. Larger DAS values correspond to larger grains, which are known to lower mechanical strength [3].

Hardness

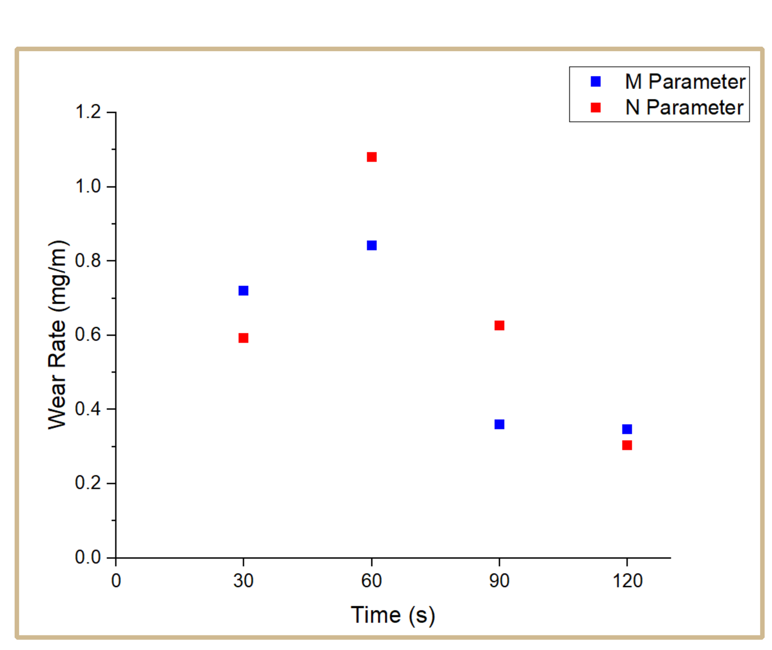


The results of the average hardness and standard deviation along the sample are shown above. The hardness measurements in column 1 of each sample were obtained on the side closest to the build plate interface and follows the pattern given in the experimental procedure. Through doing a Student's t-test between the first and last columns of each parameter, it is known with 95% certainty that there is a statistically significant difference in hardness between the build plate end and the opposite end. In addition, the diagonal of the Vickers indent measured for the N and M parameters were 43μm and 41μm and the arm spacing is 6.3μm and 5.2μm respectively. This indicates that the indents spanned multiple grains.

Through optical profilometer imaging shown to the right, it was noticed that there was pileup around the Vickers indent without noticeable cracking. This indicates the material exhibits relatively ductile behavior. The same pile up behavior was seen for both the N and M parameters.



