

UNIAXIAL COMPRESSION TEST SIMULATION OF COPPER-GRAPHENE COMPOSITE PROCESSED BY INTENSIVE PLASTIC DEFORMATION

¹Petr OPĚLA, ¹Josef WALEK, ¹Lucie JEZERSKÁ

¹VSB - Technical University of Ostrava, Ostrava, Czech Republic, EU, petr.opela@vsb.cz

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Abstract

The Cu-graphene composite combines the high electrical and thermal conductivity of copper with the extreme strength and stiffness of graphene. This composite is thus stronger, more wear-resistant and at the same time highly conductive. It is particularly suitable for new generation electrical conductors, thermal management in electronics, electrical contacts or commutators of electric motors. The addition of graphene significantly affects the plastic deformation of copper. The resulting deformation behavior is often a combination of strengthening and a change in the deformation mechanism. The presented study investigates the deformation behavior of this composite through the simulation of a uniaxial compression test using the finite element method in FORGE software (TRANSVALOR) using the Hensel-Spittel rheological model, compiled on the basis of a uniaxial compression test on the Gleeble device. The results indicate maximum effective stress values in the range from 330 MPa to 422 MPa as the strain rate increases from 0.1 s^{-1} to 100 s^{-1} . At higher strain rates, the effect of deformation heat plays a significant role, which locally leads to a significant softening of the investigated composite. This effect is all the stronger because at high strain rates the deformation process is practically adiabatic, when during deformation lasting less than a second there is not enough time for the heat generated to be dissipated. The maximum effective strain then reaches values about 1.5.

Keywords: Cu-graphene, compression test, FEM simulation, FORGE software

1. INTRODUCTION

High-performance components based on electrically conductive copper alloys and composites are essential for modern industry [1-3]. Although pure copper has excellent electrical conductivity, its low strength restricts its practical applications [2,3]. Alloying increases strength, but reduces conductivity due to electron scattering on microstructural obstacles [4]. An effective alternative is to form composites, particularly by introducing second phases, which have a less detrimental effect on conductivity [5,6]. Copper-graphene composites are especially promising in this respect, combining high strength with outstanding electrical and thermal properties [6-8]. However, they are challenging to fabricate due to differences in component densities, carbon agglomeration and the poor wettability of copper and graphene [1,5,9]. The key therefore lies in processing methods that ensure homogeneous dispersion and strong mechanical bonding without degrading the carbon phase [1,10,11]. Severe and intensive plastic deformation techniques, typically performed at low temperatures, are an efficient way of producing ultrafine-grained structures, enhancing mechanical properties and preserving high electrical conductivity [12-19].

The main objective of the presented contribution is to evaluate the deformation behavior of the studied Cu-graphene composite from the perspective of uniaxial compression testing. The sub-tasks are the implementation of experimental measurements in order to reveal the flow stress response, the construction of a flow stress model and the implementation of FEM simulations of uniaxial compression tests for various strain rates in order to reveal the stability of plastic deformation of the studied composite, especially at higher rate deformation.

2. PREPARATION OF SAMPLES

First, a portion of the original commercially pure copper powder (5 μm particle size, 99.7 % purity) was subjected to chemical vapour deposition to introduce the graphene element [1,2,17]. The enhanced powder was then mixed with additional commercially pure copper powder to create an initial powder mixture containing 1×10^{-1} wt. % graphene.

The powder mixture was subsequently canned in 25 mm diameter copper containers, vacuum sealed and consolidated directly via rotary swaging into final rods with a diameter of 10 mm [1,2]. Rotary swaging is an industrially applicable method of intensive plastic deformation. The principle behind this method is the application of gradual increments of high-shear strain to the workpieces [13,20]. This process changes the shape and dimensions of the workpiece, enabling the production of final products with theoretically unlimited lengths and the required geometry [13]. The swaging ratio applied to fully consolidate the canned powder pieces was calculated via equation (1),

$$\varphi = \ln \left(\frac{S_0}{S_n} \right) \quad (1)$$

where S_0 and S_n are the cross-sectional areas of the container filled with powder at the input and output to the swaging dies, respectively [2].

