EXPERIMENTAL STUDY ON MECHANICAL BEHAVIOUR OF ADDITIVELY MANUFACTURED 17- 4PH STAINLESS STEEL

D.O.I - 10.51201/Jusst12600
http://doi.org/10.51201/Jusst12600

Tawseef Abdullah1*, S.S Dhami2, Noor Zaman Khan3

[1] *M.E scholar, Department of Mechanical Engineering, National Institute of Technical Teachers' Training and Research (NITTTR), Chandigarh (India).*

[2] *Professor, Department of Mechanical Engineering, National Institute of Technical Teachers' Training and Research (NITTTR), Chandigarh (India).*

[3] *Assistant Professor, Department of Mechanical Engineering, National Institute of Technology (NIT), Srinagar (India).*

Abstract
Selective laser melting (SLM) is a new additive manufacturing (AM) technique that uses powder materials to build three- dimensional (3D) objects layer-by-layer guided by the CAD model. SLM is used to produce objects using various materials; these objects have properties comparable to benchmarked conventionally produced parts. This investigation focuses on the mechanical behavior of 17-4PH stainless steel parts produced by direct metal printing via SLM. Tensile strength, elongation bending strength and fracture analysis of the printed parts have been observed in this paper. These properties make 17-4PH fit for many industrial applications such as structural parts in aerospace, chemical and petrochemical industries.

Key words: *Selective laser melting, Additive manufacturing, 17-4PH stainless steel, Mechanical behaviour.*

1. INTRODUCTION

Additive manufacturing (AM) is a novel material incremental process in which material is added layer-by-layer. The process is different from conventional subtractive manufacturing in which material is removed from the work piece in the form of chips to get the desired shape. AM has gained a lot of attention over the last ten years due to its immanent advantages, such as unrivalled design freedom and decreased lead times [1-3]. Rapid prototyping (RP) is the first term used to define the creation of 3D objects using the layer-upon-layer process. The technologies that currently exist allow the manufacture of objects that can be considered to be much more than prototypes. When it becomes clear that the technology not only build prototypes but also moulds, tools and matrices the name rapid manufacturing (RM) comes into picture [4]. As compared to RP, RM, and 3D Printing, AM is generally regarded as the most appropriate term to describe the processing strategy of this advanced manufacturing technology. Among various available AM techniques only a handful is able to produce metallic components. The most favored techniques in this context are electron beam melting

(EBM), laser additive manufacturing (LAM) and direct energy deposition (DED). LAM of metals is an iterative, layer wise and powder bed fusion manufacturing methodology.

SLM is a powder bed fusion technique which can fabricate 3D components directly from metallic powders with a suitable wave length to melt and solidify the selective regions layer-by-layer guided by the digital model [5-8]. The process is controlled by adjusting the process parameters such as laser power, scan speed, layer thickness, hatch spacing and build orientation. These parameters must be optimized to get the desired properties. After successful manufacturing, loose powders are removed from the building chamber with the help of a brush and the part is then removed from the substrate plate by band saw or by electrical discharge machining. The whole process takes place under controlled atmosphere of nitrogen or argon to protect the finished part from oxidation, decarburization etc. which adversely affect the mechanical properties of the manufactured object [9].

Loh et al [10] examines the effect of Gaussian beam profiles and uniform beam profiles in selective laser melting of aluminium alloy. It was observed that a uniform laser beam was able to achieve a larger melt pool width for smaller amount of melt penetration by increasing the scan speed and reducing hatch spacing. Rashid et al. [11] studied the effect of scan strategy on density and mechanical properties of 17-4PH stainless steel processed by SLM. In this study two different scan strategies were employed in which one scan strategy involved scanning each layer once named as scan ‘O’ and the other strategy involved scanning each layer twice named as scan ‘X’. It was observed that the printed parts produced by double scan strategy possess high relative density with improved hardness as compared with the parts produced by single scan strategy. Irrinki et al. [12] studied the effect of powder characteristics and energy density on the densification and mechanical behavior of 17-4PH alloy processed by SLM. It was found that the density, ultimate tensile strength and hardness of both the gas and water atomized powders increases with increased energy density. This finding confirmed that the inexpensive water-atomized powder is also feasible to manufacture components with better properties by using SLM. As per the available reviewed literature, very less and systematic studies are available for the evaluation of mechanical properties for the selected material processed by SLM. So in this study an attempt is being made to study the mechanical behaviour of additively manufactured parts produced by SLM.

