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# Detailed Research About Use of 3D Printing above Casting of Nickel and Cobalt Superalloys for Extreme Stress Conditions and Its Production Cost Comparison

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**Abstract** – *As the technologies evolves, there are requirements of new materials with more ideal properties for extreme physical conditions of operation. In this paper we have provided research about how to use Nickel and Cobalt Superalloys are manufactured and machined for these specific purposes. Use of 3D Printing technology to manufacture solid Single Crystal Structures and reduction in dendrite formation to endure Extreme Stress Conditions like in Gas Turbine Blades, Nuclear Reactors, Heat Exchangers and Chemical and Petrochemical Reaction vessels etc. As high structural stability and maximum deformation resistance is required to handle Very high temperature, pressure, flow and chemical corrosion.*

***Key Words***: **Additive manufacturing, 3D metal printing, solid state sintering, liquid particle sintering, metal laser sintering (mLS), single crystal structure, casting process, nickel superalloy, cobalt superalloy, mass production, production costs.**

## 1. INTRODUCTION

This paper is about the research conducted to understand and define the difference between use of additional manufacturing and casting of metal in terms of its uses in Extreme stress conditions requiring high Tensile strength, High temperature resistance, High melting point, High creep fatigue life and Maximum deformation resistance.

## 2. NICKEL AND COBALT SUPERALLOYS

Nickel and Cobalt superalloys are high performance materials for demanding applications that require high tensile and yield strength, and ductility, over a wide temperature range. They are usually composition of Aluminium, Titanium, Tungsten, Chromium, Zirconium, Copper, Iron, Molybdenum etc. The following are the detailed information and composition of the superalloys.

### 2.1 Nickel Superalloys

Nickel superalloys generally contain at least 50% nickel, and may contain significant amounts of chromium and molybdenum. These metals were developed to provide greater strength at high temperatures, and greater corrosion resistance (including high temperature corrosion) than could be obtained from iron and steel. Some of these include INCONEL [600, 617, 625, 690, 718, X-750, 751, 792], NIMONIC [75, 80A, 90, 105, 263], IN100.

INCONEL is a family of austenitic Nickel-Chromium superalloys. Inconel alloys are oxidation-corrosion-resistant materials well suited for service in extreme environments subjected to pressure and heat. When heated, Inconel forms a thick, stable, passivating oxide layer protecting the surface from further attack. Inconel retains strength over a wide temperature range, attractive for high temperature applications where aluminium and steel would succumb to creep as a result of thermally induced crystal vacancies. Inconel's high temperature strength is developed by solid solution strengthening or precipitation hardening, depending on the alloy.[1]

Inconel 600: Solid solution strengthened
Inconel 617: Solid solution strengthened (nickel-chromium-cobalt-molybdenum), high-temperature strength, corrosion and oxidation resistant, high workability and weldability. [2]
Inconel 625: Acid resistant, good weldability. The LCF version is typically used in bellows.
Inconel 690 Nuclear: Low cobalt content for nuclear applications, and low resistivity. [3]
Inconel 718: Gamma double prime strengthened with good weldability. [4]
Inconel X-750: Commonly used for gas turbine components, including blades, seals and rotors.
Inconel 751: Increased aluminium content for improved rupture strength in the 1600 °F range. [5]
Inconel 792: Increased aluminium content for improved high temperature corrosion properties, used especially in gas turbines.