3. UNIAXIAL COMPRESSION TEST EXPERIMENT

In order to map an unknown flow stress evolution of the examined Cu-graphene composite, processed by intensive plastic deformation, and gain basis for intended FEM simulation, it was approached to realize uniaxial compression tests on the Gleeble 3800-GTC thermal-mechanical simulator. The initial cylindrical samples with a diameter of 10 mm and a height of 15 mm were compressed with a true height strain of -1.0 at three temperatures (20, 160 and 300 $^{\circ}\text{C}$) combined with three strain rates (0.1, 1 and 10 s^{-1}). Tantalum foils and lubricating grease were applied to protect anvils and impede friction forces on the anvils–sample interface. By regression analysis of the resulting experimental flow curves, the Hensel-Spittel rheological model was subsequently obtained (see equation (2) and **Table 1**), allowing the prediction of flow stress and thus forming the basis for FEM simulations:

$$\sigma = A \cdot e^{m_1 \cdot T} \cdot \varepsilon^{m_2} \cdot \dot{\varepsilon}^{m_3} \cdot e^{m_4 / \varepsilon} \quad (2)$$

where T ($^{\circ}\text{C}$), ε (-), $\dot{\varepsilon}$ (s^{-1}) and σ (MPa) represent deformation temperature, true strain, strain rate a true flow stress, respectively. Material parameters A and m_1 – m_4 are presented in **Table 1**. Pearson's correlation coefficient R is then equal to 0.962, indicating a good curve fit.

Table 1 Hensel-Spittel material parameters of Cu-graphene composite

A	m_1	m_2	m_3	m_4
$4.23 \cdot 10^{+02}$	$-1.54 \cdot 10^{-03}$	$1.10 \cdot 10^{-02}$	$3.33 \cdot 10^{-02}$	$-2.37 \cdot 10^{-03}$

4. UNIAXIAL COMPRESSION TEST SIMULATION

4.1 Preprocessing

To be able to map the deformation behavior of the given Cu-graphene composite under uniaxial compression test, FEM simulations of selected uniaxial compression tests were carried out (specific thermomechanical conditions – 20 $^{\circ}\text{C}$ and strain rates from 0.1 to 100 s^{-1} , with true strain of -1.0). The simulations have been performed in the FORGE NxT 3.0 environment. Basically, a uniaxial compression test (UCT) is generally very similar to a classic upsetting forging technology, which can be in the FORGE software environment assembled very easily. However, unlike the upsetting, the UCT procedure has to fulfill two essential requirements. First of

all, a tested sample is during the test permanently held at the prescribed testing temperature, i.e., heat transfer to the anvils and surroundings had to be restricted. Besides the temperature, a strain rate value has to be also during the UCT held on the constant level. So, the anvil move rate had to be driven on the basis of the following equation:

$$v = h_0 \cdot \dot{\varepsilon} \cdot e^{-\dot{\varepsilon} \cdot t} \quad (3)$$

where, h_0 (mm), t (s), v (mm·s⁻¹) and $\dot{\varepsilon}$ (s⁻¹) represent initial sample height, compression test time, upper anvil velocity and strain rate, respectively. In order to simulate the friction conditions at the anvil-sample interface, a friction coefficient of 0.15 was adopted for this purpose, as it exactly matches the friction coefficient of the practically applied nickel-based lubricant.

4.2 Postprocessing

Figure 1 offers a comparison of the distribution of the temperature field in the longitudinal section of compressed samples. At first glance, there is an obvious development of deformation heat, which spreads from the central parts to the edge parts. For a sample deformed at a strain rate of 0.1 s⁻¹, this temperature increase is about 100 °C. However, the temperature field is essentially homogeneous here, which is given by practically isothermal conditions, when the temperature gradient is almost imperceptible due to the very slow deformation (lasting 11 s). The situation then changes with the increase in strain rate. The higher the strain rate, the more intense the temperature increase and the temperature field becomes more heterogeneous. From a rate of 10 s⁻¹ onwards, the process can be considered practically adiabatic, when deformation lasting only 0.11 s (10 s⁻¹) or 0.011 s (100 s⁻¹) does not allow heat dissipation and the temperature gradient is very high. An extreme case is a strain rate of 100 s⁻¹, where the local temperature increase is close to the recrystallization temperature of the alloy under investigation (approx. 270 °C) – so, the cold forming almost goes to be hot forming. This can have an adverse effect on the resulting mechanical properties (affecting strength and toughness) – inhomogeneous microstructure, reduced strength in warmer areas.

