

Identification of Material Parameters and Material Model for 3D Printed Structure

FUSEK M.^{1,a}, PAŠKA Z.^{1,b}, ROJÍČEK J.^{1,c}

¹Department of Applied Mechanics, Faculty of Mechanical Engineering, VŠB – Technical University of Ostrava, 17. listopadu 2172/15, 708 00 Ostrava, Czech Republic

^amartin.fusek@vsb.cz, ^bzbynek.paska@vsb.cz, ^cjaroslav.rojicek@vsb.cz

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Abstract. The paper focuses on the determination of material parameters of the Anand material model for ABS-M30 material. The material parameters were determined by the method of Genetic algorithm (GA) using FEM calculations. Several experimental tensile and indentation tests were performed. The configuration of the individual tests was chosen to capture relaxation and creep, which are important for this type of material. The FEM simulations were then adjusted to the experimental tests carried out to achieve the greatest possible agreement.

Introduction

One of the most advanced methods of component manufacture is the 3D printing process. For the needs of the correct design of components it is necessary, among other things, to know the correct material parameters. The parameters of printed 3D structures are highly dependent on the technology of 3D printing, the laying of the filament and the setting of the printing process (e.g. temperature). This article describes the procedure for determining the material parameters of a printed structure produced by the 3D printing process using printer Fortus 450mc [1]. The material used for printing is ABS-M30 [2].

Experiments

The experiments were performed on a Testometric M500 50CT testing machine at room temperature. The mentioned test machine will soon be supplemented by a furnace, so that it will be possible to perform further experiments at different temperatures. The following tests were performed: Indentation tests, tensile tests, and relaxation tests. The load was applied in different ways so that the specimen was tested in all directions to detect the anisotropy of the test material.

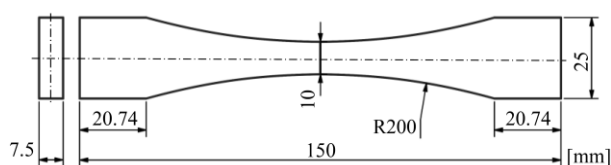


Fig. 1: Specimen scheme for tensile and relaxation tests

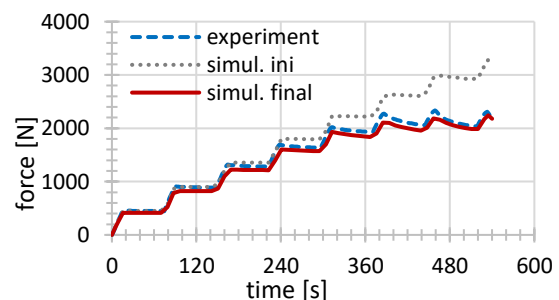


Fig. 2: Graded tensile test and FEM simulation (identification)

The specimen shown in Fig. 1 was used for the tensile test and the relaxation test. All tensile tests were deformation-controlled. Fig. 2 shows a graded tensile test with the following configuration: The specimen was elongated by 0.25 mm at an elongation rate of 0.017 mm s⁻¹. Time delay at the given strain value was always 60 s. This was done until the specimen failed. During the graded tensile test, the phenomenon of creep was partially detected. Up to the value of the tensile force of approx. 800 N, there is no significant relaxation of the tension, see Fig. 2. Fig. 3 is a simple tensile test in which the crossbeam is moved at rate of 0.017 mm s⁻¹ until the specimen failed. Fig. 4 is a tensile test with this configuration: The crossbeam rate was 0.017 mm s⁻¹. At a specimen elongation value equal to 1 mm, the time delay was 60 s. This was followed by the displacement of the crossbar at the same rate until the specimen failed.

A cube-shaped specimen with a side length of $s = 50$ mm was used for the indentation test. The indentation test was carried out with an indenter in the form of a sphere with a radius of 2.5 mm. The indenter rate, the load values and the loading modes were chosen differently to obtain more data that better characterize the behaviour of the printed material. With the help of FEM calculations, it was determined how precisely determined material parameters of the material model corresponds to the results of experimental tests - the validation was done by a graphical comparison of the results of FEM solution and indentation (experiment).