| ELEMENTS (PROPORTION BY MASS %) | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| INCONEL | Ni | Cr | Fe | Mo | Nb & Ta | Co | Mn | Cu | Al | Ti | Si | C | S | P | B |
| 600 | ≥72.0 | 14.0–17.0 | 6.0–10.0 | - | - | N/A | ≤1.0 | ≤0.5 | - | - | ≤0.5 | ≤0.15 | ≤0.015 | -- | |
| 617 | 44.2–61.0 | 20.0–24.0 | ≤3.0 | 8.0–10.0 | - | 10.0–15.0 | ≤0.5 | ≤0.5 | 0.8–1.5 | ≤0.6 | ≤0.5 | 0.05–0.15 | ≤0.015 | ≤0.015 | ≤0.006 |
| 625 | ≥58.0 | 20.0–23.0 | ≤5.0 | 8.0–10.0 | 3.15–4.15 | ≤1.0 | ≤0.5 | - | ≤0.4 | ≤0.4 | ≤0.5 | ≤0.1 | ≤0.015 | ≤0.015 | - |
| 690 | ≥58 | 28–31 | 7–11 | - | - | ≤0.10 | ≤0.50 | ≤0.50 | - | - | ≤0.50 | ≤0.04 | ≤0.015 | - | - |
| 718 | 50.0–55.0 | 17.0–21.0 | Remainder | 2.8–3.3 | 4.75–5.5 | ≤1.0 | ≤0.35 | ≤0.3 | 0.2–0.8 | 0.65–1.15 | ≤0.35 | ≤0.08 | ≤0.015 | ≤0.015 | ≤0.006 |
| X-750 | ≥70.0 | 14.0–17.0 | 5.0–9.0 | - | 0.7–1.2 | ≤1.0 | ≤1.0 | ≤0.5 | 0.4–1.0 | 2.25–2.75 | ≤0.5 | ≤0.08 | ≤0.01 | - | - |

**Table 1:** Elements (by mass in INCONEL)

**Table 2:** Percentage composition of Cobalt superalloys

| PERCENTAGE BY MASS COMPOSITON OF COBALT SUPERALLOYS | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Co | Cr | Mo | Fe | Ni | Mn | W | C | N | Si | Al | Ti | P | S | B |
| 30075 | 58.7-68 | 27-30 | 5-7 | 0.75 | 0.5 | 1 | 0.2 | 0.35 | 0.25 | 1 | 0.1 | 0.1 | 0.02 | 0.01 | 0.01 |
| 31537 | 58.9-69 | 26-30 | 5-7 | 0.75 | 1 | 1 | - | 0,14 | 0.25 | 1 | - | - | - | - | - |
| F90 | 58-61 | 19-21 | - | ≤3 | 9-11 | 1-2 | 14-16 | 0.05-0.15 | - | ≤1 | - | - | ≤0.4 | - | - |
| HAVAR | 42 | 19.5 | 2.2 | 19.8 | 12.7 | 1.6 | 2.7 | 0.2 | - | - | - | - | - | | - |

## 2.2 Cobalt Superalloys

At the beginning of the nineteenth century, the cobalt–molybdenum alloy which was called "Stellite" was developed by Haynes. It exhibited better strength at high temperatures as well as better corrosion resistance when compared to other superalloys.

Cobalt superalloys consist of matrix phases that have close-packed structures like fcc or hcp. which are associated with inherent ductility at ambient temperatures and a low diffusivity due to their close packing, resulting in good creep resistance. High strength and good creep resistance at elevated temperatures arise due to stronger bonding, which is reflected in high elastic modulus. Superalloys contain one or more dispersed ordered intermetallic phases to varying extents

The ease of fabrication and the range of properties available for cobalt superalloys make them ideal for a wide range of orthopedic applications, including all metallic components of all joint replacements as well as fracture fixation devices.

They are also used in Gas Turbine combustion chambers and bearings. Some of the Cobalt based superalloys are HAVAR, UNS [R30005, R31538], MP1 (CoCrMo), ASTM F75, F799, F1537, F90, F562.

UNS 30090 or F90 is an alloy of 60% cobalt, 20% chromium, 15% tungsten, and other substances. The alloy used in dentistry and artificial joints, because of its resistance to corrosion. It is also used for components of turbochargers because of its thermal resistance. UNS 30075 was developed by Albert W. Merrick for the Austenal Laboratories in 1932. [6]

## 3. ADDITIVE MANUFACTURING PROCESS

Additive manufacturing is the formalized term for what used to be called rapid prototyping and what is popularly called 3D Printing. Additive Manufacturing (Referred to in short as AM), the basic principle of this technology is that a model, initially generated using a three-dimensional Computer-Aided Design (3D CAD) system, can be fabricated directly without the need for process planning. Although this is not in reality as simple as it first sounds, AM technology certainly significantly simplifies the process of producing complex 3D objects directly from CAD data. The key to how AM works is that parts are made by adding material in layers; each layer is a thin cross-section of the part derived from the original CAD data. Obviously in the physical world, each layer must have a finite thickness to it and so the resulting part will be an approximation of the original data.