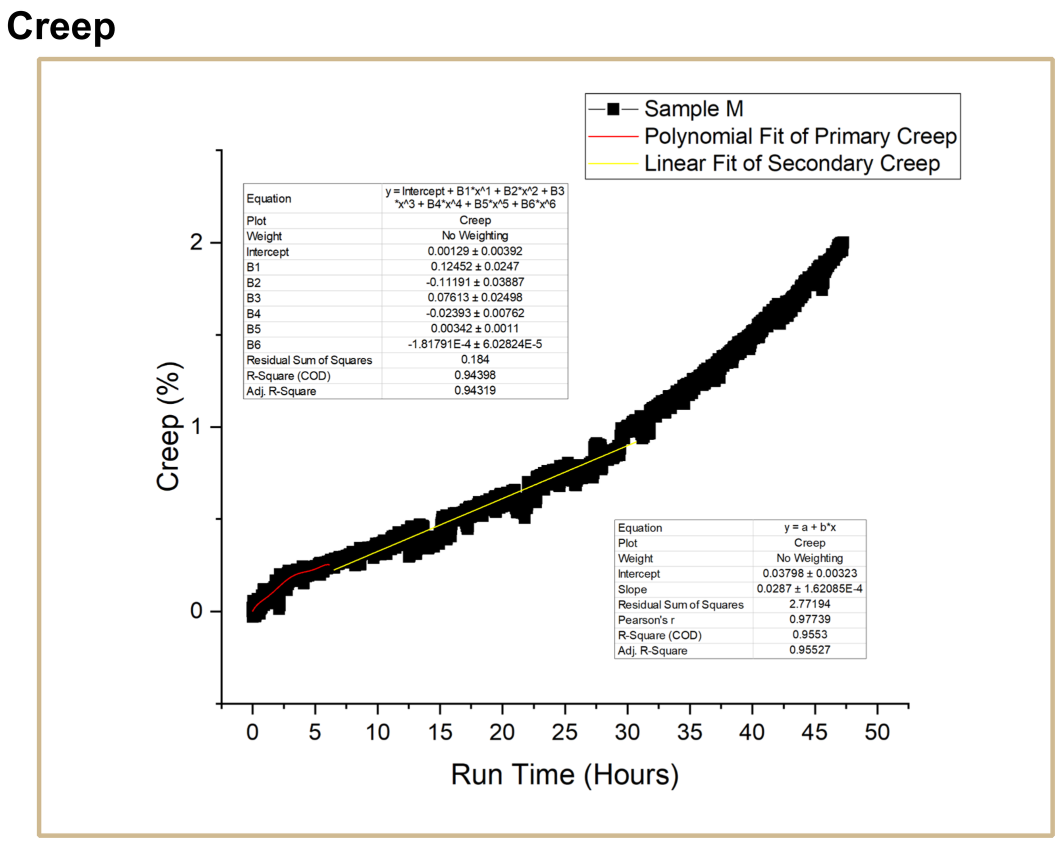
Wear

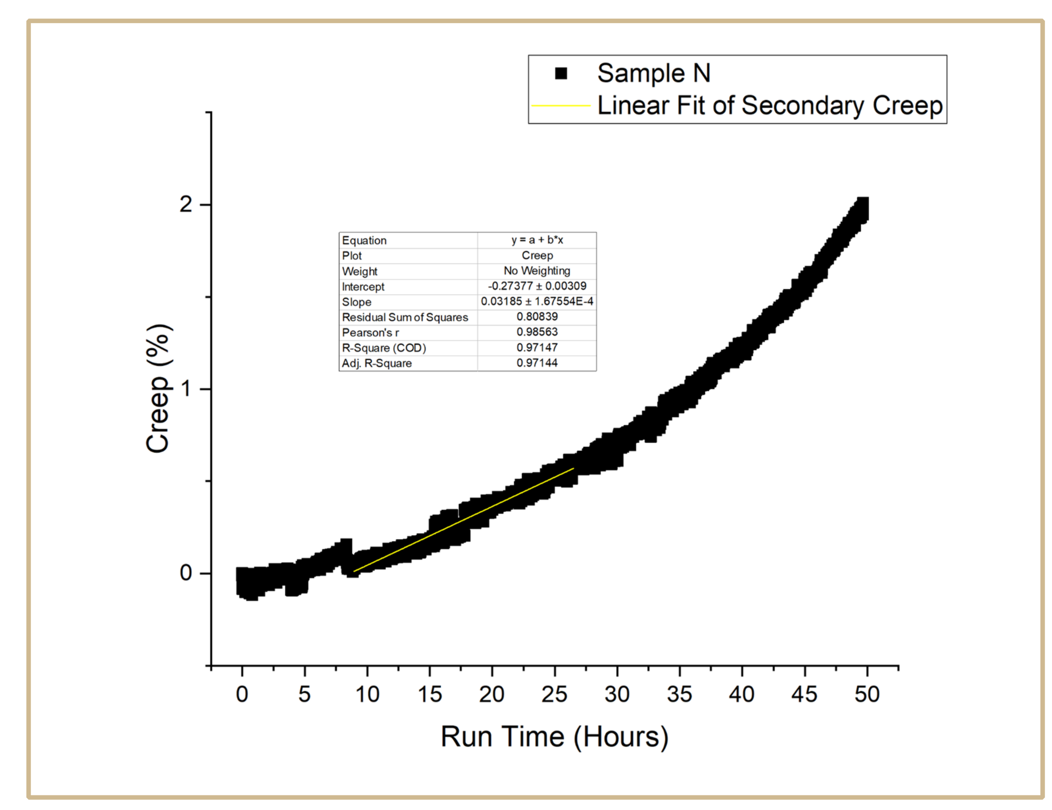


Above are the results from the wear test. There was a variation in the wear rate between each of the thirty second intervals. Initially, the wear rate went up between the 30s and 60s intervals because of an increase in contact area between the wear disk and wear pin. The wear rate then decreases during the 90s and 120s intervals. This could be due to the difference in the hardness. The hardness results above indicated that hardness decreases as distance from the build end increases. The decrease in wear rate as the distance from the build plate increases is consistent with this trend.

Results

Creep





These graphs are the compression creep responses of samples built using laser parameters M and N. The red line on the sample M graph corresponds to primary creep, and the yellow lines on both graphs correspond to secondary/steady-state creep. The minimum creep rate can be calculated from these lines. Sample N did not exhibit primary creep behavior. The minimum creep rate for sample M was 7.97x10^{-6} mm/mm/s and was 8.85x10^{-6} mm/mm/s for sample N. Comparatively, compressive creep data of laser powder bed fusion fabricated IN718 using testing parameters 630ºC at a stress of 900 MPa suggests that minimum creep rates were 10^{-6} and 10$^{-6.9}$ mm/mm/s [4]. The dominant creep mechanism for samples tested in this poster was likely dislocation glide due to the testing temperature and stress [5].

Future Work

To continue the work from this semester, macrohardness should be explored to reduce the probability of a non-homogeneous material affecting hardness measurements. Larger samples than what were used for this project will need to be produced to pursue macrohardness. It is also important to test larger samples to investigate if they have also have a hardness gradient similar to what was observed for Vickers hardness.

It is also recommended that more wear tests are conducted so a statistically significant result can be obtained. Additionally, a more representative abrasive material, such as low carbon steel or cast iron, may be found to more accurately simulate the application of RAM-3 in a gas turbine engine. Additionally, exploring the relationship between wear and hardness is important to understand the behavior of the material.

More creep samples should be tested at various stresses to determine if there is a trend between force applied and creep rate.

References

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