All indentation tests were deformation-controlled. In Fig. 5 is an indentation test with the following settings: The indenter was gradually pressed into the surface of the specimen with rate 0.017 mm s⁻¹ to a depth of about 0.8 mm and then the indenter was gradually pulled out of the specimen without delay. In Fig. 6, is a test with the following settings: The indenter rate is 0.017 mm s⁻¹ to a depth of 0.8 mm. This is followed by a time delay of 600 s. The indenter is then pulled out at the same speed.

At the same time, specimens with different orientations in the chamber of the 3D printer were examined in this way. The different orientation of the specimen in the chamber of the 3D printer results in different laying of the individual material fibres and leads to anisotropy.

Material model

One of the material models used for the visco-plastic materials is the Anand material model [3]. The Anand model was proposed for use in the analysis of the rate-dependent deformation of metals at high temperatures. The Anand visco-plastic model is pre-built in commercial finite-element software system Ansys. The Anand model is typically used for solder alloys [4] but previously mentioned benefits led us to test it for materials used in 3D printing (ABS-M30). Anand material model [3] does not allow anisotropy, so only 4 selected tests with the same fibre orientation were used for identification. (3 tensile tests and 1 indentation test) and in this phase of material model testing with a one temperature 20°C. The indentation test was then used to validate the numerical results with the experiments. The material model is given by 11 material parameters: Poisson ratio (μ), Young's modulus (E), Initial value of deformation resistance (s_0), Activation energy/Universal gas constant (Q/R), Pre-exponential factor (A), Stress multiplier (x_i), Strain rate sensitivity of stress (m), Hardening/softening constant (h_0), Coefficient for deformation resistance saturation value (\hat{S}), Strain rate sensitivity of saturation (deformation resistance) value (n) and Strain rate sensitivity of hardening or softening (a).

Algorithm for material parameters identification

The material parameter identification can be described mathematically as:

$$f(X) = \text{minimum}, \quad (1)$$

where $f(X)$ is an objective function and X represents a vector of material parameters. For minimization, the Finite Element Model Updating (FEMU) approach was used, which is described in [5]. In short, the material parameters were determined by repeated calculations - optimization in our own program written in Python. The solution procedure is as follows: First, FEM models are created (with APDL) to simulate experiments. These models/simulations were created in a commercial program (Ansys) as blocks, where the input is the values of material parameters and the output is the value corresponding to the data set obtained from the measurement (load, displacement and time). The difference between the results of the simulations and the measured data is represented by the value of the objective function. These simulations are solved in cycles in which the input values change in relation to finding the minimum value of the objective function. All experiments were deformation-controlled, so that the values of the forces were chosen for the design of the objective function. The difference between the measured data and the data from the simulations for an experiment was solved as follows (an individual objective function $f_i(X)$ for i -th experiment):

$$f_i(X) = \sum_{j=1}^{N_i} \left| \frac{F_j^{EXP} - F_j^{FEM}(X)}{F_j^{EXP}} \right|, \quad (2)$$

where N_i is number of measurement points for i -th experiment, F_j^{EXP} is an experimental force, $F_j^{FEM}(X)$ is a force obtained from simulation.

The value of objective function for all experiments ($f(X)$) was solved as:

$$f(X) = \sqrt{\frac{\sum_{i=1}^N f_i(X)^2}{N}}, \quad (3)$$

where N is a number of experiments.

One of the algorithms used to identify material parameters is GA, see e.g. [6]. A detailed description of GA can be found e.g. in [7]. This GA is relatively simple and available in a variety of variants. The advantage lies in its easy programmability and can be used for parallel solutions (supercomputers). For these reasons, this GA is chosen. The chromosome is given by a set of material parameters and a gene is a one material parameter:

$$X = \left\{ E, \mu, s_0, \frac{Q}{R}, A, x_i, m, h_0, \hat{S}, n, a \right\}. \quad (4)$$

