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STRAIN-RATE AND PRINTING DIRECTION DEPENDENCY OF COMPRESSIVE BEHAVIOUR OF 3D PRINTED STAINLESS STEEL 316L

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Abstract. The paper is focused on evaluation of the relation between mechanical properties of 3D printed stainless steel 316L-0407 and printing direction (i.e. the orientation of the part which is being printed in the manufacturing device) subjected to compressive loading at different strain-rates. In order to evaluate the strain rate dependency of the 3D printed material's compressive characteristics, dynamic and quasi-static experiments were performed. Three sets of bulk specimens were produced, each having a different printing orientation with respect to the powder bed plane (vertical, horizontal and tilted). To assess the deformation behaviour of the 3D printed material, compressive stress-strain diagrams and compressive yield strength and tangent modulus were evaluated.

Keywords: 3D printing, selective laser sintering, stainless steel 316L, printing direction, split Hopkinson pressure bar.

1. Introduction

Selective laser sintering (SLS) is an additive manufacturing/3D printing method based on sintering of powdered material (e.g. metal or alloy powder) into a solid body using a precisely focused laser beam with a specific power. Due to its principle, it is a viable procedure for production of parts with a complex geometry that would not be easy or even possible to produce by conventional manufacturing procedures [1]. Using this method, required part is directly sintered according to its CAD model. To be able to reliably predict mechanical properties of the parts produced in such a way, it is necessary to know the characteristics of the sintered material itself. Such a knowledge enables to tune the material model for numerical simulations which allows to obtain more reliable results of computational analysis and to optimize the design of 3D printed parts [2].

In general, there are a lot of parameters affecting the quality of the final material produced by SLS, such as laser power, printed layer thickness, granularity of the powdered material or the orientation of the part during its production [3]. This study is focused on the dependency of mechanical behaviour of SLS printed austenitic steel 316L-0407 on the printing direction (i.e. the orientation of the printed layers of the material with respect to the powder bed plane). Moreover, the presented study aims also on evaluation of the strain-rate dependency of mechanical characteristics of the material, which is necessary for designing parts tailored to their applications.

2. Materials and Methods

Experimental study presented in this paper consisted of two types of experiments, quasi-static and dynamic, which were performed with the SLS printed bulk specimens of austenitic steel 316L-0407. In order to assess the strain-rate sensitivity as well as the effect of printing direction on the compressive behaviour of the investigated material, three different sets of specimens, each with different printing orientation, were tested at various strain-rates. The quasi-static experiments were performed using electro-mechanical loading device and dynamic experiments were conducted using Split Hopkinson Pressure Bar (SHPB) experimental apparatus [4].

2.1. Specimens

All the specimens were designed using a parametric modeller and produced by Renishaw AM250 3D printing device. The most important parameters of the SLS procedure used for the specimens production are listed in Tab. 1. The mean density of the SLS printed material (measured of reference cylinder) was 7.52 ± 0.17 g/cm^3. According to the material sheet provided by Renishaw [5], the density of wrought material is 7.99 g/cm^3. Thus, it can be assumed there is a 6% porosity in the material produced by the SLS method, which corresponds to the difference in the values of density.

The design of the specimens differed for quasi-static and dynamic experiments due to the limits of the experimental devices used for their testing. The particular designs are thus described in the following subsections.

Parameter	Value
Scanning strategy	Chessboard
Laser power	max 200 W
Powdered material particle size	15-45 μm
Layer thickness	50 μm

Table 1. Parameters of SLS procedure

2.1.1. Specimens for Quasi-static Experiments

The specimens for quasi-static experiments had cylindrical shape with diameter of 5 mm and height of 10 mm. Therefore, the height to diameter ratio was 2. The specimens were printed with three different orientations - vertically, at the angle of 0°, horizontally, at the angle of 90° and tilted,at the angle of 45° in every case related to the powder bed plane (see Fig. 1).

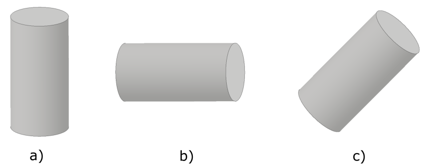

Figure 1. Orientation of the specimens durig production: a) vertical, b) horizontal and c) tilted.

