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Tensile fracture analysis of 3D printed Inconel 718

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Abstract

The article deals with the fracture analysis of uniaxial tensile stressed samples made of Inconel 718 alloy by DMLS (Direct Metal Laser Sintering) technology. The samples were heat treated according to AMS 5664 procedure. The material sheet of the EOS Nickel Alloy IN718 provides the tensile properties of the heat-treated samples built only in Z-direction, so the authors decided to also explore the tensile behaviour of the 3D-prinied samples in individual X- and Y-directions. Further to tensile testing, fracture surface observations were performed to identify the principal failure modes. Fractographic investigation on tensile fractures, revealed predominantly a quasi-ductile failure mechanism, showing fine size dimple formation.

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Keywords: : tensile behaviour; Inconel 718; failure analysis; 3D printed material

1. Introduction

3D printing technology is currently one of the fastest-developing technologies. Currently, many issues exist with additive manufacturing that need to be addressed to use this technology. One of the largest issues is the selection of materials and their impact on the design. (Scott et al., 2012) In most cases, the selection of a material for a part, in

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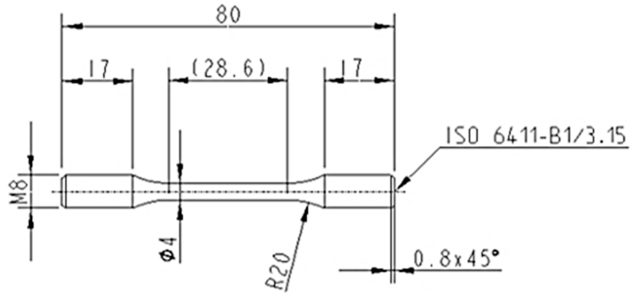
combination with a specific process, defines the geometric limitations of the design of the part and its application. The components made of metallic materials by the additive approach are used where safety, reliability and trouble-free operation of the equipment is required. (Gubeljak et al., 2009) Therefore, it is necessary to investigate and interpret the behaviour of components that are produced by an additive approach under different technological conditions or with different orientations in the space of a 3D printing machine. Based on the results it will be possible to predict the possibility of failure of the 3D-printed components that are going to operate under different types of loading. (Ravichander et al., 2021; Mlikota et al, 2021)

The goal of the present research was to investigate a tensile behaviour of the dogbone samples, axes of which were positioned in X- and Y-directions during the DMLS (Direct Metal Laser Sintering), since the material sheet of the EOS Nickel Alloy IN718 provides the tensile properties only of the heat-treated samples printed in Z-directions. The authors also focused on the fracture analysis of these uniaxial tensile stressed samples (ISO 6892-1, 2019) in this paper.

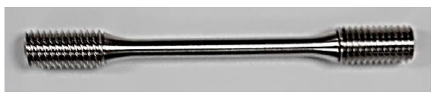
2. Materials and methods

In the additive production method, the production time is given by the height of the component in the Z-direction, which is equal to the printing direction. One of the most effective ways to reduce production time and thus production costs is to choose the building orientation of the component corresponding to the lowest size. To reduce the height, the parts can in some cases be arranged in an oblique direction. (Mikula, et al., 2021) In this approach, however, it is often necessary to fix the next layer to something, usually the previous layer, which requires the use of so-called "support". Unfortunately, the support increases the time of production and also the time of further processing (cleaning, finishing). If the amount of support can be reduced, the efficiency of the process will increase. (Yao, at al., 2020) From these points of view, the orientation of the samples in the X and Y axes seems to be the primary choice of the manufacturer. The question is how much the orientation of the samples/parts affects their mechanical properties.

In the present research, the tensile and fracture properties of 3D printed dogbone samples were investigated, which were made so that their axes were oriented in the basic horizontal X- and Y-directions given by the area of a building platform. However, if a thin part of the geometry were parallel to the re-coating blade, the blade could tend to "bounce" off the parallel wall, and the built part itself would not have to withstand the force of the blade when building. To avoid collisions of the construction samples with the re-coating blade, the samples were rotated in the X-direction by angle of 5 degrees (not to be parallel to the blade) so that the blade touched the sample at a point, not in the face. (Khosravani at al., 2021) Basic dimensions and a representative of tensile test specimen are in Fig. 1.



a)



b)

Fig. 1. Tensile test specimen, (a) basic dimensions, (b) a representative.

