

INFLUENCE OF GRAIN SIZE DISTRIBUTION ON THE MECHANICAL BEHAVIOR OF MATERIALS IN A WIDE RANGE OF STRAIN RATES

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ABSTRACT

This work compares the mechanical behavior of alloys with influence of grain size distribution on the in a wide range of strain rates. Constitutive model was proposed for describing the inelastic deformation and damage of alloys with face centered cubic and hexagonal close packed structures and distribution of grain sizes. It was shown that the dependences of the yield stress on logarithm of normalized strain rate for aluminium and magnesium alloys with a bimodal distribution of grains and coarse-grained alloys are similar. The yield stress at room temperature of the magnesium and aluminium alloy increased on 10 - 15 % in comparison with a coarse-grained alloy if the volume fraction of the UFG grains is close to the percolation threshold.

Keywords: grain size, high strain rates, light alloys, bimodal grain size distribution, strength, ductility, ultrafine-grained alloy, aluminium, magnesium.

INTRODUCTION

In recent years, the interest in the question of the impact of grain structure on the mechanical properties of metals and alloys increased continuously. Technologies of severe plastic deformation (SPD) allow creating an ultrafine-grained structure with a unimodal and bimodal distribution of grain size in metals and alloys.

By improving the Electron Backscattering Diffraction (EBSD) method was received new data on the texture formation and the evolution of a grain size distribution in coarse grained and ultrafine-grained metals and alloys under different impacts (Cayron, 2006, Sakai, 2014, Tamiyu, 2016).

It was shown that nanostructured and ultrafine-grained metals and alloys have excellent physical and mechanical properties significantly superior the strength over their coarse-grained counterparts (Valiev, 1991, 1993, Herzig, 2008, Skripnyak, 2012, Garkushin, 2015, Li, 2017).

Steels and alloys with a bimodal grain size distribution demonstrate a unique combination of high yield and ultimate strength with satisfactory plasticity (Pozdnyakov, 2007, Malygin, 2008, Valiev, 2010, Dapeng, 2011). These materials are becoming increasingly important in the development of advanced construction techniques.

The influence of the grain size distributions on mechanical behavior of metal alloys at high strain rates and intense dynamic effects are not studied systematically. It was shown the

influence of average grains size on the yield stress at compression and tension was established earlier for aluminium, titanium, and magnesium alloys.

It was found that with a decrease in the average grain size of metals and alloys to less than several microns, the flow stress at room temperature of metal alloys is increased, but the elongation to fracture is reduced (Prasad, 2009, Valiev, 2010, Dapeng, 2011). Light alloys with a bimodal grain size distribution possess a negative strain rate sensitivity of the yield stress and higher ductility at quasi static loadings (Fan, 2006, Ahn, 2008). Cracks growth resistance in UFG alloys with a bimodal grain size distribution increases due to deflection of microcracks on borders between UFG and coarse grained (CG) regions. Distribution effect of grain size on the mechanical behaviour of light alloys at high strain rates have been investigated insufficiently.

The aim of this study was to obtain estimates of the impact of the distribution of the grain size on the mechanical behavior of the alloys in a wide range of strain rates.

COMPUTATIONAL MODEL

Mechanical behavior of coarse grained and ultrafine-grained polycrystalline alloys can be described by the constitutive equations with explicit accounting for the effective grain size (Herzig, 2008, Skripnyak, 2012, Lim, 2011). Constitutive equations developing in the framework of continuum damage mechanics is convenient to use for solution of dynamic problems (Herzig, 2008, Skripnyak, 2012, Wang, 2013).

The constitutive equation can be used in the form

$$\sigma_{ij} = \sigma_{ij}^{(m)} \varphi(D), \quad \sigma^{(m)}_{ij} = -p^{(m)} \delta_{ij} + S_{ij}^{(m)}, \quad (1)$$

where σ_{ij} is components of the Cauchy stress tensor, p is the pressure, S_{ij} is components of the deviatoric stress tensor, the superscript m indicates the condensed phase of the damaged material, $\varphi(D) \approx 1 - D$ is the function of damage, and D is the damage parameter.

The local damage parameter D is introduced to the material particle of a continuous medium or of a representative volume of the material:

$$D = \int_0^{t_f} \frac{\dot{\epsilon}_{eq}^n}{\epsilon_f^n} dt \quad (2)$$

where $\dot{\epsilon}_{eq}^n = \left(\frac{2}{3} \dot{\epsilon}_{ij}^n \dot{\epsilon}_{ij}^n \right)^{1/2}$, $\dot{\epsilon}_{ij}^n$ is a components the inelastic strain rate tensor, ϵ_f^n is a strain to fracture, t_f is a loading time.

The bulk inelastic strain rate can be calculated by relation:

$$\dot{\epsilon}_{kk}^n = \frac{1}{3} \frac{\dot{D}}{(1-D)}, \quad (3)$$

where symbol « $\dot{\cdot}$ » denote the time derivative.

The pressure is calculated by equation of state (McQueen, 1960, Fomin, 2004). The deviatoric stress is calculated by the equation:

$$DS_{ij}^{(m)} / Dt = 2\mu(\dot{\epsilon}_{ij} - \dot{\epsilon}_{ij}^n), \quad (4)$$

where D/Dt is the Jaumann derivative, μ is the shear modulus, $\dot{\epsilon}_{ij}$ is the deviator of the strain rate tensor, and $\dot{\epsilon}_{ij}^n$ is the deviator of the inelastic strain rate tensor.

