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Processing and Characterization of Inconel 718 Alloy Metal by Using Selective Laser Sintering Method

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ABSTARCT

Direct Metal Laser Sintering (DMLS) is an additive manufacturing process that uses a high-powered laser to selectively fuse metal powder particles to create fully dense metal parts layer by layer. The process is commonly used for producing complex and intricate metal components with high accuracy. Inconel 718 is a high-strength, corrosion-resistant nickel-based super alloy. It is one of the most widely used materials in demanding applications where high-temperature and extreme environment resistance is required. In present research work the IN718 samples are manufactured by using DMLS and modeled by using CAD as per ASTM Standards. The modeled samples were saved in STL file and fabricated by DMLS method in different orientations. To know the mechanical properties of additively manufactured INCONEL 718 samples by mechanical tests like Tensile, compression, impact wear and corrosion tests will be performed. The results obtained for both the set of samples fabricated in different orientations will be compared with the values of wrought or casted samples of INCONEL 718 alloy and determine the DMLS fabricated parts has good mechanical properties compared to casted samples of INCONEL 718.

Keywords: *Inconel 718, DMLS Process, Horizontal, Vertical, Tensile and Compression Strength, impact strength.*

1.0 INTRODUCTION:

To a large extent, the advantages of modern civilization can be attributed to the higher standard of goods that now have access to. The quality of goods can be improved through proper design, which takes into account both functional and manufacturing requirements. Products are made by converting raw materials into finished goods, which include the design and production of goods using a wide range of techniques and methods. Subtractive manufacturing and additive manufacturing are the two broad categories under which the manufacturing industry can be divided. Nickel superalloys as Inconel are materials widely used in the aerospace industry among others for diffusers, combustion chamber, shells of gas generators and other, exposed to high temperature and pressure [3].

1.1 HISTORY OF ADDITIVE MANUFACTURING

In the early 2000s, additive manufacturing (AM) became popular because of the idea of materials being combined. As an alternative, the term "subtractive manufacturing" was coined to refer to a broad range of machining methods in which material removal is the primary method of producing a finished product. However, in the views of the general public, 3D printing still meant mainly polymer technologies, and the name AM was more commonly associated with the metalworking industry than polymer, inkjet, or stereolithography enthusiasts. Despite its invention in 1950, inkjet technology was the least known and, due to its complexity, was also the most misunderstood [6].

1.2 DIRECT METAL LASER SINTERING (DMLS)

Direct laser metal sintering (DLMS), also referred to as direct laser metal forming (DLMF) and selective laser melting (SLM), is a method wherein a highly intensive laser beam is directed onto a metal powder bed and fused metal particles according to a computer-aided design file (Shibli *et al.*, 2013). This technology is an extension of the SLS process, which also regenerates real 3D parts from layer-by-layer additions of fused metal powder. This technology allows the fabrication of human implants in minimum processing time, directly from computer-aided design models (Traini *et al.*, 2008). Laser-forming methods, like DLMS, allow the fabrication of functionally graded metallic implants with a gradient of porosity perpendicular to the long axis, which is helpful for bone in-growth. Schematic diagram of DMLS process is shown below:

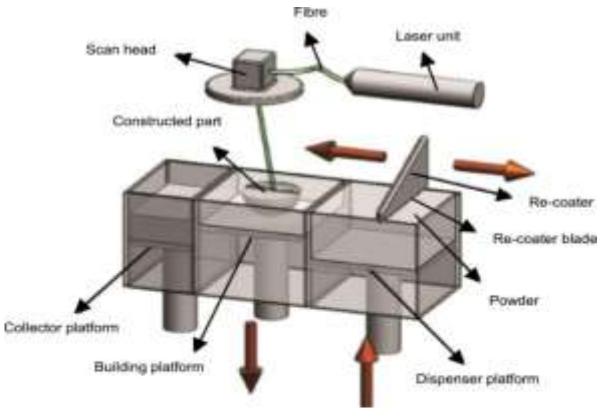

Figure 1.1: Schematic Diagram of DMLS

DMLS has the ability to produce fine features and thin walls, with good accuracy, resolution, and mechanical properties of the finished parts.

