Mechanical Properties of Inconel Alloy 718 Produced by 3D Printing using DMLS

Milan Daňa, Ivana Zetková, Josef Mach
Regional Technological Institute, University of West Bohemia – Faculty of Mechanical Engineering, Univerzitní 8, Pilsen 306 14, Czech Republic. E-mail: danam@rti.zcu.cz, zetkova@rti.zcu.cz, machj@rti.zcu.cz

Additive manufacturing (AM) allows printing from different materials: from wax to plastic and even metal. This paper concentrates on Direct Metal Laser Sintering (DMLS), which allows printing to create complex parts from different kinds of metal. Inconel 718 was chosen for this research. This material is used especially in the aerospace industry and in other demanding applications due to its characteristic properties, which include high strength at high temperatures, corrosion resistance, low thermal conductivity, high hardness, work hardening and low thermal conductivity. Components used in aeroplanes must be very reliable, lightweight and their mechanical stresses must be accurately described, because the components are designed with respect to these criteria. For this reason, each material must be perfectly described in terms of mechanical properties and their minimum limits must be identified. Tensile testing is the best way to find the basic set of mechanical properties of a material. The samples were printed in two different orientations on a building platform and the differences in mechanical properties were investigated. The effect of machining on mechanical properties was also investigated.

Key words: 3D print, DMLS, Inconel 718, Tensile strength

1 Introduction

Additive Manufacturing (AM), also known as 3D Printing, is a technology that produces three-dimensional parts layer by layer. There are many methods of 3D printing, but only a few are able to create parts from metal, especially from Inconel 718. DMLS (Direct Metal Laser Sintering) is one of these methods. The principle of this method is based on the application of thin layers of metal powder using a recoater blade. The metal powder is sintered by a collimated laser beam, which fuses the particles of the metal together and creates a solid material. The 3D model of the part is cut into individual slices, and the width of individual cuts depends on the thickness of the applied layer of the powder. The printed parts are composed from a large number of layers. [1,2]

Machining Inconel 718 is very difficult by conventional methods and machines due to excessive tool wear and hardening during machining. This means it is advantageous to use additive manufacturing, because this method allows the creation of very complex parts with minimal stock removal. 3D printing even allows the creation of parts that are very difficult or impossible to manufacture with conventional machining methods, for example the lightweight parts of aircraft engines with internal cavities or channels. [3,4]

Reference [5] compares the mechanical properties of Inconel 718 components created using 3D printing, casting and forging. The authors state that the printed Inconel 718 achieves the same and, in some cases, better results than the cast and forged materials. The measurements carried out show that the microstructure of the printed material is much finer than in forged and cast materials. Then the author verified the mechanical properties at higher temperatures at which the material usually works. The tensile strength test was performed at 450 °C and 650 °C and compared with properties at room temperature. The author states that the printed material has the same properties as forged material at elevated temperatures. Reference [6] states that '*After heat treatment, the tensile properties of printed and wrought material were comparable. However, ductility and rupture life were significantly reduced in the sintered material due to the presence of porosity'*.

Reference [7] provides very substantial information about the mechanical properties of Inconel 718 produced by 3D printing using DMLS. This study includes the very latest research and describes the microstructure of this material relative to build direction and heat treatment.

The material produced in the conventional manner has approximately the same mechanical properties in each direction. However, materials produced by additive manufacturing (3D print) have small differences in mechanical properties depending on the build direction of the part (XYZ). These differences are not as radical as in composite materials, but it is necessary to know about them. The values of the mechanical properties are approximately the same in the X and Y directions. The biggest difference in the values of the mechanical properties is in the Z direction. [4,5,8,7,9],

2 Experimental device and adjustment

2.1 Inconel 718

The official name for the material used for additive manufacturing is UNS N07718, W.Nr. 2.4668, which is most often known by its tradename Inconel 718. This super-alloy belongs to the nickel-based alloys and has special properties which normal materials cannot achieve. These special properties are for example high strength at high and low temperatures (can withstand temperatures up to +700 °C), high corrosion resistance at high temperatures, fatigue, creep, etc. Table 1 shows the material composition. [9,10]

