Residual Stress from a Uniform Heat Source in an Additive Manufacturing Directed Energy Deposition Process

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Executive Summary

Simulating a DED process with a uniform heat source is ample for providing rapid model verification. However, a fine mesh may be required in some circumstances in order to produce a verified analysis. This study showed how refining the mesh for a uniform heat source provides accurate results that could help a part or assembly move through the design and manufacturing verification process.

Introduction

In Additive Manufacturing (AM) a technique often used for part fabrication is Directed Energy Deposition (DED). In DED, a laser is used to effectively weld new material, layer by layer, to a part using a metal powder. Due to the rapid heating and cooling that occurs during the fabrication of parts using DED, residual stresses reside in the parts that can affect the integrity of the part itself after the manufacturing process is complete. The purpose of this report was to study the difference between modeling a concentrated heat source and a uniform heat source during the additive manufacturing process. A uniform heat source was modeled and analyzed in this report in order to see which modeling method best simulates DED.

Methods

For this study Dassault's SIMULIA Abaqus 2020 software version was used to model, mesh, and analyze the comparison between a concentrated and uniform heat source. The part modeled was provided by Dr. Petrella from Colorado School of Mines. The part file name was "plate_mechanical_visco_relief_moving_source.cae". In addition to the .cae file, the input file titled "plate_thermal_moving_source.inp" was edited and used to help model the uniform heat source. The part was titled "Plate" and was 250 mm x 10 mm x 80 mm. Below in Figure 1, an isometric view of the "Plate" part modeled in SIMULIA Abaqus. The Plate is a half-symmetry model in order to reduce solution time.

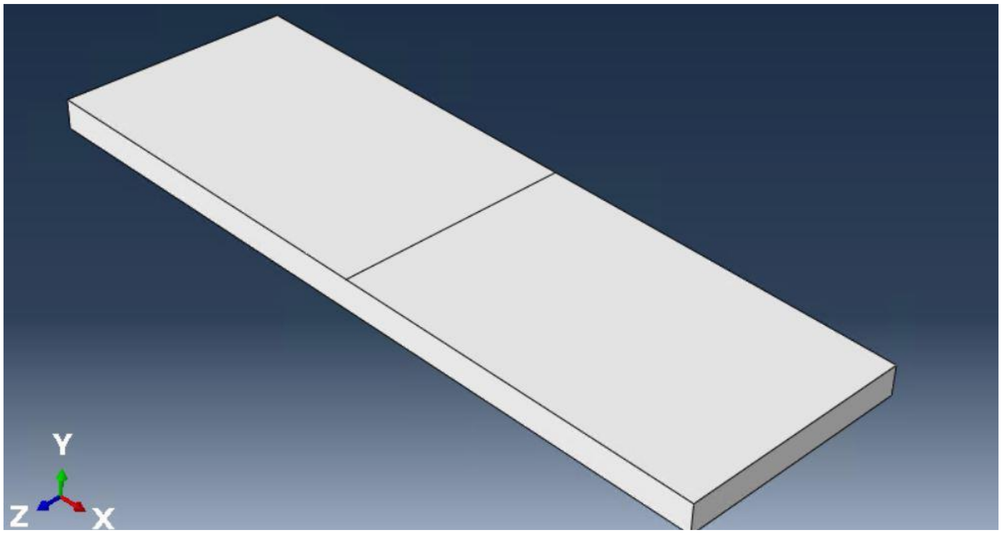

Figure 1. "Plate" modeled in SIMULIA Abaqus

The "Plate" had Boundary Conditions fully constraining the Plate's movement in the X, Y, and Z directions. Specifically the plate had the four bottom corners constrained in the Y direction, the Z direction is constrained on the top and bottom of the "front" of the plate, furthest from the origin. The X direction is constrained at (0,0,80) or the "front left" of the part in accordance to Figure 1. The plate was also constrained symmetrically since it is a half-symmetry plate.

