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Simulation Analysis of Additive Manufacturing of Impeller

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Abstract: **An Impeller is the rotating component of a pump; it transfers the energy from the motor to the fluid and accelerates the fluid to build up pressure. Impellers are manufactured using Additive Manufacturing (AM) technology. It is a technology that produces three-dimensional parts layer by layer from a variety of materials such as plastics, polymers and metals. The impeller is usually made up of Stainless Steel 316L, Inconel 718. AM technique used to manufacture impeller is Direct Metal Laser Sintering (DMLS). The main objective of this paper is to conduct simulation analysis of additive manufacturing of an impeller by varying process-parameters such as Power, Wall-thickness and Angle and recommend a suitable material with minimum von-misses stress, minimum displacement and minimum of maximum temperature using Amphyon software. Simulation analysis is performed on two different materials i.e., Stainless Steel 316L and Inconel 718 by varying process parameters such as Power at 200 to 400W, Wall thickness at 0.5 to 0.8mm and Angle at 0^0 to 6^0. Amphyon is a modular pre-processing and simulation software for Laser Beam Melting (LBM) processes. The simulation results were analyzed and optimization for Stainless-Steel 316L material impeller was done using one of the MADM methods i.e., Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method. Later, the results of the two different materials (i.e., Stainless Steel 316L and Inconel 718) were compared. Stainless Steel 316L was found to have minimum von-misses stress, minimum displacement and minimum of maximum temperature at 200W power, 0.5mm wall-thickness and 0^0 angle.**

Index Terms: **Impeller, Additive Manufacturing, Direct Metal Laser Sintering (DMLS), Amphyon, MADM, TOPSIS.**

I. INTRODUCTION

Impeller is a rotating element of a centrifugal pump which helps to accelerate the fluid outward from the center of the rotation, thereby transferring energy required from the motor that drives the pump to the motor driven by the fluid [1,2]. Various manufacturing techniques are used to build an impeller such as traditional manufacturing (i.e., casting), Additive Manufacturing (i.e., powder bed fusion method) and Hybrid Manufacturing which combines both traditional and additive manufacturing methods that makes it more effective [3]. The Additive manufacturing (AM) or 3D printing techniques have gained immense popularity for its ability to make complex objects such as impeller [4]. It also introduces the possibility for new products, largely due to greater design liberty. AM is a preferred process as it adds material layer by layer thereby reducing the wastage of material when compared to traditional manufacturing which removes the material. AM has a wide range of applications with different variety of materials such as plastics, polymers and metals [5]. The impeller is usually made of Stainless Steel 316L and Inconel 718 as both these materials have high corrosion resistance. Both these materials are anisotropic in nature i.e., they show different behaviour along the different directions of the materials. It has been observed that the maximum anisotropic deformation is found at 450 for both the materials [6,7]. The AM method used to manufacture metal products is Laser Power Bed Fusion method. One of the LPBF technique used to manufacture impeller is Direct Metal Laser Sintering (DMLS) [8,9,10,11,12] as it has a wide range of materials such as Stainless steel 316l, Inconel718, Ti6Al4V, Stainless steel 17-PH. The principle behind this method is the application of thin layers of metal powder using a re-coater blade. The metal powder is sintered by a collimated laser beam, which fuses the particles of the metal together to create a solid material. The main objective of this paper is to conduct a simulation analysis of additive manufacturing of an impeller and to recommend a suitable material for manufacturing with minimum Von-misses stress, minimum Displacement and minimum of maximum Temperature by varying various process-parameters such as Power (200W to 400W), Wall-thickness (0.5mm to 0.8mm) and Angle (0^0 to 6^0) using Amphyon software. Amphyon is a modular pre-processing and simulation software for Laser Beam Melting (LBM) processes. The values of power, wall-thickness and angles are considered based on the following recommendations. The wall thickness above 0.5mm is considered to avoid warpage in the components [13,14]. The power impacts the micro-structure of the material thus two different laser powers are being considered [15] and according to the Amphyon software simulation assessment these orientations angles (i.e., 0^0 to 6^0) with respect to build plate was recommended for the material and build conditions mentioned earlier. Based on the above build parameters EOSINT M280 machine is considered for simulation. The simulation values were recorded. The simulation results of stainless steel were analyzed and optimization was performed using one of the Multi Attribute Decision Making (MADM). The technique used to perform optimization was Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) [16].

