SOME ASPECTS OF ELASIC AND PLASTIC DEFORMATION OF Cu–Ag METASTABLE METAL-MATRIX COMPOSITES

[1]Pavel LEJČEK, [1]Angelina STRAKOSOVA, [2]Filip PRŮŠA, [1]Drahomír DVORSKÝ, [3]Martin KOLLER, [3]Hanuš SEINER

[1]Institute of Physics, Czech Academy ofSciences, Prague, Czech Republic, lejcekp@fzu.cz, strakosova@fzu.cz, dvorsky@fzu.cz

[2]University of Chemistry and Technology, Department of Metals and Corrosion Engineering, Prague, Czech Republic, prusa@vscht.cz

[3]Institute of Thermomechanics, Czech Academy of Sciences, Prague, Czech Republic, koller@it.cas.cz, hseiner@it.cas.cz

https://doi.org/10.37904/metal.2024.4899

Abstract

Metal-matrix composites (MMCs) are usually characterized by soft matrix and hard reinforcement. In contrast, we focused in this work on the production and properties of metastable MMCs formed by pure Ag matrix and pure Cu particulates. To conserve the metastable character of these MMCs, they were produced by spark plasma sintering of the Cu@Ag core-shell powders with the volume ratios Cu:Ag being 55:45 and 82:18. These m-MMCs exhibit specific mechanical properties. Some of them, Young modulus and the shape of the curves of plastic deformation, are discussed in this work.

Keywords: Metal-matrix composites, Ag-Cu system, spark plasma sintering, elastic and plastic deformation

1. INTRODUCTION

To improve the mechanical properties of soft materials, reinforcing particles can be added to the matrix. The reinforcement particles can be introduced either as dispersive and intact particulates or can be formed in situ in the material matrix by decomposition of oversaturated solid solution, phase transformation, etc. [1]. However, such processes result in changes in chemical composition, in the vicinity of the particulates and thus, forming concentration gradients in the systems with non-negligible solid solubility. To avoid these chemical gradients, the process of formation of the MMCs must be quick and efficient. Then the metastable MMCs (m-MMCs) occur. One of the ways enabling the formation of such m-MMCs is spark plasma sintering (SPS) [2]. A specific effect in this field is also the compaction of the core-shell powders by SPS [3].

As mentioned above, the MMCs exhibit different mechanical properties compared to the pure metals. Usually, less deformable particulates, such as oxide particles [4] or hard metals [5], are applied in such MMCs. In this way, the values of the yield stress (YTS), ultimate strength (UTS) as well as hardness are substantially increased [2, 4, 5].

A question arises about the mechanical behavior of the m-MMCs formed by a soft matrix and well-deformable particulates. To study such a system, m-MMCs produced by SPS compaction of the Cu@Ag core-shell powders were prepared, and their tensile characteristics were compared to those of the pure Cu and Ag metals.

2. EXPERIMENTAL

The Cu@Ag (55:45 and 82:18, both in volume %) core-shell powders of a mean grain size of about 25 μm were purchased from SAFINA a.s., Czech Republic [6]. They were compacted by SPS (FCT System HP-D)

for 5 minutes at 700 °C under the hydrostatic pressure of 80 MPa. The details of the procedure as well as of the structure of the m-MMC are described in Ref. [3]. As a result, the discs 20 mm in diameter and 6 mm thick were produced. They consisted of an Ag matrix with spherical Cu particulates (**Figure 1**).