1.1 Materials available for powder bed fusion (PBF)

The quality of the feedstock that is used in the AM process affects the quality of the finished part. The common feedstock materials that are used in laser additive manufacturing are in the form of powder, wire or sheets. The recent list of materials that can be used with powder bed fusion include stainless steel (17-4PH and 316L), Nickel based alloys (625 and 718), Aluminium, cobalt based super alloys, copper, beryllium and niobium [13]. Research is underway to expand the technology on titanium and its alloys and some new entrants in the market. Since titanium and its alloys have high melting temperature, low fluidity, complex features and have tendency to react with surrounding environment, it is difficult to manufacture these components with conventional processes like casting, forging, extruding etc. [14].

2. OBJECTIVE

Components made by additive manufacturing of alloy 17-4PH, a chromium-nickel-copper precipitation hardenable stainless steel with an addition of silicon and manganese. The combination of desirable properties for instance high tensile strength, high toughness and good corrosion resistance makes the 17-4PH SS suitable for making structural parts/components in aerospace, surgical instruments in biomedical, gate valves, chemical and petrochemical industries etc. [15-19]. The present work focuses investigations on mechanical behaviour viz tensile strength and flexural strength along with the fracture surface of 17-4 precipitation hardening (PH) stainless steel.

3. EXPERIMENTAL WORK

The feedstock material that is used in this experimental work is gas atomized 17-4PH stainless steel also known as alloy 630, supplied by 3D systems.17-4PH stainless steel powder of 20 to 40 micron size was used as base material for performing experiments. The gas medium that is used to produce the powder is inert gas viz. nitrogen to prevent oxidation and contamination.

The elemental composition of the selected powder was reported by energy dispersive X-ray spectroscopy (EDS) embedded with scanning electron microscope (JEOL –IT100) and the morphology of the powder, shown in Fig. 1, is almost spherical which is desirable for SLM.