All AM Process involves a number of steps that move from the virtual CAD description to the physical resultant part. The Steps are as follows:

1. Computer Aided designing (CAD) of the Part
2. Conversion of CAD to STL File Format
3. STL File transfer to AM Machine and File manipulation
4. Machine Setup
5. Automated Part Building
6. Removal of Part from AM Machine
7. Post Process Machining and Finishing
8. Application of the Manufactured part

Metal Additive Manufacturing process is also known as Powder Bed Fusion (PBF) process. All PBF processes share a basic set of characteristics. These include one or more thermal sources for inducing fusion between powder particles, a method for controlling powder fusion to a prescribed region of each layer, and mechanisms for adding and smoothing powder layers. The most common thermal sources for PBF are lasers. PBF processes which utilize lasers are known as metal Laser Sintering (mLS) machines.

Types of PBF for metal parts:

1. Solid State Sintering (SLS) or Selective laser Sintering (SLS)
2. Liquid Particle Sintering (LPS)
3. Full Melting

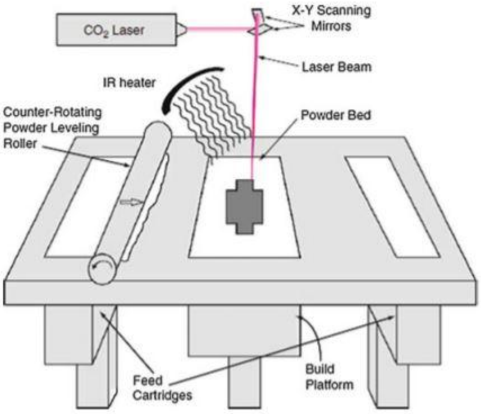


**Fig 1**: Powder Bed Fusion Machining Process

### 3.1 Solid State Sintering [7]

Sintering, in its classical sense, indicates the fusion of powder particles without melting (i.e., in their “solid state”) at elevated temperatures. This occurs at temperatures between one half of the absolute melting temperature and the melting temperature. The driving force for solid-state sintering is the minimization of total free energy of the powder particles. The mechanism for sintering is primarily diffusion between powder particles.

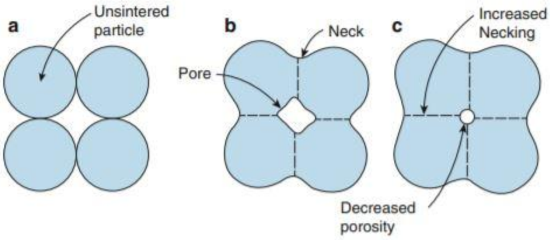


**Fig 2**: Process of Solid-State Sintering [7]

### 3.2 Liquid Particle Sintering

Liquid Particle Sintering the fusion of powder particles when a portion of constituents within a collection of powder particles become molten, while other portions remain solid. In LPS, the molten constituents act as the glue which binds the solid particles together. As a result, high temperature particles can be bound together without needing to melt or sinter those particles directly.

### 3.3 Full Melting or Metal Laser Sintering [7]

Full melting (mLS) is the mechanism most commonly associated with PBF processing of engineering metal alloys and semi-crystalline polymers. In these materials, the entire region of material subjected to impinging heat energy is melted to a depth exceeding the layer thickness.