***Tab. 1** Material composition [9]*

Fe	Ni	Cr	Nb	Mo	Ti	Al	Co	Mn, Si	Cu	C	S, P	B
Balance	50-55	17-21	4.75-5.5	2.8-3.3	0.65-1.15	0.5-0.8	≤1.0	≤0.35	≤0.3	≤0.08	≤0.015	≤0.006

2.2 Experimental details

3D metal printing was performed using DMLS. The EOS M290 printer works on the basis of this method, and it was used for printing a semi-finished product for the tensile test samples. This 3D printer for metal parts allows very fast, flexible production from various metallic materials. The maximum size of the printed part is 250 x 250 x 325 mm. The high quality 400-watt fibre laser provides a very good speed up to 7 m/s while preserving the beam quality with stable performance. The parameters used for printing are: hatching distance 0.11 mm, laser speed 960 mm/s, laser power 285 W, beam offset 0.015 mm and stripe overlap 0.08 mm. These parameters are used for the core of the part and the skin of the part has different parameter values. The layer thickness of the powder was 40 micrometres, this parameter has a huge influence on the value of each parameter. '*The processing parameters also affect micro-structure, mechanical properties and residual stress'*. [10]The above parameters are among the most important parameters for 3D metal printing. [9,11]

Figure 1 shows the print directions on the building platform. Only directions 0_x and 90 (Z) were selected for this experiment, because these build directions were selected based on the literature search on this topic. These directions show the greatest differences in the values of the mechanical properties.

The test samples were printed with stock removal. Two versions of the semi-finished products were designed. The ø10 x 95 mm cylinder was the first. The second semi-finished product copies the surface of the final sample with a 1.5 mm addition of material.

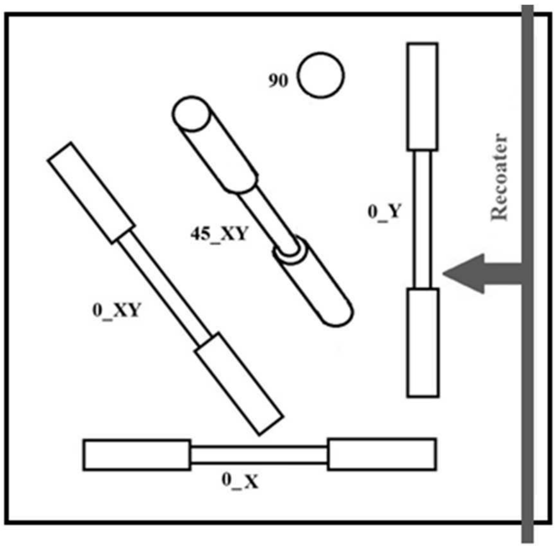

***Fig. 1** Orientation of samples*

Post-processing heat treatment is typically applied to improve properties of DMLS parts because DMLS microstructures usually contain non-equilibrium phases as well as very high residual thermal stresses.' [8] This is extremely important for metal components that will operate under high stress, such as aerospace or automotive parts. The course and setting of heat treatment is shown in Fig. 2. This heat treatment is recommended by the manufacturer. The hardness after printing can be approximately 30 HRC and hardness can be increased up to 47 HRC using heat treatment. The heat treatment significantly increases the mechanical properties; for example, tensile strength may be increased from 1000 MPa up to 1400 MPa. [9]