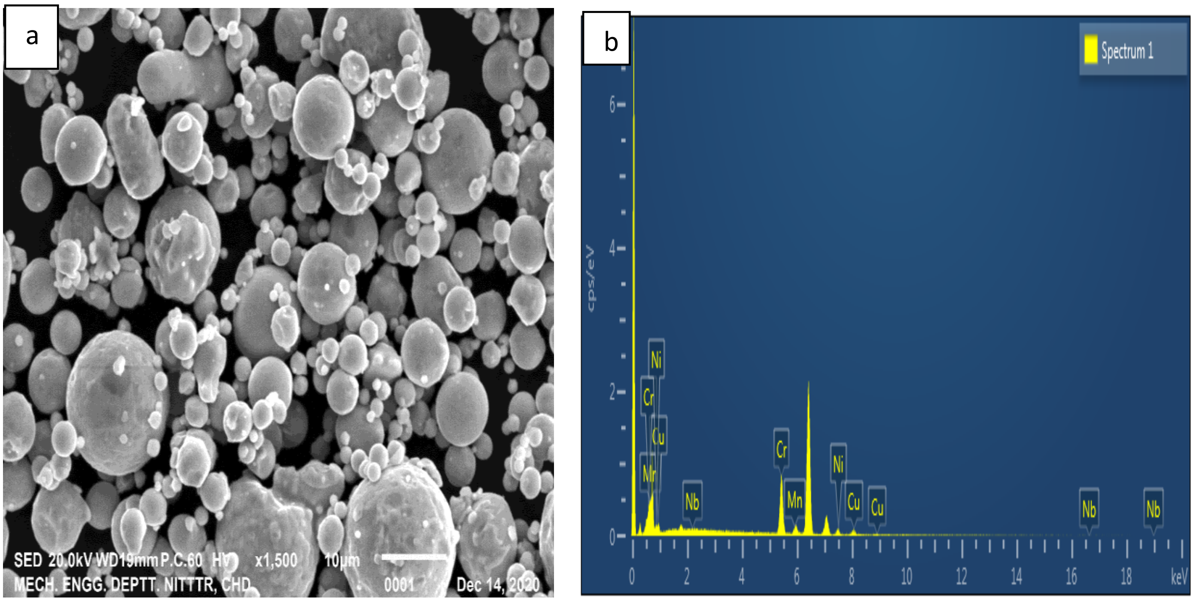

Fig.1 (a) SEM micrograph and (b) EDS of 17-4PH SS powder.

Table 1 gives the elemental composition of the powder that is used to manufacture the parts by SLM.

Table 1 Chemical composition of 17-4PH stainless steel

Element	Cr	Ni	Cu	Si	Nb	Mn	Fe
Weight %	17.50	3.95	4.10	0.60	0.04	0.74	73.07

Fabrication of 3D shapes made of 17-4PH Stainless Steel powder was carried out on a SLM machine (3D Systems, ProX DMP 200).The machine has a build volume of 140×140×115 mm[16]. SS 430F was used as substrate plate to build the samples. The CAD file was prepared by using 3DXpert software as shown in Fig. 2.

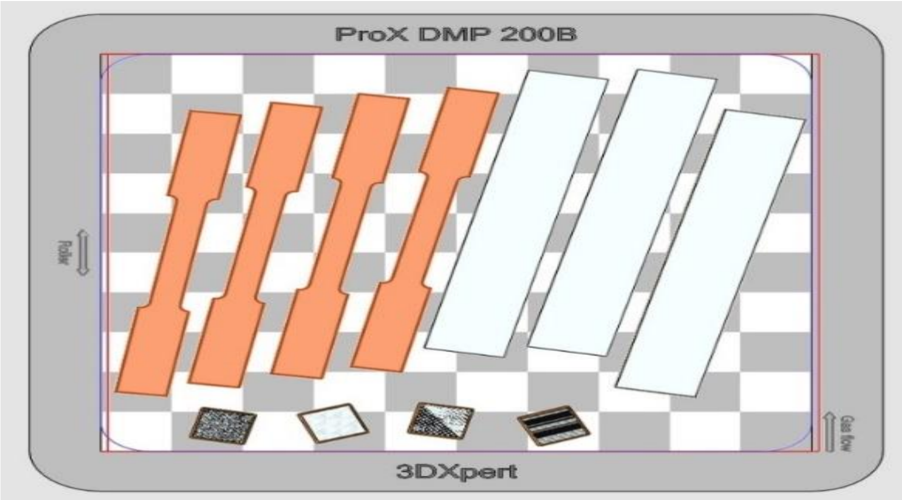

Fig. 2 Orientation of samples in 3DXpert

The orientation and part slicing were done in addition to provide support structure. Solid supports with a height of 0.5 mm from the substrate plate of the same size were provided as an allowance for wire EDM. All specimens were built in horizontal direction. Tensile test specimens were designed according to ASTM E8 sub-size

The hexagonal scanning pattern was used to produce the parts which are the default parameter set by 3D systems. The printing of the parts takes place inside the build chamber which was kept under controlled atmosphere of nitrogen to prevent oxidation and contamination. The time taken to manufacture one build was noted as 7 hours 24 minutes. After successful manufacturing the samples were removed from the build plate by wire EDM. Tensile and bending tests were performed by using universal testing machine (UTM) having 500 kN of maximum load capacity with a resolution of 1 N at an environmental temperature of 24 °C. The fractured surfaces of the tensile test specimen were observed by scanning electron microscope.