The Uniform Heat Source and the Concentrated Heat Source were applied, in separate instances, on separate models, across the top edge of the displayed part. Specifically the Uniform Heat Source approximately travelled from (0,0,80) to (250,0,80). In Figure 2 below, the Heat Source path can be seen on the Plate part.

The heat source was modeled using characteristics from SIMULIA's ABAQUS documentation. The Heat Source modeled was approximately 2 kW in power and had a spot size on the Plate's surface of 4 mm in diameter (Smith). The laser was modeled at a speed of 10.6 mm/second.

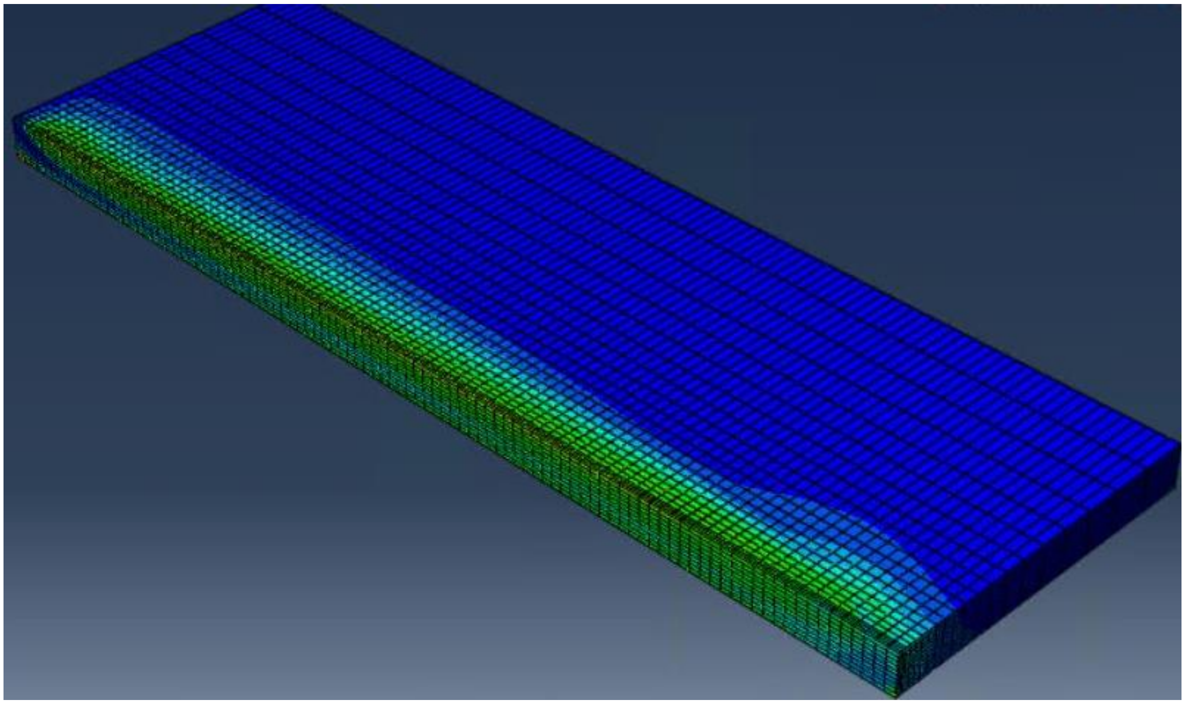

Figure 2. Uniform Heat Source Path Across the Plate

The material that the Plate was modeled with was SAE 316L Stainless Steel, and the specific material properties can be found in the appendix, which is the last section of this report. The material properties that were associated with the heat transfer of the Uniform Heat Source are conductivity and specific heat which have the largest effect on the residual stresses that reside in the material. Following the level of impact of conductivity and specific heat, would be convection and radiation but those two properties are dependent on the environment where the DED process is taking place which was not accounted for in this model. Creep, density, elasticity, plasticity, and thermal expansion are characteristics of Stainless Steel 316L but they are temperature dependent properties that contribute toward the residual stress left in the Plate after exposure to the heat source.

