DETERMINATION OF DYNAMIC PROPERTIES OF 3D PRINTED G3SI1 STEEL

PETR SVOBODA[1], MIROSLAV JOPEK[1], ONDREJ SVOBODA[2], MARTIN HARANT[1]

[1]Brno University of Technology, Faculty of Mechanical Engineering, Institute of Manifacturing Technology, Department of Metal Forming and Plastics, Brno, Czech Republic

[2]Brno University of Technology, Faculty of Mechanical Engineering, Brno, Czech Republic

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e-mail : 209148@vutbr.cz

Taylor anvil test is one of the dynamic test method used to determine the dependences of strain rate, strain and temperature on flow stress. This method can be used to determine the stress and strain at any point in the specimen at different temperatures and strain rates. The paper deals with the description of the Taylor anvil test experiment for G3Si1 welding wire. The experiment was carried out in the laboratory of high strain rates at the Faculty of Mechanical Engineering of Brno University of Technology. ANSYS Explicit dynamics software was used to simulate the material behaviour during the test. The Johnson-Cook constitutive relation was used to describe the material behaviour. The simulation results were compared with the experiment.

KEYWORDS

Taylor anvil test, high strain rate, 3D printing, Johnson-Cook, G3Si1 steel, finite element method

1 INTRODUCTION

Nowadays, one of the rapidly developing manufacturing technologies is 3D printing. 3D metal printing has seen a great spread in the aerospace and medical industries and is still growing [DebRoy 2018], [DebRoy 2019]. Manufacturing metal parts within high-tech industries offers distinct benefits, including shortened lead times for component production, the ability to create customized and optimized parts as needed, the potential to consolidate multiple components into single units with fewer connections, and the capacity to introduce intricate features and designs that were previously unattainable through traditional manufacturing methods [Leary 2021]. To properly understand the behaviour of a material, it is necessary to know its behaviour under dynamic loading conditions in addition to its quasi-static behavior [Jopek 2021].

The Taylor Anvil Test (TAT) is an example of a suitable experimental method used to investigate a material under high strain rates, especially mechanical strain rates [Taylor 1948].

Key material characteristics include the relationship between stress and strain. The dependence determines the onset of plastic deformation, i.e. the yield strength. It is also essential to describe the material behaviour in numerical simulations, and for most common simulation programs such as ANSYS, SINUFACT, PAM STAMP and others. In order to develop accurate and reliable simulation models, material models that describe in detail the material behaviour during the simulation are essential. Numerical modelling, such as the finite element method (FEM) combined with constitutive material models, has proven to be an extremely effective and reliable method for predicting material behaviour during deformation. Constitutive material models are mathematical expressions that explain how stress, strain rate and temperature of a material are related [Jopek 2021b]. One of these constitutive material models is the Johnson Cook (JC) material model. This material model has proven to be suitable for modelling ballistics and high velocity impacts, i.e. processes occurring at high strain rates [Trimble 2017].

The application of the JC constitutive material model is so accurate that it can predict stress and strain during forming at low and high strain rates [Burley 2018]. The model extrapolates the material behavior obtained from both, quasi-static tests ($\dot{\varphi} \leq 10^0\ s^{-1}$) and dynamic tests ($\dot{\varphi} \in \langle 10^2; 10^4 \rangle$). The material model includes a mathematical description of stresses that details the material behaviour with respect to deformation effects, strain rates and temperature variation [Trimble 2017].

2 JOHNSON-COOK KONSTITUTIVE MODEL

The JC material model is a special type of plasticity condition according to von Mises. It also considers the strain hardening law and strain rate dependence, which describe the material behaviour at high strain rates and high temperatures [Burley 2018]. Using the JC model, the flow stress can be determined as:

$$\sigma_d = (A + B \cdot \varphi^n) \cdot \left(1 + C \cdot \ln\left(\frac{\dot{\varphi}}{\dot{\varphi}_0}\right)\right) \cdot \left(1 - \left(\frac{T - T_O}{T_M - T_O}\right)^m\right) \quad (1)$$

where A is yield strength of material [MPa], B is hardening constant [MPa], C is strain rate constant [1], m is thermal softening exponent [1], n is hardening exponent [1], T is material temperature [K], T_M is material melting temperature [K], T_O is ambient temperature [K], φ is true plastic strain [1], $\dot{\varphi}$ is strain rate [s^{-1}] and $\dot{\varphi}_0$ is reference strain rate [s^{-1}].

