INFLUENCE OF DEFORMATION TEMPERATURE AND STRAIN RATE ON THE MAXIMUM FLOW STRESS LEVEL OF THE 3D PRINTED AISI 316L STEEL

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Abstract

The AISI 316L stainless steel is one of the most used 3D printed powder materials due to its good properties. It goes without saying that the properties of the 3D printed steel are naturally less or more different compared to the material which was prepared conventionally. One of the important material characteristics is its flow stress evolution under various thermomechanical circumstances, which has a direct connection to the deformation behavior. The hot deformation behavior of the examined 3D printed steel is in the frame of the submitted research studied with regard to the peak stress levels experimentally achieved under a wide temperature and strain rate range, as well as from the point of view of the onset of a dynamic softening phenomenon – in addition with an emphasis on the corresponding mathematical description. The obtained results indicate a minimal and maximal flow stress level of 65 MPa and 381 MPa as for the combination of 1,523 K – 0.1 s^{-1} and 1,173 K – 100 s^{-1}, respectively. The experimentally achieved peak point coordinates have been described with a good accuracy – corresponding to the Pearson's correlation coefficient of 0.8238 and 0.9919 as regards to the peak strain and peak stress, respectively.

Keywords: AISI 316L steel, 3D printing, hot deformation, peak stress, softening onset

1. INTRODUCTION

Additive manufacturing, or 3D metal printing, is one method of additive technology that allows complex parts to be created by melting metal powder layer by layer using a laser. The advantage of additive technologies is fast production. However, printed materials also have disadvantages such as limited dimensions, surface roughness, internal porosity or residual stress. The combination of additive technology and plastic deformation may be one way to improve the properties of 3D printed materials [1]. It can be assumed that the preparing of the studied material via the 3D printing technology will have a certain impact on the subsequent deformation behavior. In other words, the deformation behavior of the studied 3D printed steel should be naturally different compared to the same material prepared via a traditional methodism. The main aim of the submitted research is thus reveal the influence of a deformation temperature and applied strain rate level on the deformation behavior of the 3D printed AISI 316L steel with a closer focus on the achieved peak stress levels and the onset of dynamic recrystallization.

2. PEAK POINT DATA

2.1 Hot Compression Testing

Utilizing a hot compression testing procedure, it was possible to acquire the hot flow curves of the examined 3D printed AISI 316L steel covering a wide range of thermomechanical circumstances – specifically the temperature levels of 1,173 K, 1,273 K, 1,373 K, 1,523 K, strain rate levels of 0.1 s^{-1}, 1 s^{-1}, 10 s^{-1}, 100 s^{-1}, and true strains up to 1.0, i.e., 16 flow curves in total. The applied testing attributes were as follows: cylindrical hot compression samples with a diameter of 10 mm and a height of 15 mm, testing chamber under vacuum, the sample-anvils interface separated by tantalum foils and a nickel-based grease, direct electrical resistance heating, a temperature control via thermocouple wires, sample heating directly up to a deformation temperature, dwell-time of 300 s. Analyzing the acquired flow curves, it was possible to gain the global maximum (peak point) coordinates (i.e., peak strain and peak stress) corresponding to each tested temperature and strain rate combination.

2.2 Assembling a Forecasting Relationship

The obtained peak point coordinates have been subsequently processed via a regression analysis in order to assembly a functional relationship between the predictors (i.e., deformation temperature, T (K) and strain rate, $\dot{\varepsilon}$ (s^{-1})) and corresponding outcomes (i.e., peak strain, ε_p (-) and peak stress, σ_p (MPa)). The resulting relations are given by equation (1) and (2):

$$\varepsilon_p = 0.0219 \cdot Z^{0.0605} \quad (1)$$

$$\sigma_p = \frac{1}{0.0104} \cdot \operatorname{arcsinh} \sqrt[4.9096]{\frac{Z}{2.1350 \cdot 10^{16}}} \quad (2)$$

In these equations, Z (s^{-1}) represents the Zener-Hollomon parameter [2], and its specific form can be in the case of this research formulated as follows:

$$Z = \dot{\varepsilon} \cdot \exp\left(\frac{482.1683}{R \cdot T}\right) \quad (3)$$

In equation (3), R embodies the universal gas constant (i.e., 8.314 J·K^{-1}·mol^{-1}). The initial (rough) estimates of the presented material constants were calculated via a procedure known from previous studies (see e.g., [3,4]) when employing the well-known Garofalo's relation [5]. These estimates were then subsequently refined via a nonlinear regression analysis when utilizing the Levenberg-Marquardt iteration optimization algorithm [6,7]. The differences between the initial and refined estimates are then documented in **Figure 1**. Highly noticeable is the accuracy rising especially with respect to the model (2). Considering the refined estimate, a corresponding good regression fit is also supported by the Pearson's correlation coefficient [8] of 0.8238 and 0.9919 as regards to the peak strain and peak stress, respectively.