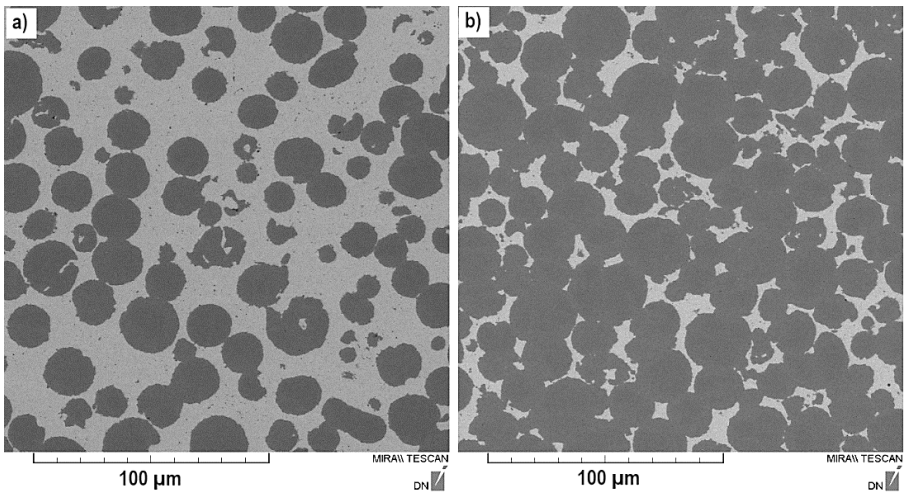

Figure 1 Microstructure of Cu–Ag m-MMCs: (a) 55:45 vol%; (b) 82:18 vol%. Scanning electron microscopy: bright field – Ag matrix, dark areas – Cu particulates

The dog-bone-shaped samples of the square cross-section, 7.0 mm long, 2 mm wide, and 0.55 mm thick, were cut by an electro-spark cutting machine (Agiecharmilles FI240 EEC). They were deformed by tension (Instron 5882 machine) with a deformation rate of 10^{-3} s^{-1}. Additionally, a contactless laser-based modification of Resonant Ultrasound Spectroscopy (RUS) [7] was applied to the samples of the dimensions 4×3×2 mm^3 to determine the value of Young modulus *E* of the m-MMCs as well as of the 5N pure metals. A Nd:YAG laser (Quantel ULTRA, nominal wave length 1.064 µm, pulse duration 8 ns, pulse energy 25 mJ) was used to induce ultrasonic vibrations in the sample. The vibrational response of the sample was recorded at 20 °C by a Polytec Micro-System Analyzer MSA-600 equipped with a laser vibrometer. The obtained spectra covered the frequency range of 100 kHz–3 MHz, the resolution of the method was 15 Hz. The elastic moduli were obtained by the inverse procedure, described in more detail in [7], under the assumption of elastic isotropy. The density of the samples was determined by Archimedes method, i.e. by measuring their weight in air and in water.

3. RESULTS AND DISCUSSION

The obtained characteristic stress-strain curves from the tensile tests are shown in **Figure 2**. The Young modulus *E*, obtained by RUS, and the basic characteristics of the dependences shown in **Figure 2** are listed in **Table 1**.

Table 1 Mechanical characteristics of the m-MMCs, Cu, and Ag [3]

Characteristics	Ag	Cu	Cu–Ag (55:45 %)	Cu–Ag (82:12 %)
E (GPa)	82.3±0.6	129.8±1.3	97.4±0.9	118.3±0.6
YTS (MPa)	50±4	56±2	143±3	170±30
UTS (MPa)	128±7	182±7	310±20	430±70
Prolongation to fracture (%)	31±1	38±2	24±5	39±1

