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OPTIMIZATION OF JOHNSON–COOK CONSTITUTIVE MODEL PARAMETERS

In modern machining industry, the concept of process optimization has gained widespread recognition. FEM simulations are commonly used for the optimization of machining operations, allowing for a proper choice of tool geometry and process parameters to obtain results that are in accordance with end user criteria. However, one has to be wary that a good agreement of experimental and simulation results is mandatory if the simulation is to be used as a basis for optimization of a real-life process. Therefore, a proper choice of constitutive model parameters is vital. Those parameter values are dependent on many variables. Constitutive model parameter values are determined experimentally – therefore, they are accurate only for the conditions (temperature, strain rate etc.) under which the experiment was performed. The alteration, or *optimization* of model parameters is necessary if cutting and experiment conditions differ, if one wishes to obtain applicable results. In this work, the authors aim to present a method of optimizing the Johnson–Cook constitutive model parameters to obtain a better fit with experimental data.

1. INTRODUCTION

Numerical simulations play a significant role in modern scientific research related to the investigation of machining-associated phenomena, while also being widely used in industrial applications, for example by cutting tool manufacturers to test new designs. Optimization of cutting processes is another area of application of FEM simulations. The concept of process optimization has gained considerable recognition in both scientific works and industrial application. In relation to machining processes, the optimization can be understood as seeking a best available solution in accordance to user-assumed criteria, without exceeding the assumed boundary conditions [1].

Basing on the information contained in the previous paragraph, the application of FEM simulations in machining processes can be broken down into three main areas: investigation

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of occurring phenomena, testing of process parameters, tool designs [2] or even calculations regarding proper installation of machine tools on foundations [3], and finally, process optimization. It is very important to stress here that regardless of potential area of application, a good agreement of simulation results with real-life measurements and conditions is vital to successful utilization of FEM simulations. Properly setting up an FEM simulation is a complex task, as it is necessary to adequately represent a number of phenomena associated with the machining process. Those include friction, stress, strain or heat transfer between the tool and workpiece amongst others. The accuracy of numerical simulations is also dependent on the used constitutive model and the correct determination of its parameter values. Numerous works by other authors show noticeable differences in both simulation results and Johnson–Cookconstitutive model parameter values for the same tool-workpiece material combination [4–11]. However, it is noteworthy that some differences in simulation results may have been the effect of different simulation setups, FEM software etc. A significant effect of Johnson–Cook model parameters on simulation results while keeping the simulation setup intact was shown in previous work by the authors [12]. In this work, the authors aim to present a method of numerically optimizing the constitutive model parameters to obtain a better fit with experimental data, therefore potentially improving the accuracy of the FEM simulations of machining processes.

2. JOHNSON–COOK CONSTITUTIVE MODEL

Decohesion of workpiece material and resultant chip formation are an essential part of the machining process. A constitutive model that is applicable to FEM simulation of machining processes has to accurately describe the stress-strain relation occurring within the workpiece material, up to the point of reaching yield strength and material separation. Moreover, an appropriate constitutive model has to take into account the effect of various phenomena on material behaviour. These include, but are not limited to: strain hardening, effect of strain rate and thermal softening.

Several material models are used in machining simulations. These include the Johnson–Cook, Zerilla-Armstrong and Power Law models. Moreover, Baummann–Chiesa–Johnson and Nemat–Nasser models are also mentioned in literature [9]. Moreover, several modified versions of the Johnson–Cook model have been proposed by Ozel et al. [9] to reflect the effect of strain hardening on material behaviour more accurately. These models reflect real-life conditions more closely, however they require determination of additional model parameters.

$$\sigma_p = \underbrace{\left[A + B(\varepsilon^p)^n\right]}_{1.1} \underbrace{\left[1 + C \ln\left(\frac{\dot{\varepsilon}^p}{\dot{\varepsilon}^0}\right)\right]}_{1.2} \underbrace{\left[1 - \left(\frac{T - T_{ot}}{T_t - T_{ot}}\right)^m\right]}_{1.3} \qquad (1)$$

where: σ_p – equivalent plastic stress, MPa; ε^p – plastic strain; $\dot{\varepsilon}^p$ – strain rate, 1/s; $\dot{\varepsilon}^o$ – reference strain rate, 1/s; T – temperature, ºC; T_t – melting temperature, ºC; T_{ot} – room temperature, ºC; *A, B, C, m, n* – material specific model parameters.