The process parameters were selected after pilot study in order to get better mechanical properties. The laser power was chosen to maximize the laser processing efficiency. Too high laser power will result in voids/porosity due to vaporization and low laser power will result in un-melted powder in the parts. So in the present work, the process parameter combination which produces denser parts are used in order to obtain better tensile and flexural strength as tabulated in Table 3.

Table 3. Process parameters selected in this experiment

Laser power (Watt)	Scanning speed (mm/s)	Layer thickness (μm)	Hatch spacing (μm)
105	2500	30	50

4. RESULTS AND DISCUSSIONS

Parts of different shapes made up of 17-4PH stainless steel powder were successfully produced by SLM process. Tensile and flexural tests were carried out on the fabricated parts. The surfaces of all 3D parts produced by SLM were observed to be smooth and did not possess any surface defects as shown in Fig. 3.

Fig. 3 Sample in as-fabricated state on the substrate plate

4.1 Tensile strength

The overall length of the dog-bone shape tensile test specimen was 100 mm, initial cross sectional area 24 mm^2, gauge length of 32 mm with a thickness of 4 mm as shown in Fig. 4. The values of applied loads on UTM were used to calculate the ultimate tensile strength of three as-fabricated tensile test specimens and the average value was calculated. The experiments were conducted under environmental conditions (24 °C) with a strain rate of 0.001/s.

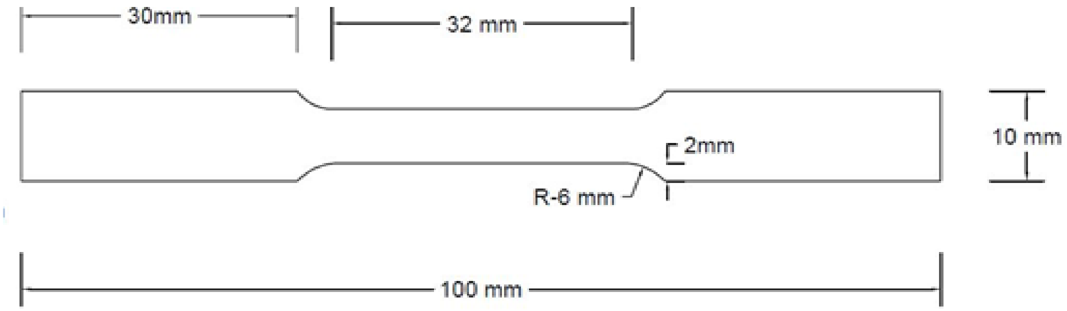

Fig. 4. Configuration of the Tensile Test Specimen.

Three samples for tensile and three for bending were processed by selective laser melting to determine the mechanical behaviour of selective laser melted parts.

Table 4. Ultimate Tensile Strength Measurements of the Test Specimen

Test sample	Applied load P (kN)	Ultimate Tensile strength (MPa) ($\sigma_{uts} = P/A_0$)	Average UTS (MPa)
1	25.50	1062.5	1076
2	26.22	1092.5	
3	25.75	1072.9	

The average value of ultimate tensile strength of 17-4PH stainless steel parts was observed to be 1076 MPa with an average percentage elongation of 15%. The measured values when compared with the conventionally produced 17-4PH stainless steel reported by Mower et al. (2016) shows comparable tensile strength with that of additively manufactured parts. The ultimate tensile strength of wrought 17-4PH stainless steel parts reported was reported as 1085 MPa. Also it was reported that the ultimate tensile strength of as-fabricated 17-4PH stainless steel parts produced by direct metal laser sintering (DMLS) as 1072 MPa, built in horizontal direction with different process parameters [20].

4.2 Flexural strength

The CAD design of the flexural test specimen is shown in Fig. 5. The average value of load at which bending of the specimen occurred was 10.8 kN. The flexural strength of the test specimen was calculated by using equation (1).

– **(1)**

Where σ is the flexural strength (MPa), P is the applied load (kN), l is the length (mm), w is the width (mm) and d is the depth (mm).