2. LITERATURE REVIEW

The experimentally investigated the mechanical properties of the components through DMLS process .mechanical properties of a component fabricated through DMLS process is more inferior to traditional manufacturing process. Process parameters such as layer thickness, scan speed, laser power has showing large impact on hardness [1].The study of the effect of tensile and fatigue properties of Inconel 718. Premature necking is generally seen in the specimen having t/d <1.Miniature specimens of Inconel718 has t/d>4 which provide good yield strength and uniform elongation and fatigue limit [2]. Investigated the fracture behaviour of nickel super alloy obtained from cast and additive manufacturing process [3]. Crack initiation has been significantly differs from microstructure of specimens. Specimen manufactured with additively manufacturing process has high fracture toughness at initiation and subsequent crack propagation [4].Analyzed the corrosion behavior of Inconel 718 manufactured with DMLS process is with commercial alloy. DMLS samples gives good corrosion resistance rather than commercial alloy due to high precipitation. In EDL analysis it was found that iron element is more in commercial alloy and nickel element is more in DMLS alloy [5].Experimentally investigated about build surface quality and fatigue behavior of additively manufactured Inconel718. SLM of Inconel 718powder is increasingly used to fabricate customized parts of jet engine. Surface quality of SLM parts is influenced by powder characteristics, process parameters and the layer wise fabrication [6].

3. METHODOLOGY

Selection of Material:

Material used for the present work is additively fabricated inconel718 samples, which is taken in powder form. Material composition will be mentioned below

Table 3.1: Chemical composition of In718 (Metal Composition Data)

Element	Sample composition (%)	Standard composition (%) [2]
Ni	53	55.0-55.5
Cr	18.2	17.0-21.0
Fe	18.1	18.5
Mo	2.8	3.0
Ti	1.1	0.65-1.15
Co	0.98	1.00
Nb+Ta	5.2	5.1

3.1 MATERIAL DESCRIPTION AND FABRICATION

Material used for fabrication of samples is inconel718. Initially the material is taken in the form of powder. In718 powder was obtained from EOS engineering Inc. The powder is sieved with a mesh size of 90 µm to avoid inhomogeneity in the distribution of the particle size. Table 3 represents the chemical composition of the employed Inconel 718 powder. The prepared files were transferred to a DMLS EOS M280 metal 3D printer (EOS GmbH Electro Optical Systems, Germany), equipped with a 400 W Ytterbium fiber laser. All samples were fabricated in 200 sliced layers.

3.2 MACHINE DESCRIPTION

The machine which is used for fabricating the samples is EOSM290.

Figure 3.1: EOSM280

(INTECH DMLS, Pvt Ltd, Bangalore**)**

EOS M 280 Produces highest quality metal parts in additive manufacturing. The robust system design and the powerful 400-watt fiber laser enable a reliably high performance day in, day out. The exceptional high beam quality of the laser spot and its excellent detail resolution is ideal for manufacturing highly complex DMLS components ensuring homogeneous part properties from part-to-part, job-to-job and machine-to-machine. The intuitive, open and productive CAM tool EOSPRINT allows optimization of CAD data ensuring a quick and easy job and workflow management.

Table 3.2: EOSM280 Machine specifications

(INTECH DMLS, Pvt Ltd, Bangalore**)**

Building volume	250 x 250 x 325 mm (9.85 x 9.85 x 12.8 in) (height incl. build plate)
Laser type	Yb fibre laser; 400 W
Precision optics	F-theta lens; high speed scanner
Layer thickness	40 microns
Scanning speed	960 mm/s
Focus diameter	100 µm (0.004 in)
Power consumption	MAX. 8,5 kW/ average 2,4 kW/with platform heating up to 3,2 Kw
Inert gas supply	7,000 hPa; 20 m³/h (102 psi; 706 ft³/h)
Dimensions (W x D x H)	2,500 x 1,300 x 2,190 mm (98.4 x 51.2 x 86.2 in)
Scan Strategy	Stripes

Powder bed fusion (PBF) is an additive manufacturing process and works on the same basic principle in that parts are formed through adding material rather than subtracting it through conventional forming operations such as milling**.** The PBF process begins with the creation of a 3D CAD model, which is numerically 'sliced' into several discrete layers.

