Determination of Johnson-Cook material constants for Copper using traction tests and inverse identification

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Abstract. Copper and its alloys have specific properties - electrical and thermal conductivity, ductility, mechanical strength, corrosion resistance - which make it a material used in various industrial applications. However, these materials are difficult to weld by conventional processes due to their high thermal conductivity and high rate of oxidation at temperatures close to melting. To be able to join copper-based materials, friction stir welding seems to be a promising possibility. The quality of the assembly obtained strongly depends on the parameters of the process chosen to generate a temperature close to the optimum value. So, to find these parameters, it is necessary to carry out experimental test campaigns which are generally very expensive in terms of time and equipment. An alternative will be to use the numerical simulations of the FSW process to find the optimal parameters. Numerical simulation contributes also to a better understanding of the influence of input parameters on the phenomena in the process and the connections made. To develop a numerical model, it is necessary to use a constitutive equation that defines the behavior of the material throughout the process. The most commonly constitutive equation used for FSW modeling is Johnson-Cook. The paper describes the strategy of identifying the constants of the material, respectively the method of inverse identification of the parameters. The constants of the thermo-mechanical behavior (both elastic and plastic) are identified by coupling the finite element method with Abaqus and Matlab software. This strategy tries to minimize the quadratic deviation between the response of the model and the experimental tests. Tensile tests were carried out on quasi-pure copper CU-DHP samples, at temperatures of 22°C, and 500°C, for speeds of 3 mm/min and 30 mm/min, respectively. The validation of the model thus identified was carried out on tensile tests at a temperature of 300°C, by comparing the curves obtained with the Johnson-Cook model and those obtained experimentally.

1. Introduction
Copper welding is difficult using conventional welding processes due to the high thermal diffusivity, which is at least ten times higher than that of most steels. In order to reduce temperature losses, it is advantageous to use a welding process that is carried out at lower temperatures. The FSW process is characterized as a feasible welding process for joining copper [1-5].

In general, experimental investigations have a high cost, with a period of execution and implementation, often much too long. For the prediction of the mechanisms that take place during the
welding processes, solutions are established based on the finite element method, specific to the mechanics of continuous media, but also to describe the behaviors of the investigated materials, through certain constitutive equations.

Tensile tests for different speeds and temperatures are required to identify the parameters of a material. The most commonly used model of plastic behavior of the material for FSW welding processing is the Johnson-Cook model [6-8].

The investigated material is a deoxidized copper with phosphorus content, between 0.015-0.04% P (Cu-DHP), which has high thermal conductivity, with good behavior in FSW friction welding processes [1-5].

This paper describes the strategy by which the material constants of Cu-DHP for the elastic and plastic domains are determined, using the tensile test and the inverse identification method. For this, tensile stresses were achieved for speeds of 3 mm/min and 30 mm/min at temperatures of 22°C and 500°C. The validation of the model being thus achieved by comparing the curves obtained experimentally with those obtained following the use of the Johnson-Cook model.

2. The experimental and numerical procedure

2.1 Material and specimen geometry

Copper and copper-based alloys have electrical and thermal conductivity, mechanical strength, and formability and corrosion resistance being used in a wide range of engineering applications. Friction stir welding (FSW) is a solid-state welding process performed at temperatures lower than the melting temperature of the base material. This feature makes it suitable for welding pure copper and its alloys, whose thermal diffusivity is much higher than that of most steel alloys. The Johnson-Cook law constants determined in this paper will be used in the simulation of the copper joint by FSW. To obtain simulation results close to the experimental ones, the material must be precisely defined.

Table 1. Properties of DHP Copper.

| Material | Density [kg/m³] | Young’s modulus [GPa] | Poisson’s Ratio, ν | Thermal conductivity, k [W/m°C] | Specific heat, c [J/Kg °C] | Thermal Expansion, [10⁻⁶ °C] |
|----------|----------------|-----------------------|-----------------|-------------------------------|------------------------|-----------------------------|
| Cu-DHP   | 8913           | 117.2                 | 0.33            | 388                           | 385                    | 16.8                        |