2.1.2. Specimens for Dynamic Experiments

"Dog bone" shaped specimens with overall dimensions of 18 × 16 mm were used for dynamic experiments. The particular design of the specimens for dynamic tests (see Fig. 2) was selected due to the parameters of the used SHPB apparatus. The contact faces of the specimens needed to have a wider diameter in order to achieve similar material impedance as has the material of the bars. In this regard, the deformation wave is not reflected at the bar-specimen interference but is transmitted into the specimen without any significant loss. However, the center part of the specimen needed to be thinner in order to achieve a sufficient deformation during the dynamic experiments. The specimens were also 3D printed with the same three different orientations with respect to the powder bed plane (see Fig. 3).

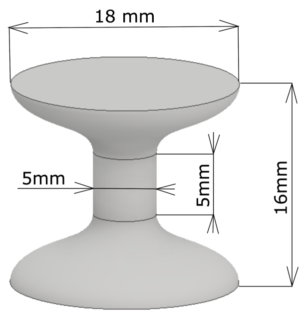

Figure 2. Dimensions of dog bone shaped specimen used for dynamic experiments.

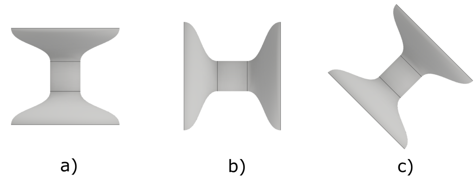

Figure 3. Orientation of the specimens durig production: a) vertical, b) horizontal and c) tilted.

2.2. Experimental Setup

To assess the strain-rate dependency of mechanical behaviour of the investigated material, two different loading devices were used depending on the type of the experiments. Each of the experimental setups is described in following subsections.

2.2.1. Quasi-static Experiments

Electro-mechanical loading device 3382 (Instron, USA) was used for the quasi-static experiments. The loading procedure was displacement controlled with the loading velocity of 1 mm/min which yielded in a strain rate of approx. 0.002 s^{-1}. Applied force was measured using a 100 kN load cell.

2.2.2. Dynamic Experiments

The dynamic experiments were conducted using SHPB apparatus equipped with high-strength aluminium alloy bars (EN-AW-7075) having a diameter of 20 mm. Depending on the required strain-rate, two different striker bars were used in the experiments: striker bar with the length of 500 mm for higher strain-rate and of 650 mm for lower strain-rate. Using the striker bars of different lenghts enables to achieve the same deformation range at both the strain-rates. The incident and the transmission bar had each the length of 1600 mm. Foil strain gauges 3/120 LY61 (HBM, Germany) with active length of 3 mm wired in the Wheatstone half-bridge arrangement were used for the instrumentation of the bars. In order to reduce the wave dispersion effects, the pulse-shaping technique was engaged using cylindrical soft copper shapers with diameter of 7 mm and thickness of 1 mm. Described experimental setup can be seen in Fig. 4.

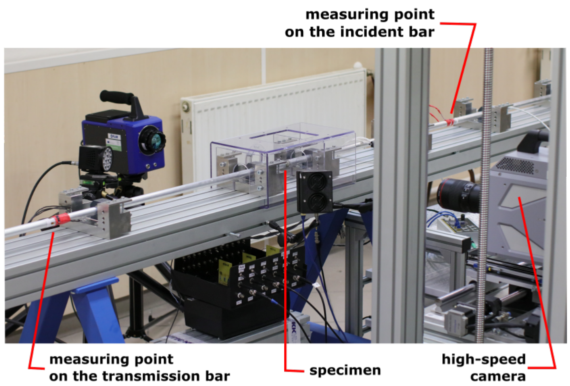

Figure 4. Overview of the SHPB apparatus used for dynamic experiments.

3. Results

For each printing orientation and each strain-rate, three experiments were performed yielding in 9 quasi-static and 18 dynamic experiments in total. Compressive behaviour of the investigated material under quasi-static loading conditions is expressed by the mean stress-strain curves in Fig. 5. Note, that the values of strain were evaluated based on the cross-head displacement. Each curve in the above-mentioned figure corresponds to a different printing orientation. The diagram also shows the standard deviation of each of the curves. The deformation behaviour is very similar up to the strain of 0.2. For the higher strain values, changes in the slope of the curves occur as the material was densifying and the specimens were bulging out in a form of a barrel. At that the slope of the curve differ for each of the printing direction, too. The densification effects are apparent for all the specimens no matter the printing orientation. However, for the specimens printed horizontally are these effects a little more significant as the mean stress for these specimens reaches the highest values.