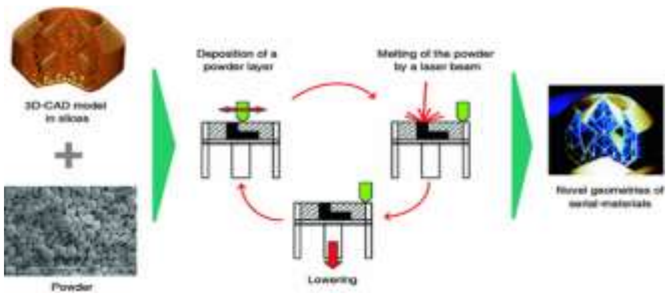

Figure 3.2: Powder Bed Fusion Method

In horizontal orientation we are taking length of the specimen in z direction and height of specimen in y direction.

Specimen length is along z direction =120mm

Specimen length is along y direction =2.50mm

One ends while the other end is fixed. We keep increasing the weight while at the same time measuring the change in the length of the sample. The tensile test is performed individually on both horizontal and vertical orientation and the results are compared. The material has known dimensions like length and cross sectional area .we then begin to apply weight to the material gripped.

Table 3.3: UTM specifications

Model	UTE 40
Max Capacity	400 KN
Measuring Range	0 – 400 KN
Clearances between columns	500 mm
Power supply	3Ø, 440 V, 1.7 KW

3.7.3 Dimensions of tensile Inconel 718 samples:

Dimensions of horizontal orientation sample for tensile test:

Figure 3.4: vertical orientation specimen

Tensile test is performed on the above mentioned dimensions of the specimen and the results are carried out. Dimensions of vertical orientation sample for tensile test:

In vertical orientation we are taking specimen length in x direction and height of the specimen in z direction.in our study we are considering only length and height of the specimen for tensile test.

Figure 3.5: l Horizontal orientation specimen

As per the ASTM standards

Specimen length is along x direction =120mm

Specimen height is along z direction = 2.50mm

Figure 3.6: Tensile Inconel specimens

Tensile test is performed on this vertical orientation specimen and the results are carried out.

After getting results of individual orientations of both the specimens we then compared their results .it was noticed that percentage of elongation tends to starts at tensile load of 78 N nearly. In which orientation better results are obtained are taken into consideration.

3.7.4 Compression test experimentation:

A compression test is a method for determining the behavior of materials under a compressive load. UTM is used for compressive test.

Compression test are conducted by loading the test specimen between the two plates and then applying a force to the specimen by moving the crossheads together.

Compression test generally used to determine mechanical properties such as elastic limit, proportional limit, yield point, yield strength and compressive strength.

During this test the specimen is compressed and deformation versus the applied load is recorded.

3.7.5 Dimensions of compression Inconel 718 samples:

Dimensions of compression test horizontal orientation specimen as per ASTM standards is as follows: in our study we are considering only length and height of the specimen for compression test.

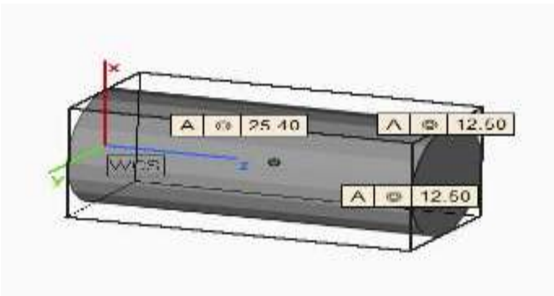

Figure 3.7: Compression specimen of horizontal orientation

Specimen length is along z direction =25.40mm

Specimen length is along x direction =12.50mm

Compression test is performed on these dimensions of the specimen and the results are carried out.