The deviator of the inelastic strain rate tensor is written as:

$$\dot{\epsilon}_{ij}^n = (3/2)[S_{ij} \dot{\epsilon}_{eq}^n / \sigma_{eq}], \quad (5)$$

where $\sigma_{eq} = [(3/2)S_{ij}^{(m)}S_{ij}^{(m)}]^{1/2}$ is the equivalent shear stress.

The plastic deformation of metals and alloys depends on the strain, the strain rate and the deformation temperature. Therefore the flow stress can be written as:

$$\sigma_s = \sigma_s(\epsilon_{eq}^n, \dot{\epsilon}_{eq}, T), \quad (5)$$

where ϵ is the true strain, $\dot{\epsilon}_{eq} = [(2/3)\dot{\epsilon}_{ij}\dot{\epsilon}_{ij}]^{1/2}$ is the equivalent true strain rate, and T is temperature.

The yield stress can be predicted using the modified Zerilli -Armstrong constitutive model for alloys with Face Centered Cubic structure (FCC), Body-Centred Cubic structure (BCC), and Hexagonal Close Packed (HCP) structure (Zerilli, 1992):

$$\sigma_s = \sigma_{s0} + [C_6 d_g^{-1/2} + C_5 (\epsilon_{eq}^p)^{n_1}] \exp[-T \ln(\dot{\epsilon}_{eq} / \dot{\epsilon}_a)] + C_1 \exp[-C_3 T + C_4 T \ln(\dot{\epsilon}_{eq} / \dot{\epsilon}_b)] \quad (\text{HCP alloys}), \quad (6)$$

$$\sigma_s = \sigma_{s0} + C_6 d_g^{-1/2} + C_2 (\epsilon_{eq}^p)^{1/2} \exp[-C_3 (1 - \ln \dot{\epsilon} / \ln \dot{\epsilon}_b) T] + C_4 [\epsilon_r (1 - \exp(-\epsilon_{eq} / \epsilon_r))]^{1/2} \exp[-TC_7 (1 - \ln(\dot{\epsilon}_{eq} / \ln \dot{\epsilon}_a))] \quad (\text{HCP alloys}), \quad (7)$$

$$\sigma_s = \sigma_{s0} + C_6 d_g^{-1/2} + C_5 (\epsilon_{eq}^p)^{n_1} + C_1 \exp[-C_3 T + C_4 T \ln(\dot{\epsilon}_{eq} / \dot{\epsilon}_{eq0})] \quad (\text{BCC alloys}), \quad (8)$$

$$\sigma_s = \sigma_{s0} + C_6 d_g^{-1/2} + C_2 (\epsilon_{eq}^p)^{1/2} \exp[-C_3 T + C_4 T \ln(\dot{\epsilon}_{eq} / \dot{\epsilon}_{eq0})] \quad (\text{FCC alloys}), \quad (9)$$

where $C_1, C_2, C_3(d_g), C_4(d_g), C_5, C_6, C_7, n_1, \epsilon_r, \dot{\epsilon}_a, \dot{\epsilon}_b$ are material constants, T is the temperature of loading in Kelvin, d_g is the average size of grains.

Estimation of effective grain size d_g in ultrafine-grained alloys or alloys with a bimodal distribution of grains sizes requires a detailed analysis of the grain structure of the alloys. Grain size distribution in steels and metal alloys can be determined by Electron Backscattering Diffraction (EBSD) method. The EBSD map of the grain size after ECAP of 1560 aluminium alloy is shown in Fig. 1. Studies of the grain structures was carried out by EBSD method (DOE) using the electron microscope Tescan Vega II LMU (Moskvichev, 2016).

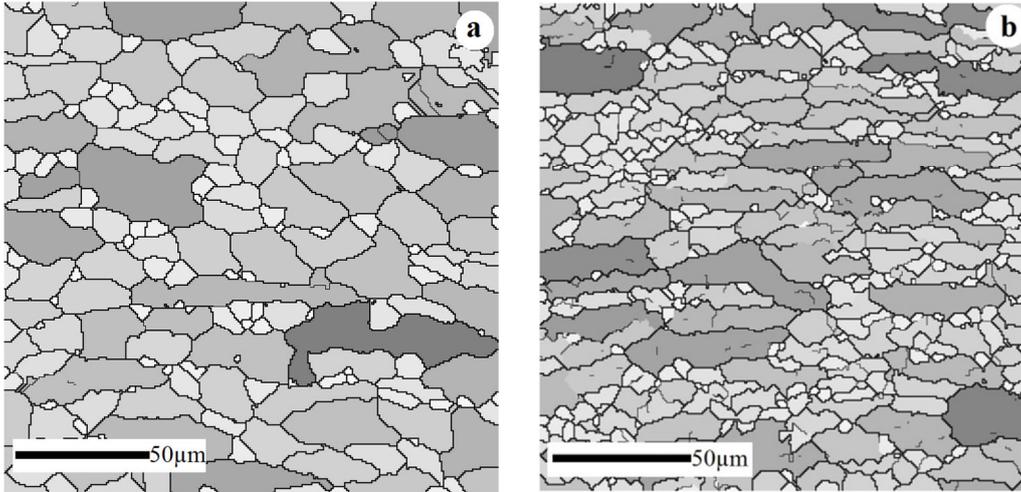


Fig. 1 - EBSD maps of the grain structure of aluminium alloy 1560 (a) as-received condition, (b) after 4 cycles of groove pressing technique

Analysis of the distribution of grain size of metallic alloys have shown that there are several characteristic types of distributions: unimodal, bimodal and multimodal distributions. Unimodal distribution of grain size in metals can be described by the formula log normal distribution (Berbenni, 2007):

$$f_k(d_g) = \frac{1}{\sqrt{2\pi} d_g S_n} \exp\left[-\frac{1}{2} \left(\frac{\ln(d_g / d_{g_m})}{S_n}\right)^2\right], \quad (10)$$

where d_g is the grain size, d_{g_m} is the median grain size of the distribution and S_n is the standard deviation in a number weighted grain size distribution.