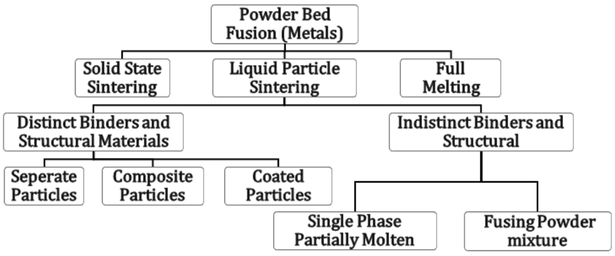


**Fig 3:** Powder Bed Fusion Methods for Metals & Alloys

## 4. SINGLE CRYSTAL STRUCTURES

Single-crystal superalloys (SC or SX) are formed as a single crystal using a modified version of the directional solidification technique, so there are no grain boundaries in the material. The mechanical properties of most other alloys depend on the presence of grain boundaries, but at high temperatures, they would participate in creep and must be replaced by other mechanisms. In many such alloys, islands of an ordered intermetallic phase sit in a matrix of disordered phase, all with the same crystalline lattice. This approximates the dislocation-pinning behavior of grain boundaries, without introducing any amorphous solid into the structure. The absence of the defects associated with grain boundaries can give monocrystals unique properties, particularly mechanical, optical and electrical, which can also be anisotropic, depending on the type of crystallographic structure. This composition also improves physical properties like ultimate and tensile strength, increasing creep life and high temperature and structural stress resistance.

Single crystal (SX) superalloys have wide application in the high-pressure turbine section of aero and industrial gas turbine engines due to the unique combination of properties and performance. Since introduction of single crystal casting technology, SX alloy development has focused on increased temperature capability. [8]