II. Materials and Machine Specification

A. Materials

The materials used to manufacture impeller are Stainless Steel 316L and Inconel 718 as they have high corrosion resistance.

Stainless Steel: The composition and mechanical properties are shown in Table I and Table II.

Material properties:

1. High hardness and toughness.
2. High corrosion resistance.
3. High machine-ability.
4. Can be highly polished.

TABLE I.
PROPERTIES OF STAINLESS STEEL 316L

Property	Value
Ultimate tensile Strength	1467 MPa
Yield Stress	1150 MPa
Young's modulus	205 GPa
Poisson's ratio	0.3

TABLE II.
COMPOSITION OF STAINLESS STEEL 316L

Element	Concentration [Wt.%] Acc. ASTM A276
Carbon	$\leq$ 0.03
Manganese	$\leq$ 2
Silicon	$\leq$ 1
Nitrogen	$\leq$ 0.1
Phosphorous	$\leq$ 0.045
Sulphur	$\leq$ 0.015
Molybdenum	2-3
Chromium	16-18
Nickel	10-14
Iron	Balance
Manganese	$\leq$ 0.03

Inconel 718: The composition and mechanical properties are shown in Table III and Table IV.

Material properties:

1. Retains strength up to 650 °C.
2. High creep resistance.
3. High corrosion resistance.
4. Solidification properties suit additive manufacture.

TABLE III.
COMPOSITION OF INCONEL 718

Element	Mass (%)
Nickel	50-55
Chromium	17-21
Niobium and tantalum	4.75-5.5
Molybdenum	2.80-3.30
Titanium	0.65-1.15
Cobalt	$\leq$ 1.00
Aluminum	0.20 -0.80
Manganese	$\leq$ 0.35
Silicon	$\leq$ 0.35
Copper	$\leq$ 0.30
Carbon	0.02 – 0.05
Nitrogen	$\leq$ 0.03
Oxygen	$\leq$ 0.03
Phosphorous	$\leq$ 0.015
Sulphur	$\leq$ 0.015
Calcium	$\leq$ 0.01
Magnesium	$\leq$ 0.01
Selenium	$\leq$ 0.005
Boron	$\leq$ 0.005
Iron	Balance

TABLE IV.
MECHANICAL PROPERTIES OF INCONEL 718

Property	Value
Ultimate tensile Strength	676 MPa
Yield Stress	541 MPa
Young's modulus	178 GPa
Poisson's ratio	0.3

B. Machine Specifications

The machine used is EOSINT M 280. The machine comprises a process chamber with recoating system, elevating system and platform heating module, an optical system with laser, a process gas management system, a process computer with process control software, and a set of standard accessories. The machine components are integrated into a robust machine frame. During operation the process chamber is secured by interlock. The specifications are shown in the Table V.

TABLE V.
EOSINT M 280 MACHINE TECHNICAL DATA

Effective building volume	250mm×250mm×215mm
Building speed (material-dependent)	2-20 mm3/s (0.0001 – 0.001 in3/sec)
Laser Power	200 W or 400 W
Laser Type	Yb-fiber laser
Scan Speed	Up to 7.0 m/s
Power Supply	32A
Layer Thickness	20 – 60 µm
Power Consumption	Max 8.5kW/ typical 3.2 kW
Precision Optics	F-theta- lens, high- speed scanner
Variable focus diameter	100 – 500 µm
Nitrogen generator	Standard
Dimensions:	
System	2000mm×1050mm×1940mm
Recommended installation space	Approx. 3.5m×3.6m×2.5m
Weight	Approx. 1130kg

C. Amphyon Software

Amphyon is a modular pre-processing and simulation software for laser beam melting (LBM) processes. The Amphyon modules can be used in pre-processing chains from CAD to build job by replacing or improving several stages. Driven by industrial needs and requirements in LBM processes, an innovative new pre-process chain was derived. Three main stages on the way to a stable, efficient and reliable process were identified.