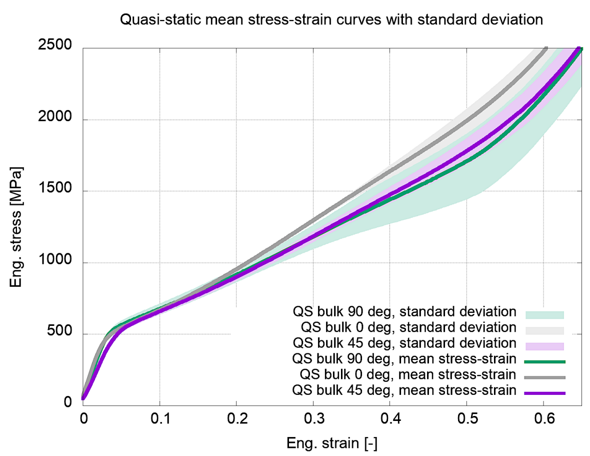

Figure 5. Mean stress-strain curves evaluated from quasi-static experiments

Compressive yield strength and tangent modulus at the beginning of the plastic region were evaluated from the quasi-static experiments. The mean values of these characteristics for each of the printing directions are together with the standard deviations listed in Tab. 2. The yield strenght evaluated for the specimens printed with vertical direction has the same value (considering the standard deviation) as the value listed in the material sheet [5]. However, for the vertical printing direction the value estimated from the experiments is smaller by approx. 25 % than the value presented in the same material sheet.

For the purpose of comparison, the quasi-static compressive response of dog bone shaped specimens was also evaluated. The stress-strain curves for these specimens together with the diagrams for the cylindrical specimens can be seen in Fig. 6.

Printing direction	σ_y [MPa]	E_t[GPa]
0°	415 ± 34	2.48 ± 0.13
90°	496 ± 33	2.23 ± 0.11
45 °	443 ± 4	2.32 ± 0.12

Table 2. Mean values and standard deviation of Young's modulus and Yield strength evaluated from quasi-static experiments

The compressive response of the dog bone shaped specimen corresponds well to the behaviour of the cylindrical specimens taking into account the standard deviation of the results. Nevertheless, there is one significant difference. For the cylindrical specimes, there are noticeable changes in the slopes of the stress-stain curves around the strain of 0.5 but for the dog bone shaped specimens the slopes remain invariable. This indicates that the densification and barreling effects are not so significant for the dog bone shaped.

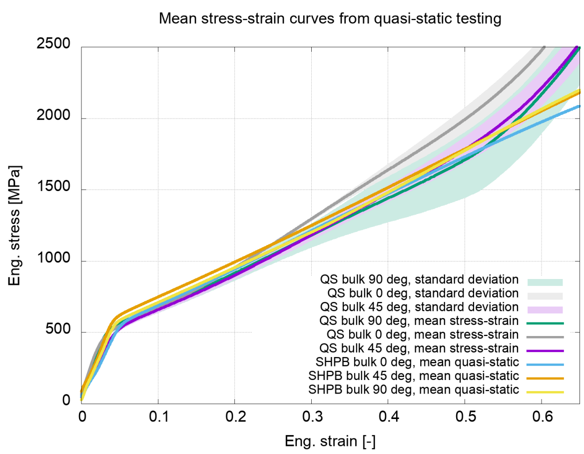

Figure 6. Mean stress-strain curves for cylindrical and dog bone shaped specimens evaluated from quasi-static experiments

The difference between quasi-static and dynamic compressive response of the material arises from the stress-strain curves in Fig. 7, where all the mean stress-strain and strain-rate-strain curves are shown. The strain-rate-strain diagrams show that similar strain-rates were achieved in all dynamic experiments. The higher strain rate was approx. 6000 s^{-1} and the lower was approx. 2000 s^{-1}. As can bee seen from the stress-strain curves, higher values of stress were achieved during the dynamic compression compared to the results of the quasi-static experiments. In other words, the material exhibits a higher strength at dynamic loading conditions.

The particular stress-strain diagrams supplemented by the standard deviation plots for each of the

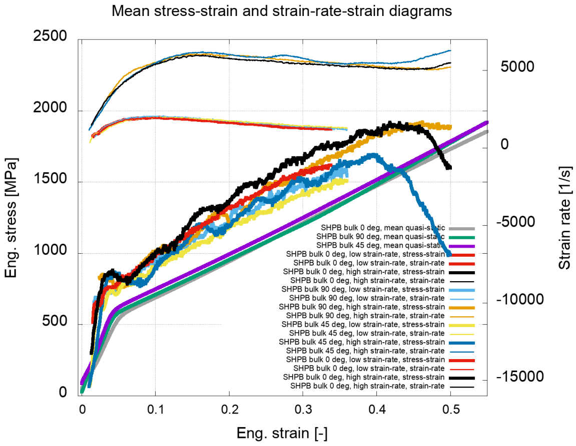

Figure 7. Mean stress-strain and strain-rate-strain curves evaluated from quasi-static and dynamic experiments with dog bone shaped specimens