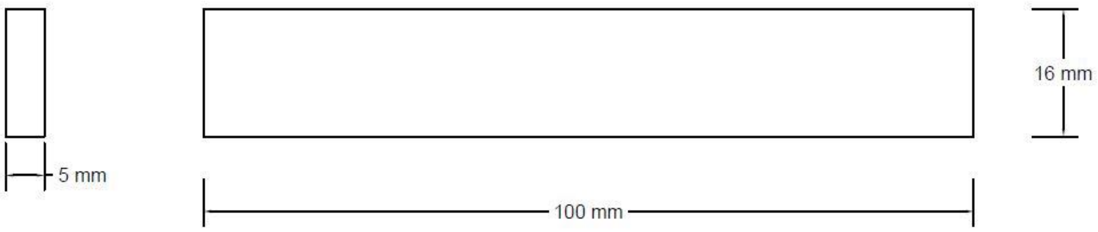

Fig. 5. Configuration of the Flexural Test Specimen.

Flexural strength represents the maximum stress that materials possess due to three or four point flexural loads. The results obtained after performing the flexural test of three samples are summarized in the Table 5.

Table 5. Flexural measurements of the test specimen

Test sample	Applied load P (kN)	Flexural strength (MPa)	Average Flexural strength (MPa)
1	11.2	4200	4050
2	10.8	4050	
3	10.4	3900	

The average value of flexural strength of 17-4PH stainless steel parts was observed to be 4050 MPa.

4.3 Fractography

The fractured samples after performing the tensile and bending tests are shown in Fig. 6


Fig. 6 Fractured Samples of Tensile and Bending Specimen

Fractography of fractured tensile specimen was performed to understand the fracture mechanism of the fabricated parts. Fracture mechanism of as-fabricated part is described by the typical SEM micrographs at mid-section of the fractured tensile specimens as shown in Fig.7.