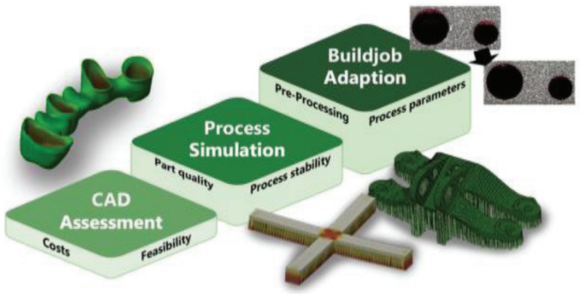


Figure 1. The ASAP Principle

The mechanical simulation model in Amphyon uses an approach called Inherent Strain approach. The basic principle of the inherent strain approach for additive manufacturing is that if no external loads are applied, the inherent strains is defined as the sum of plastic and thermal strains which completely defines the stress state and the deformation within a given domain. The inherent strain approach for additive manufacturing is also called Mechanical Layer Equivalent (MLE) Method.

The thermal simulation model in Amphyon uses an approach of Global Thermal Analysis. The build rate and the amount of time for cooling down between consecutive layers is one of the most important influencing factors for the macro scale thermal simulation of the process. If the cool down time between layers is increases by a factor of two, the macro scale thermal field is reduced by approximately the same factor if non-linear influences such as radiation, convection, absorption etc. are neglected.

D. Methodology

The steps involved in the simulation analysis is shown in the Figure 2. Twelve different simulation analysis are done for each material by varying the power (200W, 400W), wall-thickness (0.5mm, 0.8mm) and angle (0^0, 2^0, 5^0) respectively. The impellers with different angles with respect to build plate and their supports are shown in the Figure 3.

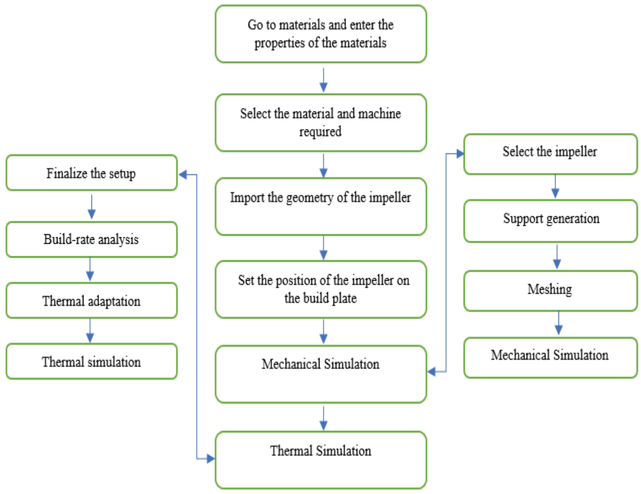
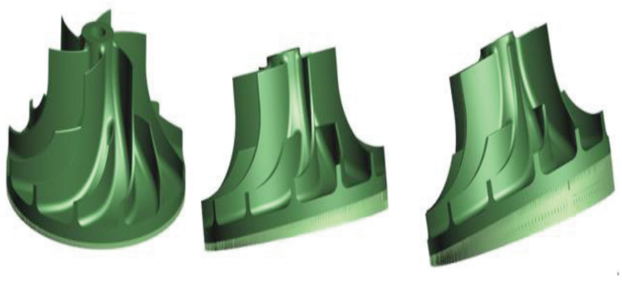


Figure 2. Flow-chart of steps involved in Simulation process



(a) (b) (c)

Figure 3. Supports generated to impeller build at different angles w.r.t build plate. (a) 0^0 angle (b) 2^0 angle (c) 5^0 angle

E. Boundary conditions

Mechanical simulations:

- Material is anisotropic, max deformation at 45^0.
- Heat treatment: After the release of the base, stresses to zero

Thermal simulations:

- Preheating of the build area at 50^0 C.
- Energy transferred into the part.
- Evaporation the material
- Convection on the outside surface of Heat affected zone.