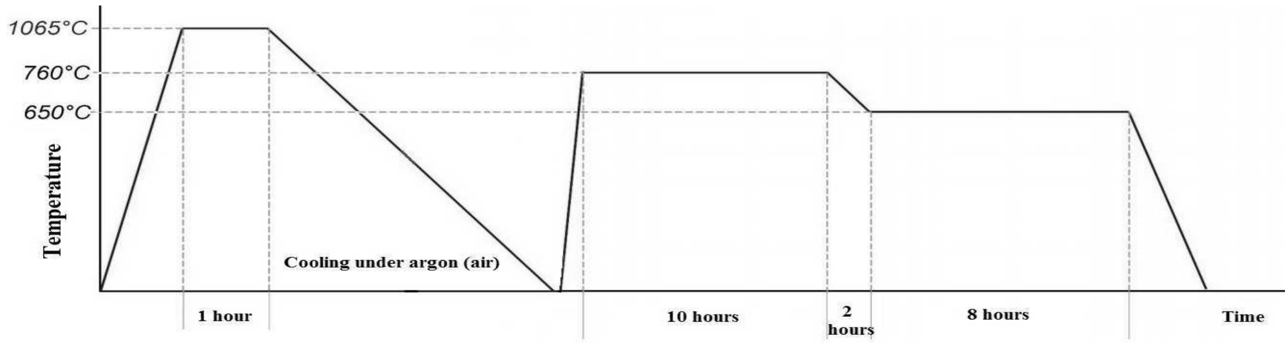

***Fig. 2** Heat treatment [9]*

The tensile test samples were produced according to standard DIN 50125 Form B. Figure 3 shows the sample with dimensions and tolerances for manufacturing. The machining of samples was carried out on a CNC lathe - EMCO MAXXTURN 25, using carbide tools. The cutting conditions were the same as for conventionally produced Inconel 718.

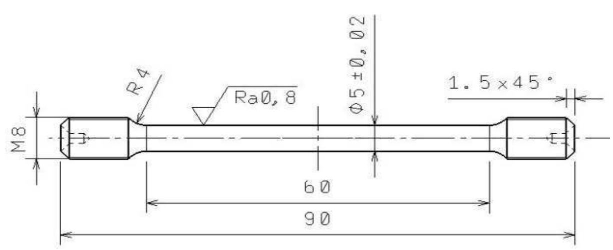

***Fig. 3** Test samples according to DIN 50125 Form B*

Tensile testing was performed using the Zwick Z250 electromechanical testing machine. This machine allows a tensile test with a force up to 250 kN. The test was carried out at room temperature. The test was performed in accordance with CSN EN ISO 6892 - 1. The pre-load was set at 2 MPa. Tensile test speed was set to 0.0067 1/s. If the tensile speed is multiplied by original gauge length Lo, then the real tensile speed is obtained in mm/s.

3 Results

All test samples were measured in the same way and under the same conditions. The values of the mechanical properties are given in Table 2.

***Tab. 2** Measured values*

Sample	Direction	Semi-finished product	$R_{p0.2}$ MPa	R_m MPa	A %	E GPa
1	0_X	cylinder	1269	1470	11.1	201
2	0_X	cylinder	1253	1440	11.3	203
3	Z	cylinder	1206	1377	11.8	183
4	Z	cylinder	1209	1387	14.6	182
5	Z	cylinder	1206	1380	12.1	188
6	0_X	Addition	1272	1475	11.8	201
7	0_X	Addition	1273	1472	11.5	205
8	0_X	Addition	1265	1466	12.1	202
9	0_X	Addition	1278	1470	11.2	201
10	Z	Addition	1214	1382	9.0	183
11	Z	Addition	1205	1385	14.0	177
12	Z	Addition	1212	1390	10.2	176

Where:

Cylinder …Cylindrical semi-finished product 10x95mm

Addition … semi-finished product with addition of 1.5mm of material in diameter and length

The stress-strain curves obtained from the individual tensile tests are plotted in one graph for clear comparison. The big differences of strain in the individual samples are distinctly shown in this graph. The range of tensile strength was chosen from 1100 to 1500 MPa due to better chart readability. The stress-strain curves were almost the same up to 1100 MPa. It is also clearly seen that the building direction of the samples has a significant influence on the mechanical properties. The samples oriented in the X direction achieve better results in tensile strengths, yield strength and Young's modulus of elasticity.