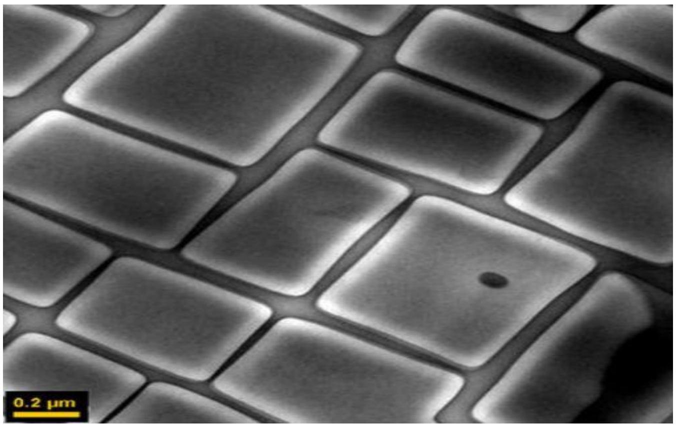


**Fig 4:** Single Crystal Structure of UNS 30075

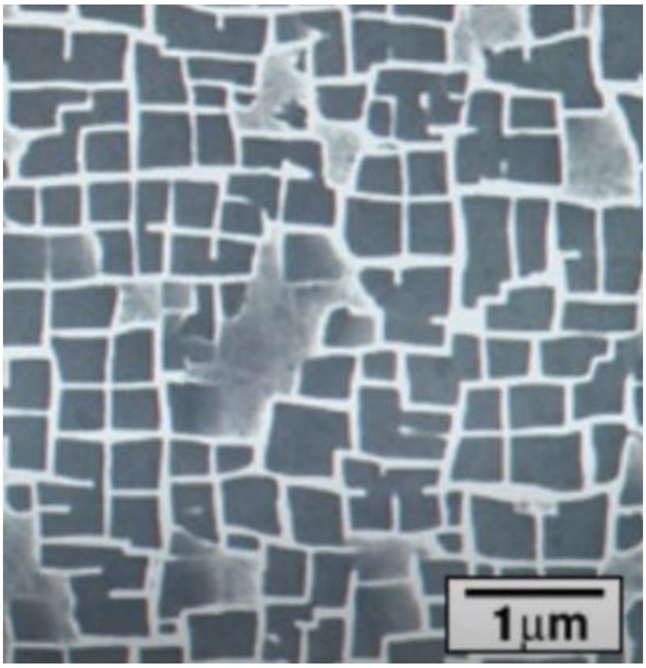


**Fig 5:** Single Crystal Structure of F90

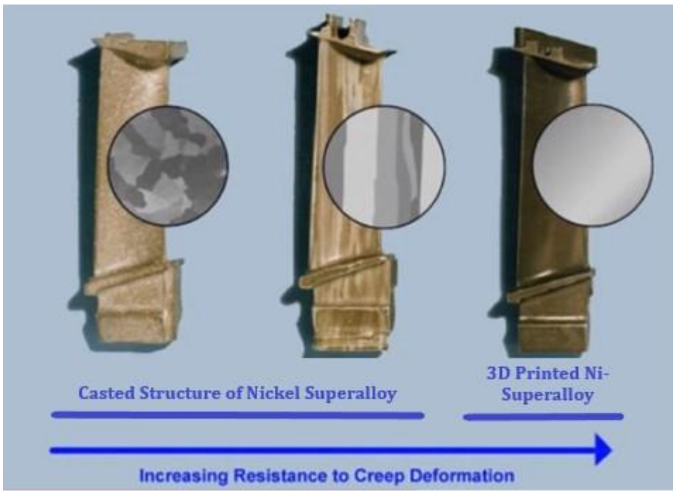


**Fig 6:** Resistance to Creep Deformation [12]

## 5. DENDRITES

Dendrites in metallurgy is a characteristic tree-like structure of crystals growing as molten metal solidifies, the shape produced by faster growth along energetically favorable crystallographic directions. This dendritic growth has large consequences in regard to material properties. An application of dendritic growth in directional solidification is gas turbine engine blades which are used at high temperatures and must handle high stresses along the major axes. At high temperatures, grain boundaries are weaker than grains. In order to minimize the effect on properties, grain boundaries are aligned parallel to the dendrites. Uni-directional dendritic growth resulted in blades with high strength and creep resistance extending along the length of the casting, giving improved properties compared to the traditionally-cast equivalent, whereas random dendritic growth can result in uneven grain boundaries with large reduction in creep life with greater chance of deformation and fatigue failure. [9]

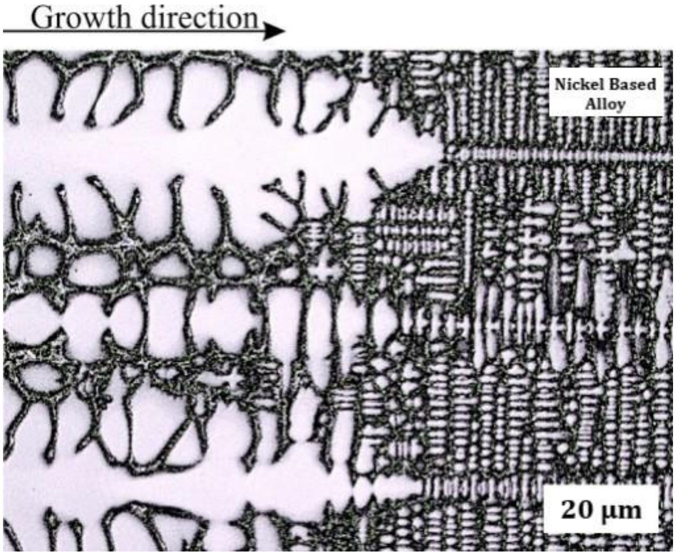


**Fig 7:** Uni-directional Dendrites growth in Nickel Superalloy [10]

## 6. DIFFERENCE BETWEEN 3D PRINTING AND CASTING OF SUPERALLOYS

Additive Manufacturing Process, Specifically Powder Bed Fusion (mLS, SSL, LPS) produces the parts in layer by layer manner by melting the fine powder pool and cooling it causing formation of uniform single crystal structures with uni-directional dendrite growth; Whereas in casting there are very high chances of uneven cooling causing uneven grain boundary formation which reduces the chance of creating single crystal structures, irregular and random dendritic growth is also a great possibility which cause reduction in structural strengths.

According to the tests conducted by us we took two samples of similar dimensions i.e. Cylindrical Specimen of Cobalt Superalloy Co28Cr6Mo (F90) of dimensions according to ASTM E8-13: "Standard Test Methods for Tension Testing of Metallic Materials" (2013). [11] Specimen 1 was 3D Printed and Specimen 2 was made by Casting. Then the samples were put in a Universal Testing Machine. As the results in the **Fig 9**, we can see that increase in Physical properties of the structure is substantial with use of Additive manufacturing over Casting. The Breaking Elongation percentage for Specimens 1 and 2 were ≥40 % and ≥32 % respectively.