III. Results

The results of the simulation are shown in the Table VI and Table VII. The tables consist of the values of von-misses stress, displacement and maximum temperature of Stainless steel 316L and Inconel 718.

TABLE VI.
VALUES OF INCONEL 718

Power (W)	Wall Thickness (mm)	Angle	Von-Misses (MPA)	Max Temperature (C)	Displacement (mm)
200	0.5	0	0.118	59.504	0.245
200	0.5	2	0.7448	59.74	0.288
200	0.5	5	0.303	62.328	0.370
200	0.8	0	0.1669	59.560	0.300
200	0.8	2	0.190136	59.649	0.337
200	0.8	5	0.600	67.9	0.439
400	0.5	0	0.1539	69.23	0.246
400	0.5	2	0.5120	69.97	0.285
400	0.5	5	0.555	75.15	0.369
400	0.8	0	0.1948	69.468	0.300
400	0.8	2	0.3127	69.656	0.335
400	0.8	5	0.53029	86.12	0.438

TABLE VII.
VALUES OF STAINLESS STEEL 316L

Power (W)	Wall Thickness (mm)	Angle	Von-Misses (MPa)	Max Temperature (C)	Displacement (mm)
200	0.5	0	0.118	59.504	0.245
200	0.5	2	0.7448	59.74	0.288
200	0.5	5	0.303	62.328	0.370
200	0.8	0	0.1669	59.560	0.300
200	0.8	2	0.190136	59.649	0.337
200	0.8	5	0.600	67.9	0.439
400	0.5	0	0.1539	69.23	0.246
400	0.5	2	0.5120	69.97	0.285
400	0.5	5	0.555	75.15	0.369
400	0.8	0	0.4912	69.05	0.269
400	0.8	2	0.4589	69.226	0.322
400	0.8	5	0.3039	85.644	0.412

Optimization: Table VIII shows minimum stress and displacement at 200W, 0^0 and 0.5mm wall-thickness and minimum value of maximum temperature occurs at 200W, 5^0 and 0.5mm wall-thickness. To resolve this ambiguity, one of the MADM techniques i.e., Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is used. The process is carried out as follows:

Step 1: Create an evaluation matrix

TABLE VIII.
DECISION TABLE

			Beneficial		
Power (W)	Wall Thickness (mm)	Angle	Von-Misses (MPa)	Max Temperature (^{0}C)	Displacement (mm)
200	0.5	0	0.071665	58.1	0.189
200	0.5	2	0.2580	57.17	0.241
200	0.5	5	0.156	47.4	0.343
200	0.8	0	0.114	59.40	0.266
200	0.8	2	0.209	59.75	0.323
200	0.8	5	0.546	53	0.411
400	0.5	0	0.0729	69.206	0.1905
400	0.5	2	0.4089	69.59	0.242
400	0.5	5	0.2058	75.71	0.3427
400	0.8	0	0.4912	69.05	0.269
400	0.8	2	0.4589	69.226	0.322
400	0.8	5	0.3039	85.644	0.412

Step 2: Obtain normalized decision matrix $X_{ij}^* = \frac{Xij}{\sqrt{\sum Xi^2}}$

TABLE IX.
VALUES OF Xi^2 AND $\sqrt{\sum Xi^2}$

Xi^2	1.20991799	51057.4803	1.11354354
SQRT($\sum Xi^2$)	1.09996272	225.959024	1.05524572

TABLE X.
NORMALIZED TABLE

Power (W)	Wall Thickness (mm)	Angle	Von-Misses (MPa)	Max Temperature (^{0}C)	Displacement (mm)
200	0.5	0	0.0051358	3375.61	0.035721
200	0.5	2	0.066564	3268.4089	0.058081
200	0.5	5	0.024336	2246.76	0.117649
200	0.8	0	0.012996	3528.36	0.070756
200	0.8	2	0.043681	3570.0625	0.104329
200	0.8	5	0.298116	2809	0.168921
400	0.5	0	0.0053144	4789.4704	0.03629025
400	0.5	2	0.1671992	4842.7681	0.058564
400	0.5	5	0.0423536	5732.0041	0.11744329
400	0.8	0	0.2412774	4767.9025	0.072361
400	0.8	2	0.2105892	4792.2390	0.103684
400	0.8	5	0.0923552	7334.8947	0.169744

