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DETERMINATION OF FRICTION COEFFICIENTS AT ELEVATED TEMPERATURES FOR SOME Al, Mg AND Ti ALLOYS

WYZNACZANIA WSPÓŁCZYNNIKÓW TARCIA W PODWYŻSZONYCH TEMPERATURACH DLA WYBRANYCH STOPÓW Al, Mg ORAZ Ti

The results of research on friction conditions of alloys: magnesium Mg4AlZn, titanium Ti6Al4V and aluminum 6101A are presented in this paper. The aim of these research was determining values of friction factors and coefficients, which characterize constant friction model and Coulomb's model within the range of hot metal forming temperatures at various lubrication conditions. In the research works the ring tests were applied. For the alloy Mg4AlZn the samples were heated to the temperatures: 250°C, 350°C and 450°C, for aluminum alloy 6101A to the temperatures: 350°C, 400°C, 450°C and for alloy Ti6Al4V to the temperatures: 850°C, 900°C, 950°C. Tests were made in conditions of friction without lubrication and with the application of lubricants: tallow with graphite, Aquagraphite CP, Lubrodal-F318 and on the basis of molybdenum disulfide.

Friction factors and coefficients values were determined on the basis of comparison of experimental research results wih results of the conducted tests simulations. The value of factor and coefficient which guaranteed the best convergance of theoretical and experimental dimensions of upset samples was assumed as optimal. On the basis of the obtained results the influence of temperature on friction conditions and effectiveness of the used lubricants were determined in relation to analyzed alloys.

Keywords: friction coefficient, friction factor, magnesium alloy, aluminium alloy, titanium alloy

W opracowaniu przedstawiono wyniki badań warunków tarcia stopów: magnezu Mg4AlZn, tytanu Ti6Al4V oraz aluminium 6101A. Celem badań było wyznaczenie wartości czynników i współczynników tarcia charakteryzujących odpowiednio model tarcia stałego oraz model Coulomba w zakresie temperatur obróbki plastycznej na gorąco przy różnych warunkach smarowania. W badaniach zastosowano metodę spęczania próbki pierścieniowej. Dla stopu Mg4AlZn próbki nagrzewano do temperatur: 250°C, 350°C oraz 450°C, dla stopu aluminium 6101A do temperatur: 350°C, 400°C, 450°C oraz dla stopu Ti6Al4V do temperatur: 850°C, 900°C, 950°C. Testy wykonano w warunkach tarcia suchego oraz z zastosowaniem smarów: łoju z grafitem, Akwagrafitu CP, Lubrodalu-F318 oraz na bazie dwusiarczku molibdenu.

Wartości czynników i współczynników tarcia wyznaczono na podstawie porównania wyników doświadczalnych z rezultatami symulacji przeprowadzonych testów. Za optymalną przyjmowano taką wartość współczynnika lub czynnika tarcia, która zapewniła najlepszą zbieżność pomiędzy teoretycznymi i doświadczalnymi wymiarami spęczonych próbek. Na podstawie uzyskanych rezultatów określono wpływ temperatury na warunki tarcia oraz skuteczność użytych smarów w odniesieniu do badanych stopów.

1. Introduction

Recently, a fast development of non-ferrous metals forming technology has been observed. A wide application of aluminum, magnesium and titanium alloys in aviation and automotive industries is connected with good mechanical characteristics at their small density (Mg –1,78 g/cm^3, Al – 2,7 g/cm^3, Ti – 4,5 g/cm^3). Alloys of light metals are used for production of especially loaded and exposed to large temperatures planes and helicopters body paneling. Machine parts made from alloys Al, Mg and Ti, on the basis of modern metal forming technologies, show more favorable mechanical properties in comparison with parts made by means of other methods e.g. casting [1]. This fact justifies the necessity of research works connected with improvement of metal forming methods of these alloys in hot conditions. Softwares based on finite element method are used for the metal forming process analysis. A crucial influence on precision of simulations results has a proper description of boundary conditions of the modeled process, including friction conditions at the deformed material-tool