Basing on the literature research conducted by the authors, it can be stated that the Johnson–Cook model is most commonly used for FEM simulations of machining processes [4–9, 11]. A basic form of this model is given in equation (1). It describes the effects of strain hardening (1.1), strain rate (1.2) and thermal softening (1.3) on material properties.

Values of Johnson–Cook model parameters for different workpiece materials can be found in open literature. It is easy to notice values of J-C model parameters for the same workpiece material vary between publications. Material-specific Johnson–Cook model parameters have to be obtained in the course of experimental testing, for example with the use of Split Hopkinson bar tests. Experimental data is obtained at room temperatures and for much lower strain values and strain rates than the ones typically observed in machining, therefore the obtained data is extrapolated into the range of temperatures, strains and strain rates typically extant in the shear zone [9]. This fact, along with inconsistency of chemical and mechanical properties within the same material grades, discrepancies in test results depending on the method used and poor availability of data for some materials are a source of significant difficulties in FEM simulations of the machining processes [10, 13].

3. OPTIMIZATION OF JOHNSON–COOK MODEL PARAMETERS

As it was mentioned in the previous paragraph, constitutive model parameter values are determined experimentally – therefore, they are accurate only for the conditions (temperature, strain rate etc.) under which the experiment was performed. The alteration, or optimization of material-specific model parameters is necessary when cutting conditions differ from the ones typically observed in machining, if one wishes to obtain applicable results. In this work, the Optimization Toolbox module of MATLAB software was used to obtain a best possible fit of Johnson–Cook model parameters with available experimental data.

3.1. EXPERIMENTAL TESTS

The first step of the optimization procedure was to obtain experimental data. Experimental tests with the use of a Bahr 850 D/L dilatometer an INSTRON 5982 static testing system were performed on Ti6Al4V grade titanium alloy. Tests were performed for a range of temperatures and at two constant strain rates, different for tensile and compression tests. Sample temperature during the experiment was monitored with the use of a K type thermocouple. The experimental setup is described in Table 1.

Table 1. Experimental setup for tensile and compression tests

Tensile tests							
Temperature T, °C	20	100	200	300	400	500	600	700
strain rate $\acute{\varepsilon}$, 1/s	0.002604							
Compression tests							
Temperature T, °C	500	600	700	800	900	1000		
strain rate $\acute{\varepsilon}$, 1/s	12.5							

A graphical representation of experiment results is presented in Figs 1 and 2.
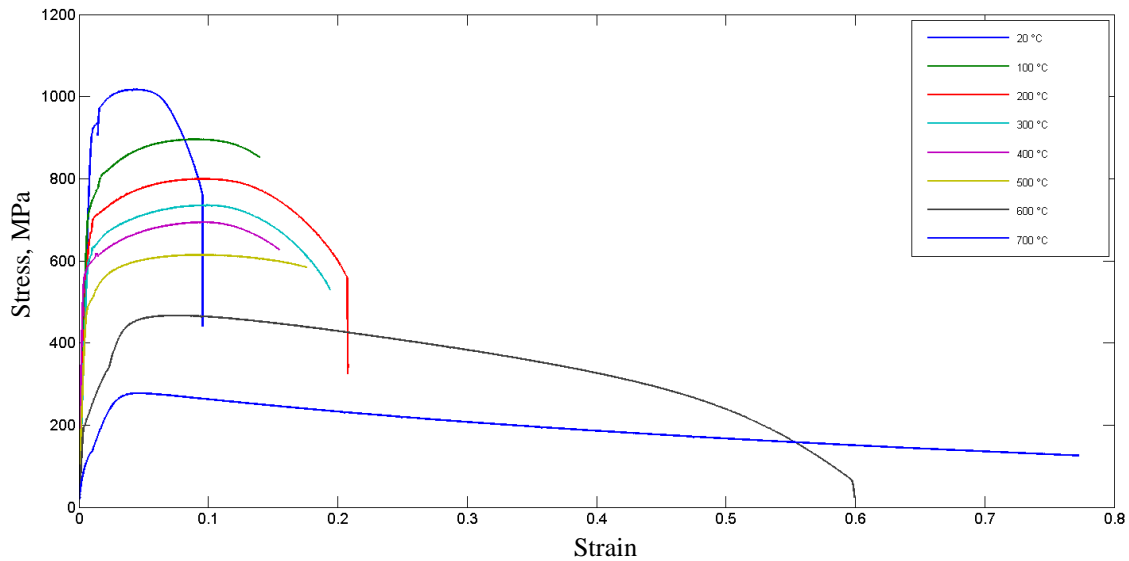

