INFLUENCE OF INCONEL PARTICLES ON MECHANICAL AND PHYSICAL PROPERTIES OF AN EXTRUDED MAGNESIUM

TROJANOVÁ Zuzanka[1], LUKÁČ Pavel[1], MINÁRIK Peter[1], NÉMETH Gergely[1], GUPTA Manoj[2], SEETHARAMAN Sankar[2], DI FABIO Giorgio[3]

[1]*Charles University in Prague, Faculty of Mathematics and Physics, Department of Physics of Materials, Prague, Czech Republic, EU*
[2] *National University of Singapore, Mechanical Engineering, Singapore*
[3]*Marche Polytechnic University, Department of Mechanical Engineering, Ancona, Italy, EU*

Abstract

The influence of Inconel 718 particles on the mechanical and physical properties of magnesium has been investigated in this study. Magnesium samples with 0.7, 1.4 and 2.4 vol.% of Inconel particles were prepared using disintegrated melt deposition technique followed by hot extrusion.

The microstructures of the extruded composites were examined by light and electron microscopy. Information on the crystal orientation including grain size and texture was analyzed using a FEI Quanta 200 FX scanning electron microscope equipped with EDAX EBSD camera. OIM software was utilized for EBSD observations. A significant effect of nanoparticle content on the grain size in nanocomposites was revealed.

Composites were deformed in tension and in compression over a wide temperature range from room temperature to 300 °C at a constant crosshead speed giving an initial strain rate of $5.5{\cdot}10^{-3}$ s^{-1}. The true stress-true strain curves were determined. The flow stress is significantly influenced by the test temperature; it is rapidly decreasing with increasing temperature. A substantial asymmetry in the tensile and compressive properties was observed.

Keywords: Magnesium composites, microhardness, mechanical properties, texture, twinning

1. INTRODUCTION

Magnesium and its alloys as the lightest metallic materials have attached great attention in many industrial applications. Besides of their light weight, they have a relative high specific strength (the ratio of strength to density). The methods how to increase the strength have been intensively studied. One of the methods is preparation of composite materials. In the case of magnesium composites, Mg or Mg alloys are reinforced with fibres or particulates. The following strengthening mechanisms are considered as significant: (a) solution hardening, (b) dispersion strengthening, (c) grain refining, (d) load transfer and (e) thermal mismatch between reinforcements and matrix. Some examples describing correlations between mechanical properties of Mg matrix composites and microstructure can be found in many studies [1 -10]. One can find there careful analyses of the effects of strengthening mechanisms on the strength of magnesium-based composites. The mechanical properties of composites are also influenced by the composite fabrication such as e.g. squeeze casting, hot extrusion consolidating process, mechanical mixing. The microstructure might be significantly changed during composite processing. Bonding between magnesium matrix and ceramic or metallic nanoparticles has also important influence on the resulting properties of nanocomposites [11-13].

The main objective of this study is to investigate the microstructure, microhardness, tensile and compression behaviour of the microcrystalline Mg reinforced with three different additions of 718 Inconel sub-micron particles.

2. EXPERIMENTAL PROCEDURE

Mg reinforced with Inconel 718 composites (hereafter Mg+In718) were prepared in the National University of Singapore using the disintegrated melt deposition. Magnesium chips together with the commercially available Inconel powder (0.2-5 µm) were melted and heated up to 750 °C, then stirred for 5 min under an argon atmosphere. The composite melt was disintegrated by argon gas current oriented normal to the melt stream before being deposited onto a metallic substrate (for more details see [14]). Processed ingots with a diameter of 36 mm were homogenised for 1 h at 400 °C and subsequently hot extruded to the resulting diameter of 8 mm. For comparison, samples from pure Mg were prepared with the same technology.