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surface of contact. The most important parameters characterizing friction models are: friction factor or friction coefficient. Hence, for a proper modelling of metal forming processes, the knowledge of these parameters values is required. Because of that, it is purposeful to determine values of friction factors and coefficients for chosen alloys within the scope of forming temperatures in hot conditions. Research works were done in conditions of dry friction and with application of chosen lubricants used in metal forming processes. Additional effect of the research works, apart from quantitative analysis of parameters characterizing friction phenomenon, is estimation of effectiveness of the applied lubricants. The obtained results will be used for further theoretical and experimental works concerning forming processes of chosen aluminum, magnesium and titanium alloys, and, it is assumed that this will allow for increase of the conducted research quality.

2. Experimental research

Research on friction conditions were done for alloys: magnesium Mg4AlZn, titanium Ti6Al4V and aluminum 6101A, which chemical compositions are shown in Table 1÷3.

A method of upsetting of ring-shaped samples of diameters: external diameter D_0=20 mm, internal diameter d_0=10 mm and height $H_{0=}$7 mm (Fig. 1a) was applied [5, 6]. Samples from alloy Mg4AlZn were heated to temperatures: 250°C, 350°C, 450°C, from aluminum alloy 6101A to temperatures: 350°C, 400°C, 450°C, and from alloy Ti6Al4V to temperatures: 850°C, 900°C, 950°C.

TABLE 1

Chemical composition of magnesium alloy Mg4AlZn (% wt) [2]

Fe	Si	Mn	Ni	Al	Cu	Be	Zn	Other	Mg
$\leqslant 0,05$	$\leqslant 0,1$	0,15÷ 0,5	$\leqslant 0,005$	3÷4	$\leqslant 0,05$	$\leqslant 0,02$	0,2÷ 0,8	0,3	94,4÷ 97,65

TABLE 2

Chemical composition of titanium alloy Ti6Al4V (% wt) [3]

O	V	Al	Fe	H	C	N	Ti
$\leqslant 0,20$	3,5	5,5	$\leqslant 0,30$	$\leqslant 0,0015$	$\leqslant 0,08$	$\leqslant 0,05$	rest

TABLE 3

Chemical composition of aluminum alloy 6101A (% wt) [4]

Si	Fe	Cu	Mg	Other	Al
0,3÷0,7	0,4	0,05	0,4÷0,9	$\leqslant 0,1$	rest

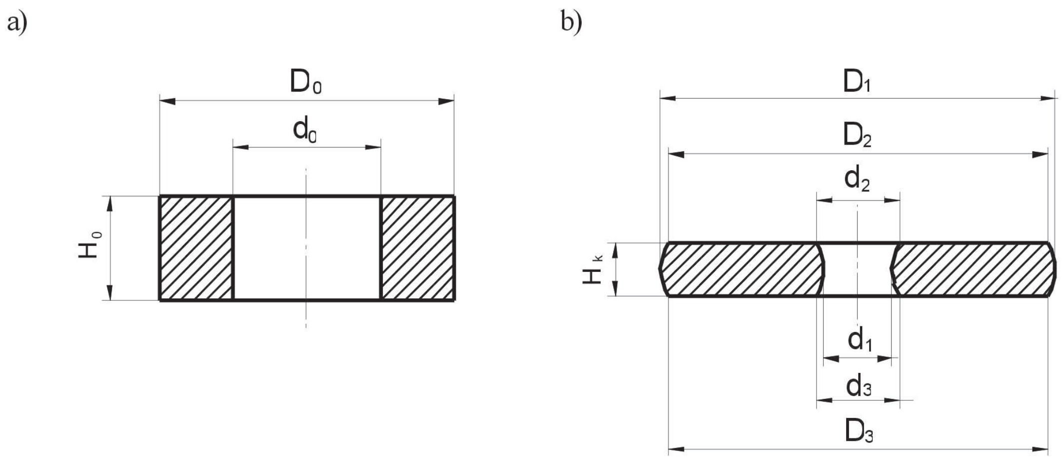

Fig. 1. Sketch of ring-shaped samples applied in experimental research with marked dimensions before upsetting (a) and after upsetting (b)

Next, they were upset between flat steel plates on forging press to the height H_k lower than half of the initial height H_0. After upsetting, the height and external and internal diameters of samples (Fig. 1b) were measured. Due to samples shape after upsetting, often far from axi-symmetrical, measurements were made at various planes and results were averaged.