The converged mesh had 24,442 elements. The element size decreased as the elements approached the area where the heat source was applied to. The element type was C3D8 and the size of the element in the critical area of the model was 2.5 mm x 1 mm x 0.667 mm. Mesh convergence was performed by looking at the midline stress at the end of the mechanical step, prior to heat treatment. This midline can be seen below in Figure 3. The max S33 stress value was plotted in an XY graph, where the max value was compared to the previous mesh in order to find convergence. The mesh was considered converged when it was within 5% of the refined mesh's max S33 stress value along the plotted midline in Figure 3. Another factor for convergence was the shape of the graph as it increased to the peak S33 value on the Z axis, if the peak resembled a spike and not a rounded shape, the mesh would not be considered converged. The mesh was seeded on the edge that runs along the Z axis. The mesh was originally 2.5 x 1 x 1 mm and was biased toward the heat source, to refine the mesh the Z edge was refined to an approximate size of 0.6 mm along the Z axis.

For verification purposes, additional refinement was performed. In this scenario the approximate element size along the Z axis was reduced further to 0.5 mm using single bias edge seeding with a minimum element size of 0.5 mm and a maximum size of 10.0 mm. A detailed view of this mesh can also be seen below in Figure 4. This mesh used 25,000 elements, C3D8 elements, and had a size of 2.5 x 1 x 0.5 mm near the heat source scaling up to 10 mm away from where the uniform heat source was applied to. This analysis was performed to create a larger sample size for verification purposes.

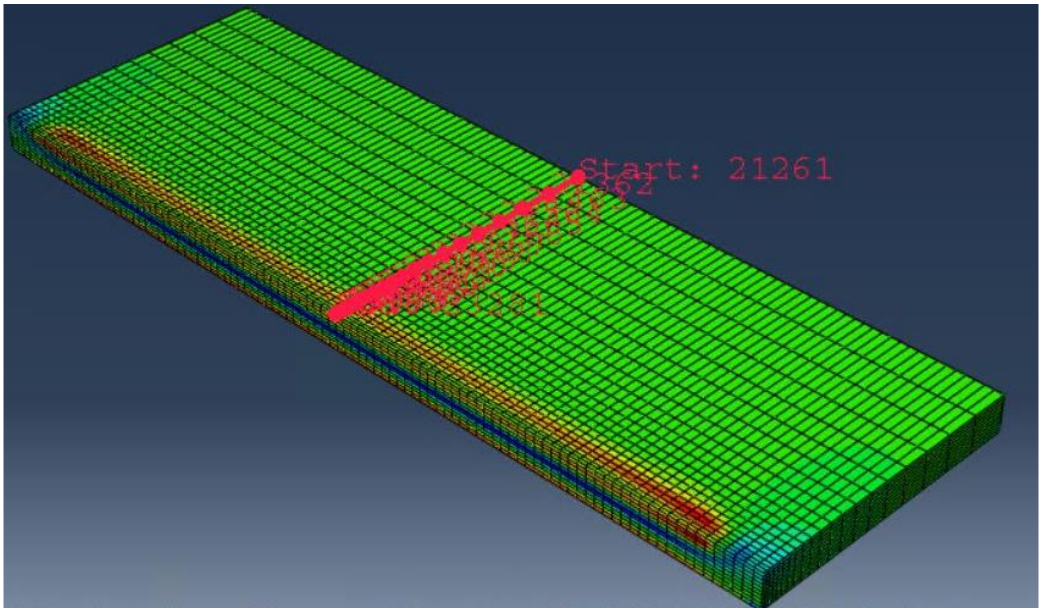

Figure 3. Mesh with the midline annotated with node numbers in red, at the end of the Mechanical Step