Compression test on the vertical orientation specimen:

In vertical orientation we are taking specimen length in z direction and height of the specimen in y direction.

Specimen length is along z direction =25.40mm

Specimen length is along y direction =12.50mm

Compression test is performed on this vertical orientation specimen and the results are carried out. It was noticed that compression tends to start at a compressive load of 120N.

In which orientation specimen will give best results are taken into consideration.

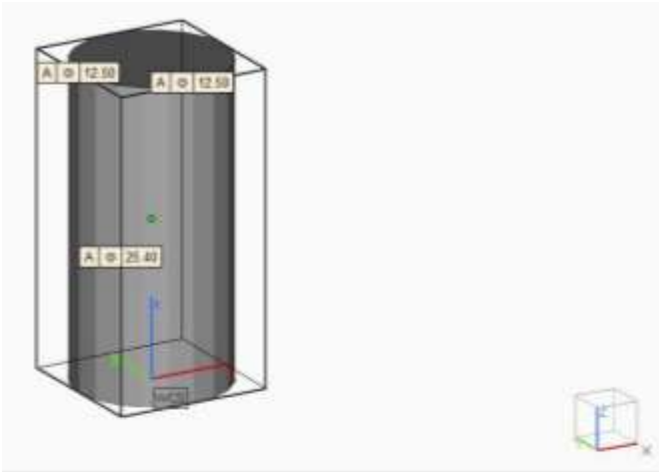

Figure 3.8: Compression specimen of vertical orientation

3.7.6 Impact test experimentation:

Figure 3.9: Charpy impact test machine

The process of impact testing is used to study the various characteristics of materials. These include toughness, hardness, ductility, and strength. It involves sudden application of a load to a specimen in order to determine its impact value.

Charpy impact test:

This test measures the amount of impact energy absorbed by the specimen when it is hit by pendulum and is considered as a good metal impact tester, it shows whether a specimen can be classified as ductile or brittle especially ferritic steels.

Table 3.4: Impact test machine specifications

Suitable for	**Charpy Tests**
Initial potential energy (joules)	300
Pendulum drop angle (degree)	140
Striking velocity of pendulum (m/sec)	5.182
Length of the pendulum (mm)	775
Effective weight of pendulum (kg)	22.5
Distance between pendulum and charpy impact specimen	± 7.75 mm Max

3.7.7 Dimensions of impact Inconel 718 samples:

Dimensions of impact test horizontal orientation of the specimen should be as follows: in our study we are considering only length and height of the specimen for the impact test

Figure 3.10: Impact specimen of horizontal orientation

Specimen length is along x direction = 55.00mm

Specimen height is along y direction =10.00mm

Impact test is performed on the specimen and results are carried out.

Vertical orientation of the specimen:

In vertical orientation of the specimen the dimensions is as follows:

Specimen length is along x direction = 55.00mm

Specimen height is along y direction = 10.00mm

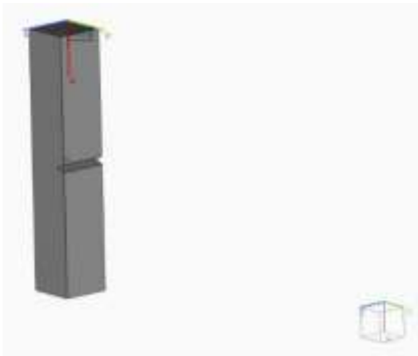

Figure 3.11: Impact specimen of vertical orientation

Results of vertical orientation are compared with horizontal orientation results.it was noticed that maximum energy absorbed by the specimen is at a impact load of nearly 250J. Better results are taken into consideration.