In the equation, the first bracket expresses the elastic-plastic region in which the deformation strengthening of the material occurs as a result of reaching the yield strength. The second bracket expresses the strain rate sensitivity, which is manifested by an increase in yield strength at higher strain rates. The last bracket describes the decrease in yield stress due to an increase in material temperature [Burley 2018].

3 TAYLOR ANVIL TEST

The principle of the TAT is that a cylindrical specimen is shot onto a solid wall at different impact velocities. The design of the TAT approximates the actual load due to changes in the test specimens and geometry. The initial cylindrical specimen, Fig. 1, is placed in a carrier and subsequently accelerated by expanding air in a pneumatic cannon towards the impact site. The sample is separated from the carrier before it hits the measuring rod. The resulting impact of the specimen on the measuring rod results in deformation, Fig. 2. The measuring rod used behaves only elastically, no plastic deformation is allowed. Impact produces a compressive elastic pulse, which is recorded by resistance strain gauges on a measuring rod connected to a full Wheaston bridge and by dynamometer that is placed behind the measuring rod. The output voltage from both devices (strain gauge and dynamometer) is fed through an amplifier to a memory oscilloscope [Slais 2010], [Slais 2016]. The data is then transferred to a computer for further processing.

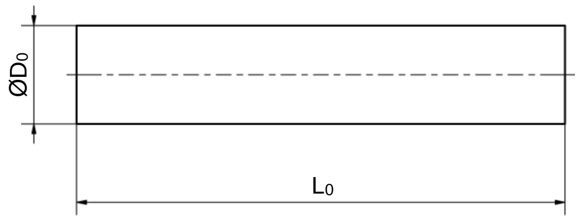

Figure 1. Specimen before loading

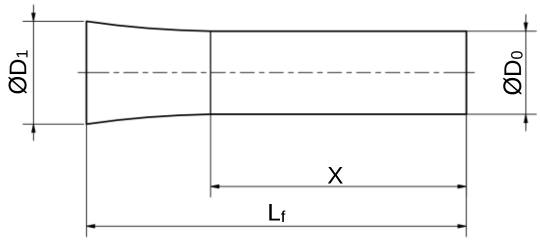

Figure 2. Specimen after loading

The samples were fabricated from G3Si1 material by 3D printing using a wire-arc additive manifacturing (WAAM) method. The chemical composition of this material is found in Table 1.

Element	C	Si	Mn	P	S	Cu
wt. %	0.11	0.85	1.3	0.025	0.025	0.35
Element	Cr	Ni	Mo	Al	V	Fe
wt. %	0.15	0.15	0.15	0.02	0.03	rest

Table 1. Chemical composition of G3Si1 material

4 DISCUSSION OF RESULTS

Experiments were performed using TAT. Johnson Cook's constitutive equation was chosen and used to mathematically describe the material behaviour. A summary of the material constants is given in Table 2.

Parameter	Value
A	431 MPa
B	848 MPa
C	0,014
n	0,501
m	0,329

Table 2. Parameters of the Johnson Cook constitutive equation

The fact that the material constants given in the constitutive relation are correct is demonstrated by the agreement with the measured data in both the quasi-static and dynamic tests, Fig. 3 and Fig. 4.