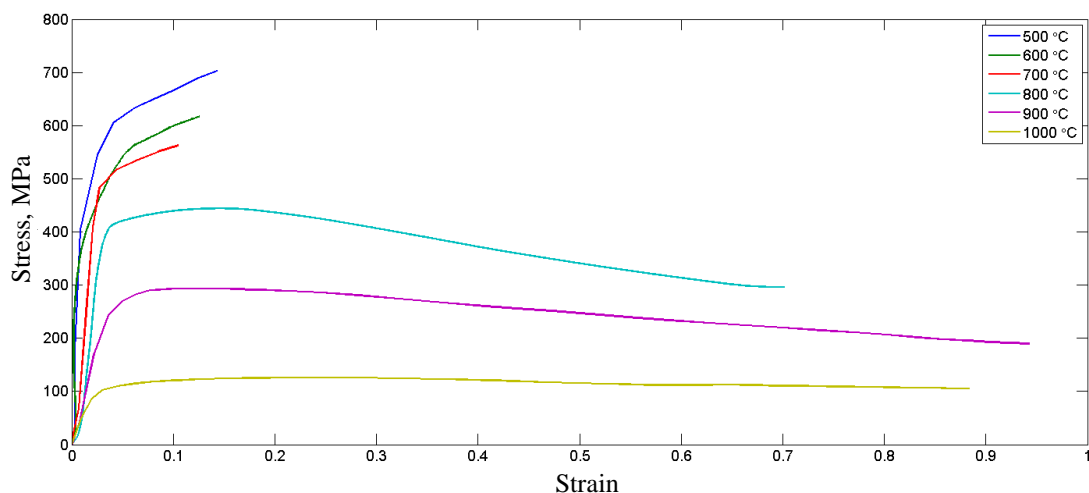
Fig. 1. Experimental results for tensile tests

Fig. 2. Experimental results for compression tests

By analysing the data presented in Figs 1 and 2, it can be inferred that the temperature has a visible effect on stress-strain relations in the sample material. The effect of thermal softening is especially evident in the case of compression tests performed at a higher strain rate than tensile tests. True strain increases greatly in the range of temperatures above 800°C. The highest strain was observed for the temperature of 900°C, whereas the lowest true stress was noted for compression tests performed at 1000°C. The effect of thermal softening is visibly less evident in the case of tensile tests, where stress decreases with temperature, but no significant changes in strain were observed for the temperature range of 20–400°C. Strain increases approximately twofold for the temperature of 600°C in comparison to 400°C. The highest strain values in the case of tensile tests were observed for the temperature of 700°C. Likewise, the lowest stress was observed at this temperature.

3.2. OPTIMIZATION OF PARAMETER VALUES

The first step was to select a set of Johnson–Cook model parameters available in open literature for Ti6Al4V that provided a closest match to the obtained experimental data. Basing of comparisons and a literature research, the authors have decided that parameter values presented in research [11] show the best agreement with experimental results. Therefore, they were chosen as a basis for optimization. Parameter values are given in Table 2.

Table 2. J-C model parameter values for Ti6Al4V from open literature [11]

A, MPa	B, MPa	C, MPa	n, –	m, –
968	380	0.0197	0.421	0.577

A PC computer equipped with an Intel Core i5-4570 (4th gen Haswell) 3.20 GHz quad-core CPU and 16 GB of DDR3 1600 MHz RAM memory was used for calculations . The optimization of model parameters was conducted with the use of the Optimization Toolbox add-on software designed for MATLAB. An additional Genetic Algorithm sub-toolbox provided with the software for optimizing non-linear functions was employed in this research. This tool is equipped with a Graphic User Interface (GUI) which allows for intuitive operation and a generation of a complete MATLAB file that is ready for use, provided that input data (experimental results in this case) has already been imported into MATLAB environment.