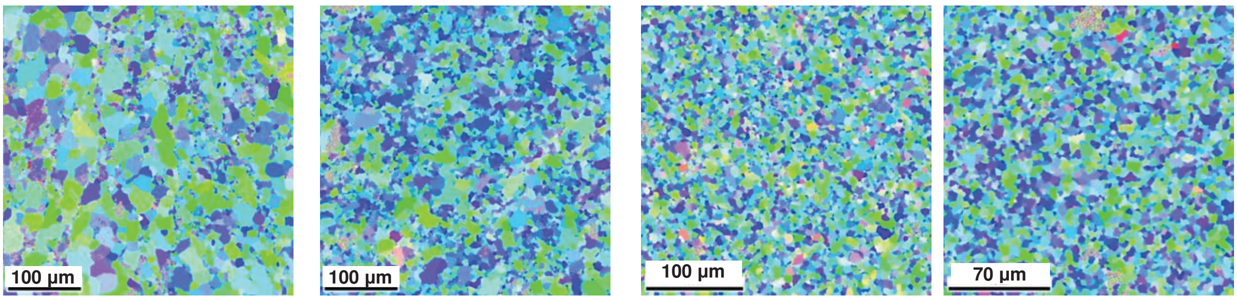
The microstructures of composites were observed by a FEI Quanta 200 FX scanning electron microscope equipped with EDAX EBSD camera. OIM software was utilized for EBSD observations. The grain size was estimated in a light microscope Olympus using the special software Lucia. The microhardness of samples was measured using Qness Q10 automatic microhardness tester with a Vickers indenter. The tests were performed at room temperature in the sections along extrusion direction (L) and perpendicular to the extrusion direction (T). The indenting load and its application time were 25 g and 15 s, respectively.

The tensile tests were conducted on cylindrical samples with a diameter of 5 mm and an active gauge length of 18 mm. Cylindrical samples with a diameter of 8 mm and length of 10 mm. were used for compression tests. Tensile and compression experiments were performed in an Instron 1186 testing machine at temperatures from 23 up to 300 °C with a constant crosshead speed giving an initial strain rate of $1x10^{-3}$ s^{-3}.

Magnesium samples with 0.7, 1.4 and 2.4 vol.% of particles were depicted as Mg+0.7In718, Mg+1.4In718 and Mg+2.4In718.

3. RESULTS AND DISCUSSION

The microstructures of samples taken perpendicular to the extrusion direction are introduced in **Figure 1**. Samples exhibited a significant basal texture typical for the magnesium materials prepared with the extrusion technique. The grain sizes measured in the perpendicular sample sections are given in **Table 1**. It is obvious that the grain size decreases with increasing volume fraction of Inconel nanoparticles. The recrystallization process occurring during hot extrusion is influenced with the presence of particles.



a) b) c) d)

Figure 1 Microstructure of Mg+In718 composites: a) pure Mg, b) Mg+0.7In718, c) Mg+1.4+In718 and d) Mg+2.4In718

Nes et al. [15] and Hunderi et al. [16] studied the Zener drag i.e. movement of the grain boundary during the recrystallisation in the material containing incoherent particles. They estimated that the boundary bulges out between the particles and moves forward by an unzipping process. They considered that this process is similar to the dislocation motion in the field of local obstacles. The intergranular particles retard the grain growth during the dynamic recrystallisation leading to the finer grains in nanocomposites with the higher volume content of particles. Microhardness H_V measured in two directions (longitudinal L and transversal T related to the extrusion direction) increased with increasing volume fractions of particles as it is obvious from **Table 1**. The measured values in the both directions are comparable; variations are in the frame of the standard deviation.