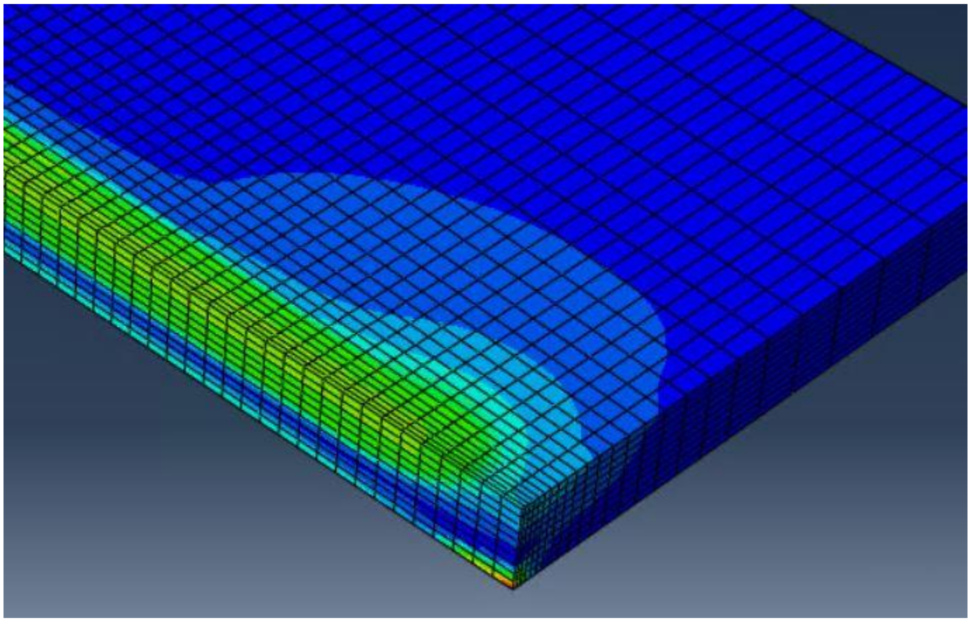

Figure 4. Single Bias Mesh with a minimum element size along the Z direction of 0.5 mm scaling to 10.0 mm

Results

The results for the mesh convergence study can be found below in Table 1. The peak S33 stresses were found in the coordinate range of 70 mm to 80 mm on the Z axis which is the direct area on which the uniform heat source was applied to. This is also where the mesh was the most refined. The peak S33 stress found on the converged mesh was 170.0 MPa. The converged mesh had an element size of 2.5 mm x 1 mm x 0.667 mm. The percent difference from the converged mesh was 0.23% and for verification purposes a more refined mesh was used and the percent difference for S33 peak stress was 3.11% along the midline. One could argue that due to the plot seen in Figure 5 below, that the mesh may not be considered converged.

Table 1. Mesh Convergence Data for the Uniform Heat Source

	Number of Elements (C3D8)	Peak S33 Stress Along Midline (MPa)	Percent Change (%)
Mesh 1	23331	171.4	0.23 %
Mesh 2	24442	170.0	3.11 %
Mesh 3	25000	164.8	N/A

The initial mesh's graph had a sharp peak, this peak is indicative of a non-converged mesh. The mesh with a sharp peak can be seen below in Figure 5, with S33 Stress plotted on the Y-axis and the Z-coordinate plotted across the X-axis.