Impact specimen testing:

Figure 3.12: impact specimen before testing

Figure 3.13: Impact specimen after testing

The toughness of Inconel718 is determined by performing Charpy Impact test. The energy absorbed during the material fracture is given as **258 Joules.**

3.7.8 Corrosion test experimentation:

There are various types of corrosion tests.in our experiment we are using electro chemical corrosion testing. A potentiostat instrument is usually used to perform this sort of this test. A three electrode setup, including working electrode, reference electrode and counter electrode are usually used. Potential, current, and time are three important parameters in electrochemical tests.in these tests an applied potential generally scans in a certain range and the current is measured. In this test current is measured when the applied potential scans in a narrow range (-20mv) from lower to higher than corrosion potential.

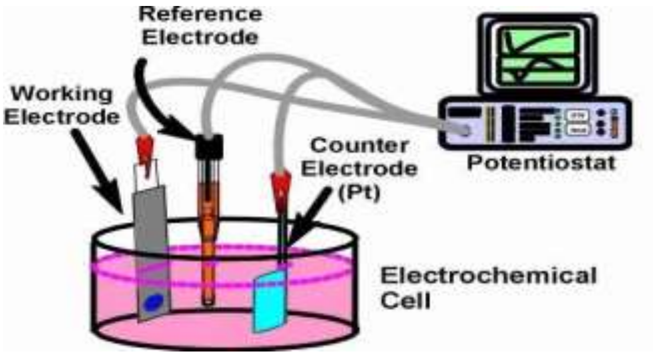

Figure 3.15: Schematic diagram of corrosion test

3.7.9 Dimensions of corrosion Inconel 718 samples:

Specifications of horizontal orientation specimen are as follows:

Specimen length is along x direction = 20.00mm

Specimen width is along y direction = 19.96mm

Specimen height is along z direction = 3.00mm

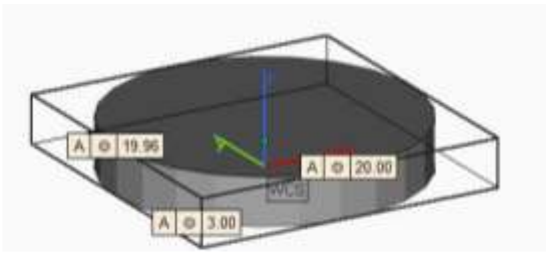

Figure 3.16: Corrosion specimen of horizontal orientation

Results are performed on the specimen and carried out.

Vertical orientation of corrosion specimen:

Specimen length is along y direction =20.00mm

Specimen width is along x direction

= 19.96mm

Specimen height is along z direction =3.00mm

3.8 SUMMARY:

In this chapter the properties of the material, process parameters, characteristics of the material and experimental setup are discussed briefly. The methodology and experimental procedure for fabrication are discussed elaborately.

4. RESULTS AND DISCUSSIONS

In this chapter experimental results obtained from the tensile test, compression test, corrosion test, wear test, of horizontal and vertical orientation Inconel 718 samples has been discussed.

4.1 Tensile test:

After performing the tensile test on Inconel 718 specimens of both horizontal and vertical layer orientations which are fabricated through DMLS process, the results obtained are yield strength and tensile strength, which is tabulated in table 4.1:

Table 4.1: Results of yield strength, tensile strength, % of elongation of horizontal and vertical layer orientation specimens as per ASTM standards are tabulated below

Tensile test results	**Horizontal orientation specimen**	**Vertical orientation specimen**
Yield strength (MPA)	787.52	794.18
Tensile strength (MPA)	974.67	885.30
% of elongation	17.18	36.18

From the above table it is observed that tensile strength for horizontal orientation specimen is higher than vertical orientation specimen. The reason behind that is, in horizontal layer orientation the tensile load applied is parallel to the layer fabrication and the bonding between the layers is more when compared to the vertically layer oriented Inconel specimen which results in more tensile strength.