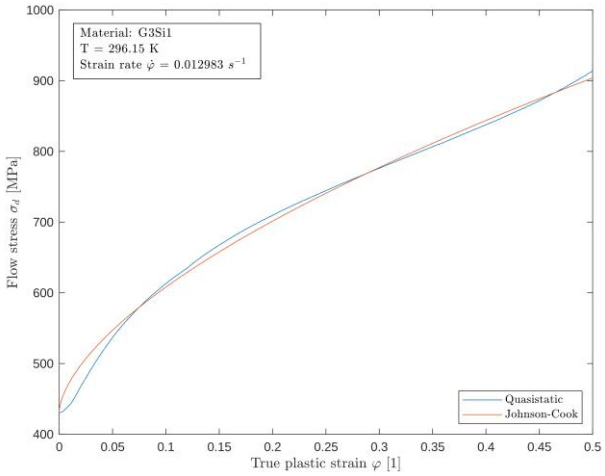

Figure 3. Comparison of experiment and simulation – quasi-static loading

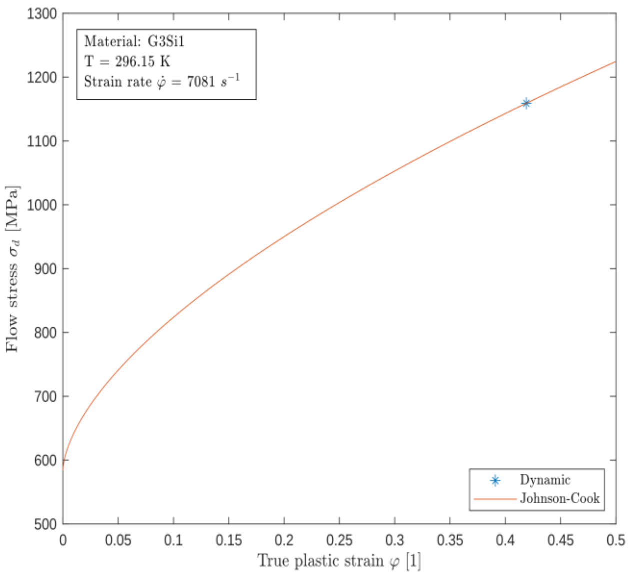

Figure 4. Comparison of experiment and simulation – dynamic loading

Next, the value of the strain stress calculated by JC was compared with the value calculated from the values measured after the experiment. The d'Alembert principle of calculation was used to determine the value. The value of the flow stress is determined:

$$\sigma_d = \frac{4 \cdot F_{max}}{\pi \cdot {d_1}^2} \tag{2}$$

where d_1 is the largest diameter of the sample after the test [mm], see Fig. 2, and F_{max} is impact force [N].

The value of impact force is calculated:

$$F_{max} = m_s \cdot \frac{{v_0}^2}{\Delta L} \tag{3}$$

where m_s is weight of the sample [kg], v_0 is impact velocity [$m \cdot s^{-1}$] and ΔL is change in sample length [m].

The change in sample length is calculated:

$$\Delta L = \frac{L_0 - L_f}{1\ 000} \tag{4}$$

where L_0 is initial length of sample [mm], Fig. 1, and L_f is length of sample after test [mm], Fig. 2.

To enter the JC relation, it is necessary to know the value of the strain and the strain rate:

$$\varphi = \ln\left(\frac{{D_1}^2}{{D_0}^2}\right) \tag{5}$$

$$\dot{\varphi} = \frac{v_0 \cdot \varphi}{4 \cdot \Delta L} \tag{6}$$

The measured and calculated values from the experiment are shown in Table 3. The measured and calculated values from the Johnson-Cook constitutive equation are shown in Table 4.

L_0 [mm]	L_f [mm]	ΔL [m]	v_0 [$m \cdot s^{-1}$]
25.006	22.938	$2.07 \cdot 10^{-3}$	139.86
m_s [kg]	F_{max} [N]	d_1 [mm]	σ_d [MPa]
$3.7 \cdot 10^{-3}$	34 997.668	6.198	1 159.968

Table 3. Resulting values of the experiment

φ [1]	$\dot{\varphi}$ [s^{-1}]	$\dot{\varphi}_0$ [s^{-1}]	T [K]
0.419	7 081	0.0129	296.15
T_M [K]	T_O [K]	σ_d [MPa]	
1809.15	296.15	1 160.411	

Table 4. Resulting values of the Johnson-Cook constitutive relation

The dimensions of the specimen before and after the test (Table 3) were measured using a Dial Snap Meter with a tolerance of ±0.001 mm.

Based on the comparison of experiment and simulation, stress-strain curves were designed for different strain rates and different temperatures, Fig. 5, Fig. 6, Fig. 7 and Fig. 8.

