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 (200 to 400W), Wall-thickness at 0.5 to 0.8mm and Angle at 0° to 60°. Amphyon is a module 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° 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 to the pump 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 recommends 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 behavior 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 metallic powder using a recoater 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° to 60°) using Amphyon software. Amphyon is a module 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° to 60°) 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.

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.

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

| Property | Value |
|----------|-------|
| Carbon | ≤ 0.03 |
| Manganese | ≤ 2 |
| Silicon | ≤ 1 |
| Nitrogen | ≤ 0.1 |
| Phosphorous | ≤ 0.045 |
| Sulphur | ≤ 0.015 |
| Molybdenum | 2-3 |
| Chromium | 16-18 |
| Nickel | 10-14 |
| Iron Balance | |
| Manganese | ≤ 0.03 |

| 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 | ≤ 1.00 |
| Aluminium | 0.20-0.80 |
| Manganese | ≤ 0.35 |
| Silicon | ≤ 0.35 |
| Copper | ≤ 0.30 |
| Carbon | 0.02 – 0.05 |
| Nitrogen | ≤ 0.03 |
| Oxygen | ≤ 0.03 |
| Phosphorous | ≤ 0.015 |
| Sulphur | ≤ 0.015 |
| Calcium | ≤ 0.01 |
| Magnesium | ≤ 0.01 |
| Selenium | ≤ 0.005 |
| Boron | ≤ 0.005 |
| Iron Balance | |

| 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.
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.

### C. Amphyon Software

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| 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 | 32 A |
| 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 |

**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 are 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°, 2°, 5°) respectively. The impellers with different angles with respect to build plate and their supports are shown in the Figure 3.

### E. Boundary conditions

**Mechanical simulations:**

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

**Thermal simulations:**

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

**Table V. EOSINT M 280 MACHINE TECHNICAL DATA**

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

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

| 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       | 0.8                 | 5     | 0.303            | 62.328                | 0.370             |
| 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             |

Optimization: Table VIII shows minimum stress and displacement at 200W, 0° and 0.5mm wall-thickness and minimum value of maximum temperature occurs at 200W, 5° 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

| Power (W) | Wall Thickness (mm) | Angle | Von-Misses (MPa) | Max Temperature (°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 $X^*_j = \frac{X_{ij}}{\sqrt{\sum X_{ij}^2}}$

| Xi² | 1.20991799 | 51057.4803 | 1.11354354 |
| Sqrt(ΣXi²) | 1.09996272 | 225.959024 | 1.05524572 |

TABLE VI.
VALUES OF INCONEL 718

TABLE VII.
VALUES OF STAINLESS STEEL 316L

TABLE IX.
VALUES OF Xi² AND $\sqrt{\sum X_{ij}^2}$

TABLE X.
NORMALIZED TABLE
Step 3: Calculate the weighted normalized decision matrix

| S. No. | Von-Misses (MPa) | Max Temperature (°C) | Displacement (mm) |
|-------|------------------|----------------------|------------------|
| 1     | 0.06515221       | 0.25712672           | 0.1791052        |
| 2     | 0.2345534        | 0.25301048           | 0.22838283       |
| 3     | 0.14182299       | 0.20977255           | 0.32504278       |
| 4     | 0.10363988       | 0.26287952           | 0.25207399       |
| 5     | 0.19006644       | 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     | 0.18707972       | 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       |

Step 5: Calculate Separation Measures

\[
S = \sqrt{\sum_{j=1}^{n} (V'_j - V)^2} \\
S^* = \sqrt{\sum_{j=1}^{n} (V'_j - V^-)^2}
\]

| 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  | 0.15971  |
| 7      | 0.031852 | 0.071405 |
| 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 4: Determine the worst and the best alternative.

\[
V^* = 0.02169569, 0.06922494, 0.05910472 \\
V^- = 0.16529469, 0.12507808, 0.12884203
\]

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

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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° and 0.5mm wall-thickness and minimum of max temperature occurs at 200W, 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° 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° 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° and 0.5mm wall-thickness and minimum of max temperature occurs at 200W, 0° and 0.5mm wall-thickness. To resolve this optimization is done using TOPSIS technique and best result was obtained at 200W, 0° and 0.5mm wall-thickness.
5. Finally, when the results of both the materials were compared, Stainless steel 316L at 200W, 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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