**Table 3:** Parameters and Dimensions of Cobalt Based superalloy Specimens 1 and 2

| PARAMETERS OF SPECIMEN | DIMENSIONS (MM) (ASTM E8-13) |
|---|---|
| Gauge Length | 50 ± 0.1 |
| Diameter | 12.5 ± 0.2 |
| Fillet Radius | 10 |
| Length of Reduced Section | 56 |
| Length of Grip Section | 35 |
| Diameter of Grip (Width) | 20 |
| Overall Length | 145 |

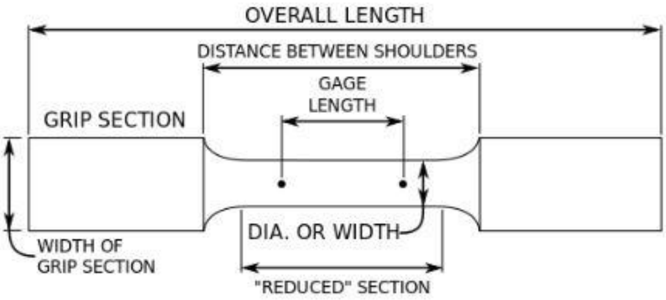


**Fig 8:** Engineering Drawing of the Specimens 1 and 2

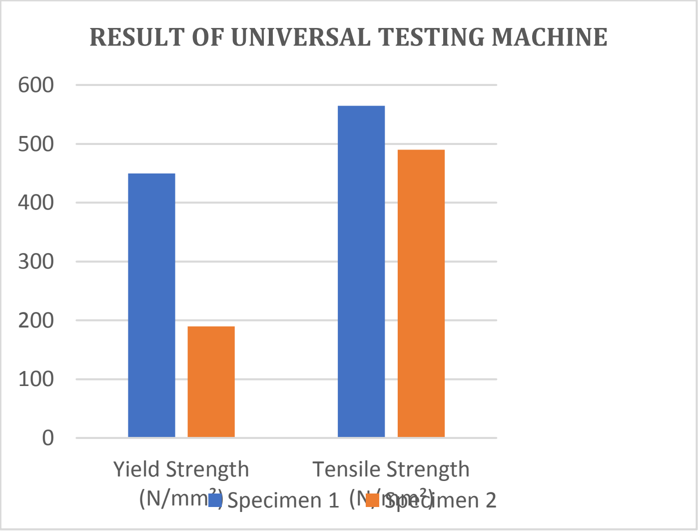
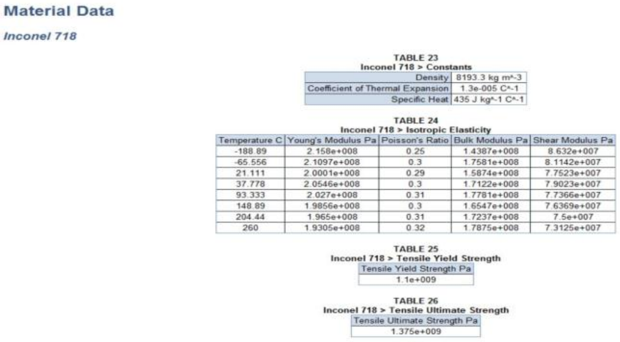


**Fig 9:** Result of UTM Test of the Cobalt superalloy Specimens 1 and 2

Then, we designed a gas turbine blade CAD model with properties of INCONEL 718 and microstructures of both 3D Printing and Casting. The methods assumed for 3D printing is Liquid Particle Sintering (LPS) and for Casting is Vacuum Induction Melting and Bottom Pouring. The Material properties are shown in **Fig10**. The Virtual analysis was conducted through ANSYS Workbench 16.0 software using Finite Element Analysis (FEM). The Analysis parameters of the testing is given in the **Table 4**.