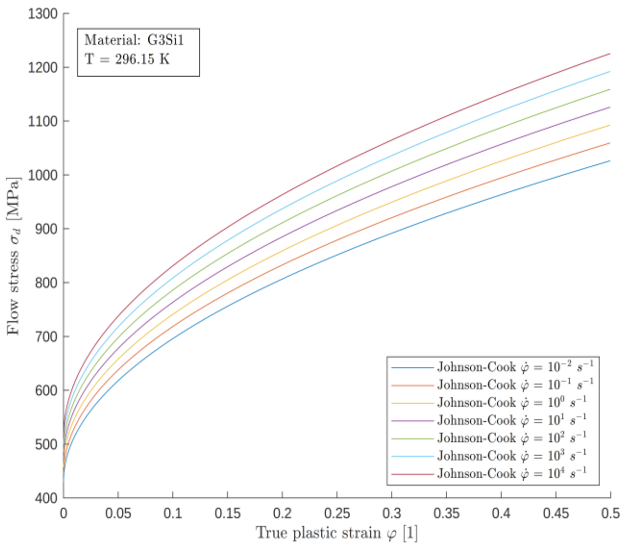

Figure 5. Strain-stress curves – temperature 296.15 K

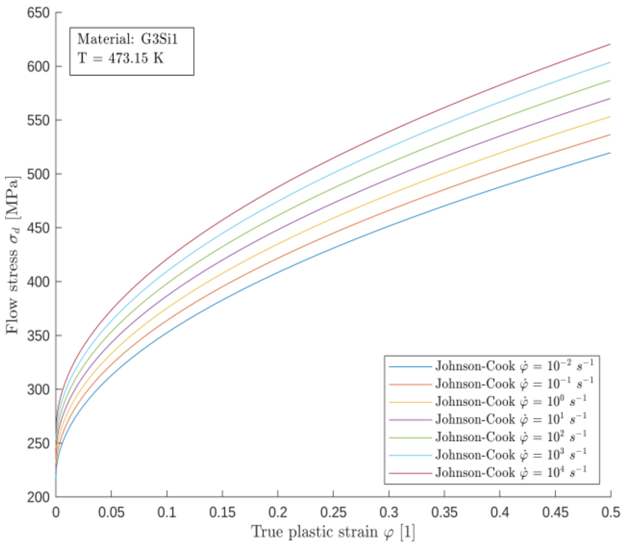

Figure 6. Strain-stress curves – temperature 473.15 K

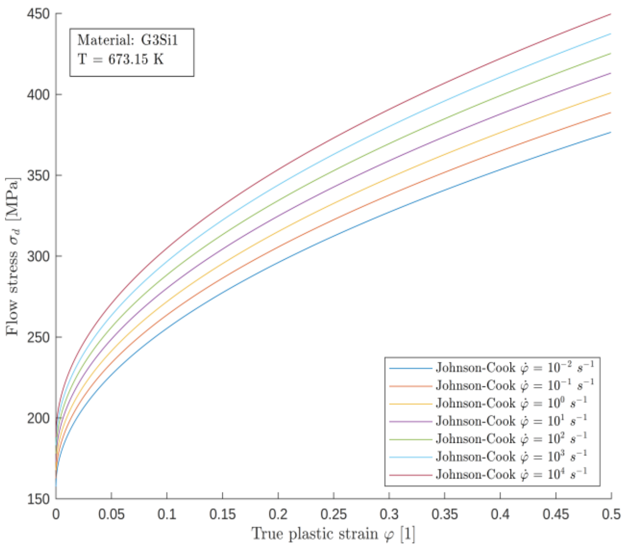

Figure 7. Strain-stress curves – temperature 673.15 K

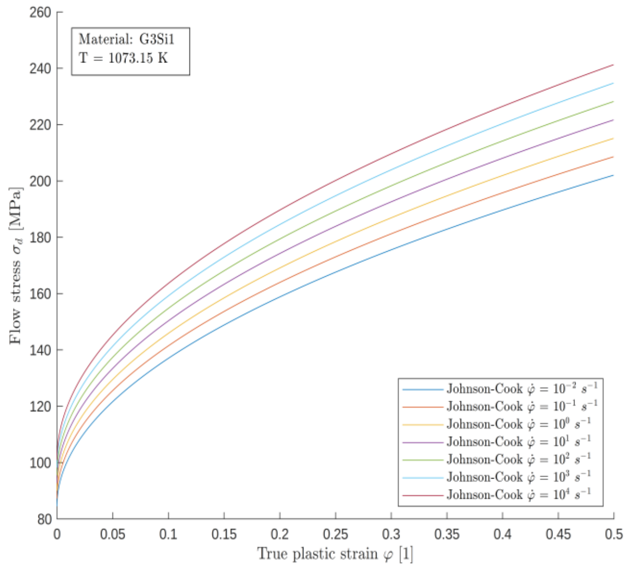

Figure 8. Strain-stress curves – temperature 1073.15 K

The figures illustrate the increase in flow stress with increasing strain and strain rate. They also show a decrease in flow stress with increasing material temperature.