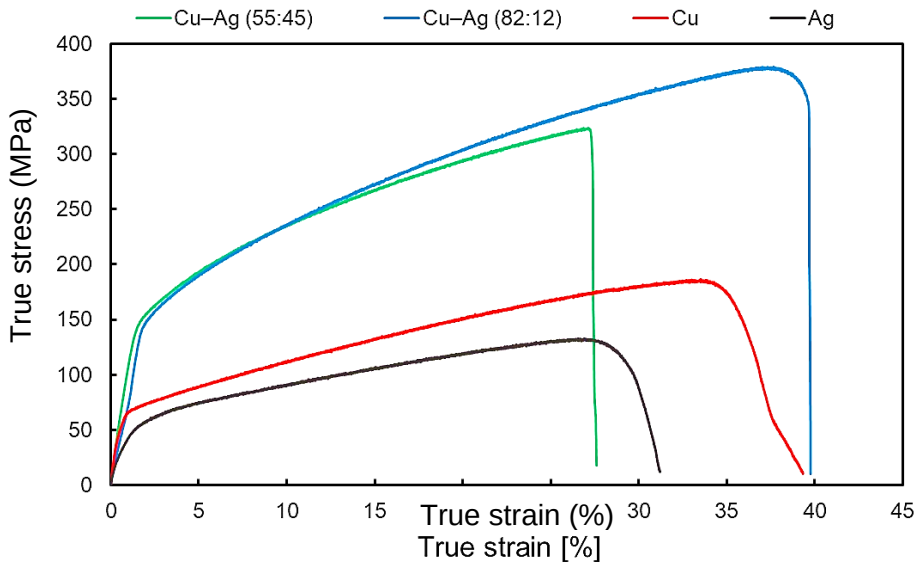

Figure 2 Stress-strain curves of the tensile deformation of Cu–Ag m-MMCs, and pure Ag and Cu [3]

3.1 Elastic deformation

During elastic deformation, it is accepted that both components – matrix, and particulates – are strained with the same deformation, i.e.,

$$\boldsymbol{\varepsilon_c = \varepsilon_m = \varepsilon_p} \tag{1}$$

where:

ε_i- the deformations of the m-MMC (c), matrix (m), and particulate (p)

Similarly, it is accepted that there exists a simple relationship between the values of the Young modulus of the composite, matrix, and particulate. It can be expressed according to various models, e.g., Voigt [8],

$$\boldsymbol{E_c = v_m E_m + v_p E_p} \tag{2}$$

Reuss [8],

$$\boldsymbol{E_c = \left(\frac{v_m}{E_m} + \frac{v_p}{E_p}\right)^{-1}} \tag{3}$$

or Tsai and Halpin for spherical particulates [9],

$$\boldsymbol{E_c = E_m \frac{1 + 2\mu_p v_p}{1 - \mu_p v_p} \text{with} \quad \mu_p = \frac{E_p - E_m}{E_p + E_m}} \tag{4}$$

where:

E_i- the Young moduli of the m-MMC (c), matrix (m), and particulate (p)

v_i- the volume ratios of the matrix (m) and particulates (p)

However, the values of *E* for the m-MMCs do not seem to fit with the above dependences but rather in a parabolic dependence (**Figure 3**)

$$\boldsymbol{E_c = E_m + (E_p - E_m) v_p^2.} \tag{5}$$

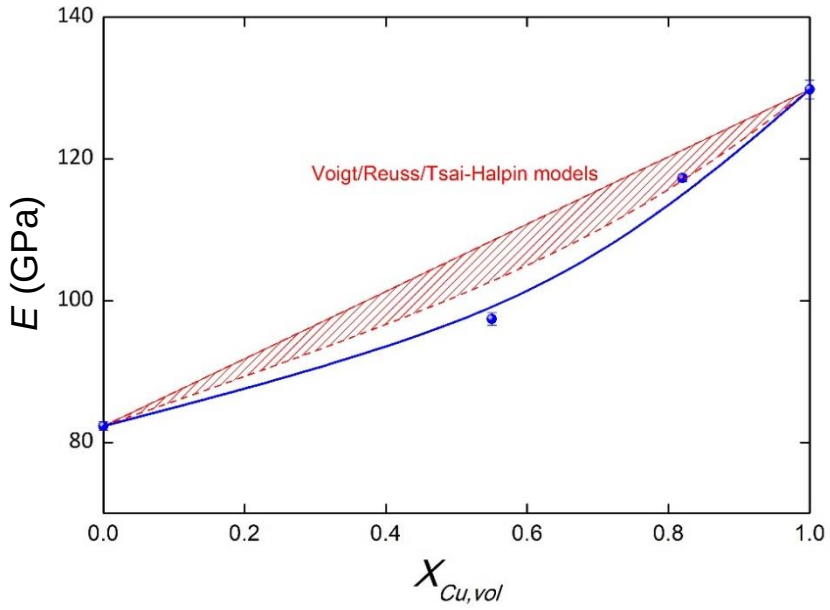

Figure 3 Dependence of the values of the Young modulus, *E* for Cu–Ag m-MMCs and the area covering the models of Voigt, Reuss, and Tsai-Halpin. The circles are measured values of *E*, and the blue full line represents **Equation (5)**