The material analyzed is Cu-DHP, which is a deoxidized phosphorus copper with a purity of 99.9%, which has only 0.015 - 0.04% phosphorus. The values of its properties that were used in the development of numerical simulations were taken from the property tables of the material [9], table 1. In the numerical model, the plastic behavior of pure copper is established by the Johnson-Cook empirical law (can see in equation 1) which is integrated into Abaqus / Explicit, which characterizes the relationship between flow stress σ, plastic deformation rate ε, and temperature T, according to the following relationship [10]:

$$
\bar{\sigma} = \left[A + B \cdot (\varepsilon^{pl})^n\right] \left[1 + C \cdot \ln\left(\varepsilon^{pl} / \varepsilon_0\right)\right] \left[1 - \left(\frac{T - T_{ref}}{T_{melt} - T_{ref}}\right)^m\right]^{m}
$$  

(1)

with: $\bar{\varepsilon}$ is normal strain rate; $\varepsilon^{pl}$ the effective plastic strain; $\varepsilon^{pl}$ is the effective plastic strain rate; $\varepsilon_0$ is the normalizing strain rate; $A$, $B$, $C$, $n$, $T_{melt}$ and $m$ are material constants; the $n$ exponent takes into consideration the hardening of the material, while $m$ depends on its melting; $C$ is influenced by the speed of deformation; $T_{ref}$ is the ambient temperature, which is 22°C in this case and at which we determine the parameters $A$, $B$, $n$; $T_{melt}$ is the material’s melting temperature.

The Johnson-Cook constants initially used in the simulation are shown in table 2 [3]:

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Table 2. Johnson-Cook constants.

| Material | \(T_{\text{melt}}\) [°C] | A [MPa] | B [MPa] | C  | n  | m  |
|----------|----------------|--------|--------|----|----|----|
| Cu-DHP   | 1083           | 90     | 292    | 0.025 | 0.31 | 1.09 |

The identification of the elastic parameters of the material and a part of the constants of the Johnson-Cook law (A, B, n) is done by the inverse method, using the simulation of the tensile test. The identification of the other constants of the Johnson-Cook law of behavior will be made starting from the results of the traction test, performed at different speeds and temperatures. The geometry of the specimen used in the simulation corresponds to the experimental one and is presented in figure 1.

![Figure 1. Standard specimen.](image1)

![Figure 2. Experimental assembly.](image2)

The specimen is mounted with bolts, figure 2. The bolts were preferred to the detriment of the screws, because the material of the test piece, namely copper, at different temperatures and over time, can oxidize so that the thread of the screws can deform. Because the assembly is made for tensile stress, the lower part of the device will be mounted in the traction machine and will remain fixed, and the upper part of the device will move in the axial direction.

2.2 Experimental procedure

To identify all the parameters of the Johnson-Cook model, tests are required at least two load speeds and at two different temperatures. Thus, tensile tests were performed at temperatures of 22°C, 300°C and 500°C, respectively, and at speeds of 3 mm/min and 30 mm/min, respectively.

Figure 3 shows the experimental device. It consists of the hydraulic traction machine INSTRON 1342 (100KN), on which an oven is mounted. The specimen is placed inside the oven, which is fixed to the bottom and top of the machine using two rods and the cooling system. The specimen is positioned between the two contact rods utilizing the fastening system. The cooling system aims to ensure the ambient temperature of the extremities (fasteners), to highlight temperature changes.

To know the values of the temperatures that take place during the process, three thermocouples were inserted: one in the upper part of the machine, one in the lower part, and another inserted in the oven, thermocouple that comes into contact with the specimen, to be able to check and measure the actual temperature of the specimen during the test.
2.3 Numerical procedure
The tensile test is the test most often used to characterize the mechanical behaviour of a progressively stressed material with a low or medium loading speed. This test allows, among other things, the study and identification of the physical mechanisms of plastic deformation, which govern the mechanisms of plasticity. In order to analyze the behavior of the material, both elastic and plastic properties, several simulations of tensile tests, at different speeds and temperatures were performed using Abaqus software. Simulations were performed at temperatures of 25 °C, 300 °C and 600 °C, respectively, and at speeds of 0.1 mm/s, 1 mm/s, and 10 mm/s, respectively.

The geometry used in the simulation corresponds to the geometry used experimentally. Thus, the cylinders at the bottom are embedded, and those at the top were applied a displacement of 10 mm, figure 4.

