COMPARATIVE TRIBOLOGICAL PROPERTIES OF AZ91D MAGNESIUM ALLOY AFTER STRENGTHENING BY SiC POWDER AND AFTER SEVERE PLASTIC DEFORMATION

СРАВНИТЕЛЬНЫЕ ТРИБОЛОГИЧЕСКИЕ СВОЙСТВА МАГНИЕВОГО СПЛАВА AZ91D ПОСЛЕ УПРОЧНЕНИЯ ПОРОШКОМ КАРБИДА КРЕМНИЯ И ПОСЛЕ ИНТЕНСИВНОЙ ПЛАСТИЧЕСКОЙ ДЕФОРМАЦИИ

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Abstract. *The paper presents the results of studies of tribological properties of the contact of the tool steel composition Fe-18W-4Cr-1,2V with the magnesium alloy AZ91D strengthened by submicron powder filling out of SiC and severe plastic deformation (SPD), namely equal-channel angular pressing (ECAP). It is stated that introduction of SiC powder filling to the magnesium alloy the friction coefficient on the moving frictional contact increases, the wear rate reduces. These tribotecnical characteristics are influenced by the size and volume of the particles of powder filling, normal loading force and slip rate. SPD of the initial material results in reduction of the adhesion constituent of the friction coefficient.*

KEYWORDS: *MAGNESIUM ALLOY; METALLIC COMPOSITE MATERIAL; POWDER FILLING; SEVERE PLASTIC DEFORMATION; EQUAL-CHANNEL ANGULAR PRESSING; SILICIUM CARBIDE; FRICTION COEFFICIENT; ADHESIVE BOND SHEAR STRENGTH ; WEAR RATE.*

Introduction

In modern mechanical engineering, in particular in friction knots, one of the ways to reduce the weight of cars is to apply light alloys with enhanced mechanical properties. Magnesium is attractive to be applied as structural material due to attractive strength-to-weight ratio that exceeds the one for aluminum and other light metals and alloys [1-3]. High damping capacity of magnesium alloys allows using them effectively to manufacture automobile and aircraft wheels, various components for motor-and-tractor and aerospace engineering, rollers for cargo conveyors [6, 7] etc. The strength of magnesium could be enhanced without significant change in the strength due to addition of small amount of submicron powder filling of SiC [3-5]. Besides, severe plastic deformation is known to effectively increase the strength of bulk metals due to fabrication of ultrafine-grained structure [8, 9]. SPD techniques can be considered as alternative techniques to dispersion strengthening of composite materials.

However, tribological behavior of these materials is studied insufficiently for application in friction knots [10, 11].

In this paper the results of definition of wear rate of the magnesium alloy, the friction coefficient and its molecular constituent depending on the content of the powder filling are given. Comparative evaluation of the adhesive bond shear strength and molecular constituent of the friction coefficient of the magnesium alloy *AZ91D* strengthened by *ECAP* in the slipping tribological contact with the tool steel composition *Fe-18W-4Cr-1,2V* is presented.

Experimental procedure and materials

Magnesium alloy *AZ91D* (*89.89%Mg-9.0%Al-0.68%Zn-0.13%Mn*) was used as material for study. In comparative tests there were employed matrix composite materials, containing submicron powder filling out of *SiC*, and the magnesium alloy *AZ91D* after *2 ECAP* passes.

The variants of investigated composite materials differing in dispercity and amount of added powder of *SiC* and strain-hardened magnesium alloy of the initial state are the following: *AZ91D* in the initial state*; AZ91D + 3% SiC* with an average particle size of *5 μm; AZ91D + 3% SiC* with an average particle size of *11 μm; AZ91D + 6% SiC* with an average particle size of *11 μm; AZ91D + 3% SiC* with an average particle size of *15 μm; AZ91D* after 2 *ECAP* passes.

Tribological tests of the initial alloy and dispersion-strengthened composite materials were carried out on the friction machine "Timken". Fig. 1 presents the set and the processing scheme.