Another explanation of this apparent discrepancy, we should solve the following expression,

$$\boldsymbol{E_c\varepsilon_c = v_mE_m\varepsilon_m + v_pE_p\varepsilon_p}. \quad (6)$$

Supposing the validity of Equation (2), accepting $\boldsymbol{v_m = 1 - v_p}$, we can modify Equation (6) as

$$\boldsymbol{\left[(1 - v_p^2)E_m + v_p^2E_p\right]\varepsilon_c = (1 - v_p)E_m\varepsilon_m + v_pE_p\varepsilon_p}. \quad (7)$$

Equation (7) has the solution for

$$\boldsymbol{\varepsilon_p = v_p\varepsilon_c \text{ and } \varepsilon_m = (1 + v_p)\varepsilon_c}, \quad \textbf{i. e.}, \quad \boldsymbol{\varepsilon_p = \varepsilon_m\frac{v_p}{1 + v_p}}. \quad (8)$$

This would mean that the tougher particulates deform elastically less than the softer matrix. This might reflect the fact that the value of the E_{Cu} is 50% higher than E_{Ag} (**Table 1**) and at a constant stress, the deformation of Cu is lower than that of Ag. Different elastic deformation might be possible in the case when the particulate is not present in the form of prolonged fibres which should copy the elastic deformation of the matrix. In the case of spherical particulates, different elastic deformation is imaginable. Nevertheless, this conclusion was done from limited number of data and needs more experimental evidence.

3.2 Plastic deformation

As discussed in more detail in [3], the course of the plastic deformation of the m-MMCs can be approximated by various deformation laws, power (Ludwik, Hollomon, Krupkowski-Swift [10-12], Ramberg/Osgood [12]), and exponential (Voce) [10]).

The best fit of the courses of the plastic deformation measured on Cu–Ag m-MMCs corresponds to a polynomial dependence of the 2nd order (i.e., parabolic law) [3],

$$\boldsymbol{\sigma = A\varepsilon^2 + B\varepsilon + \sigma_0}. \quad (9)$$

where:

σ_0- the stress of the m-MMC at the yield point,

A, B – constants.

The parameters of **Equation (9)** are listed in **Table 2.**

Table 2 Parameters (in MPa) of **Equation (9)** for plastic deformation of m-MMCs, Ag, and Cu [3]

	Ag	Cu	Cu–Ag (55:45)	Cu–Ag (82:12)
A	–486	–561	–1647	–1220
B	288	377	790	734
σ_0	50	56	145	146