The standard tensile test specimens with threaded ends were made of EOS NickelAlloy IN718 that has chemical composition corresponding to UNS N07718, W.Nr 2.4668, DIN NiCr19Fe19NbMo3. This kind of precipitation-hardening nickel-chromium alloy is characterized by having good tensile, fatigue, creep and rupture strength at temperatures up to 700 °C. (Saberi et al., 2020; Yong et al., 2020; Ji et al., 2021) Samples were heat treated according to procedure corresponding to AMS 5664. After solution annealing at 1065 °C for 1 hour and inert gas cooling, it followed the ageing treatment at 760 °C for 10 hours, furnace cooling down to 650 °C in 2 hours, holding at 650 °C for 8 hours and inert gas cooling.

The producer of the material states in the Material data sheet, the typical tensile strength R_m in Z-direction is

1380 ±100 MPa (minimum 1241 MPa), typical yield strength $R_{p0.2}$ 1240 ±100 MPa (minimum 1034 MPa), and typical elongation A_{35} is 18 ±5 % (minimum 12 %). (EOS NickelAlloy IN 718, 2014)

Tensile testing was performed on dogbone specimens at ambient temperature, according to ISO 6892-1 standard. (ISO 6892-1, 2019) The test equipment employed was a 250 kN Instron 8802 servohydraulic machine, under position mode and 1 mm/min cross head speed (Fig. 2).

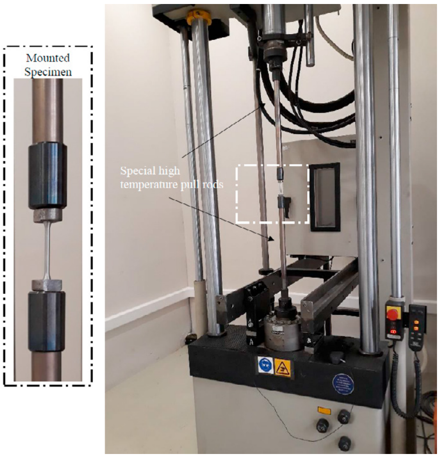


Fig. 2. Tensile test set-up showing the tensile test equipment (servohydraulic Instron 8802) in operation. See detail of the boxed area showing the mounted specimen

Stereo-microscopic observation of the tubes was performed with a Nikon SMZ 1500 stereo-microscope. Higher magnification microscopic observations (at the centre and close to the circumference) was performed using a JEOL IT-800 HL Scanning Electron Microscope (SEM) under 20 kV accelerating voltage, coupled with an EDAX Apollo XF equivalent to Octane Super EDS, silicon drift detector (SDD) in cooperation with TEAM software.

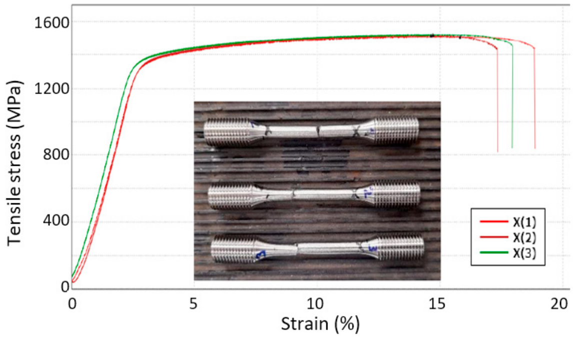
3. Results and discussion

The design rules for DMLS are based on the efficiency of the build process and it needs to consider the construction of the part layers throughout the process, particularly those stages when the part will be inherently weak. The orientation of the components is critical, especially in relation to the re-coating blade, the minimization of the supports and due to the partial heterogeneity of the mechanical properties (Wittke, et al., 2019).

The measured values for Yield strength ($R_{p0.2}$), Tensile strength (R_m) and Elongation (A_{35}) results along with the corresponding stress-strain curves are presented in the Table 1 and in Figure 3, respectively. It can be said that a high repeatability was observed among the tested triplicates.

Table 1. Tensile test results of X- and Y-orientation samples.