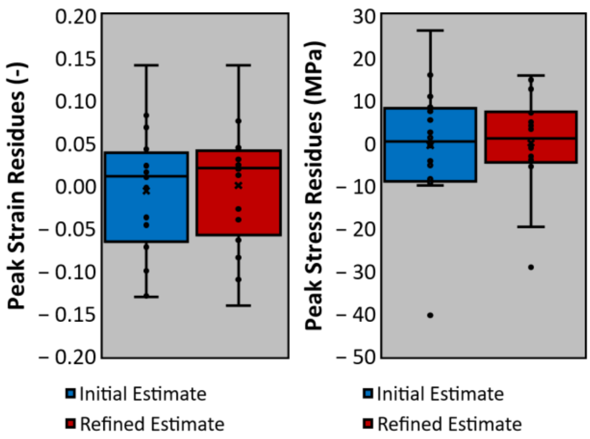

Figure 1 Residues returned after the application of initial or refined materials constants

3. RESULTS AND DISCUSSION

The experimentally gained as well as the calculated peak point coordinates are graphically expressed in the dependency on the corresponding predictors in **Figure 2**. Taking into account the peak stress levels and the corresponding predictor influence, it is clear that the higher the deformation temperature, the lower the stress values. The strain rate influence is then exactly opposite. This is valid for both the experiment data and the model (2) data. The observed peak stress data then indicate a minimal and maximal flow stress level of 65 MPa and 381 MPa as for the combination of 1,523 K – 0.1 s^{-1} and 1,173 K – 100 s^{-1}, respectively. The situation around the peak strain values is, however, somewhat different. Considering the experimental data, it can be seen that the strain rate influence does not comply with the generally accepted and many times proved assumption about the onset of dynamic recrystallization. In the case of the studied material, it is obvious that the peak strain values decrease as a reaction on the declining strain rate level only if this strain rate declining takes place between 10 and 100 s^{-1}. Unless a deformation temperature drops below ca 1,373 K, another decrease in the strain rate has a practically negligible effect. The situation below the aforementioned 1,373 K can be then marked as entirely unexpected – the decreasing strain rate level causes a significant peak strain increase. It is thus not surprising that the applied model (1) is not able to handle this situation correctly, so the calculated data are less or more out of the experimental trends. Hypothetically, the raised approximation issue can be solvable via some alternative approaches – see e.g., a multivariate polynomial methodism in [3] or an artificial neural network solution in [3].