Step 3: Calculate the weighted normalized decision matrix

TABLE XI.
CALCULATION OF WEIGHTS

S. No.		Von-Misses (MPa)	Max Temperature (^{0}C)	Displacement (mm)
	Weights	0.33	0.33	0.33
1		0.06515221	0.25712627	0.1791052
2		0.2345534	0.25301048	0.22838283
3		0.14182299	0.20977255	0.32504278
4		0.10363988	0.26287952	0.25207399
5		0.19000644	0.26442847	0.30608984
6		0.49638046	0.2345558	0.38948274
7		0.06627497	0.30627677	0.18052667
8		0.37173987	0.30797619	0.22933047
9		0.18709725	0.33506075	0.32475848
10		0.44656059	0.30558638	0.25491693
11		0.41719596	0.30636528	0.3051422
12		0.27628209	0.37902447	0.39043039

TABLE XII.
NORMALIZED WEIGHT TABLE

S. No.	Von-Misses (MPa)	Max Temperature (^{0}C)	Displacement (mm)
1	0.02169569	0.08485167	0.05910472
2	0.07810628	0.08349346	0.07536633
3	0.04722705	0.06922494	0.10726412
4	0.03451208	0.08675024	0.08318442
5	0.06327214	0.0872614	0.10100965
6	0.16529469	0.07740341	0.12852931
7	0.02206957	0.10107133	0.0595738
8	0.12378938	0.10163214	0.07567906
9	0.06230338	0.11057005	0.1071703
10	0.14870468	0.10084351	0.08412259
11	0.13892625	0.10110054	0.10069693
12	0.09200194	0.12507808	0.12884203

Step 4: Determine the worst and the best alternative.

TABLE XIII.
VALUES OF V^+ and V^-

V^+	0.02169569	0.06922494	0.05910472	V^+
V^-	0.16529469	0.12507808	0.12884203	V^-

Step 5: Calculate Separation Measures

$$(S)^+ = \sqrt{\sum_{j=1}^{m} (V_{ij} - V^+)^2} \qquad (S)^- = \sqrt{\sum_{j=1}^{m} (V_{ij} - V^-)^2}$$

TABLE XIV.
NORMALIZED WEIGHT TABLE

S. No.	S^+	S^-
1	0.015627	0.164627
2	0.060417	0.110412
3	0.054509	0.132383
4	0.032423	0.143728
5	0.061725	0.112309
6	0.15971	0.047676
7	0.031852	0.160897
8	0.108388	0.071405
9	0.075291	0.106242
10	0.133255	0.053501
11	0.128409	0.045413
12	0.113692	0.073293

Step 6: Calculate relative closeness to positive ideal solution $Pi = \frac{S^-}{S^- + S^+}$ and rank them.

TABLE XV.
RANK TABLE

$S^- + S^+$	P_i	Rank
0.180254	0.913307	1
0.170828	0.646331	5
0.186891	0.708341	4
0.176151	0.815938	3
0.174034	0.645329	6
0.207386	0.229889	12
0.192749	0.834749	2
0.179794	0.397151	8
0.181533	0.58525	7
0.186756	0.286476	10
0.173823	0.261262	11
0.186985	0.391972	9

From the above table we can conclude that the best optimal result is found at 200W, 0^0 angle and 0.5mm wall-thickness.

Comparison of Stainless steel 316L and Inconel 718: Fig.4, Fig.5 and Fig.6 shows the comparison of the materials drawn from the results obtained.