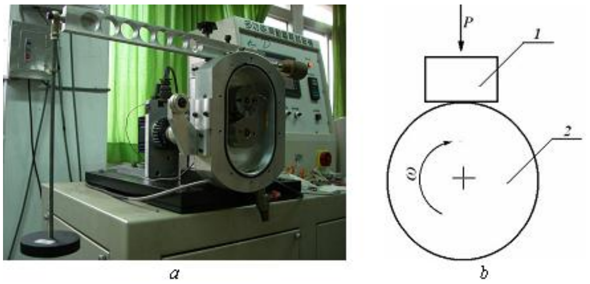

Fig. 1. *Machine of friction "Timken" (a) and testing scheme (b): 1 – tested sample; 2 – rotating steel disk.*

Testing of the initial and dispersion-strengthened materials was conducted under normal loading of *10N* and *50N* and a disk rotation speed of *250* min^{-1} and *1000* min^{-1}, the slip distance was *1650 m* in all the tests.

Friction force *(F)*, loss of sample mass *(Q)* and geometric area of the contact (S_c) were recorded during tests. The wear rate (J_h) value was defined with the help of the mentioned parameters.

The diameter of the disk out of tool steel composition *Fe-18W-4Cr-1,2V* was *70 mm*, the thickness was *20 mm*. The wear of the disk quenched to the hardness of *HRC58…65* was neglected due to its low value as compared to the wear of the tested samples.

The friction coefficient *f* was calculated according to the formula:

$$f = \frac{F}{P}, \qquad (1)$$

where *F* – friction force, *N*; *P* – normal loading force, *N*.

The wear rate J_h value was defined according to the formula:

$$J_h = \frac{Q}{qS_c L}, \tag{2}$$

where Q – sample mass loss, g; q – material density, g/cm^3; S_c – geometrical area of the contact, cm^2; L – slip distance, *cm*.

Fig. 2 presents the *ECAP* scheme that was chosen for strain hardening of the initial material [12, 13].

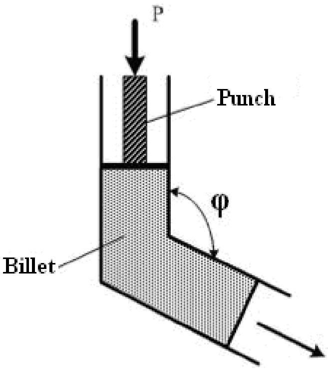

Fig. 2. *ECAP scheme.*

The employed scheme allows achieving high degrees of accumulated strain as a result of shear in the conjugating channels. In this case the angle between the conjugating channels φ was 120^o.

Studies on the evaluation of the adhesive bond shear strength and molecular constituent of the friction coefficient were carried out on the one-ball machine of friction at temperatures of *20*, *150* and $300\ ^oC$ according to the scheme that is presented in Fig. 3 [14].

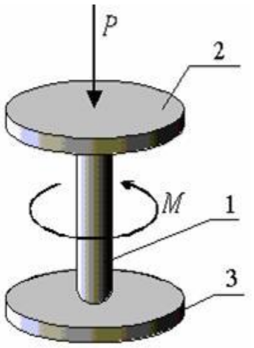

Fig. 3. *Scheme of testing of molecular constituent of the friction coefficient: 1 – tool steel R18 indentor; 2 – tested samples.*

Adhesive bond shear strength τ_n was defined from the ratio:

$$\tau_n = 0{,}75 \cdot \frac{M}{\pi \cdot \left(\frac{d_{1,2}}{2}\right)^3}, \tag{3}$$

where $d_{1,\,2}$ – diameters of prints on the tested samples, mm; M – indentor rotary moment, *N mm*.

Adhesive (molecular) constituent of the friction coefficient was defined as:

$$f_M = \frac{\tau_n}{p_r}, \tag{4}$$

where p_r – normal pressure, *MPa*

$$p_r = \frac{P}{\pi \cdot \left(\frac{d_{1,2}}{2}\right)^2} \tag{5}$$

where P – force of sample compression, *N*.

Results of experiments and their discussion

Figs. 4 and 5 present the charts with the results of tribological tests conducted according to the scheme “block-disk” (Fig.1).