The degree of hardening can be defined as

$$\vartheta = \frac{d\sigma}{d\varepsilon} = 2A\varepsilon + B. \tag{10}$$

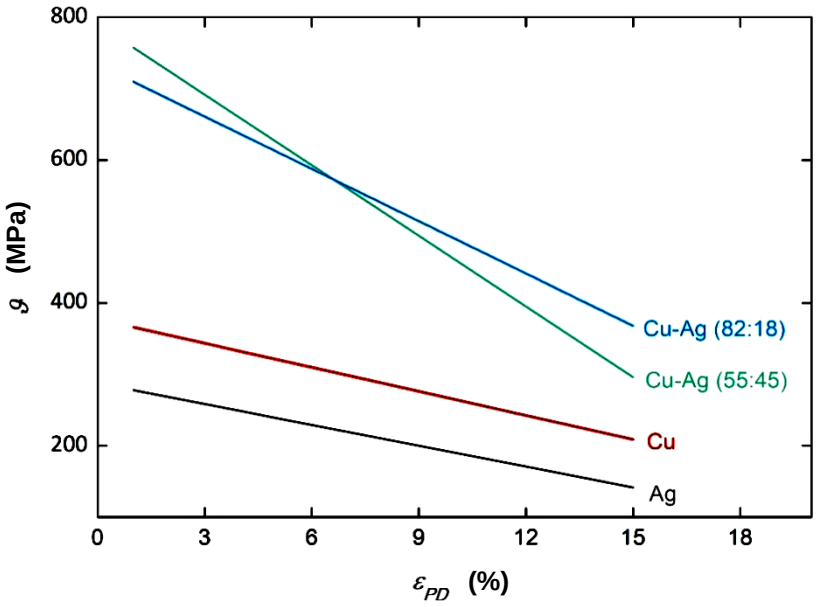

Figure 4 Dependence of the values of the degree of hardening, ϑ, for individual material

ACKNOWLEDGEMENTS

This work was financially supported by the Czech Science Foundation under the grant No. 23-05139S.

REFERENCES

[1] ARUNKUMAR, S., SUBRAMANI SUNDARAM, M., SUKETH KANA, K.M., VIGNESHWARA, S., A review on aluminium matrix composite with various reinforcement particles and their behaviour. *Materials Today: Proceedings*. 2020, vol. 33, pp. 484-490.

[2] JOSEPH A, GAUTHIER-BRUNET, V., JOUAIN, A., BONNEVILLE, J., DUBOIS. S., MONCHOUX, J.-P., PAILLOUX, F., Mechanical properties of Al/ω-Al-Cu-Fe composites synthesized by the SPS technique. *Materials Characterization*. 2018, vol. 145, pp. 644-652.

[3] STRAKOSOVA, A., DVORSKÝ, D., PRŮŠA, F., ALARCON, E., ROUDNICKÁ, M., PAIDAR, V., HABR, S., SVOBODA, J., SEDLÁŘOVÁ, I., LEJČEK, P. Structure and plastic deformation of metastable Ag–Cu metal matrix composites produced by a bottom-up way from Cu@Ag core-shell powders. *Journal of Materials Science*. 2024, submitted.

[4] HAN Q., SETCHI, R., LACAN, F., GU, D., EVANS, S.L. Selective laser melting of advanced Al-Al2O3 nanocomposites: simulation, microstructure and mechanical properties. *Materials Science and Engineering A*. 2017, vol. 698, pp. 162-173.

[5] LI, R.T., WANG, Z.Y., SUN, W., HU, H.L., KHOR, K.A., WANG, Y., DONG, Z.L. Microstructure and strengthening mechanisms in the Al/Al–Cu–Cr–Fe composites consolidated using spark plasma sintering. *Materials Characterization*. 2019, vol. 157, No. 109917.

[6] *Core-Shell Powders*. https://www.safina.eu/product/core-shell-powders/.

[7] SEDLÁK, P., SEINER, H., ZÍDEK, J., Janovská, M., LANDA, M. Determination of all 21 independent elastic coefficients of generally anisotropic solids by resonant ultrasound spectroscopy: benchmark examples, *Experimental Mechanics*. 2014, vol. 54, pp. 1073–1085,

[8] JAGADESH, G., GANGI SETTI, S. A review on micromechanical methods for evaluation of mechanical behavior of particulate reinforced metal matrix composites. *Journal of Materials Science*. 2020, vol. 55, pp. 9848-9882.

[9] HIMMLER, D., RANDEZHOFER, P., KÖRNER, C. In-situ Al3Ti particle reinforcement for stiff aluminum die castings. *Journal of Alloys and Compounds*. 2022, vol. 904, no. 163984.

[10] RATKE, L., WELCH, P.I. Questionability of empirical work hardening laws. *Zeitschrift für Metallkunde*. 1983, vol. 74, pp. 226-232.

[11] BÉRES, G., TISZA, M. Investigation of constitutive equation parameters on dual phase steel sheets. IOP Conference Series: *Materials Science and Engineering*. 2018, vol. 448, no. 012059.

[12] SOŁTYSIAK, R. Analysis of structure and material properties in individual zones of welded joint. *Journal of Constructional Steel Research.* 2021, vol. 187, no. 106978.