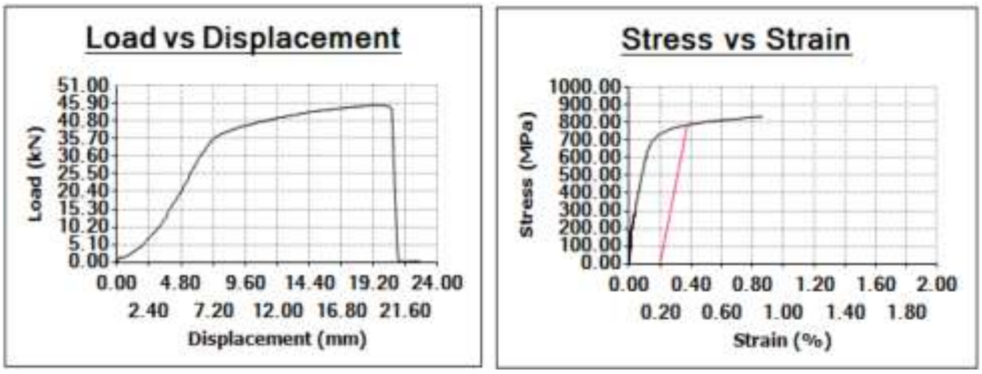

Figure 4.1: Stress strain graph of horizontal orientation Inconel tensile specimen:

Figure 4.1 shows the stress strain relationship of vertically oriented tensile specimen. From the graph it is observed that percentage of strain 0.36% is occurred when the stress of 794.18 MPA is applied on the specimen.

4.1.2 Compression test:

After performing the compression test on Inconel 718 specimens of both horizontal and vertical layer orientations which are fabricated through DMLS process, the results obtained are compression strength, which is tabulated in table 5.2:

Table 4.2: Results of compression strength of both horizontal and vertical layer orientation Inconel 718 specimen as per ASTM standards is tabulated below:

Compression test results	**Horizontal orientation specimen**	**Vertical orientation specimen**
Compression strength (MPA)	918.23	1156.29

From the above table it is observed that the compression strength of vertically oriented fabricated Inconel sample is higher than horizontally oriented fabricated sample. The reason behind that is in vertically oriented Inconel sample the no of specimen layers is more which offers more resistance to deformation. In horizontal orientation Inconel specimen the no of layers fabricated is less which offers less resistance to deformation.

Table 4.3: Results of corrosion resistance performed on horizontal and vertical orientation Inconel 718 specimens:

Corrosion test results	**Horizontal layer orientation Inconel sample**	**Vertical layer orientation Inconel sample**
Corrosion potential (Ecorr) mV	-305.110	-233.377
Corrosion current (I corr) uA	3.843	1.039
beta c (mV)	132.6	22.1
beta a (mV)	421.7	53.7

Chi²	25.0757	187.687
Chi / sqrt(N)	0.193315	2.7398
Equivalent weight(g/eq)	18.408	7.380
Density (g/cm3)	0.834	0.495
Surface area (cm2)	1.000	1
Corrosion rate (mmpy)	0.2337539	1.99518

With the help of tafel fit graph analysis tool, the corrosion rate can be determined if the user enters the values of equivalent weight, material density and the active surface area.

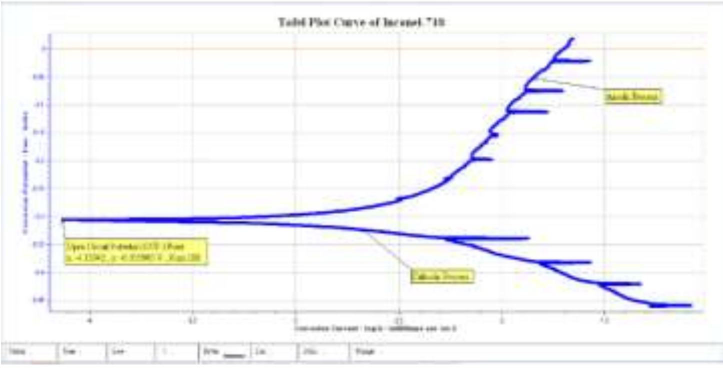

Figure 4.3: Tafel plot curve of Inconel 718 horizontal oriented specimen

Hardness test is performed on both horizontal and vertical layer orientation Inconel 718 samples. The results obtained are Rockwell hardness (HRC) and Vickers hardness (HV) values which are tabulated in the table 5.4