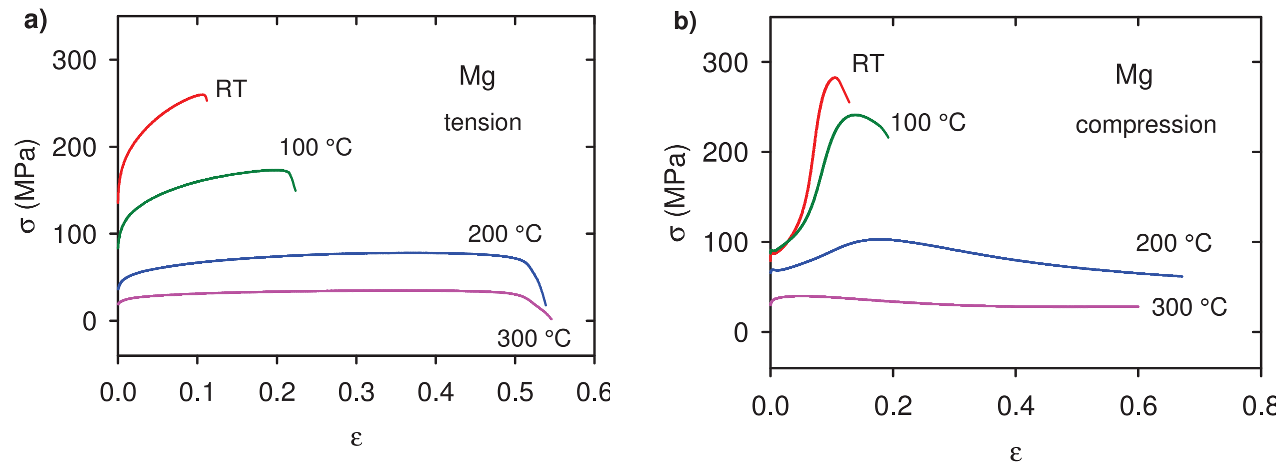


Figure 2 True stress-true strain curves obtained for pure Mg in tension (a) and compression (b)

The true stress-true strain curves obtained for various temperatures in tension and compression are shown in **Figure 2**. A substantial difference in the shape of both sets of curves is obvious. The curves obtained in tension have a typical shape usually observed for polycrystals with the significant strain hardening occurring at room temperature (RT) and 100 °C and flat curves obtained at temperatures higher. On the other hand, typical feature of curves achieved in compression is a local maximum at a strain of 0.15-0.2.

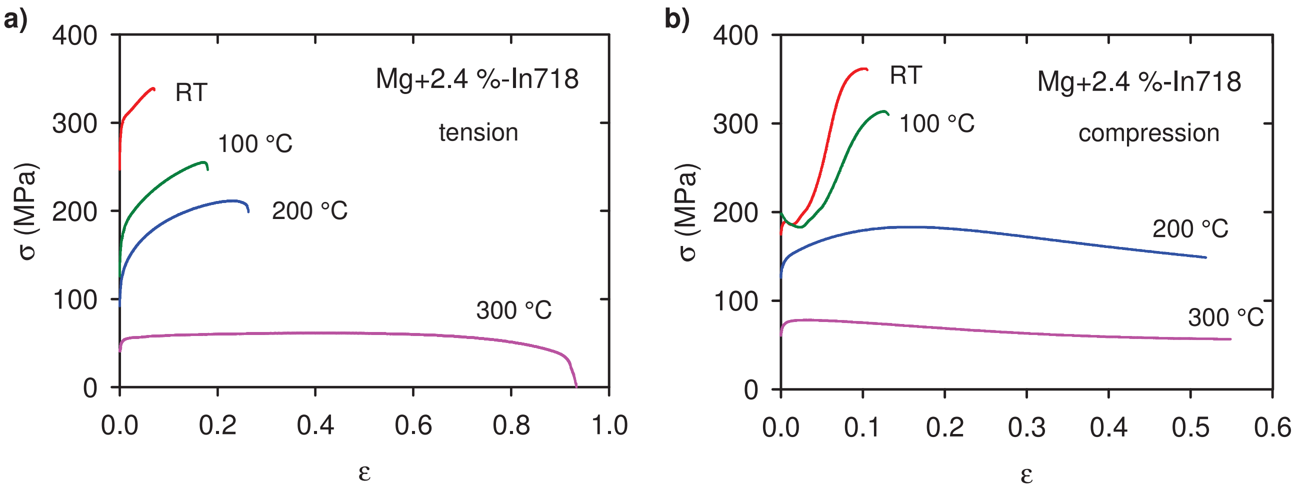


Figure 3 True stress-true strain curves obtained for Mg+2.5In718 in tension (a) and compression (b)

Similar course of the true stress-true strain curves in tension as well as in compression was found for composites. Curves obtained for the highest particles content are introduced in **Figure 3**. Characteristic stresses the yield stress in tension (TYS), compression (CYS) and ultimate tensile strength (UTS) and ultimate compression strength (UCS) were evaluated form the curves. Values obtained at room temperature are introduced in **Table 1**.