The distribution of the grain sizes of aluminium alloy 1560 (a) for as-received condition, and (b) after after 4 cycles of groove pressing technique is shown in Fig. 2.

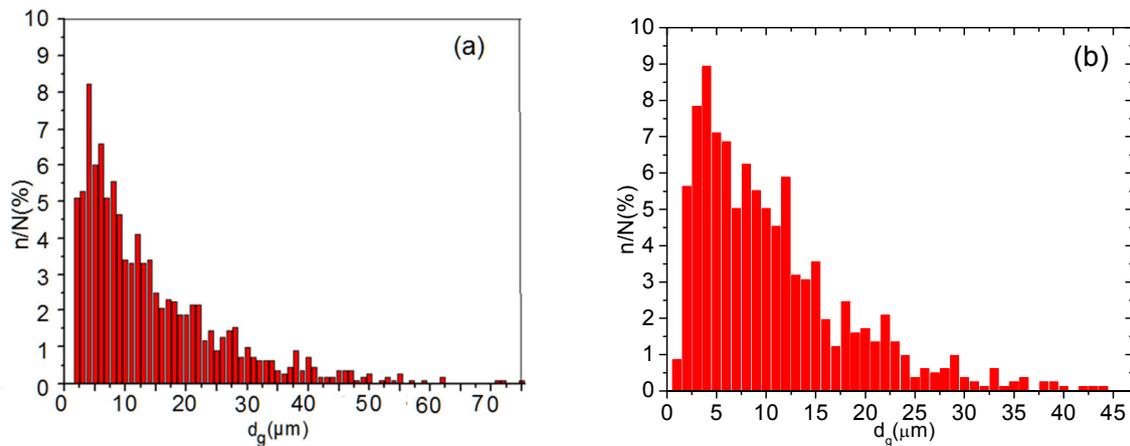


Fig. 2 - Distribution of the grain sizes of aluminium alloy 1560: (a) - as-received condition, (b) - after 4 cycles of groove pressing technique

The Weibull distribution function can be used for description of the unimodal distribution of grain size in metal alloys (Skripnyak, 2012, 2014, 2015):

$$f_k(d_g) = f_0 + \frac{b}{a} \left[\frac{d_g - c}{a} \right]^{b-1} \exp \left[- \left(\frac{d_g - c}{a} \right)^b \right], \quad (11)$$

where d_g is the grain size, b is the shape parameter, a is the scale parameter, and c is the location parameter of the Weibull distribution function.

The bimodal or multimodal probability density function can be presented as sum of probability density function of coarse grains, fine grains, and ultra fine grains:

$$f(d_g) = \sum_{k=1}^m \lambda_k f_k(d_g), \quad \sum_{k=1}^m \lambda_k = 1, \quad (12)$$

where d_g is the grain size, $f_k(d_g)$ is the unimodal probability density functions of grain size distribution, λ_k is weighting coefficients.

A multimodal distribution of the grain sizes of aluminium alloy 1560 after 4 cycles of groove pressing technique is shown in Fig.3

The specific volumes of UFG (with grain size $50 \text{ nm} < d_g < 1 \text{ }\mu\text{m}$ fine grains ($1 \text{ }\mu\text{m} < d_g < 10 \text{ }\mu\text{m}$), and coarse grains ($10 \text{ }\mu\text{m} < d_g < d_{g \text{ max}}$) are described using probability density functions f_1, f_2, f_3 of UFG, FG, and CG grain systems, respectively:

$$C_{\text{UFG}} = \int_{d_g^{\text{min}}}^{1\mu\text{m}} f_1(x) dx, \quad C_{\text{FG}} = \int_{1\mu\text{m}}^{10\mu\text{m}} f_2(x) dx, \quad C_{\text{CG}} = \int_{10\mu\text{m}}^{d_g^{\text{max}}} f_3(x) dx, \quad (13)$$

where $C_{\text{UFG}}, C_{\text{FG}}, C_{\text{CG}}$ are the volume fraction of ultra fine grains, fine grains and coarse grains, respectively.

Statistical samplings of large and fine grains can be combined into a single sampling. In this case, the distribution of grains sizes is considered as bimodal distribution.

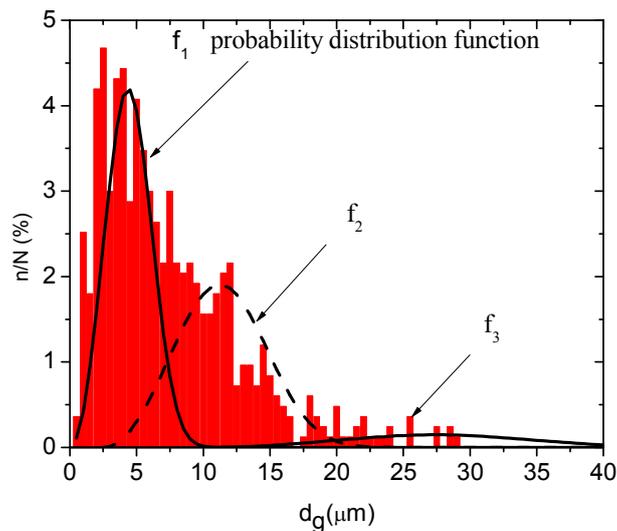


Fig. 3 - Multimodal distribution of the grain sizes of aluminium alloy 1560 after 4 cycles of groove pressing technique

The volume fraction of coarse grains $C_{CG} \approx 0.363$ corresponds to the percolation threshold of large grains in the representative volume of the material (Skripnyak, 2014, 2015).