A population was given by 10 solutions and it was generated randomly by Hill climbing algorithm [8]. For example, for the first parameter was used:

$$E_{New} = E_{Best} [1 + \text{Rand}(-0.01, 0.01)], \quad (5)$$

where E_{New} is a new value of the parameter, E_{Best} is a value of parameter for the solution with the minimum value of the objective function for actual population, and Rand generates random values (uniform distribution) from the interval. The population is modified in each cycle. With a probability of 40%, a randomly generated incomer is added, which is generated with the Hill climbing algorithm" (previous equation). With a probability of 60% a child (crossover) is added. The child chromosome was created from three chromosomes of parents, where the

parents were randomly selected from the population (uniform distribution). The calculation a value of a gene is presented only for the first parameter (E), the other parameters are calculated by the same approach. The values are calculated from ($\Delta E = k(E_1 - E_2)$) and ($\Delta E = k(E_1 - E_3)$), where equations are selected randomly (with 70% and 30% probability, respectively), E_1 is the gene value of the first parent, E_2 is the gene value of the second parent, E_3 is the gene value of the third parent, ΔE is gene change proposal and k is an increase coefficient (0.1 – 1.0). The parents are ordered by its value of the objective function (the first parent has a minimum value and parent three has a maximum value). The value of ΔE must place to interval ($0.0001|E_{Best}|, 0.05|E_{Best}|$) or it is generated randomly by:

$$\Delta E = \text{Rand}(-0.001, 0.001)E_{Best}. \quad (6)$$

The child value of the gene (E_{Child}) is finally calculated as:

$$E_{Child} = E_{Best} + \Delta E(1 + \text{Rand}(-0.01, 0.01)). \quad (7)$$

The initial value of material parameters follow: The value of the Poisson ratio $\mu = 0.3$ and the value of Young's modulus $E = 1950$ MPa were taken from [9] for material ABS-M30. The Anand material parameters were taken from [10] for material SAC309 (Sn-3.0Ag-0.5Cu), these parameters were primarily identified by the algorithm. The initial parameters are shown in Table 1.

Table 1: Initial parameters of Anand material model

$s_0[MPa]$	Q/R	$A[1/s]$	x_i	m	$h_0[MPa]$	$\hat{S}[MPa]$	n	a
21	9320	3501	4	0.25	180000	30.2	0.01	1.9

Due to the data set used to identification, the Poisson ratio was not identified. Due to the use of a limited data set, the effect of individual parameters on the value of the objective function was tested. The procedure is presented for the first parameter again. Three values of the objective function were calculated with an analysed value of parameter:

$$\begin{aligned} f &= f\left(\left\{E, \mu, s_0, \frac{Q}{R}, A, x_i, m, h_0, \hat{S}, n, a\right\}\right), \\ f^{+\Delta E} &= f\left(\left\{E(1 + 0.05), \mu, s_0, \frac{Q}{R}, A, x_i, m, h_0, \hat{S}, n, a\right\}\right), \\ f^{-\Delta E} &= f\left(\left\{E(1 - 0.05), \mu, s_0, \frac{Q}{R}, A, x_i, m, h_0, \hat{S}, n, a\right\}\right). \end{aligned} \quad (8)$$

The first criterion for excluding a parameter is ($f \approx f^{+\Delta E} \approx f^{-\Delta E}$) with respect to the behaviour of the criterion for other parameters. This criterion show that the parameter has a negligible effect on the result with respect to the other parameters. The second criterion for excluding a parameter is ($f^{+\Delta E} \gg f \ll f^{-\Delta E}$) with respect to the behaviour of the criterion for other parameters. The second criterion shows that the parameter has in the value the local minimum. On the other side, the optimum parameter for identification meets conditions ($f^{+\Delta E} < f < f^{-\Delta E}$) and ($f^{+\Delta E} > f > f^{-\Delta E}$), respectively.

Four experiments was used for identification (Fig. 2, 3, 4 and 5), the fifth experiment was used to material parameter validation (Fig. 6). The identification process required 200 cycles, the values of the objective function are in Table 2 and $f_V(X)$ represents the value of objective function for the verification experiment.

Table 2: Values of the objective functions

	$f_1(X)$ [%]	$f_2(X)$ [%]	$f_3(X)$ [%]	$f_4(X)$ [%]	$f(X)$ [%]	$f_V(X)$ [%]
final	2.2	5.8	3.2	12	6.94	10.6

The resulting parameters of the Anand material model are summarized in a Table 3 and the value of the Poisson ratio is $\mu = 0.33$ and the Young's modulus is $E = 1780$ MPa.