printing orientations can be seen in Figs 8, 9 and 10. The dependency of the strain-rate sensitivity and the printing direction of the material is noticable when comparing these diagrams. The specimens with horizontal printing orientation embodied the most significant differences (on average 28%) between the stresses achieved during the quasi-static and the dynamic loading. The smallest differences (on average 14%) in the values of stress concentrated in the material during the quasi-static and the dynamic experiments were noted for the tilted printing orientation. The average difference of the stress values evaluated from quasi-static and dynamic testing of vertically printed specimens was 21%.

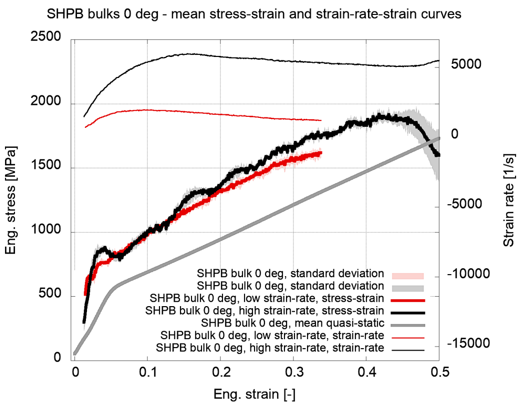

Figure 8. Mean results for the specimens printed at the angle of 0°

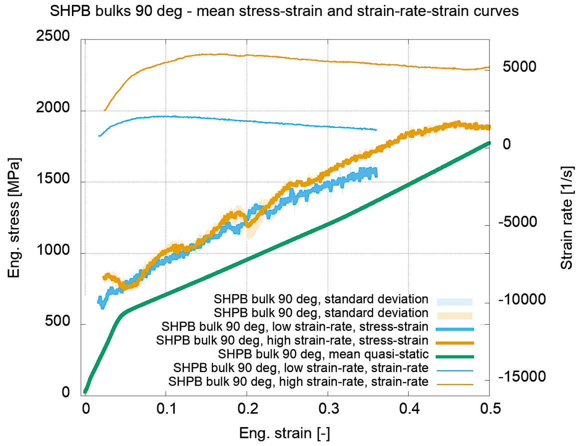

Figure 9. Mean results for the specimens printed at the angle of 90°

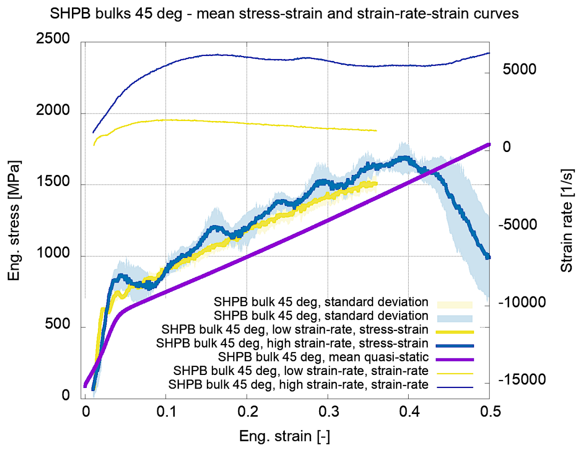

Figure 10. Mean results for the specimens printed at the angle of 45°

4. Conclusions

Experimental study presented in this paper revealed a strain-rate sensitivity of mechanical response of SLS printed austenitic stainless steel 316L. A significant increase (up to 28% on average) in evaluated stress values occured for dynamic experiments compared to the values obtained from quasi-static experiments. Moreover, the effect of printing direction of the material on its mechanical response was studied. At quasi-static loading conditions, only a minor effect of this characteristic of SLS printed material was noticed. The specimens printed horizontally exhibited an increased compressive strength compared to the other investigated printing directions. More significant effect of printing direction occured during the dynamic experiments. The specimens printed horizontally exhibited the most strain-rate sensitive mechanical behaviour as the stress values evaluated from quasi-static and dynamic experiments differed by 28% on average. The average difference in the stress values evaluated for the other investigated printing directions, vertical and tilted, were 21% and 14% respectively. All the evaluated dependencies should be considered when designing any part produced using the SLS production method. Especially the knowledge of the strain-rate sensitivity can be conveniently used when designing parts exposed to dynamic loading conditions.

Acknowledgements

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