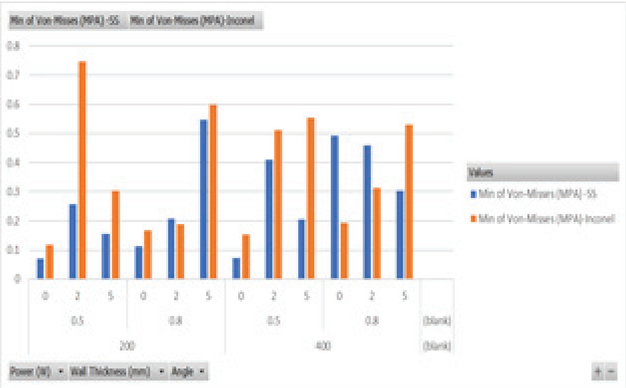


Figure 4. Variation of von-misses stress w.r.t Power, angle and wall-thickness

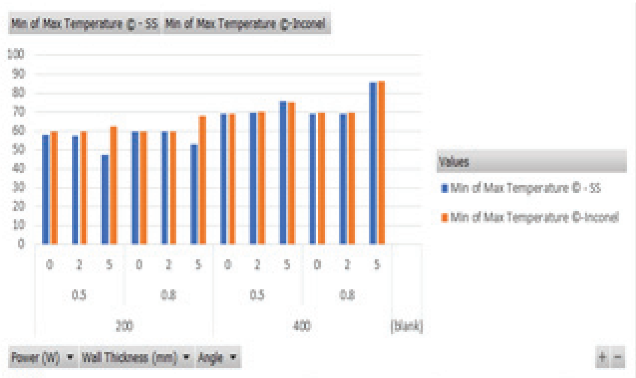


Figure 5. Variation of Maximum temperature w.r.t Power, angle and wall-thickness

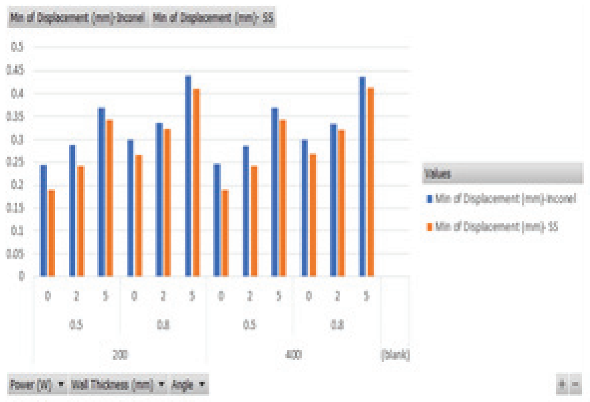


Figure 6. Variation of Displacement w.r.t Power, angle and wall-thickness

IV. DISCUSSION

The minimum stress and minimum displacement occur at 200W, 0^0 and 0.5mm wall-thickness and minimum of max temperature occurs at 200W, 5^0 and 0.5mm wall-thickness. To resolve this ambiguity, one of the MADM technique i.e., Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is used. As result, it was found that optimal value occurs at 200W, 0^0 and 0.5mm wall-thickness. Later, the graphs are plotted between both the materials to find out which material gives better results. It is observed that Stainless Steel 316L at 200W, 0^0 and 0.5mm wall-thickness gives us better results.

V. CONCLUSIONS

From the present study the following conclusions can be drawn:

1. Stainless steel 316L and Inconel 718 are selected for manufacturing the impeller is because both the materials have high corrosion resistance.
2. Amphyon software gives us the mechanical and thermal results using inherent strain method and thermal global analysis method respectively.
3. The minimum Von-misses stress, minimum Displacement and minimum of max Temperature are recommended to avoid failure in the supports and work-piece.
4. Based on the simulation results of Stainless steel 316l, the minimum stress and minimum displacement occurs at 200W, 0^0 and 0.5mm wall-thickness and minimum of max temperature occurs at 200W, 5^0 and 0.5mm wall-thickness. To resolve this optimization is done using TOPSIS technique and best result was obtained at 200W, 0^0 and 0.5mm wall-thickness.
5. Finally, when the results of both the materials were compared, Stainless steel 316L at 200W, 0^0 and 0.5mm wall-thickness had minimum von-misses stress, displacement and minimum of max temperature. Thus, the material recommended is stainless steel 316L.

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