The end user has to specify several characteristics optimization parameters, such as maximum number of iterations, upper and lower limits for output values of optimized parameters, function tolerance, population size, number of generations etc. Values of those parameters were specified using the trial-and-error method to determine what values produce best results without excessively increasing computation time. The software searches for J-C model parameter values that allow for modelling material behaviour to reflect input experimental data as closely as it is possible. The output result is a set of accordingly modified J-C model parameter values. The software also displays a series of graphs depicting stress-strain relations in the material for experimental data and Johnson–Cook model in the user-defined range of temperatures for comparison purposes.

4. OPTIMIZATION RESULTS

The values of Johnson–Cook parameters calculated in MATLAB software are presented in Table 3.

Table 3. Johnson–Cook model parameter values for Ti6Al4V titanium alloy after optimization

A, MPa	B, MPa	C, MPa	n, –	m, –
750	455.03	–0.176	0.162	0.647

A graphical representation of results in the form of stress-strain graphs comparing experimental results with base and modified parameters of Johnson–Cook model are shown in Figs 3–6. All presented results are for a strain rate of ($\varepsilon = 12.5$ 1/s). The presented results are within a temperature range typically encountered when machining Ti6Al4V [14].
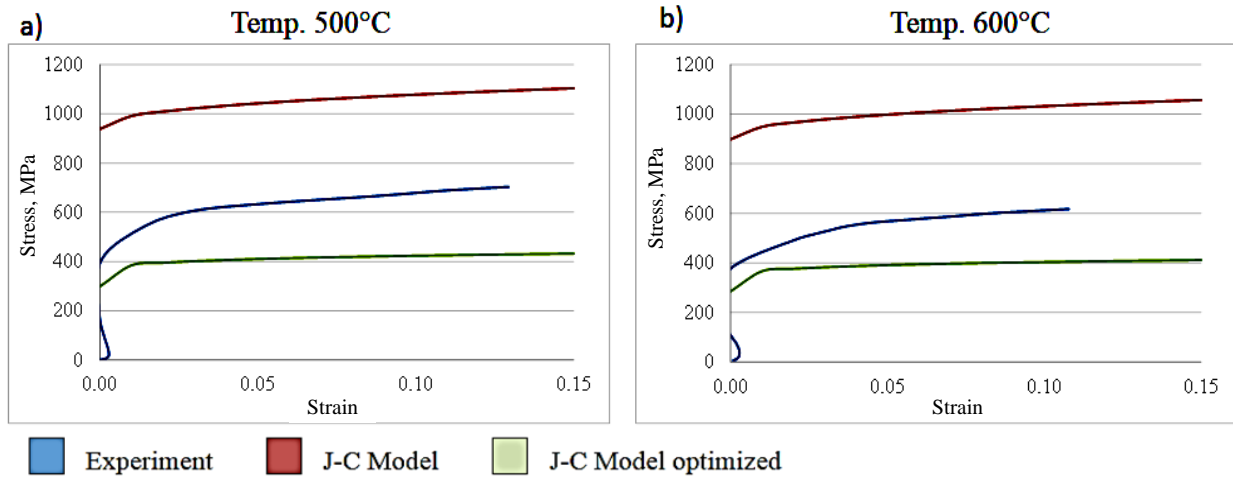

Fig. 3. A comparison of experimental data with a Johnson–Cook model for temperatures of 500 and 600°C
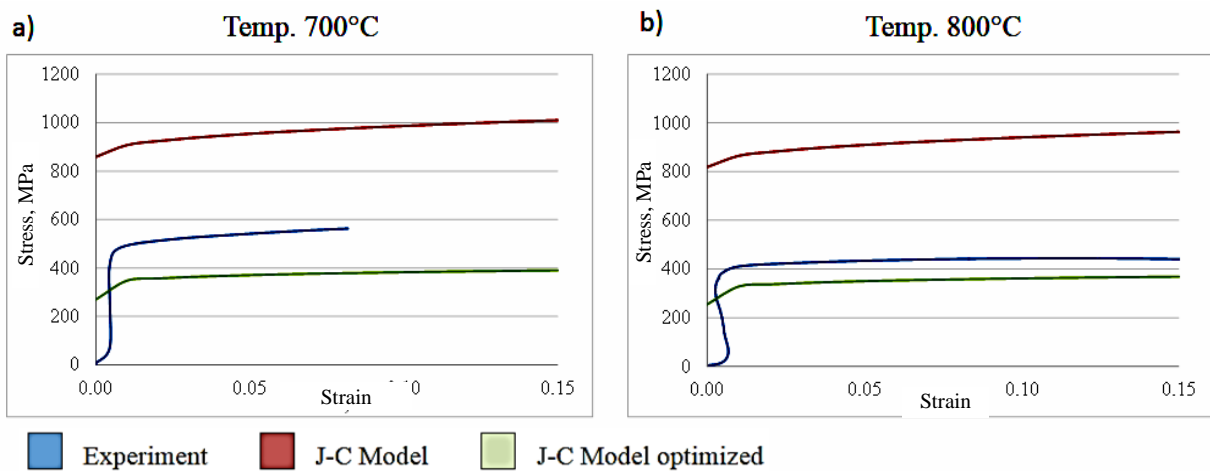