Metal alloys with the volume fraction of coarse grains in the range $0.363 < C_{CG} < 0.637$ have some similarities with composite materials. The average grain size or the effective grain size are used for prediction grain-size hardening of polycrystalline alloys after the pioneering research of Hall and Petch (Valiev, 1993).

The average grain size can be defined for unimodal distributions of grain size and effective grain size is used for bimodal or multimodal distributions of grains sizes.

The average grain size \bar{d}_g was related to the median grain size d_{gm} of unimodal grain size distribution (Zhu, 2005, Gollapudi, 2012):

$$\bar{d}_g = d_{gm} \exp(S_n^2 / 2), \quad (14)$$

where d_g is the grain size, d_{gm} is the median grain size of the distribution and S_n is the standard deviation in a number weighted grain size distribution (See Eq. (1)).

The effective grain size $d_{g\text{eff}}$ in a bimodal grain structure can be determined by the relation:

$$d_{g\text{eff}}^{-1} = C_{CG} d_{g\text{cg}}^{-1} + C_{UFG} d_{g\text{ufg}}^{-1}, \quad (15)$$

where C_{CG} is a volume fraction of coarse grains, C_{UFG} is a volume fraction of ultra fine grains, $d_{g\text{cg}}$ and $d_{g\text{ufg}}$ are the average grain sizes of coarse and ultra fine grain fraction, respectively.

Weighted-average grain size (d_{wt}) can be defined as (Dapeng et al., 2011):

$$d_{g\text{wt}} = \sum_{i=1}^N d_{gi} f_{ai}, \quad (16)$$

where d_{gi} is the size of grain (i) and f_{ai} is the area-fraction of that grain.

Strain to failure ε_f^n at quasi static loadings increases proportionally to the inverse of the square root of the effective grain size (Lukač, 2011).

$$\varepsilon_{f\text{st}}^n = \varepsilon_{f0}^n [1 + D_{\varepsilon f} d_g^{-1/2}] / (1 - \theta), \quad (17)$$

where $\varepsilon_{f\text{st}}$ is the strain to fracture at quasi static loading, ε_{f0} , $D_{\varepsilon f}$ are material constants, $\theta = (T - T_r) / (T_m - T_r)$, T is the temperature, $T_r = 295$ K, T_m is the melting temperature.

The strain to failure ε_f^n at dynamic loadings describes by relation:

$$\varepsilon_{f\text{st}}^n / \varepsilon_{f\text{dyn}}^n = [1 + C_{\varepsilon f} \lg(\dot{\varepsilon}_{\text{eq}} / \dot{\varepsilon}_0) H(\dot{\varepsilon}_{\text{eq}} / \dot{\varepsilon}_0 - 1)], \quad (18)$$

where $\varepsilon_{f\text{dyn}}$ is the strain to fracture under tension at high strain rate, $\dot{\varepsilon}_{\text{eq}} = [(2/3)\dot{\varepsilon}_{ij}\dot{\varepsilon}_{ij}]^{1/2}$, $\dot{\varepsilon}_0 = 1,0 \text{ s}^{-1}$, $C_{\varepsilon f}$ is the constant of material, $H(\cdot)$ is the Heaviside function.

The calculated by Eq. (18) values of strain to failure under dynamic loads for the CG and UFG aluminium alloys is shown in Fig. 4. The symbols, shown in Fig. 4, are experimental data at room temperature (Mukai, 2003).

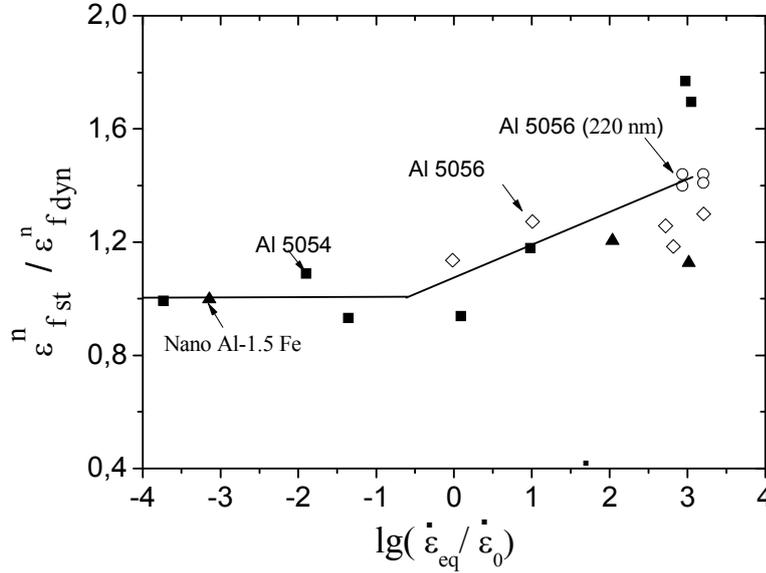


Fig. 4 - The strain to failure ϵ_f^n at dynamic loadings of CG and UFG aluminium alloys

The deformation to failure of UFG alloys can be determined by the relationship, taking into account the distribution of grain size:

$$\epsilon_f^n (d_g) / \epsilon_f^{CG} = A_2 + (A_1 + A_2) / (1 + \exp[(d_g^{-1/2} - d_{gm}^{-1/2}) / \bar{d}_g^{-1/2}]), \quad (19)$$

$$\epsilon_f^{CG} = D_1 (P^* + T^*)^{D_2}, \quad (20)$$

where ϵ_f^{CG} is the strain to fracture of coarse grained volume of material, A_1 , A_2 , d_{gm} , \bar{d}_g are the material constants, $T^* = \sigma_{sp} / p_{HEL}$, $P^* = p / p_{HEL}$, p_{HEL} is the pressure at the Hugoniyoy elastic limit, D_1 , D_2 are the material constants.