Tests were made without lubricants and with application of 4 different lubricants: Aquagraphite CP, Lubrodal F318, lubricant on the basis of molybdenum disulfide and tallow with graphite [7, 8].

Aquagraphite CP is a lubricant used in die forging in hot conditions of forgings from steel. It is present in the form of hydro-suspension diluted in relation 1:5÷1:20 depending on forging process conditions. It contains graphite and stabilizing additives as well as wetting additives.

Lubrodal F318 is lubrication emulsion present in the form of concentrate, which is used for lubricating of die forging in the process of forming in hot conditions. It has good lubricating and cooling properties and it does not leave any residues on the forgings surface.

Flexible lubricant with molybdenum disulfide Molykote Longterm 2 Plus is waterproof lubricating medium on the basis of mineral oil. This semi-liquid lubricant is used in machining processes in hot conditions and on very loaded bearings, keys, connectors and elements of drive transmission in heavy vehicles. It guarantees good lubricating properties within the scope of temperatures from 25°C to 1300°C.

Constant lubricant "tallow with graphite" is obtained from animal fat and graphite. It is used for lubricating of open chain transmission and die forgings.

All of the discussed above lubricants are used also in industrial conditions for hot forging of non-ferrous metals alloys.

3. Analysis of results

In order to determine values of friction coefficients and factors, simulations were made of the upsetting tests by means of software DEFORM 3D, based on finite element method. Heat exchange between the forging and dies, heat generating due to friction presence and changes of mechanical energy into thermal one were considered in the analysis. Applying available in the software friction models (Coulomb and constant friction models), values of friction coefficient μ and friction factor m were changed in such a way that it was possible to obtain the best convergence between theoretical and experimental dimensions of ring-shaped samples [9, 10]. Material model for magnesium alloy Mg4AlZn was worked out on the basis of own research [11], however, models of titanium alloy Ti6Al4V and aluminum alloy 6101A were taken from the software library. Optimal values of friction coefficient or factor were determined minimizing function describing relative difference between theoretical and experimental dimensions of samples after upsetting, presented as:

$$\Phi_d = \left|\frac{D_d - D_t}{D_d}\right| + \left|\frac{d_d - d_t}{d_t}\right| \tag{1}$$

where: D_d – mean external diameter of sample obtained in experiment,

D_t – mean external diameter of sample obtained in simulation,

d_d – mean internal diameter of sample obtained in experiment,

d_t – mean internal diameter of sample obtained in simulation.

Determined values of friction coefficients and factors for the smallest value of function Φ_d is shown in Table 4.

TABLE 4

Optimal values of friction coefficients and factors for alloys: magnesium Mg4AlZn, titanium Ti6Al4V, aluminum 6101A

Alloy	Temperature [°C]	Friction conditions									
		Without lubricant		Mo_2S		Tallow with graphite		Aquagraphite		Lubrodal	
		μ	m	μ	m	μ	m	μ	m	μ	m
Mg4AlZn	250	0,48	0,95	–	–	–	–	–	–	–	–
	350	0,5	1	0,06	0,1	0,11	0,25	0,12	0,25	–	–
	450	0,48	1	0,13	0,24	0,08	0,17	0,17	0,38	–	–
6101A	350	0,3	0,72	0,08	0,15	0,08	0,16	0,18	0,39	0,26	0,61
	400	0,28	0,65	0,08	0,15	0,08	0,15	0,16	0,35	0,24	0,54
	450	0,28	0,72	0,07	0,15	0,08	0,15	0,26	0,59	0,16	0,35
Ti6Al4V	850	0,35	0,72	0,19	0,41	0,28	0,67	0,38	0,85	0,31	0,73
	900	0,5	1	0,24	0,55	0,4	0,87	0,35	0,83	0,32	0,75
	950	0,5	1	0,25	0,59	0,5	1	0,5	1	0,36	0,82

Dependencies of friction factors and coefficients vs. temperature of samples heating for the three analyzed non-ferrous metals alloys are presented in Figures 2÷4.