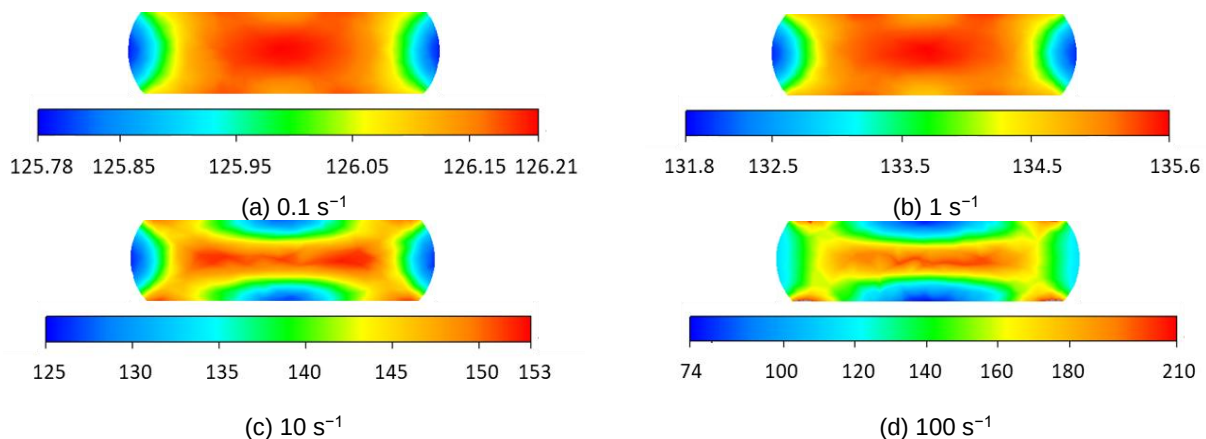


Figure 1 Temperature (°C) distribution in the compressed samples

Figure 2 shows the distribution of the effective strain field. The comparison shows that the magnitude of the embedded strain is practically identical regardless to the applied strain rate. As expected, the greatest intensity of the embedded strain can always be observed in the middle of the deformed sample. Towards the anvils, due to the friction conditions at the sample-anvil interface, the strain intensity gradually decreases. While the strain values in the inner layers reach values of up to 1.5, at the sample-anvil interface there is a very intense braking of the flow of metal particles, resulting in practically almost zero strain (significant heterogeneity of the strain field). This is also reflected in the barreling phenomenon of the samples after deformation. However, the large green regions indicate that a substantial part of the sample always has a strain around 1.0, which corresponds to the set true strain of $-\ln 0.5$.

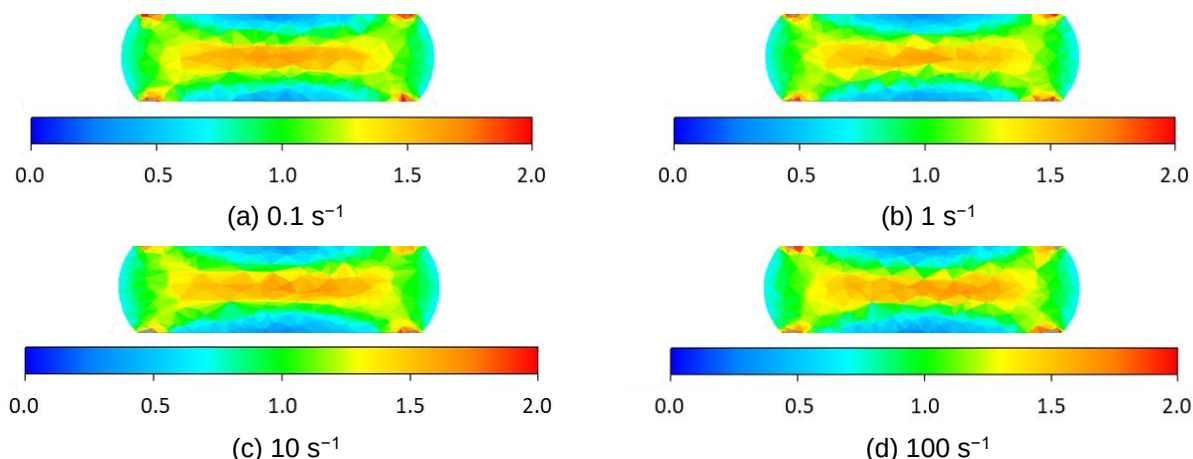


Figure 2 Effective strain (-) distribution in the compressed samples

Figure 3 displays the distribution of the effective stress field. The results essentially correspond to the temperature distribution discussed above. Here too, the heterogeneity of the field increases with increasing strain rate. This is significantly influenced by the development of deformation heat and the ability to redistribute it in the deformed sample. If we look at the effective stress values, we can observe their increase with increasing strain rate. At lower strain rates (0.1 and 1 s^{-1}), this increase is more or less homogeneously distributed throughout a sample. However, from rates of 10 s^{-1} , higher values begin to move to the sample-anvil interface. The cause here is the suppression of the deformation heat distribution discussed above. The extreme case is a strain rate of 100 s^{-1} , when the effective stress values are in the middle part almost identical with values observed during deformation at lower strain rates. **Figure 4** then shows the dependence of the effective stress on the change in the sample height in the middle part of samples. First of all, the above-discussed increase in effective stress values with increasing strain rate can be observed. It can also be observed that as the height of the test specimen decreases, the stress values also decreases. The reason is precisely the development of deformation heat. The graph then practically confirms the observed decrease in stress at a strain rate of 100 s^{-1} (**Figure 3(d)**) to the level of values observed under lower rates.