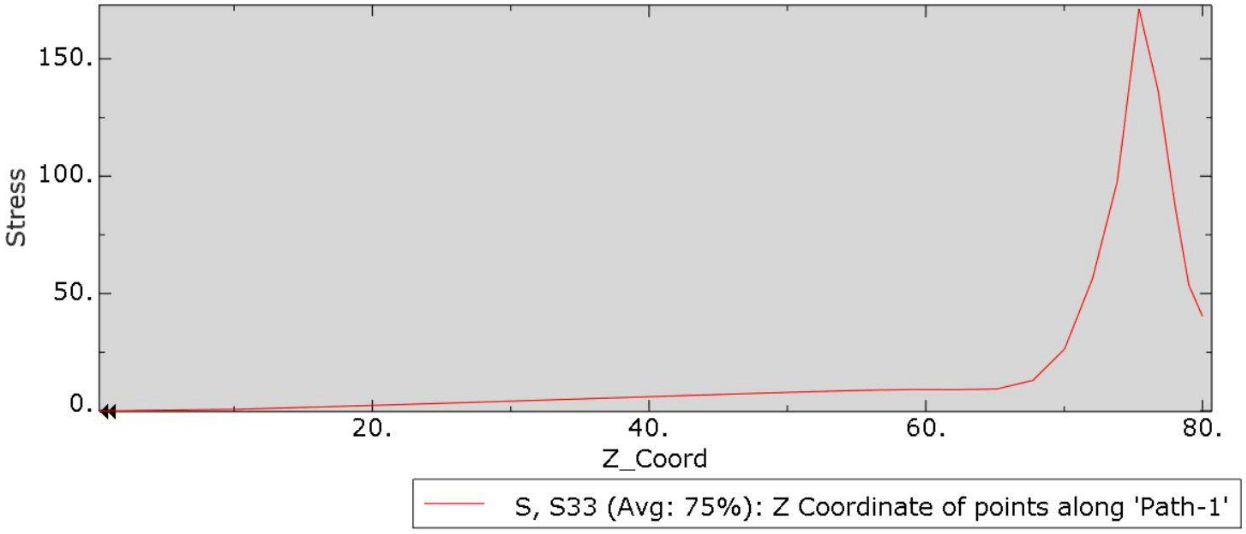

Figure 5. Converged S33 Stress plotted along the midline of the Plate part

As seen in Figure 5, the mesh showed a peak S33 stress around 171 MPa and 75 mm in the Z direction on the midline of the Plate. In Figure 6, a converged mesh plot is below, specifically this is Mesh 3.

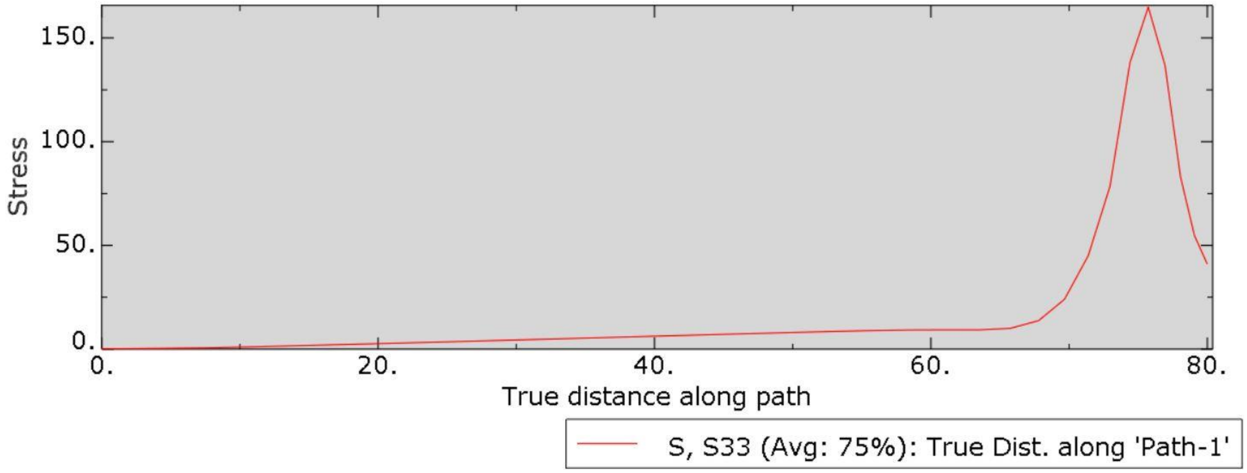

Figure 6. Refined Mesh 3, S33 Stress plotted along the midline of the Plate part

The plot in Figure 6 shows a peak S33 stress of 164.8 MPa at the end of the Mechanical Step and prior to heat treatment. This mesh had 25,00 C3D8 elements. Ultimately, due to the shape of the graph in Figure 6, the mesh may not be considered converged, but for the sake of this study, the peak residual stress along the Z axis did not have a high level of variance between Mesh 1 and Mesh 3.