Eq. (19) takes into account the influence of the grain size distribution on the ductility of steel (BCC crystalline structure) and FCC and HCP alloys. Universal dependence of $\epsilon_f^n (d_g) / \epsilon_f^{CG}$ on $d_g^{-1/2}$ for aluminium alloy Al 1100, magnesium alloy AZ31, and IF steel is shown in Fig.5. Symbols are shown experimental data (Han, 2004, Han, 2006, Fan, 2006, Nicaise, 2011).

The strain rate sensitivity of flow stress for UFG alloys can be defined as:

$$m = \left. \frac{d(\ln \sigma_s)}{d \ln (\dot{\epsilon}_{eq} / \dot{\epsilon}_0)} \right|_{T, \epsilon_{eq}^p} = m_0 + C_m d_g^{-1/2}, \quad (21)$$

where σ_s is the yield strength, $\dot{\epsilon}_{eq} = [(2/3)\dot{\epsilon}_{ij}\dot{\epsilon}_{ij}]^{1/2}$ is the equivalent strain rate, $\dot{\epsilon}_0 = 1,0 \text{ s}^{-1}$, m_0 , C_m are the material constants, d_g is the average grain size.

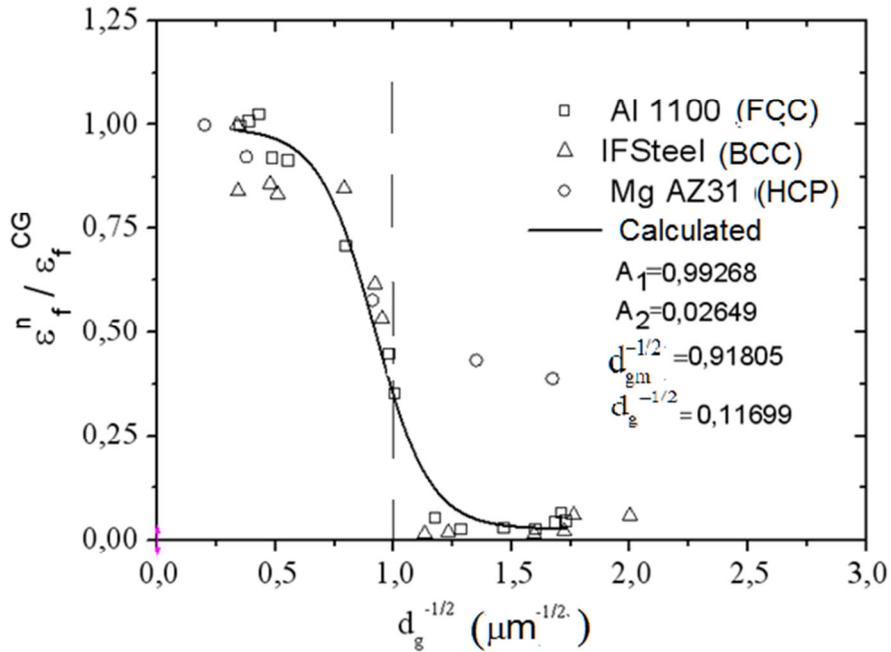


Fig. 5 - Normalized strain to fracture versus the inverse square root of effective grain size

The strain rate sensitivity of flow stress versus the inverse square root of effective grain size for FCC alloys (copper and aluminium) and HCP magnesium alloy is shown in Fig. 6. Symbols shown in Fig. 6 are experimental data (Zhu, 2005, Skripnyak, 2014).

The model was used for numerical simulation mechanical response of model volume of alloys under tension. Calibration of the constitutive equation is performed using the original data of the authors obtained during testing specimens of alloys under the quasi-static and high-speed tests (Kozulyn, 2015, Skripnyak N., 2015). Distribution of grains in the specimens was changed due to processing by severe plastic deformation (Moskvichev, 2016).

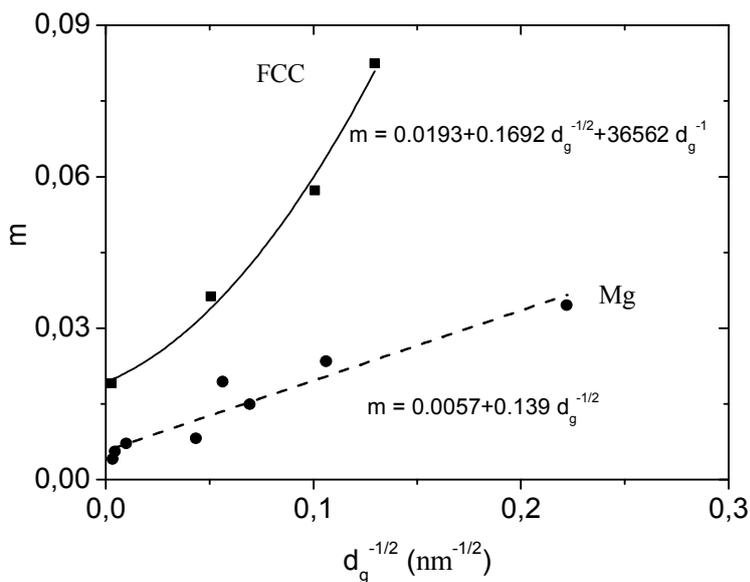


Fig. 6 - The strain rate sensitivity of flow stress versus the inverse square root of effective grain size

RESULTS

We performed a simulation of the deformation and damage of the 3D model volume of the alloy in tension at a constant speed within the range of 0.01 m/s to 15 m/s. The coarse grained and ultrafine-grained alloys were simulated in a range of strain rates from 0.1 s^{-1} to $5 \cdot 10^3 \text{ s}^{-1}$.