Sample ID	**$R_{p0.2}$ (MPa)**	**R_m (MPa)**	**A_{35} (%)**
X1	1332	1510	14
X2	1337	1517	13
X3	1344	1522	14
Average	**1338**	**1516**	**14**
Y1	1400	1586	13
Y2	1394	1582	12
Y3	1402	1585	11
Average	**1399**	**1584**	**12**



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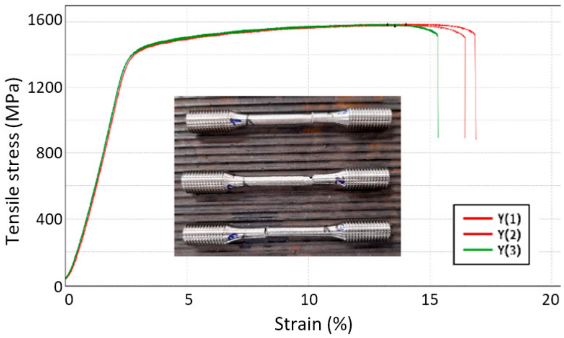


b)

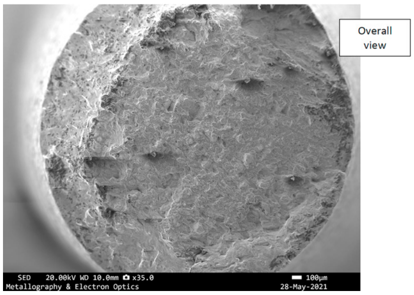
Fig. 3. Stress-strain curves corresponding to the (a) X-orientation samples, (b) Y-orientation samples.

Comparison of the experimental results with the values stated in the Material Data Sheet for parts printed in Z-direction (EOS NickelAlloy IN 718, 2014) are summarized in Table 2. It is evident that the typical values of the tensile strength and yield strength for bodies built in the Z-direction are the lowest, but the elongation is the highest.

Table 2. Comparison of X-, Y-directions results with typical values stated in the material sheet for the Z-direction.

Average/Typical	$R_{p0.2}$ (MPa)	R_m (MPa)	A_{35} (%)
X	1338	1516	14
Y	1399	1584	12
Z	1240	1380	18

Fractographic investigation on tensile fractures, identified predominantly a quasi-ductile failure mechanism, showing principally fine size dimple formation. SEM fractographs of the representatives of the specimens printed in X- and Y-directions are presented in Figures 4 and 5.

a) 

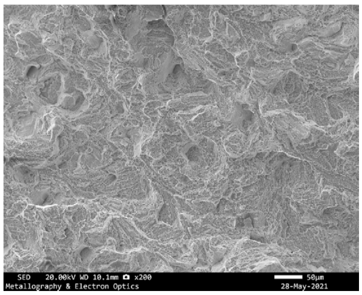
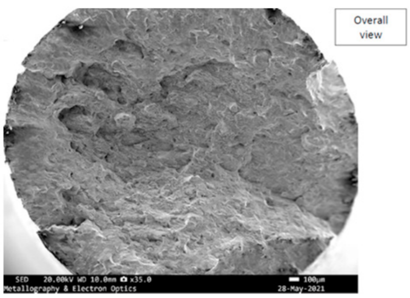
b) 

Fig. 4. SEM fractographs of specimen X2; (a) overall view – magnification 35x; (b) mixed mode fracture – magnification 200x.

a) 

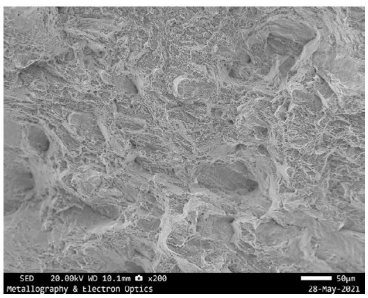
b) 

Fig. 5. SEM fractographs of specimen Y2, (a) overall view of the fracture surface – magnification 35x; (b) secondary features showing shear fractures – magnification 200x.

The specimen X2 (Fig. 4) showed that secondary cracks, which were present accompanied by tear ridges. A mixed mode of fracture was observed. The presence of fine dimples was also evident.

A decohesion was also observed at the centre of the representative Y2 of the specimens printed in Y-direction. Secondary features showing shear fractures (Fig. 5) were evident together with dimples, transgranular secondary features and cavities.

4. Conclusions

Within the presented research, the tensile properties of the dogbone specimens made of IN718 and heat treated according to AMS 5664 procedure and printed in X- and Y-directions were experimentally studied, and the tensile fracture surface was analysed.

The results have shown that the tensile properties of the experimentally tested samples from X- and Y-orientation are very similar. According to the Material data sheet and, in comparison with properties of parts printed in Z-direction, it could be said that there is a tendency of lower strength values exhibited by Z-orientation group. Fractographic investigation revealed a similar failure mechanism, showing predominantly fine size dimple formation, transgranular facets and cavities.

Further future will be focused on the influence of the orientation of samples produced under the same specific conditions on their tensile properties and behaviour so that the results can be used in modelling and numerical analysis of real components.

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