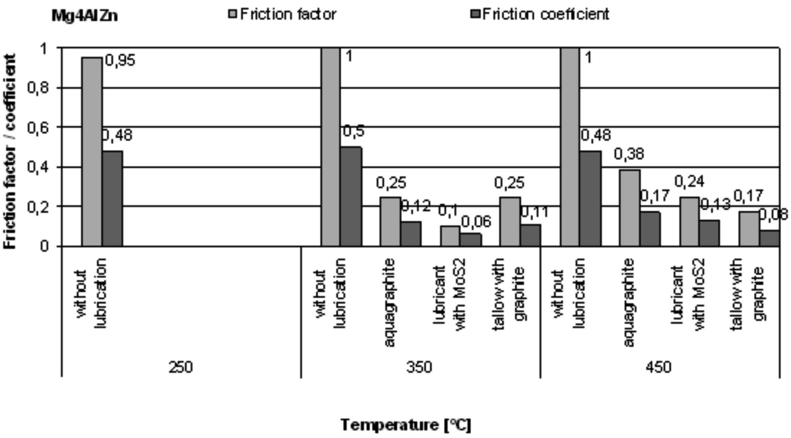

Fig. 2. Dependency of friction coefficient μ and factor m vs. temperature of heating at the application of various lubricants for magnesium alloy Mg4AlZn

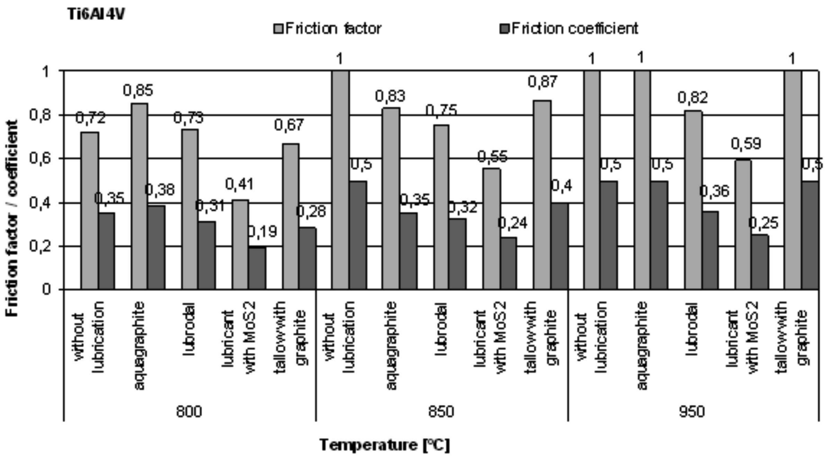

Fig. 3. Dependency of friction coefficient μ and factor m vs. temperature of heating at the application of various lubricants for titanium alloy Ti6Al4V