The calculated stress vs strain curves of magnesium alloy MA 2-1 is shown if Fig. 7. Stress-strain curves were calculated at strain rates of 0.1 sec and a temperature of 295 K.

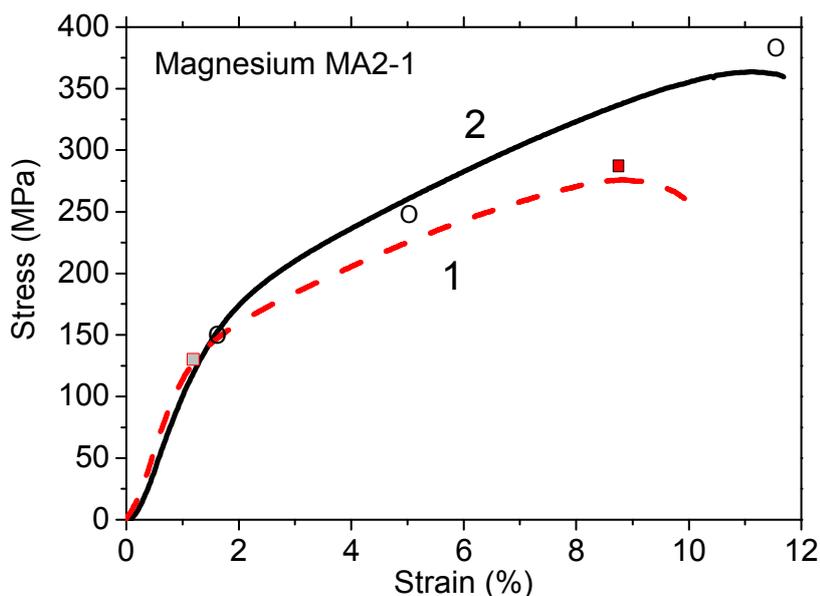


Fig. 7 - Calculated stress vs strain curves of magnesium alloy, curves (1) and (2) correspond to a unimodal and a bimodal distribution of grain size, respectively

Curve (1) was derived for unimodal grain size distribution with average grain size equal to $40 \mu\text{m}$. Curve (2) corresponds to bimodal grain size distribution. Symbols are marked original experimental data of authors. The volume fraction of ultra fine grains was equal to $\sim 35\%$. The yield stress of the alloy increased on 10 - 15 % in comparison with a coarse-grained alloy if the volume fraction of the UFG grains is close to the percolation threshold.

Calculated dependences of the yield strength on logarithm of normalized strain rate for aluminium alloys with distribution of grain sizes are shown in Fig.8. Curves (1), (2), (3) correspond to a unimodal coarse-grained structure, unimodal fine-grained structures, and bimodal distribution of grain size, respectively. Symbols shown in Fig. 8 are experimental data (Hockauf, 2006, Meyer, 2007, Skripnyak N., 2015).

Results of numerical simulation showed that the dependences of the yield stress on logarithm of normalized strain rate for alloys with a bimodal distribution of grains and coarse-grained alloys are similar. The obtained results of numerical simulation agree with the experimental data.

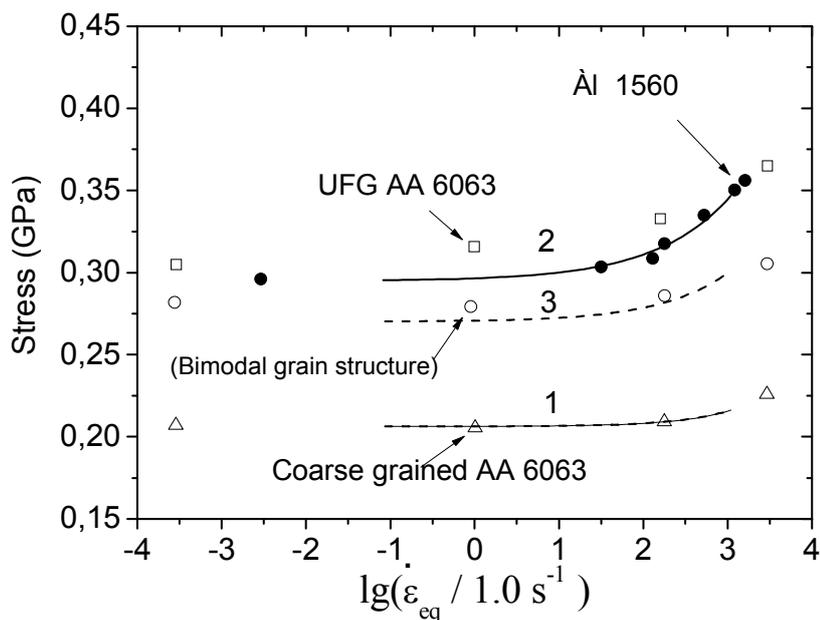


Fig. 8 - Calculated yield strength vs logarithm of normalized strain rate

CONCLUSION

The influence of grain size distribution on the mechanical behavior of magnesium and aluminium alloys in a wide range of strain rates was studied by numerical simulation method.

The model allows taking into account the distribution of grain size in HCP and FCC alloys is proposed.

The model was applied for 3D simulation of uniaxial tension of ultrafine-grained aluminium and magnesium blocks in the range of strain rate $0.1 - 10^3 \text{ s}^{-1}$.

It was shown that the dependences of the yield stress on logarithm of normalized strain rate for alloys with a bimodal distribution of grains and coarse-grained alloys are similar.