Based on the knowledge of the mathematical prescription of material behaviour, the experiment can be simulated. The simulation was performed in ANSYS Explicit dynamics. Results are shown in Fig. 9, Fig. 10 and Fig. 11.

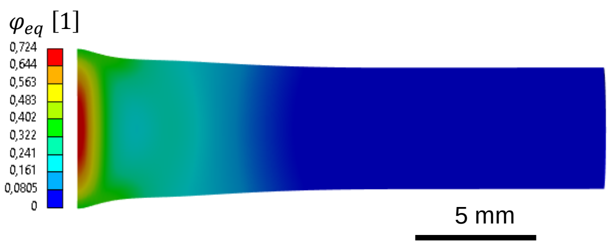

Figure 9. Equivalent true plastic strain

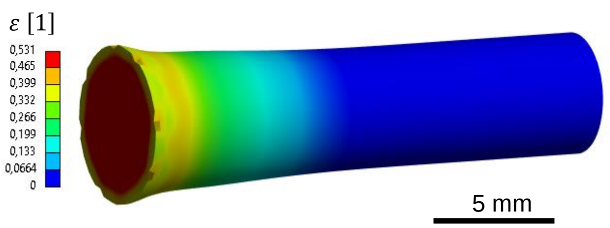

Figure 10. Engineering strain along the diameter

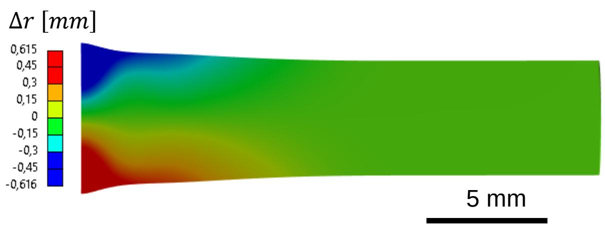

Figure 11. Deformation along the radius

The deformation along the radius shows a change of 0.616 mm at the point of impact, Fig. 11. When compared to the measured value, which achieved a radius increase of 0.599 mm, a deviation of 2.8 % is observed, which is a sufficient accuracy.

5 CONCLUSION

Johnson-Cook's constitutive equation describes the dependence of stress on strain, strain rate and temperature and describes the behavior of G3Si1 material well. The results further demonstrate that the Taylor anvil test is suitable for determining the parameters of the constitutive equation. The stress values from the experiment were compared with the value calculated by JC. The comparison shows the agreement between the formula, the constants used in it, and the actual test performed. The results of the compared flow stress values show a deviation of 0.5 MPa which is quite insignificant as it is a deviation of 0.4 ‰.

The results of the experiment were also compared with the results of the simulation performed in ANSYS Explicit dynamics. The comparison shows a good agreement between the experiment and the simulation, specifically a deviation of 0.017 mm, which is almost negligible as it is a deviation of 2.8 %.

Comparison of the JC curves with the measured experimental values shows very good agreement. From the other curve representations, a good agreement between the stress-strain curves at strain rates from 10^{-2} to 10^{4} is evident.

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CONTACTS:

Ing. Petr Svoboda
Brno University of Technology, Faculty of Mechanical Engineering, Institute of Manifacturing Technology, Department of Metal Forming and Plastics
Technická 2896/2, Brno, 616 69, Czech Republic, e-mail: 209148@vutbr.cz

Ing. Miroslav Jopek, Ph.D.
Brno University of Technology, Faculty of Mechanical Engineering, Institute of Manifacturing Technology, Department of Metal Forming and Plastics
Technická 2896/2, Brno, 616 69, Czech Republic, e-mail: jopek@fme.vutbr.cz

Ondrej Svoboda
Brno University of Technology, Faculty of Mechanical Engineering
Technická 2896/2, Brno, 616 69, Czech Republic, e-mail: 239681@vutbr.cz

Ing. Martin Harant
Brno University of Technology, Faculty of Mechanical Engineering, Institute of Manifacturing Technology, Department of Metal Forming and Plastics
Technická 2896/2, Brno, 616 69, Czech Republic, e-mail: 170977@vutbr.cz