Table 1 The grain size, microhardness and characteristic stresses estimated at room temperature in tensile and compression tests

	d (µm)	H_V L	H_V T	TYS (MPa)	CYS (MPa)	UTS (MPa)	UCS (MPa)
Mg	17.30	40.2	41.7	161.0	88.0	262.2	383.2
Mg+0.7In718	12.70	49.0	49.3	207.2	131.0	249.6	295.1
Mg+1.4In718	5.71	55.0	54.5	249.0	151.8	301.2	325.5
Mg+2.4In718	4.13	65.2	65.7	285.0	185.0	339.0	361.8

It is obvious that the values of CYS are lower for all materials comparing with the TYS values. **Figure 4** shows that both quantities follow the relationship YS ~ $c_V^{2/3}$, where c_V is the particle volume fraction. The temperature dependence of the TYS and CYS is introduced in **Figure 5** for Mg+0.7In718. It is evident that the temperature dependence obtained in compression is for lower temperatures up to 200 °C much weaker in comparison with the temperature dependence of the TYS. Similar dependences were found for other concentration of nanoparticles and also for pure magnesium.

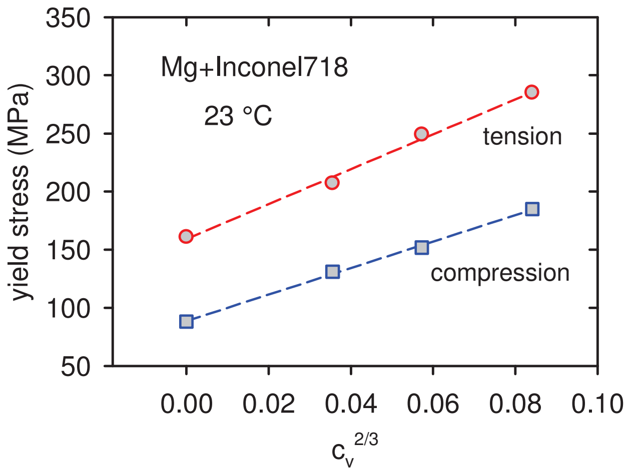


Figure 4 The yield stress obtained at room temperature in tension and compression vs the particles volume fraction

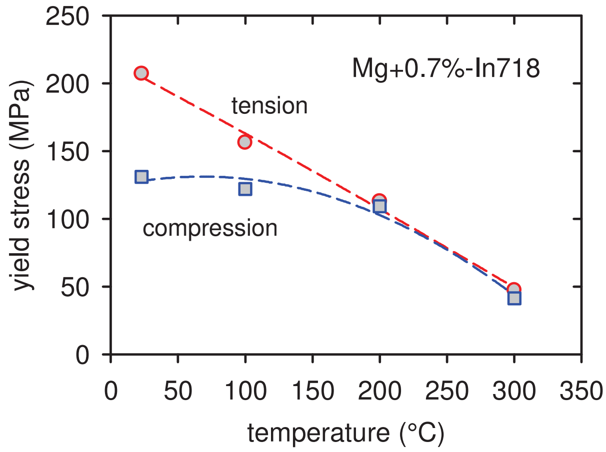


Figure 5 Temperature dependence of the yield stress obtained in tension and compression for Mg+0.7In718