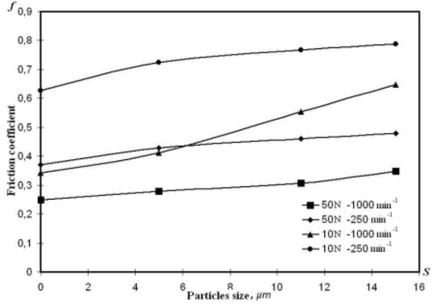

Fig. 4. *Dependence of the friction coefficient on the size of SiC particles*

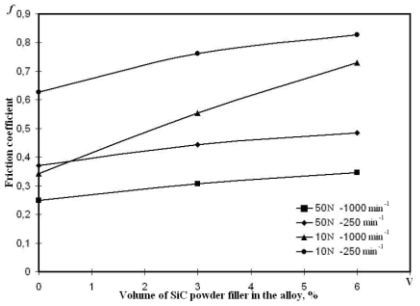

Fig. 5. *Dependence of the friction coefficient on the volume of powder filling*

It is seen from the charts that addition of powder filling of *SiC* to the magnesium alloy increases the friction coefficient. The lower the normal loading force and the slip rate, the higher friction coefficient.

In order to explain these results, let us consider the data received with the help of the one-ball machine of friction.

Fig. 6 demonstrates that the dependence of the adhesive bond shear strength τ_n on the normal pressure p_r is described by the binomial dependence:

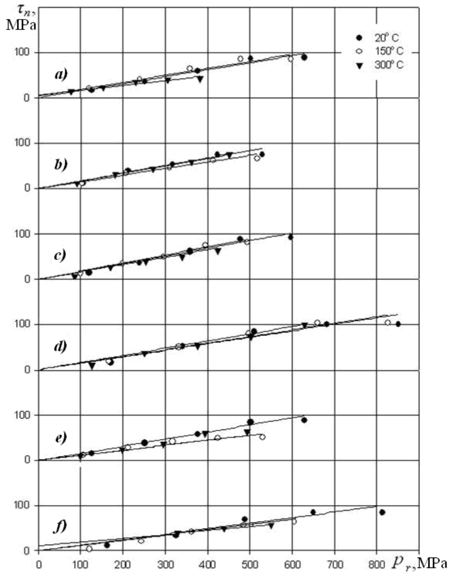

Fig. 6 *Dependence of adhesive bond shear strength on the normal pressure in the contact with tool steel composition Fe-18W-4Cr-1,2V: a) - AZ91D in the initial state; b) - AZ91D + 3% SiC with an average particle size of 5 μm; c) - AZ91D + 3% SiC with an average particle size of 11 μm; d) AZ91D + 6% SiC with an average particle size of 11 μm; e) AZ91D + 3% SiC with an average particle size of 15 μm, f) AZ91D after 2 ECAP passes.*

$$\tau_n = \tau_o + \beta\, p_r \tag{6}$$

where τ_o – adhesive bond shear strength without normal loading force; β – piezocoefficient.

The molecular constituent of the friction coefficient f_M can be defined as:

$$f_M = \frac{\tau_n}{p_r} = \frac{\tau_o}{p_r} + \beta \tag{7}$$

It is seen from formula (7) that the molecular constituent of the friction coefficient increases, when the normal pressure p_r decreases. This fact explains the enhancement of the friction coefficient when the normal loading force reduces (Figs. 4 and 5).

Decrease in the slip rate reduces the temperature of the friction contact, which according to the data in Fig. 7 enhances the molecular constituent f_m and the total friction coefficient f (Fig. 4 and 5).

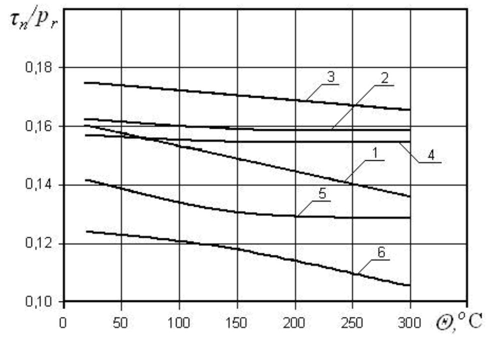

Fig. 7. *Dependence of molecular constituents of the friction coefficient on the temperature for friction couples: 1) AZ91D – Fe-18W-4Cr-1,2V; 2) AZ91D + SiC (S = 5 μm; V = 3%) – Fe-18W-4Cr-1,2V; 3) AZ91D + SiC (S = 11 μm; V = 3%) – Fe-18W-4Cr-1,2V; 4) AZ91D + SiC (S = 11 μm; V = 6%) – Fe-18W-4Cr-1,2V; 5) AZ91D + SiC (S = 15 μm; V = 3%) – Fe-18W-4Cr-1,2V, 6) AZ91D after 2 ECAP passes – Fe-18W-4Cr-1,2V.*