Results of numerical simulation are shown that the yield stress of the alloy increased on 10 - 15 % in comparison with a coarse-grained alloy if the volume fraction of the UFG grains is close to the percolation threshold.

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REFERENCES

- [1]-Ahn B., Lavernia E.J., Nutt S.R., Dynamic observations of deformation in an ultrafine-grained Al-Mg alloy with bimodal grain structure, *J. Mater. Sci.*, 2008, 43, 7403-7408.
- [2]-Barton D. C., Determination of a high strain rate fracture properties of ductile materials using a combined experimental/numerical approach, *International Journal of Impact Engineering*, 2004, 30, p. 1147-1159.
- [3]-Berbenni S., Favier V., Berveiller M., Micro-macro modelling of the effects of the grain size distribution on the plastic flow stress of heterogeneous materials, *Computational Materials Science*, 2007, 39, p. 96-105.
- [4]-Cayron C., Artaud B., and Briottet L., Reconstruction of parent grains from EBSD data, *Materials Characterization*, 2006, 57, 386-401.
- [5]-Dapeng Z., Yong L., Feng L., Yuren W., Liuji Z., Yuhai D., ODS ferritic steel engineered with bimodal grain size for high strength and ductility, *Materials Letters*, 2011, 65, p. 1672-1674.
- [6]-Fan G.J., Choo, H., Liaw, P.K., Lavernia, E.J., Plastic deformation and fracture of ultrafine-grained Al-Mg alloys with a bimodal grain size distribution, *Acta Materialia*, 2006, 54, p.1759-1766.
- [7]-Fomin V. M., Kraus E. I., Shabalin I. I., An equation of state for condensed matter behind intense shock waves, *Mater. Phys. Mech.*, 2004, 7, p. 23-28.
- [8]-Garkushin G. V., Razorenov S. V., Krasnoveikin V.A. et al. Effect of structural factors on mechanical properties of the magnesium alloy Ma2-1 under quasi-static and high strain rate deformation conditions, *Physics of the Solid State*. 2015, 57(2), 337-343.
- [9]-Gollapudi S., Grain size distribution effects on the corrosion behaviour of materials, *Corrosion Science*, 2012, 62, p. 90-94.
- [10]-Han B.Q., Huang J.Y., Zhu Y.T., Lavernia E.J., Strain rate dependence of properties of cryomilled bimodal 5083 Al alloys, *Acta Materialia*, 2006, 54, p. 3015-3024.
- [11]-Han B.Q., Huang, J.Y., Zhu, Y.T., Lavernia, E.J., Strain rate dependence of properties of cryomilled bimodal 5083 Al alloys, *Acta Materialia*, 2006, 54, p. 3015-3024.
- [12]-Han B.Q., Lee Z., Witkin D., Nutt S.R., Lavernia E.J., Deformation behavior of bimodal nanostructured 5083 Al alloys, *Metall. Mater. Trans. A*, 2005, 36, p. 957- 965.
- [13]-Herzig N., Meyer L.W., Mush D., et.al. Modeling of mechanical behavior of ultra-fine grained titanium alloys at high strain rates, in *Proc. 3-rd Int. Conf. on High Speed Forming*. March 11-12, 2008. Dortmund, Germany, 2008, p.141-150.
- [14]-Hockauf M., Meyer L.W., Halle T., Kuprin C., Hietschold M., Schulze S., Kruger L., Mechanical properties and microstructural changes of ultrafine-grained AA6063T6 during high-cycle fatigue, *International Journal of Material Research*, 2006, 97, (10), p.1392-1400.

- [15]-Kozulyn A.A., Skripnyak V.A., Krasnoveikin V.A., Skripnyak V.V., Karavatskii A.K., An investigation of physico-mechanical properties of ultrafine-grained magnesium alloys subjected to severe plastic deformation, *Russian Physics Journal*, 2015, 57(9), p. 1261-1267.
- [16]-Kozulyn A.A., Skripnyak V.A., Krasnoveikin V.A., Skripnyak V.V., Karavatskii A.K., An investigation of physico-mechanical properties of ultrafine-grained magnesium alloys subjected to severe plastic deformation, *Russian Physics Journal*, 2015, 57(9), p. 1261-1267.
- [17]-Lavergne F., Brenner R., Sab K. Effects of grain size distribution and stress heterogeneity on yield stress of polycrystals: A numerical approach, *Computational Materials Science*, 2013, 77, p. 387-398.
- [18]-Li Z., Wang B., Zhao S., Valiev R. Z., Vecchio K. S., Meyers M. A., Dynamic deformation and failure of ultrafine-grained titanium, *Acta Materialia*, 2017, 125, p. 210-218.
- [19]-Lim H., Lee M.G., Kim J.H., Adams B.L., Wagoner R.H. Simulation of polycrystal deformation with grain and grain boundary effects, *International Journal of Plasticity*, 2011, 27, p. 1328-1354.
- [20]-Lukač P., Trojanova Z. Influence of grain size on ductility of magnesium alloys, *Materials Engineering*, 2011, 18, p. 110-114.
- [21]-Malygin G.A., Strength and plasticity of nanocrystalline metals with a bimodal grain structure. *Phys. Solid State*, 2008, 50, p. 1032-1038.
- [22]-McQueen R. G., Warsh S. P. Equation of state for nineteen metallic elements from shock-wave, measurements to two megabars, *J. of Applied Physics*, 1960, 31, p. 1253-1297.
- [23]-Meyer L.W., Hockauf M., Kruger L., Schneider I., Compressive behaviour of ultrafine-grained AA6063T6 over a wide range of strain and strain rate, *International Journal of Material Research*, 2007, 98, (3) p.1-9.
- [24]-Moskvichev E., Skripnyak V., Lychagin D., Kozulin A., Skripnyak V., Influence of structure to plastic deformation resistance of aluminium alloy 1560 after groove pressing treatment, *Letters on materials*, 2016, 6(2), p 141-145.
- [25]-Mukai T, Yamanoi M., Watanabe H. et al. Effect of grain refinement on tensile ductility in ZK60 magnesium alloy under dynamic loading. *Mater. Trans.*, 2001, 42, p.1177-1181.
- [26]-Mukai T., Suresh S., Kita K. et al Nanostructured Al-Fe alloys produced by e-beam deposition: static and dynamic tensile properties, *Acta Materialia*, 2003, 51, p. 4197-4208.
- [27]-Nicaise N., Berbenni S., Wagner F., Berveiller M., Lemoine X. Coupled effects of grain size distributions and crystallographic textures on the plastic behaviour of IF steels, *International Journal of Plasticity*, 2011, 27, p. 232-249.
- [28]-Ono N., Nowak R., Miura S. Effect of deformation temperature on Hall-Petch relationship registered for polycrystalline magnesium, *Materials Letters*. - 2004. -Vol. 58. -P. 39-43.