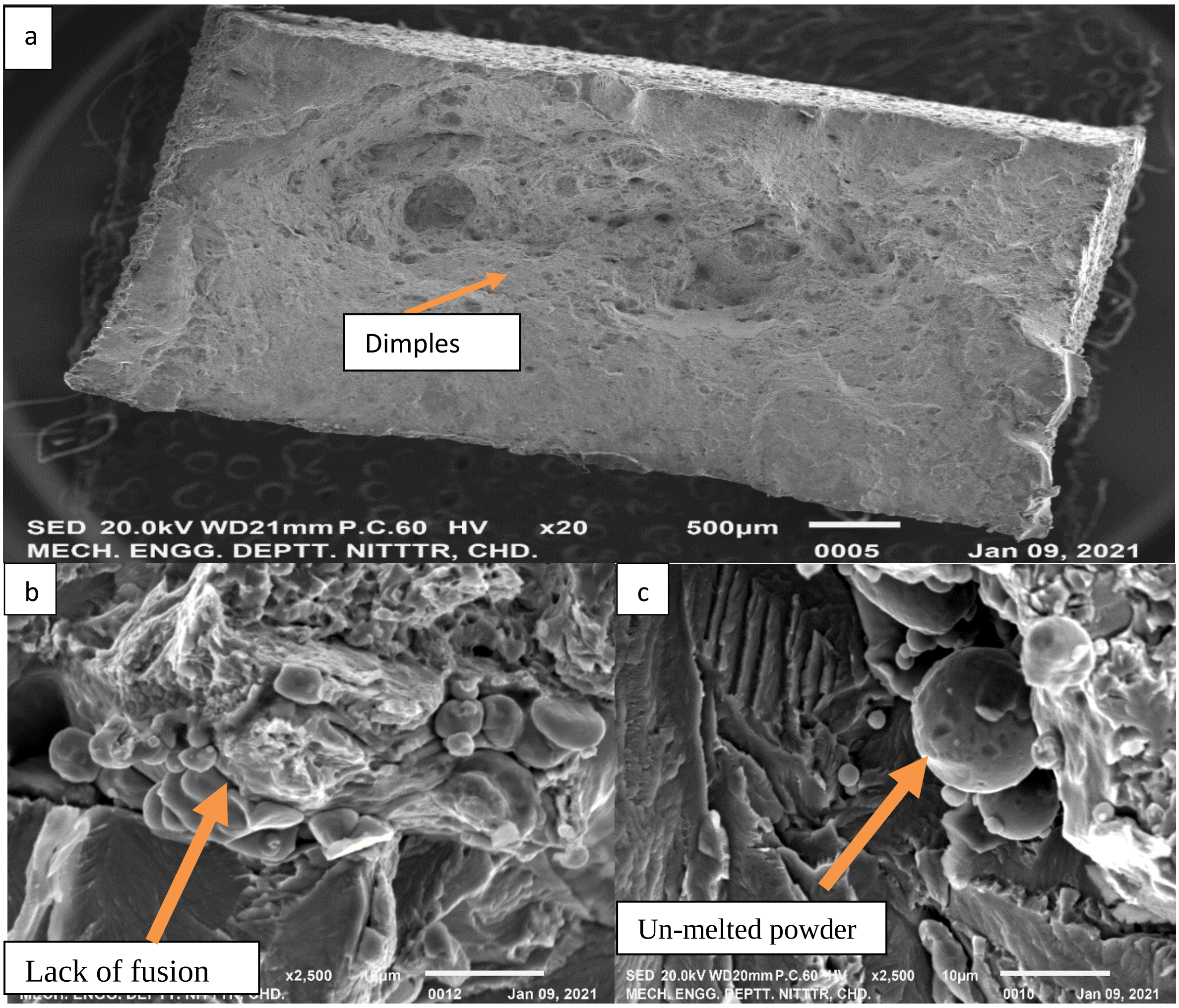

Fig. 7 (a) Fractured Surface of 17-4PH SS in As-built Condition (b) Shows Lack of Fusion (c) Un-melted Powder

From the fractography it is possible to predict the poor fracture resistance of a given material. It was observed that the main reason for failure of the tested specimen is due to un-melted powder particles indicated to be spherical structure, lack of fusion and delamination between the layers. The fractured surface consists of fine and shallow dimples as visible on the fractured cross section of the tensile test specimen.

5. CONCLUSION

Various metallic shapes were successfully manufactured by selective laser melting, an additive manufacturing technique, using 17-4PH Stainless Steel powder. Tensile and bending tests of the additively manufactured sample were performed and fractography was done to analyze the fracture mechanism of tensile specimen. Smooth surface morphology of the fabricated parts was observed without any imperfection. The average value of the ultimate tensile strength and flexural strength of the as-fabricated test specimens was observed as 1076 MPa and 4050 MPa respectively which is comparable with the conventionally produced parts. Fracture of the test specimens was occurred due to un-melted powder particles, lack of fusion and delamination between the layers.

Acknowledgement

This experimental work is supported by the National Institute of Technical Teachers' Training and Research (NITTTR), Chandigarh (India).

REFERENCES

[1] *Herzog, D., Seyda, V., Wycisk, E., & Emmelmann, C. (2016). Additive manufacturing of metals. Acta Materialia, 117, 371-392.*

[2] *Li, S., Hu, J., Chen, W. Y., Yu, J., Li, M., & Wang, Y. (2020). Evolution of cellular dislocation structures and defects in additively manufactured austenitic stainless steel under ion irradiation. Scripta Materialia, 178, 245-250.*

[3] *Deb Roy, T., Wei, H. L., Zuback, J. S., Mukherjee, T., Elmer, J. W., Milewski, J. O., ... & Zhang, W. (2018). Additive manufacturing of metallic components–process, structure and properties. Progress in Materials Science, 92, 112-224.*

[4] *Jiménez, M., Romero, L., Domínguez, I. A., Espinosa, M. D. M., & Domínguez, M. (2019). Additive manufacturing technologies: An overview about 3D printing methods and future prospects. Complexity, 2019.*

[5] *S. Li,H. Hassanin, M.M.Attallah ,N.J.E.Adkins, K.Essa, The development of TiNi-based negative Poisson's ratio structure using selective laser melting, Acta Mater.105(2016)75–83.*