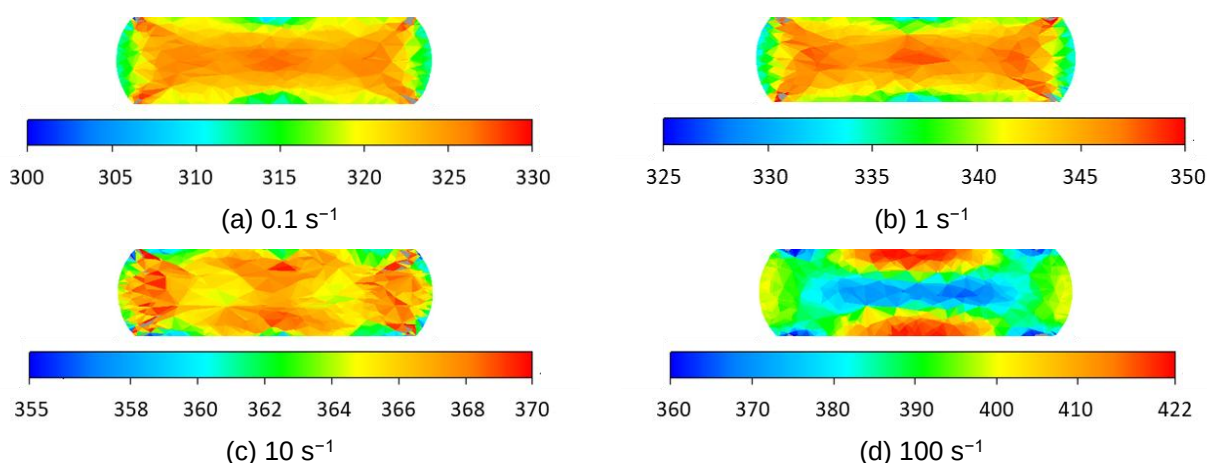


Figure 3 Effective stress (MPa) distribution in the compressed samples

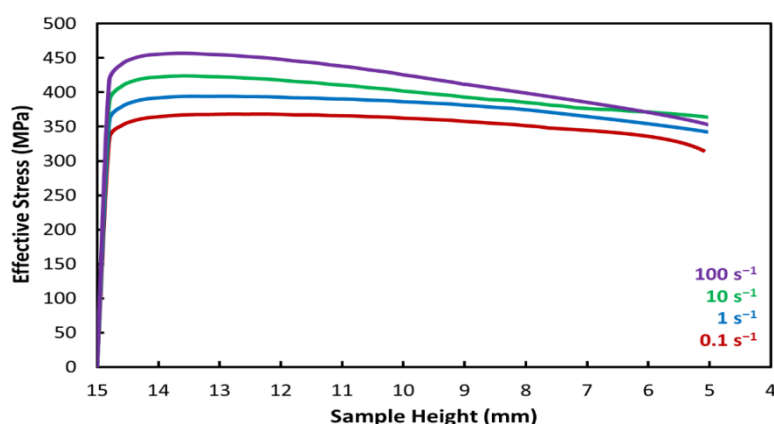


Figure 4 Effective stress in the middle of tested samples

5. CONCLUSION

Based on uniaxial compression tests and subsequent nonlinear regression analysis, a flow stress development model was built for the investigated Cu-graphene composite. The deformation behavior during compression tests was then studied using FEM simulations in FORGE software (TRANSVALOR). The simulation results show a significant influence of deformation heat and the inability of its homogeneous distribution in the compressed sample at strain rates higher than 10 s^{-1} . As a result, at higher rates (especially at a rate of 100 s^{-1}) there were significant local decreases in the effective stress. The level of effective stress values for high-rate deformation even dropped to a level comparable to deformation at lower strain rates. There is a risk of inhomogeneous microstructure and potential reduction in strength in warmer areas. The effective strain distribution was practically identical for all investigated conditions with the greatest intensity in the central areas and almost zero values at the sample-anvil interface – a significant influence of frictional forces leading to the heterogeneity of the effective strain field and barrel-like nature of the compressed samples.

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