**Material Data**

*Inconel 718*

TABLE 23
Inconel 718 > Constants

| | |
|---|---|
| Density | 8193.3 kg m^-3 |
| Coefficient of Thermal Expansion | 1.3e-005 C^-1 |
| Specific Heat | 435 J kg^-1 C^-1 |

TABLE 24
Inconel 718 > Isotropic Elasticity

| Temperature C | Young's Modulus Pa | Poisson's Ratio | Bulk Modulus Pa | Shear Modulus Pa |
|---|---|---|---|---|
| -188.89 | 2.158e+008 | 0.25 | 1.4387e+008 | 8.632e+007 |
| -65.556 | 2.1097e+008 | 0.3 | 1.7581e+008 | 8.1142e+007 |
| 21.111 | 2.0001e+008 | 0.29 | 1.5874e+008 | 7.7523e+007 |
| 37.778 | 2.0546e+008 | 0.3 | 1.7122e+008 | 7.9023e+007 |
| 93.333 | 2.027e+008 | 0.31 | 1.7781e+008 | 7.7366e+007 |
| 148.89 | 1.9856e+008 | 0.3 | 1.6547e+008 | 7.6369e+007 |
| 204.44 | 1.965e+008 | 0.31 | 1.7237e+008 | 7.5e+007 |
| 260 | 1.9305e+008 | 0.32 | 1.7875e+008 | 7.3125e+007 |

TABLE 25
Inconel 718 > Tensile Yield Strength

| Tensile Yield Strength Pa |
|---|
| 1.1e+009 |

TABLE 26
Inconel 718 > Tensile Ultimate Strength

| Tensile Ultimate Strength Pa |
|---|
| 1.375e+009 |

**Fig 10:** Material Properties of INCONEL 718

**Table 4:** Parameters of FEM Analysis in ANSYS 16.0 [15]

| PARAMETERS (UNITS) | VALUES |
|---|---|
| Pressure (kPa) | 140 |
| Operating Temperature (K) | 1293 |
| Mass Flow Velocity (m/s) | 477 |
| Air Density (kg/m$^3$) | 1.253 |
| Mesh Size (mm) | 1-2 |
| Loading Cycles | 1000 |