Fig. 4. A comparison of experimental data with a Johnson–Cook model for temperatures of 700 and 800°C

As was mentioned in the previous Chapter, thermal softening has a noticeable effect on material behaviour in case of experimental data obtained for Ti6Al4V aluminium alloy, especially for the higher strain rate ($(\varepsilon = 12.5$ 1/s)). However, it can be easily noticed that the effect of thermal softening on material behaviour is not as pronounced in the case of a Johnson–Cook model with parameters given in Table 2. Differences in stress can exceed as much as over 700 MPa, as is seen for the temperature of 1000°C (Fig. 5b). It can be expected that this will lead to discrepancies and a degree of inaccuracy in FEM simulations of cutting processes.
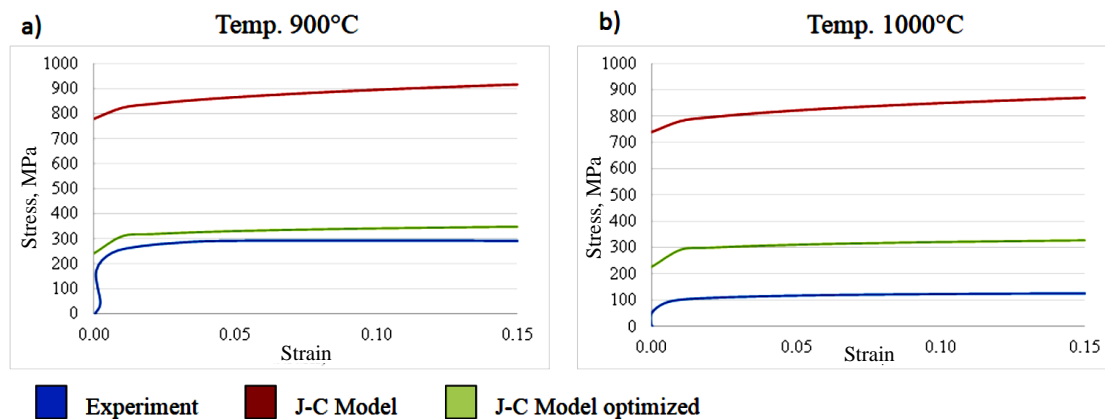
Fig. 5. A comparison of experimental data with a Johnson–Cook model for temperatures of 900 and 1000°C

A significant improvement in agreement of stress-strain relations for experimental data and a Johnson–Cook model can be seen with the use of an optimized parameter set shown in Table 3. The best agreement of results was noted in the case of 900°C, with differences not exceeding 57 MPa at 0.15 strain. Largest discrepancies were noted in the case of 500°C, namely 275 MPa at 0.13 strain.

5. SUMMARY

The optimization method presented in this research paper allows for a significant improvement in agreement of material behaviour modelled with the use of a Johnson–Cook model with experimental results. Best optimization results were obtained in the 800–1000°C temperature range. With a right choice of optimization parameters, the computation time did not exceed 10 minutes for a presented set of results. This makes the presented method convenient to use, especially when considering the improvement in agreement of results.

FEM simulations of the cutting process will have to be performed with the aim of comparing results for base and optimized J-C model parameters. Moreover, In future research the authors are planning to conduct the optimization procedure with the use of an extended Johnson–Cook model, as preliminary testing has shown that it provides a better fit to experimental data than the basic model. This will require additional experimental tests and a modification of the presented script.

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