[6] *A.J.Pinkerton,Lasers in additive manufacturing, Opt.LaserTechnol.78(2016) 25–32.*

[7] *I. Yadroitsev, P.Krakhmalev, I.Yadroitsava, S.Johansson, I.Smurov, Energy input effect on morphology and microstructure of selective laser melting single track from metallic powder,J.Mater.Process.Technol.213(4)(2013) 606–613.*

[8] *M.S. Wong, C.J. T sopanos, and I. Sutcliffe, Owen, Selective Laser Melting of Heat Transfer Devices, Rapid Prototyping J., 2007, 13(5), p 291–297.*

[9] *Spears, T. G., & Gold, S. A. (2016). In-process sensing in selective laser melting (SLM) additive manufacturing. Integrating Materials and Manufacturing Innovation, 5(1), 16-40.*

[10] *Loh, L. E., Liu, Z. H., Zhang, D. Q., Mapar, M., Sing, S. L., Chua, C. K., & Yeong, W. Y. (2014). Selective Laser Melting of aluminium alloy using a uniform beam profile: The paper analyzes the results of laser scanning in Selective Laser Melting using a uniform laser beam. Virtual and Physical Prototyping, 9(1), 11-16.*

[11] *Rashid, R., Masood, S. H., Ruan, D., Palanisamy, S., Rashid, R. R., & Brandt, M. (2017). Effect of scan strategy on density and metallurgical properties of 17-4PH parts printed by Selective Laser Melting (SLM). Journal of Materials Processing Technology, 249, 502-511.*

[12] *Irrinki, H., Dexter, M., Barmore, B., Enneti, R., Pasebani, S., Badwe, S., ... & Atre, S. V. (2016). Effects of powder attributes and laser powder bed fusion (L-PBF) process conditions on the densification and mechanical properties of 17-4 PH stainless steel. Jom, 68(3), 860-868.*

[13] *S. Biamino, A. Penna, U. Ackelid, S. Sabbadini, O. Tassa, P. Fino, M. Pavese, P.Gennaro, C. Badini, Electron beam melting of Ti-48Al-2Cr-2Nb alloy:microstructure and mechanical properties investigation, Intermetallics 19(6) (2011) 776–781.*

[14] *A. Mitchell, Melting, casting and forging problems in titanium alloys, Mater.Sci. Eng. A 243 (1) (1998) 257–262.*

[15] *Zapico, P., Giganto, S., Barreiro, J., & Martinez-Pellitero, S. (2020). Characterisation of 17-4PH metallic powder recycling to optimise the performance of the selective laser melting process. Journal of Materials Research and Technology, 9(2), 1273-1285.*

[16] *3DSystems. LaserForm 17-4PH (B) for ProX DMP 100, 200 and300 Direct Metal Printers (Accessed on 15 December 2020).*

[17] *Pasebani, S., Ghayoor, M., Badwe, S., Irrinki, H., & Atre, S. V. (2018). Effects of atomizing media and post processing on mechanical properties of 17-4 PH stainless steel manufactured via selective laser melting. Additive Manufacturing, 22, 127-137.*

[18] *Murr, L. E., Martinez, E., Hernandez, J., Collins, S., Amato, K. N., Gaytan, S. M., & Shindo, P. W. (2012). Microstructures and properties of 17-4 PH stainless steel fabricated by selective laser melting. Journal of Materials Research and Technology, 1(3), 167-177.*

[19] *Yadollahi, A., Shamsaei, N., Thompson, S. M., Elwany, A., & Bian, L. (2017). Effects of building orientation and heat treatment on fatigue behavior of selective laser melted 17-4 PH stainless steel. International Journal of Fatigue, 94, 218-235.*

[20] *Mower, T. M., & Long, M. J. (2016). Mechanical behavior of additive manufactured, powder-bed laser-fused materials. Materials Science and Engineering: A, 651, 198-213.*