3. Inverse identification of material constants in Johnson Cook's law of behavior
The simulation results were processed using Matlab software, and the stress-strain curves were obtained in order to analyze the elastic behavior of the material, respectively the way in which the values of Young's modulus of temperature and deformation velocity were influenced, figure 5 and figure 6.
Figure 5. The influence of temperature on the modulus of elasticity $E$.

Figure 6. Stress-strain curves obtained from the simulation at different speeds and temperatures.

It turned out that the value of the modulus of elasticity decreases with temperature. The stress-strain curves obtained from the experimental data from the tensile tests of three specimens at ambient temperature ($22 \, ^\circC$) are shown in figure 7.
Figure 7. Experimental stress-strain curves (nominal values $\sigma_n - \varepsilon_n$; real values $\sigma_v - \varepsilon_v$).

Real experimental curves were used for the inverse identification of the parameters. The initial values of the Young $E_0$ module and the Poisson ratio $\nu_0$ were entered to initiate the procedure. To identify the elastic parameters, the inverse identification strategy was used, which can be summarized in the following steps:

- an optimization algorithm generated a pair of parameters $(E_i, \nu_i)$. This pair of parameters was integrated into a calculation code using the finite element method, to simulate the tensile test.
- the result of the calculation with finite elements, allowed to trace the elastic macroscopic behavior of the sample associated with the pair of parameters and was compared with the experimental one.
- this comparison was made by defining an error function: $E_r = f(E_i, \nu_i)$. The optimization algorithm identified a pair of values $(E_f, \nu_f)$ that minimize the function $E_r$ built in the previous step.

The fminsearch function will generate another set of values of $E_i$ and $\nu_i$, which will be transferred to finite element calculus in Abaqus. Abaqus will identify the existence of a file with parameter values (the one generated from Scilab) and will launch the elastic calculation. After performing the calculation, the stress and strain values will be exported to build the simulated stress-strain curve. The data obtained from the finite element calculation will be compared with the experimental data and the error will be calculated. If the error is less than the tolerance defined in the fminsearch function, we will get the parameters you are looking for. Otherwise, the Scilab will generate another data set until the $E_r < \text{Tol}$ condition is met. When the condition is met, we will obtain the final values, respectively parameters $E_f$ and $\nu_f$, figure 8.

Figure 8. Logic scheme of optimization.
For example, for the experimental curve C2, from Scilab was obtained the graph with the optimization path, figure 9 and the graph of the curves $\sigma$-$\varepsilon_{xx}$ and $\sigma$-$\varepsilon_{yy}$ (actual and experimental values), figure 10.

The same was done for curves C1 and C3. Thus the following mean values of $E$ and $\nu$ were obtained:

$$E = 109364.387 \text{ [MPa]}$$  \hspace{1cm} (2)

$$\nu = \frac{\nu_1 + \nu_2 + \nu_3}{3} = \frac{0.401 + 0.372 + 0.292}{3} = 0.355$$  \hspace{1cm} (3)

Figure 12 shows the real experimental curves obtained at different deformation rates and temperatures. From the evolution of the curves, it can be seen that the effect of deformation speeds is important at high temperatures, at ambient temperature can be considered negligible.

To identify the constants of Johnson Cook's law of behavior, the Curve Fitting (cftool) application from Matlab was used. Thus, the stress-strain curves in the plastic field were plotted using experimental data and the constants of the Johnson-Cook model were identified in table 3.
Table 3. Constants of Johnson-Cook’s model for DHP copper.

| Material | $T_{melt}^{(0)}$ ($^\circ$C) | $T_{ref}^{(0)}$ ($^\circ$C) | A (MPa) | B (MPa) | C  | n   | m   |
|----------|----------------|----------------|--------|--------|----|-----|-----|
| DHP-Cu   | 1083           | 22             | 250    | 250.4  | 0.0137 | 0.81 | 0.73 |

Johnson-Cook curves were plotted compared to the experimental ones. The solid lines, red and blue, represent the experimental data, and the dotted lines represent the curve drawn with the determined Johnson-Cook model. Figure 12 shows that there is a good correlation at 22 °C. Also, the effect of deformation speed is modeled relatively well.