Magnesium alloys, with hcp structure, deform on many possible glide systems with dislocations of Burgers vector <***a***> = $\frac{1}{3}[11\bar{2}0]$ in basal, prismatic, and first–order pyramidal planes and with dislocations of Burgers vector <***c + a***> = $1/3[11\bar{2}3]$ in first– and second–order pyramidal planes. The main deformation mode in magnesium is basal slip of <***a***> dislocations. The critical resolved shear stress for <***a***> dislocations in the basal plane is much lower in comparison with the critical resolved shear stress for <***a***> and <***c*** + ***a***> in prismatic and pyramidal planes. According to von Mises criterion for compatible deformation cooperation of five independent slip systems is necessary [17]. Because the basal slip provides only two independent slip systems, activity of prismatic or pyramidal slip systems, as well as the mechanical twinning are necessary. In magnesium several potential twinning systems may be found among them the $\{10\bar{1}2\}\langle10\bar{1}1\rangle$ twinning system is often observed. The texture studies showed the ring fibre texture with the basal planes oriented parallel to the extrusion direction. From the completely different shape of the stress-strain curves for tension and compression, one may conclude that different mechanisms operate during plastic deformation in tension and compression of a textured material. The TYS is much higher than the CYS as can be seen in **Table 1**. The difference between both yield stresses exhibits from 70 MPa at pure Mg up to 100 MPa by Mg+2.4In718. The hot extruded samples with the texture where the basal planes (0001) are parallel to the extrusion direction, do not deform by twinning in the tensile experiment. On the other hand, tensile twins are activated in the compression experiment. Such twinning causes a misorientation of 86.3° between the twinned and the untwinned lattice [18]. The tensile deformation is realised at the beginning by the <***a***>dislocation motion in the basal and prismatic planes, deformation in the c-axis is realised by the activity of <***c*** + ***a***> dislocation. The high Schmid factor for twinning provides high value in compression and that is reason why twinning in compression is activated at relatively low stresses. The twinning deformation is exhausted at the plastic strain of several percent, the further deformation continues with the dislocation motion in the reoriented grains. Because twinning is not thermally activated process, the temperature dependence of the CYS is more-less constant up to 200 °C. At this temperature, the values of the TYS and CYS are approximately equal. At higher temperatures the critical resolved shear stress for <***c*** + ***a***> dislocations in the non-basal planes decreased up to the value necessary for twinning and therefore deformation at temperatures above 100 °C continues via the dislocation mode.

The influence of particles on the stress necessary for plastic deformation of the composites may be attributed to several mechanisms: (a) increase in grain boundary area due to grain refinement - the Hall-Petch strengthening; (b) increase of the dislocation density accommodating the thermal stresses in the particle/matrix interface which are induced due to a large difference in the coefficients of thermal expansion (CTE) between matrix and particles; (c) load transfer of applied stress to the well-bonded particles; (d) Orowan strengthening and (e) generation of geometrically necessary dislocations which accommodate the particle/matrix interface during plastic deformation. Knowing the particles size and their separation, the contributions (b) and (d) can be calculated under a simplified consideration that particles are uniformly distributed in the matrix. It is, depending on the manufacture technology, fulfilled very probably rarely, because particles have a tendency to form clusters. Further problem which was up to now not satisfactorily solved is how to combine individual strengthening contribution. Stress contributions, which act more or less uniformly throughout the matrix, must be superimposed linearly, whereas mechanisms of similar strengthening ability, which act unevenly throughout the matrix, are most suitably combined as the root of the sum of the squares [19].

4. CONCLUSION

Deformation experiments performed on magnesium composites reinforced with the Inconel 718 sub-micron particles showed the following main results:

- Inconel particles refine the grains structure.
- Inconel particles improved mechanical properties of magnesium at all temperatures studied.
- The dependence of the yield stress on the particle volume fraction is different for the different deformation modes.
- Texture of extruded composites causes the tension-compression asymmetry and the activity of different deformation mechanisms at temperatures below 200 °C.

ACKNOWLEDGEMENTS

Z.T. and P.L. acknowledge the support of the Grant Agency of the Czech Republic (Project Nr. 15/11879S).

REFERENCES

[1] GUPTA, M., NAI, S.M.L. *Magnesium, magnesium alloys, and magnesium composites*. Hoboken, N. J.: John Wiley, 2011.