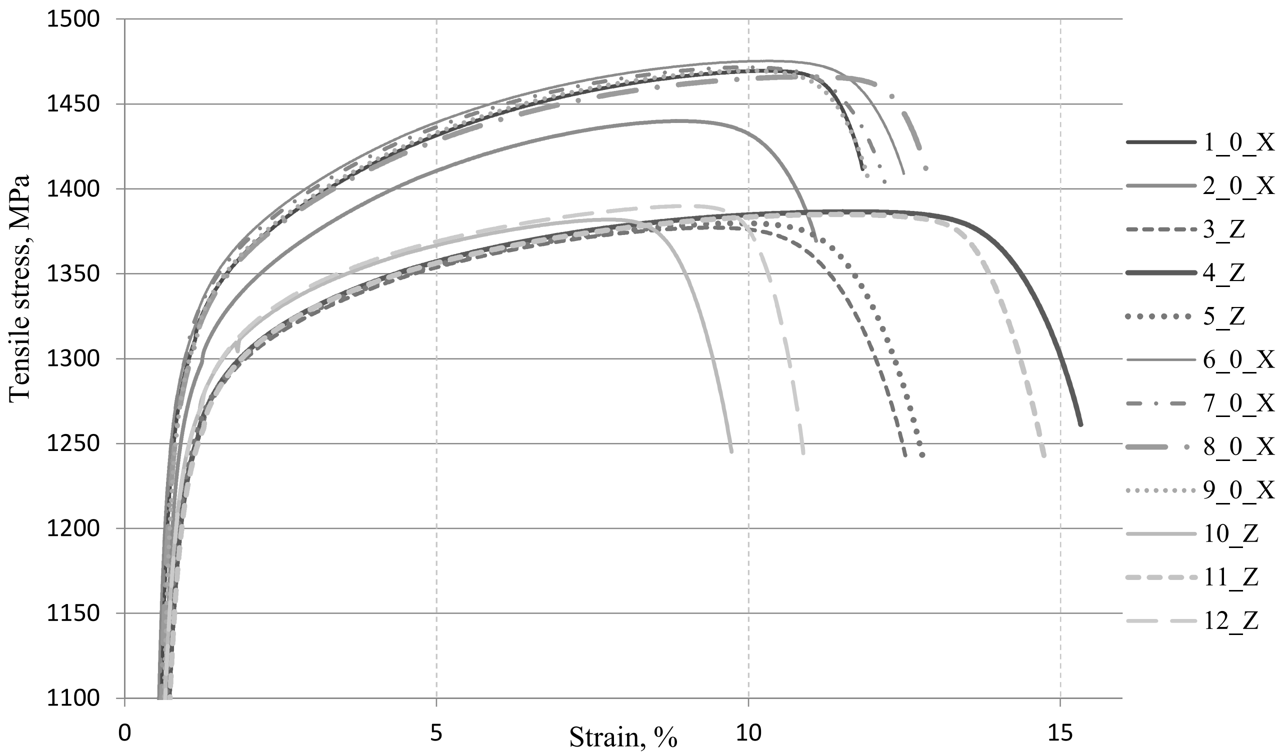

***Fig. 4** Comparison of tensile tests*

4 Conclusion

This paper presents the results of experiments conducted on test samples made from Inconel 718. These test samples were made by 3D printing using DMLS. The final shape of the test samples had to be machined to achieve precise dimensions and surface quality. The experiment confirms that the claims from references [5,7,8] about different mechanical properties depending on the build direction is true. All the tensile samples printed in 0_X direction achieved better results, as shown in Figure 4. The tensile strengths ranged from 1440 to 1475 MPa and yield strengths ranged from 1253 to 1278 MPa. However, the samples printed in the Z direction have a tensile strength approximately 80 MPa less and yield strength approximately 60 MPa less too. The difference between Young's modulus of elasticity is approximately 20 GPa. The various semi-finished products of test samples have no effect on the final mechanical properties of the material. This means that the removing of different volumes of material from the semi-finished products did not affect the test samples.