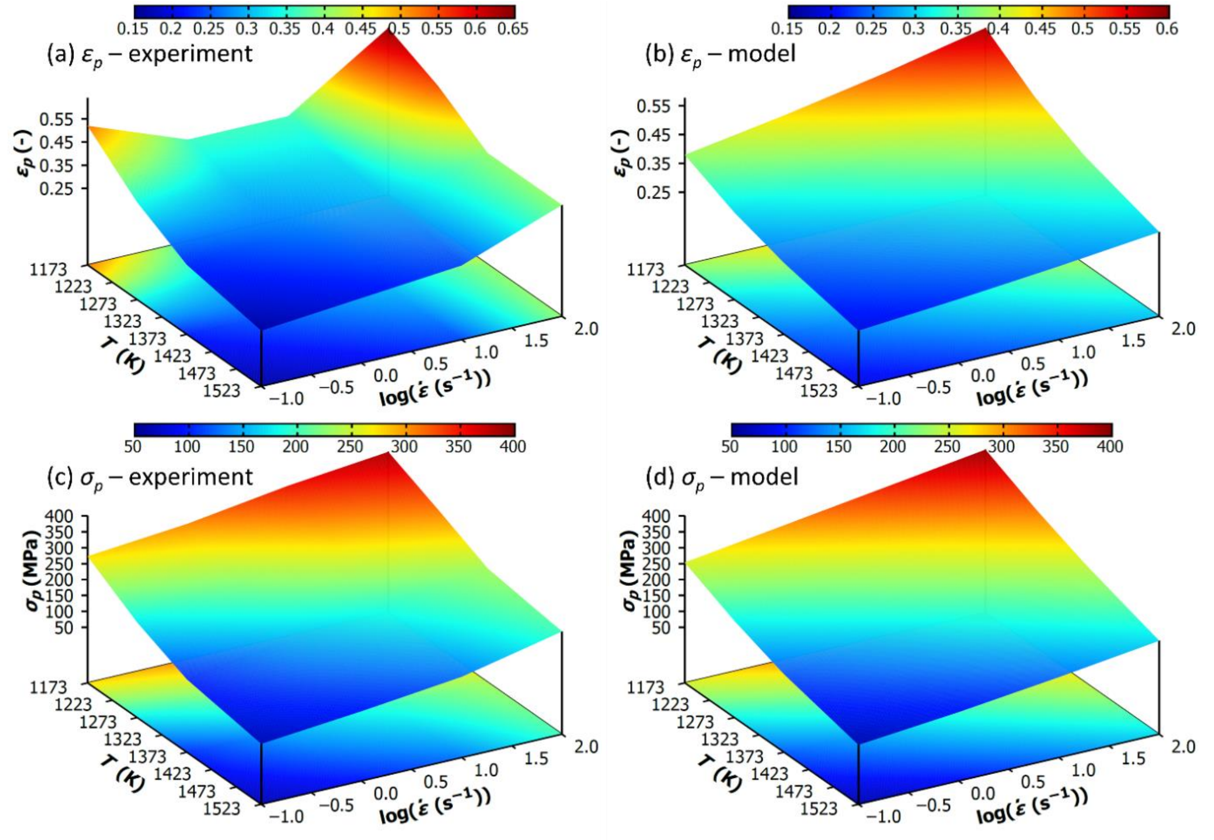

Figure 2 Experimental and modeled values of the examined peak point coordinates

4. CONCLUSION

This work investigated the effect of deformation temperature and the applied strain rate level on the deformation behavior of 3D printed AISI 316L steel with a closer focus on the reached peak stress levels and the onset of dynamic recrystallization. The flow curves obtained from the compression test results were used to obtain global peak corresponding to each tested combination of temperature and strain rate. The obtained peak point coordinates were then processed using a regression analysis to establish a Zener-Hollomon-based functional relationship between the predictors and studied outcomes. The rough estimates of the corresponding material constants were calculated via a linear least square methodism and subsequently refined by a nonlinear regression analysis using the Levenberg-Marquardt iterative optimization algorithm. The experimentally obtained and calculated peak point coordinates are expressed graphically as a function of the corresponding predictors.

In terms of peak strain and peak stress, good regression fit is supported by Pearson correlation coefficients of 0.8238 and 0.9919, respectively. For both experimental and model data, the higher the deformation temperature, the lower the peak point coordinates. The effect of strain rate is then exactly the opposite. However, the situation around the peak strain values is not so clear cut. The experimental data revealed that the effect of strain rate does not correspond to the generally accepted assumption about the onset of dynamic recrystallization. Peak strain values decrease in response to decreasing strain rate level only if this decrease in strain rate takes place between 10 and 100 s^{-1}. If the temperature does not drop below about 1,373 K, the further decrease in strain rate has a practically negligible effect. The situation below the above mentioned 1,373 K can then be described as completely unexpected – the decreasing level of the strain rate causes a significant increase in the peak strain. The applied Zener-Hollomon law is then not able to handle this situation correctly, so that the calculated data are more or less outside the experimental trends.

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REFERENCES

[1] KUNČICKÁ, L.; KOCICH, R.; NÉMETH, G.; DVOŘÁK, K.; PAGÁČ, M. Effect of post process shear straining on structure and mechanical properties of 316 L stainless steel manufactured via powder bed fusion. *Additive Manufacturing.* 2022, vol. 59, pp. 103128. Available from: https://doi.org/10.1016/j.addma.2022.103128

[2] ZENER, C., HOLLOMON, J.H. Effect of Strain Rate upon Plastic Flow of Steel. *Journal of Applied Physics*. 1944, vol. 15, no. 1, pp. 22-32.

[3] OPĚLA, P., KAWULOK, P., SCHINDLER, I., KAWULOK, R., RUSZ, S., NAVRÁTIL, H. On the Zener–Hollomon Parameter, Multi-Layer Perceptron and Multivariate Polynomials in the Struggle for the Peak and Steady-State Description. *Metals*. 2020, vol. 10, no. 11, 1413. Available from: https://doi.org/10.3390/met10111413.

[4] SCHINDLER, I., KAWULOK, P., KAWULOK, R., HADASIK, E., KUC, D. Influence of Calculation Method on Value of Activation Energy in Hot Forming. *High Temp. Mater. Processes.* 2013, vol. 32, pp. 149–155. Available from: https://doi.org/10.1515/htmp-2012-0106.

[5] GAROFALO, F. An Empirical Relation Defining the Stress Dependence of Minimum Creep Rate in Metals. *Transactions of the Metallurgical Society of the American Institute of Mining, Metallurgical, and Petroleum Engineers*. 1963, vol. 227, pp. 351-356.

[6] LEVENBERG, K. A Method for the Solution of Certain Non-Linear Problems in Least Squares. *Quarterly of Applied Mathematics*.1944, vol. 2, no. 2, pp. 164-168. Available from: https://doi.org/10.1090/qam/10666.

[7] MARQUARDT, D.W. An Algorithm for Least-Squares Estimation of Nonlinear Parameters. *Journal of the Society for Industrial and Applied Mathematics*. 1963, vol. 11, no. 2, pp. 431-441. Available from: https://doi.org/10.1137/0111030.

[8] PEARSON, K. On the dissection of asymmetrical frequency curves. *Philosophical Transactions of the Royal Society of London, Series A*. 1894, vol. 185, pp. 719-810.