Discussion

The purpose of this report was to study and understand the residual stresses that a uniform heat source produces on a 316L Stainless Steel Plate during DED. The uniform heat source was able to be accurately modeled with a refined mesh that had a single bias toward the latter Z coordinates. Residual stresses occurred in the model and were ultimately reduced with heat treatment. Other studies have found that heat treatment applied at a certain time after the SLM/DED process has occurred results in reducing residual stresses (Li). This study showed that with a fairly low element number the mesh can converge when a single bias edge seed method is implemented. It has also been found that beneficial post processing varies for different materials (Li). The results seen in this comparison study have been verified by performing a mesh convergence and some validation has taken place through consulting external sources.

References

1. Archard, John Frederick (1953). "Contact and Rubbing of Flat Surface". J Applied Physics. 24 (8): 981–988.
2. Smith, M (2009). ABAQUS/Standard User's Manual, Version 6.9. Dassault Systèmes Simulia Corp, Providence
3. Li, C., Liu, Z., Fang, X., & Guo, Y. (2018). Residual stress in metal additive manufacturing. *Procedia CIRP*, *71*, 348-353. doi:10.1016/j.procir.2018.05.039
4. Urevc, J., Koc, P., & Stok, B. (2009). Numerical Simulation of Stress Relieving of an Austenite Stainless Steel. *Journal of Mechanical Engineering*.

Appendix

SAE 316L Stainless Steel				
Conductivity Data			Density Data	
Conductivity	Temperature (C)		Mass Density	Temperature (C)
15.7	200		7.95E-09	24
18.6	400		7.92E-09	90
21.5	600		7.88E-09	200
			7.83E-09	320
			7.79E-09	430
			7.74E-09	540
			7.69E-09	650
			7.64E-09	760
			7.59E-09	870

Creep Properties for SAE 316L Stainless Steel			
Power Law Multiplier	Eq. Stress Order	Time Order	Temperature (C)
1E-22	2	0	20
1E-20	2.5	0	490
6E-20	4.8	0	550
3.13E-16	4.9	0	620
2.01E-18	5.2	0	680
3.65E-15	4.4	0	720
6.52E-16	5	0	760
3.31E-15	5.3	0	850
7.88E-14	5.1	0	900
5.9E-17	4.9	0	920
4.45E-11	3.3	0	930
7.5E-09	3.3	0	1100
4.98E-08	2	0	1125

Elastic Properties for SAE 316L Stainless Steel		
Young’s Modulus	Poisson’s Ratio	Temperature (C)
195159	0.26	24
194179	0.26	90
189275	0.26	150
185352	0.275	200
181430	0.29	260
176526	0.315	320
171623	0.34	370
163777	0.32	430
161816	0.3	480
156912	0.31	540
152989	0.32	590
148086	0.315	650
143182	0.31	700
137298	0.28	760
131414	0.24	820

Expansion Properties for SAE 316L Stainless Steel	
Expansion Coefficient	Temperature (C)
1.54E-05	100
1.56E-05	200
1.61E-05	300
1.66E-05	400
1.7E-05	500
1.71E-05	600
1.76E-05	700

1.8E-05	800

Plastic Properties for SAE 316L Stainless Steel		
Yield Stress (MPa)	Plastic Strain	Temperature (C)
290	0	21
434	0.1229	21
248	0	204
372	0.0871	204
221	0	316
331	0.0708	316
193	0	427
290	0.0571	427
179	0	538
269	0.0498	538
159	0	649
238	0.0547	649
138	0	760
207	0.0627	760
124	0	871
186	0.0827	871
80	0	1100
103	0.1	1100

Specific Heat Data for SAE 316L Stainless Steel	
Specific Heat (J/K/Kg)	Temperature (C)
452000000	20
486000000	90

528000000	200
548000000	320
565000000	430
573000000	540
586000000	650
615000000	760
649000000	870