![Johnson-Cook curves](image)

**Figure 12.** The results obtained by identifying the Johnson-Cook parameters.

4. Use of Johnson-Cook law constants establish in FSW simulation

4.1 Geometrical model and mesh

Friction stir welding (FSW) is a joining process, considered in the solid-state because the temperature during the process is lower than the melting temperature of the material. Although there is important recent progress in numerical simulation of the Friction Stir Welding process, most models have more limitations mainly due to the long computational time, but also due to the definition of the material behavior and the friction conditions. In this study, an efficient numerical model is developed to simulate the butt joint of copper sheets, starting from the FEM model presented in [11]. The simulation was performed with ABAQUS/CAE code using the Coupled Eulerian-Lagrangian (CEL) formulation, the workpieces to be welded are included in the Eulerian domain, figure 13.

![Model geometry](image)

**Figure 13.** Model geometry.
The tool is considered a rigid body, it has a monobloc structure, with a shoulder diameter Φ20 mm, and the tool pin is conical and smooth, based on the size of 4 mm, and at the top 3 mm, with a length of 2.8 mm. Welding plates are three-dimensional, solid, deformable bodies with dimensions of 100 mm x 40 mm x 3 mm. The Eulerian domain includes the workpiece.

The FSW simulation was performed using variable friction coefficient, starting from 0.2071. The heat exchange between the environment and the Eulerian domain is modeled by a heat transfer coefficient $h=30 \text{ W/m}^2\cdot\text{°C}$, which is assigned to all surfaces of the Eulerian domain. Boundary conditions imposed in the plunged phase: speed of 60 mm/min on the Y axis, with a rotation speed of 1000 rpm. The degrees of freedom on the X-axis and the Z-axis is 0.

In the welding phase, a speed of 90 mm/min is applied on the X-axis. The rotation speed remains the same throughout the process.

![Mesh model](image_url)

**Figure 14.** Mesh model.

Eulerian domain was meshed using 6000 thermally coupled 8-node Eulerian elements with 8364 nodes, figure 14. Mesh was performed progressively, increasing the width of the element from the joint line to the edge. The tool is a Lagrangian rigid body and was meshed using 785 quadratic tetrahedral elements of type C3D10M.

4.2 Simulation results

The evolution of temperature is analyzed taking into account the results in the literature. Suitable temperatures for a successful butt joining process (FSW) of copper workpieces were found between 460°C and 530°C, figure 15 [11, 12].

![Temperature and axial forces](image_url)

**Figure 15.** Analysis of temperature and axial forces [11].
Good mechanical properties of the joint are obtained if temperatures of approx. 550°C [13]. The results obtained, figure 16, were compared with the recommended temperature.

![Figure 16. Temperature profile.](image)

(a) Temperature distribution; b) Temperature evolution versus pin profiles.

As can be seen from the previous figure, the temperature increases progressively, but there are not many values above the optimum temperature, and the maximum temperature reaches about 700 °C (does not reach the melting temperature of Copper 1083 °C).

It is observed that the temperature reached when using the variable friction coefficient is close to the recommended one. For this reason, the simulations were performed using a coefficient of friction that varies with temperature and Johnson-Cook law constants establish.

5. Conclusions

Numerical simulation of processes that are still in development can reduce research costs. The accuracy of the results is influenced by several factors and the accuracy with which the material is defined. The paper presents the identification of Johnson Cook's law constants for Copper DHP using the inverse identification method and the tensile test at different speeds and temperatures.

The inverse method is used to identify the parameters of the elastic mechanical behavior starting from the tensile test. The data obtained from the finite element calculation were compared with the experimental data and the error was calculated. When an error less than the defined tolerance resulted, the identified parameters were retained. Thus, 3 parameters were identified for 3 experimental curves and the average value was retained (E = 109364.4 MPa, ν = 0.355).

Using the real stress-strain curves at different temperatures and strain rates and the Matlab program, Johnson-Cook law constants were identified. Comparing the experimentally determined curves with those calculated using the Johnson-Cook law, it was observed that there is a good correlation at 22 °C.

Using the elastic parameters and the established Johnson Cook law and variable coefficient of friction, the joint of some copper plates was simulated with the help of FSW. Temperature values close to the optimum temperature indicated in the literature were obtained.

6. References

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**Acknowledgements**
This work was supported by a grant of the Romanian Ministry of Research and Innovation, CCCDI-UEFISCDI, project number PN-III-P3-3.1-PM-RO-FR-2019-0048/01.07.2019