Increase of the friction coefficient after addition of *SiC* powder filling into the magnesium alloy can be explained by enhancement of the deformation constituent of the friction coefficient f_d (Figs. 4 and 5). It is known that in accordance with the mechanical and molecular friction theory [15] the deformation constituent of the friction coefficient is formed by the resisting forces of the deformation roller that runs in front of introduced irregularities to the surface of the softer contacting slipping bodies. The value of the deformation constituent of the friction coefficient f_d depends on the amount of introduced irregularities and their relative introduction can be defined analytically [15] or experimentally as:

$$f_d = f - f_m \tag{8}$$

The calculations of the values of the molecular constituent of the friction coefficient f_m conducted in the comparable conditions on the basis of experimental data given in Figs. 4, 5 and 7 demonstrate that addition of the *SiC* powder filling to the magnesium alloy enhances the value of the deformation constituent f_d from 0.09 to 0.20. The higher the f_d value, the higher the volume and size of *SiC* particles in the magnesium alloy. These particles characterized by high hardness are added to the contact surface of the counterbody, and the deformation constituent and total friction coefficient increase.

Solid *SiC* particles in the form of powder filling provide reduction of the wear rate of the dispersion-strengthened magnesium alloy (Fig. 8 and 9).

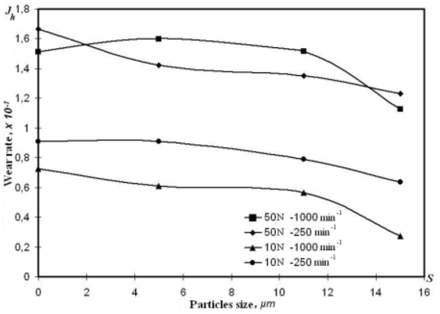

Fig. 8. *Dependence of the wear rate on the size of SiC particles*

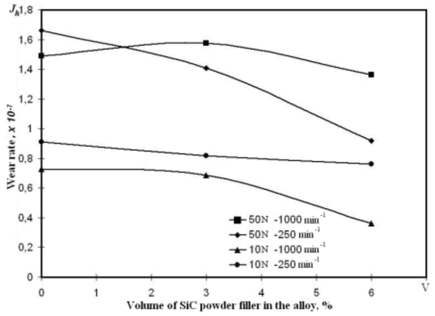

Fig. 9. *Dependence of the wear rate on the volume of powder filling*

It should be noted that the wear rate decreases with the increasing size and volume of the filling particles in the magnesium alloy, as in this case the areas containing hard-wearing *SiC* particles increase. This effect can be observed on babbit bearings. The solid filling is added to the soft matrix of bearings.

The experimental data given in Figs. 6 and 7 testify to the fact that the magnesium alloy *AZ91D* after 2 *ECAP* passes is quite alternative to the composite magnesium alloy strengthened by the powder filling out of *SiC*. The preliminary deformation treatment of the initial magnesium alloy provides lower value of the adhesive constituent of the friction coefficient at a rather high bearing capacity of the frictional contact [16]. As the research results showed (Fig. 6), the bearing capacity of the frictional contact of the material processed by *SPD* technology is comparable with the composite material on the basis of the magnesium alloy *AZ91D* that contains *3% SiC* with an average particle size of *15 μm*.

Conclusion

1. Addition of the powder filling of *SiC* to the magnesium alloy results in enhancement of the integral value of the friction coefficient, as in this case its deformation constituent increases. In the investigated range the normal loading force and the rate of relative slip impact the total value of the friction coefficient as the factors that change its molecular constituent.
2. Addition of the powder filling of *SiC* to the magnesium alloy *AZ91D* results in reduction of the wear rate, as in this case the areas containing hard-wearing *SiC* particles increase.
3. Employment of the magnesium alloy after *ECAP* in the friction knots is promising. The molecular constituent of the friction coefficient reduces significantly with the enhanced bearing capacity of the frictional contact.

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