Table 4.4: Vickers hardness (HV) and Rockwell hardness (HRC) results of horizontal and vertical orientation Inconel 718 specimens:

Hardness test	**Horizontal layer orientation Inconel 718 specimen**		**Vertical layer orientation Inconel 718 specimen**	
No of trails	**Vickers hardness (HV)**	**Rockwell hardness (HRC)**	**Vickers hardness (HV)**	**Rockwell hardness (HRC)**
Trail 1	401.1	40.9	703.2	60.2
Trail 2	465.4	46.2	541.6	51.8
Trail 3	472.2	47.1	436.5	44.2
Trail 4	452.8	45.5	418.4	42.5
Trail 5	510.8	49.8	474.7	47.2
Average Hardness Value	**460.26**		**514.88**	

It is observed that average hardness for vertically oriented Inconel 718 specimen is higher than horizontal layer oriented Inconel specimen. The reason behind that is when the load is applied vertically on the samples the strength between the layers is more which causes buckling and indentation takes at more load.

4.1.3 Wear test:

Wear test is performed on both horizontal and vertical orientation Inconel 718 specimens by using wear testing machine. The input conditions applied for testing the wear is track diameter 70mm ,disc speed =500 rpm, distance run= 1KM, load applied = 20N.The results obtained the wear test are wear rate which is tabulated in table 5.5

Table 4.5: Wear rate results of horizontal and vertical orientation Inconel 718 samples:

Horizontal orientation Inconel 718 corrosion specimen			**Vertical orientation Inconel 718 corrosion specimen**		
Weight of specimen before testing (W1)	Weight of specimen after testing (W2)	Wear rate (mg) = (W1-W2)	Weight of specimen before testing (W1)	Weight of specimen after testing (W2)	Wear rate (mg) = (W1-W2)
8.0120	8.0106	1.4	21.6075	21.6041	3.4

It is observed that the wear rate of horizontal orientation corrosion specimen is less than vertically oriented corrosion specimen because in horizontally fabricated samples the strength between the two consecutive layers is comparatively less than the strength between the particles in a layer.

Figure 4.5: Time vs wear rate graph of horizontal orientation Inconel 718 corrosion specimen

Impact test is performed on both horizontal and vertical orientation Inconel 718 samples. The toughness of Inconel 718 is determined by performing charpy impact test. The result obtained from the impact test is impact resistance which is tabulated in the table 5.6:

Table 4.6: Impact resistance results of horizontal and vertical orientation Inconel 718 samples

Layer orientation	Energy absorbed during fracture (joules)
Horizontal layer orientation	258
vertical layer orientation	210

It is observed that impact resistance for horizontal orientation specimen is higher than vertical orientation Inconel specimen .the reason behind that is when the load applied parallel to layer fabrication the strength between the layers is more which offers high resistance to deformation.

5. CONCLUSIONS

The mechanical properties such as hardness, tensile strength, compression strength, impact resistance, wear resistance, corrosion resistance of Inconel 718 specimen of both horizontal and vertical layer orientations, fabricated by powder bed fusion process was studied experimentally. The following conclusions are drawn from the experimental results. Based on the experimental results it is concluded that the ultimate tensile strength, percentage of elongation, wear resistance, wear resistance, corrosion and impact resistance of horizontally fabricated sample is higher than that of vertically fabricated sample.

6. FUTURE SCOPE

The work can be extended to analyze other parameters and other mechanical properties. The level of experiments can be increased for better results. For better results and accuracy we can also use optimization techniques like taguchi analysis, in addition to experimental analysis. Material consumption can be reduced so that cost for fabricating the part is also reduced. The experiments can be planned by varying parameters and the orientation in angular.

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