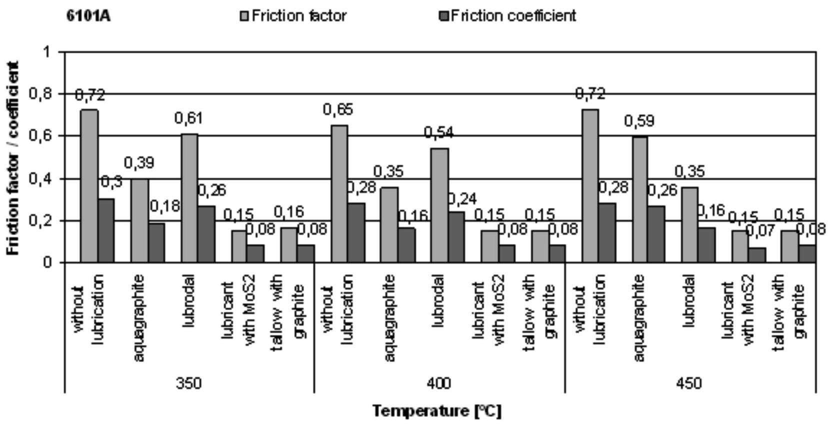

Fig. 4. Dependency of friction coefficient μ and factor m vs. temperature of heating at the application of various lubricants for aluminium alloy 6101A

On the basis of results obtained for alloy Mg4AlZn (Fig. 2), it was stated that at deformation without lubrication the limiting friction (m=1 and μ=0.5) or friction close to limiting appeared. After lubricants application, a considerable improvement of friction conditions was observed. The lubricants on the basis of molybdenum disulfide and tallow with graphite show the best effectiveness. It should be noticed that at T=250°C in the case of lubrication all samples cracked, hence, for these cases friction coefficient μ and factor m were not determined. The cracks appearance results from small plasticity of alloy at this temperature. Samples upset in condition of dry friction (without lubrication) in the same temperature conditions did not crack. In this case, large friction counteracts axial flow of material outside and samples diameter does not enlarge to such a dimension as it is in cases with lubrication. This results in relatively smaller circumferential tensile stresses at the forging external edge, and the danger of cracking is lower.

In the case of deformation of titanium alloy Ti6Al4V in conditions without lubrication, limiting friction was observed at temperatures 900°C and 950°C (Fig. 3). From analyzed lubricants the best lubricating properties guaranteed the lubricant based on molybdenum disulfide, which reduced the friction factor to the value m=0.41÷0.59, and friction coefficient to the value μ=0.19÷0.25. It should be noticed that in comparison with alloy Mg4AlZn, the applied lubricants showed much worse effectiveness. Relatively large temperature of forming of titanium alloy in hot conditions (850°C÷950°C) caused lowering of lubricating properties of analyzed substances.

In comparison with previous alloys, at deformation of aluminum alloy 6101A without lubrication there is no limiting friction presence (Fig. 4). Friction factor reaches values m=0.65÷0.72, however, friction coefficient μ=0.28÷0.30. From analyzed lubricants the best effectiveness was observed for molybdenum disulfide and tallow with graphite. In each of the analyzed temperatures these lubricants guaranteed the lowest friction, yet, their effectiveness expressed by values of friction coefficients and factors was almost identical.

4. Conclusions

On the basis of the obtained results the following conclusions were made:

- The lubricant on the basis of molybdenum disulfide is the most effective lubricant for forming in hot conditions for the three analyzed alloys: Mg4AlZn, Ti6Al4V and 6101A. Tallow with graphite guarantees also good lubricating for magnesium and aluminum alloys. However, in the case of titanium this lubricant loses its effectiveness due to too high temperatures.
- In the case of deformation of alloys Mg4AlZn and Ti6Al4V without lubrication, between deformed material and tool, limiting friction or friction close to limiting appears within the whole scope of analyzed temperatures. In the case of aluminum alloy 6101A deformed in hot conditions without lubrication lower friction is present, and values of friction factors and coefficients are m=0.65÷0.72 and μ=0.28÷0.30 respectively.
- Research results of alloy Mg4AlZn confirmed that at temperature 250°C this alloy is characterized by small plasticity. Cracks appeared in deformed samples at this temperature, with application of lubrication by means of all analyzed substances.
- Obtained results of research works, determining values of friction coefficients μ and factors m within the scope of temperatures of forming in hot conditions of analyzed alloys, allow for simulations with application of mixed friction model (Coulomb and constant friction) depended on temperature, which is implemented in software DEFORM-3D. It is expected that this model usage will allow for increase of calculation precision.

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