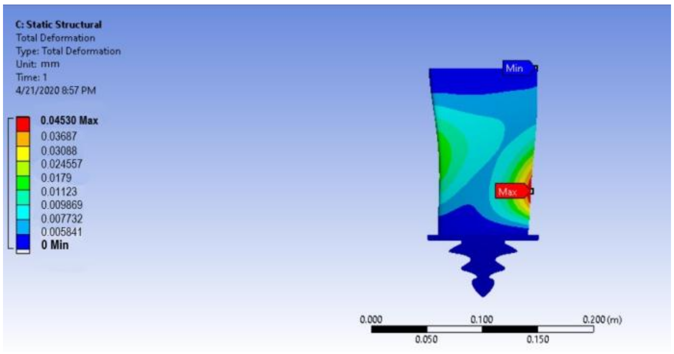


**Fig 11:** Total Deformation of Casted Turbine Blade

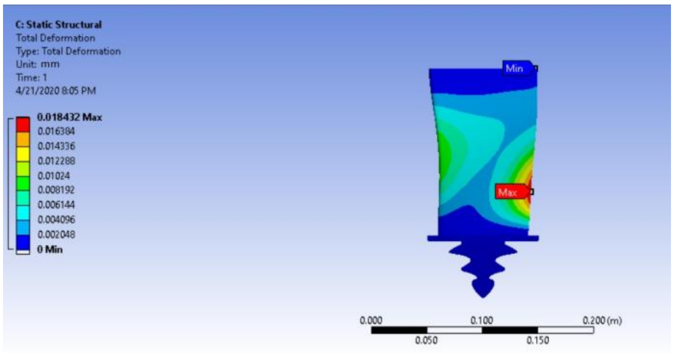


**Fig 12:** Total Deformation of 3D Printed Turbine Blade

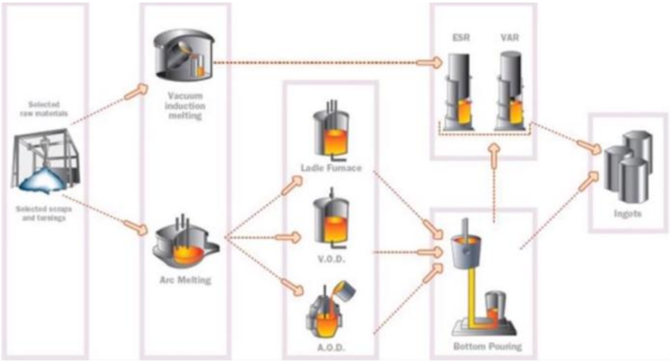


**Fig 13:** Processes of Casting of superalloys

Analyzing the Results obtained (**Fig 11** and **Fig 12**) we can surmise that per 1000 cycles of loading in above parameters part manufactured by Additive Manufacturing shows less deformation than part manufactured by Casting.

## PRODUCTION COST COMPARISION

Taking prices of Ingots and Powders of Nickel Superalloy (Inconel 718) from various vendors the following prices were averaged and taken into account.

**Table 5**: Average price of INCONEL 718 (Bulk)

| PHYSICAL FORM OF METAL | PRICE PER KG (IN $) |
|---|---|
| Ingot | 50 |
| Powder | 55 |

Then this metal was used to make a simple designed turbine blade using both the methods of manufacturing. Ingot was used in Casting and Powder was used in 3D Printing (mLS). The following trend was observed by using Production Cost Cycle.

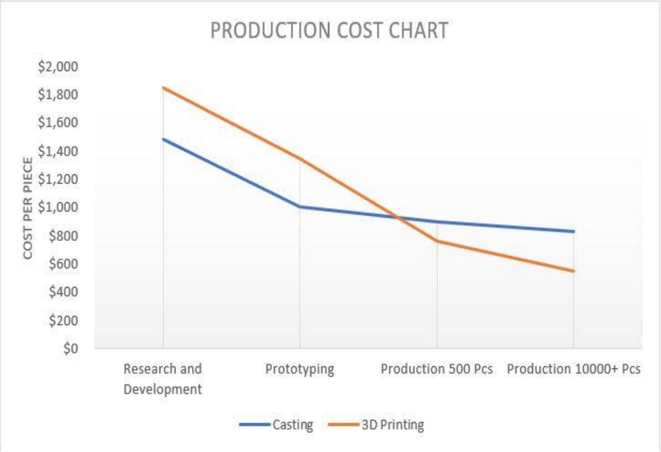


**Fig 14:** Production Cost Chart for Both Manufacturing Processes

According to the chart in initial phases of Research and Development and Prototyping the cost for producing a blade by Casting was way cheaper than 3D Printing but as bulk production started, per piece cost of 3D Printing became lower than Casting because of minimum material wastage and no need of highly complex moulds to acquire specific physical properties like Single Crystal Structures.

## CONCLUSIONS

Hence from the above Testing and Research conducted by us we can see that parts manufactured by Additive Manufacturing are 95 % more resistant to Physical Deformation under Extreme Stress Loading than the parts manufactured by Casting. Thus, we come to the conclusion that in case were parts are to operate in Extreme Stress Conditions Additive Manufacturing Process (3D Printing) is more suitable than Casting because better Structural properties can be achieved by the Additive Manufacturing Process and with less Wastage of material.

And, from above Cost comparison we can come to the conclusion that In Bulk Production of material with need of uncommon material properties like superalloys Additive Manufacturing is more Cost Saving and Viable option than Casting.

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## BIOGRAPHIES

Geet Mehta is a Plant Automation Engineer at Malwa Oxygen and Industrial Gases Pvt. Limited. He designs new automatic system structures incorporating modern day automation software and hardware to increase pharmaceutical productivity of the industry. He carried out the prototyping and test analysis of the superalloy specimens and assessed the results.

Mayank Chandwani is a Project Management Executive at JASH Engineering Limited. He handles projects for isolation gates, manual and automated screens for power, sewage, lift irrigation and desalination project location. He researched about various methods of Additive Manufacturing of metals with specific idea for 3D printing of superalloys and studied their micro structures for stress loading.