[2] CHAWLA, N., CHAWLA, K.K. *Metal matrix composites*. New York: Springer, 2006.

[3] TROJANOVÁ, Z., LUKÁČ, P., SZÁRAZ, Z., DROZD, Z. Mechanical and acoustic properties of magnesium alloys based (nano) composites. In: *Light metal alloys applications*. Rjeka: InTech, 2014, pp. 163-197.

[4] HASSAN, S.F., GUPTA, M. Development of a novel magnesium/nickel composite with improvement mechanical properties. *Journal of Alloys and Compounds,* 2002, vol. 335, no. 1-2, pp. L10-L15.

[5] HASSAN, S.F., GUPTA, M. Development of ductile magnesium composite materials using titanium. *Journal of Alloys and Compounds,* 2002, vol. 345, no. 1-2, pp. 246-251.

[6] LU, L., THONG, K. K., GUPTA, M. Mg-based composite reinforced by Mg_2Si. *Composites Science and Technology,* 2003, vol. 63, no. 5, pp. 627-632.

[7] WONG, W.L.E., GUPTA, M. Development of Mg/Cu nanocomposites using microwave assisted rapid sintering. *Composites Science and Technology*, 2007, vol. 67, no. 7-8, pp. 1541-1552.

[8] LUKÁČ, P., TROJANOVÁ, Z. Deformation and damping behaviours of microcrystalline Mg reinforced with ceramic nanoparticles. *Kovove materialy - Metallic Materials,* 2006, vol. 44, no. 5, pp. 243-249.

[9] TROJANOVÁ, Z., MIELCZAREK, A., RIEHEMANN, W., LUKÁČ, P. Cyclic bending and the damping behavior of short fibre-reinforced magnesium alloy AZ91. *Composites Science and Technology*, 2006, vol. 66, no. 3-4, pp. 585-598.

[10] RAUBER, C., LOHMULLER, A., OPEL, S., SINGER, R.F. Microstructure and mechanical properties of SiC particle reinforced magnesium composites processed by injection molding. *Materials Science and Engineering A,* 2011, vol. 528, no. 19-20, pp. 6313-6323.

[11] PARAMSOTHY, M., HASSAN, S.F., SRIKANTH, N., GUPTA, M. Enhancing tensile/compressive response of magnesium alloy AZ31 by integrating with Al_2O_3 nanoparticles. *Materials Science and Engineering A*, 2009, vol. 527, no. 1-2, pp. 162-168.

[12] RUDAJEVOVÁ, A., LUKÁČ, P. Thermal strain in Mg composites. *Acta Materialia*, 2003, vol. 51, no. 18, pp. 5579-5586.

[13] TROJANOVÁ, Z., FERKEL, H., LUKÁČ, P., RIEHEMANN, W. Two new high-damping magnesium composites. *Physica Status Solidi a*, 2002, vol. 193, no. 2, pp. 205-210.

[14] GUPTA, M., WONG, W.L.E. Magnesium based nanocomposites: Lightweight materials of the future. *Materials Characterization*, 2015, vol. 105, pp. 30-46.

[15] NES, E., RYUM, N., HUNDERI, O. On the Zener drag. *Acta Metallurgica*, 1985, vol. 33, no. 1, pp. 11-22.

[16] HUNDERI, O., NES, E., RYUM, M. On the Zener drag- Addendum. *Acta Metallurgica,* 1985*,* vol. 37, no. 1, pp. 129-133.

[17] VON MISES, R. Mechanik der plastischen Formänderung von Kristallen. *Zeitschrift für Andewandte Mathematik und Mechanik*, 1928, vol. 8, no. 3, pp. 161-185.

[18] KLIMANEK, P., PÖTZSCH, A. Microstructure evolution under compressive plastic deformation of magnesium at different temperatures and strain rates. *Materials Science and Engineering A*, 2002, vol. 324, no. 1-2, pp 145-150.

[19] CLYNE, T., WHITHERS, P.J. *An introduction to metal matrix composites*. Cambridge: Cambridge Press, 1993, p. 94.