Table 3: Result parameters of Anand material model

s_0 [MPa]	Q/R	A [1/s]	x_i	m	h_0 [MPa]	\hat{S} [MPa]	n	a
19.54	8350	3134	5.18	0.2466	183245	31.0	0.0098	1.524

In Fig. 3 the simple tensile test is compared with the FEM simulation. Fig. 4 again shows the tensile test, but at a certain value of strain of the specimen the loading was interrupted for 60 s to see if relaxation occurred, then the specimen was loaded until failure.

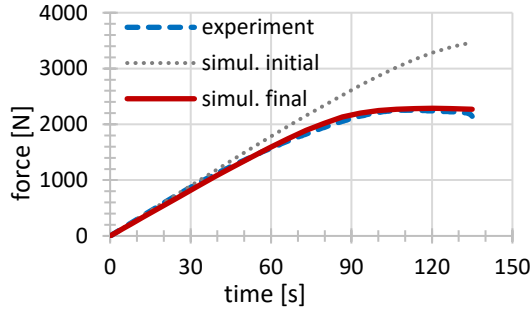


Fig. 3: Tensile test (identification)

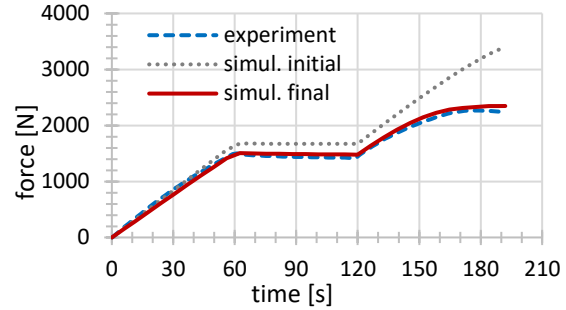


Fig. 4: Tensile test with time delay (identification)

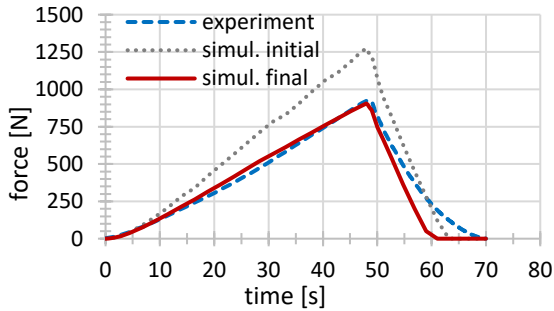


Fig. 5: Indentation with relief of load (identification)

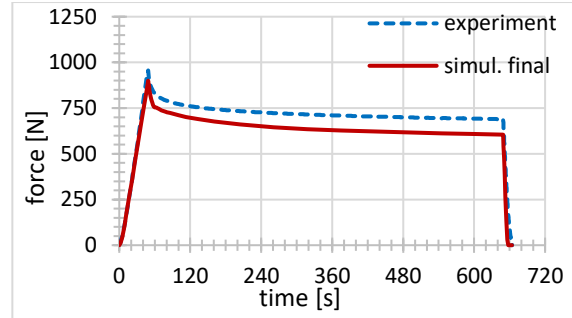


Fig. 6: Indentation with relaxation effect (validation)

Fig. 5 is a recording of the indentation test with FEM simulation. Fig. 6 compare the indentation test with the FEM simulation. This is an indentation test with a time delay to monitor the effect of material relaxation on the magnitude of the loading force.

Conclusions

The results obtained show the possibility of finding the material model parameters with help of an indentation or tensile tests. The results of the FEM calculations are in good agreement with the experimentally obtained data. Our department has recently acquired a temperature chamber and experiments under different temperatures will be possible soon. Anand material model can be used for specimens loaded at different temperatures. However, Anand model is not able to

sufficiently capture the anisotropic behaviour of the investigated material. We are currently working on the use of a more advanced material model that includes the effect of material anisotropy and the use of a complete data set from experiments.

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