- [29]-Pozdnyakov V.A., Ductility of nanocrystalline materials with a bimodal grain structure. *Tech. Phys. Lett.*, 2007, 33, p. 1004-1006.
- [30]-Prasad M.J., Suwas S., Chokshi A.H., Microstructural evolution and mechanical characteristics in nanocrystalline nickel with a bimodal grain-size distribution, *Materials Science and Engineering A*, 2009, p.503: 86-91.
- [31]-Raeisinia B., Sinclair C. W., Poole W. J., and Tome C. N., On the impact of grain size distribution on the plastic behaviour of polycrystalline metals, *Materials Science and Engineering A.*, 2008, 16, 025001.
- [32]-Sakai T., Belyakov A., Kaibyshev R., Miura H., Jonas J. J., Dynamic and post-dynamic recrystallization under hot, cold and severe plastic deformation conditions, *Progress in Materials Science*, 2014, 60, p. 130-207.
- [33]-Shekhar S., Cai J., Wang J., Shankar M.R. Multimodal ultrafine grain size distributions from severe plastic deformation at high strain rates, *Materials Science and Engineering A*, 2009, 527, p. 187-191.
- [34]-Skripnyak V.A. Mechanical behavior of nanostructured and ultrafine-grained materials under shock wave loadings. Experimental data and results of computer simulation, *Shock Compression of Condensed Matter. AIP Conf. Proc.*, 2012, 1426, p. 965-970. doi: 10.1063/1.3686438
- [35]-Skripnyak V.A. Mechanical behavior of nanostructured and ultrafine-grained materials under shock wave loadings. Experimental data and results of computer simulation, in *Shock Compression of Condensed Matter-2012*, AIP Conference Proceedings 1426, AIP, Melville, NY, 2012, p. 965-970.
- [36]-Skripnyak V.A., Skripnyak E.G., Skripnyak N.V., Vaganova I.K., and Skripnyak V.V. Failure mechanisms of light alloys with a bimodal grain size distribution, in: *11th. World Congress on Computational Mechanics (WCCM XI)*”, Barcelona, Spain, 25-29, July. 2014. 2014, IV, p.3915-3925.
- [37]-Skripnyak V.A., Skripnyak N.V., Skripnyak E.G., Mechanical behavior of light alloys with bimodal grain size distribution, *Applied Mechanics and Materials*, 2015, 756, p.205-213.
- [38]-Skripnyak N. V., The features of fracture behavior of an aluminium-magnesium alloy AMg6 under high-rate straining, *Russian Physics Journal*, 2015, 58, p. 691-697.
- [39]-Tiamiyu A.A., Eskandari M., Sanayei M., Odeshi A.G., Szpunar J.A. Mechanical behavior and high-resolution EBSD investigation of the microstructural evolution in AISI 321 stainless steel under dynamic loading condition, *Materials Science and Engineering A*, 2016, 673, p. 400-416.
- [40]-Valiev, R.Z., Enikeev, N.A., Murashkin, M.Yu. et al. On the origin of the extremely high strength of ultrafine-grained Al alloys produced by severe plastic deformation. *Scripta Materialia*, 2010, 63, p. 949-952.

[41]-Valiev, R.Z., Korznikov, A.V. Mulyukov, R.R., Structure and properties of ultrafine-grained materials produced by severe plastic deformation, *Materials Science and Engineering A*, 1993, 168, p. 141-148.

[42]-Valiev, R.Z., Krasilnikov N.A., Tsenev N.K., Plastic deformation of alloys with submicro-grained structure, *Materials Science and Engineering A*, 1991, 137, p. 35-40.

[43]-Wang Y., He H., Wang L., Critical Damage Evolution model for spall failure of ductile metals, *Mechanics of Materials*, 2013, 56, p. 131-141.

[44]-Zerilli F.J., Armstrong R.W., The effect of dislocation drag on the stress-strain behavior of fcc metals, *Acta Metall. Mater*, 1992, 40, p.1803-1808.

[45]-Zhang S., Wang Y. C., Zhilyaev A. P. et al., Effect of grain size on compressive behaviour of titanium at different strain rates, *Materials Science and Engineering A*, 2015, 64, p. 5311 -317.

[46]-Zhu B., Asaro R.J., Krysl P., Bailey R., Transition of deformation mechanisms and its connection to grain size distribution in nanocrystalline metals, *Acta Materialia*, 2005, 53, p.4825-4838.