The largest differences were observed in the strain values. The strain ranged from 9 to 14.6 %. The samples in the X direction showed very balanced results of strain. However, the samples in the Z direction showed large differences. The limit values of this range were measured on these samples. Further research will be focused on determining the cause of these differences of strain in the Z direction.

Acknowledgement

This contribution has been prepared under the project LO1502 'Development of the Regional Technological Institute' under the auspices of the National Sustainability Programme I of the Ministry of Education of the Czech Republic aimed at supporting research, experimental development and innovation.

References

[1] L. KUCEROVA and I. ZETKOVA, 'Metallography of 3D Printed 1.2709 Tool Steel', *MANUFACTURING TECHNOLOGY*, vol. 2016, no. 1, pp. 140–144.

[2] 'DMLS vs SLM 3D Printing for Metal Manufacturing | Element Materials Technology'. [Online]. Available: https://www.element.com/nucleus/2016/06/29/dmls-vs-slm-3d-printing-for-metal-manufacturing. [Accessed: 25-Jan-2018].

[3] Z. WANG, K. GUAN, M. GAO, X. LI, X. CHEN, and X. ZENG, 'The microstructure and mechanical properties of deposited-IN718 by selective laser melting', *J. Alloys Compd.*, vol. 513, no. Supplement C, pp. 518–523, Feb. 2012.

[4] M. DAŇA, M. ZETEK, and V. SCHORNÍK, 'Effect of cutting edge geometry on cutting forces when drilling Inconel 718.', *MANUFACTURING TECHNOLOGY*, vol. 2017, pp. 24–29.

[5] T. TROSCH, J. SRTOßNER, R. VOLKL, and U. GLATZEL, 'Microstructure and mechanical properties of selective laser melted Inconel 718 compared to forging and casting', *Mater. Lett.*, vol. 164, no. Supplement C, pp. 428–431, Feb. 2016.

[6] X. ZHAO, J. CHEN, X. LIN, and W. HUANG, 'Study on microstructure and mechanical properties of laser rapid forming Inconel 718', *Mater. Sci. Eng. A*, vol. 478, no. 1, pp. 119–124, Apr. 2008.

[7] D. H. SMITH *et al.*, 'Microstructure and mechanical behavior of direct metal laser sintered Inconel alloy 718', *Mater. Charact.*, vol. 113, no. Supplement C, pp. 1–9, Mar. 2016.

[8] E. CHLEBUS, K. GRUBER, B. KUZNICKA, J. KURZAC, and T. KURZYNOWSKI, 'Effect of heat treatment on the microstructure and mechanical properties of Inconel 718 processed by selective laser melting', *Mater. Sci. Eng. A*, vol. 639, no. Supplement C, pp. 647–655, Jul. 2015.

[9] EOS, 'Material data sheet EOS_NickelAlloy_IN718', 05-Jan-2018. [Online]. Available: http://ip-saas-eos-cms.s3.amazonaws.com/public/4528b4a1bf688496/ff974161c2057e6df56db5b67f0f5595/EOS_NickelAlloy_IN718_en.pdf.

[10] Y. LU *et al.*, 'Study on the microstructure, mechanical property and residual stress of SLM Inconel-718 alloy manufactured by differing island scanning strategy', *Opt. Laser Technol.*, vol. 75, no. Supplement C, pp. 197–206, Dec. 2015.

[11] EOS, 'Data Sheet EOS M290', 23-Jan-2018. [Online]. Available: https://cdn0.scrvt.com/eos/413c861f2843b377/51d966b8b31d/EOS_System_Data_Sheet_EOS_M_290_EN_V6_Web.pdf.

10.21062/ujep/137.2018/a/1213-2489/MT/18/4/559