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EFFECT OF TEMPERATURE AND STRAIN RATE ON FRICTION FACTOR DURING HOT DEFORMATION OF Al-Mg AND Al-Cu-Mg Al-ALLOYS

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Abstract

The paper is linked to the investigation of the effect of temperature as well as strain rate on friction properties of lubricants for hot-die forging. Friction factor was chosen as one of the criteria for the estimation of the mentioned effects. The research on friction has been done for Al-Mg and Al-Cu-Mg aluminium alloys at elevated temperatures. The lubricants' behaviour was investigated within the temperature range of 200-470^{o}C. Physical and numerical investigations of friction were performed. The conditions of experimental investigation corresponded to the forging processes of Al-alloys under study with the help of the hydraulic press and screw press as well. The ring upsetting technique in combination with FE-simulation was chosen for the numerical investigation of the effect of temperature and strain rate on friction factor value. The regressions for the relationship between friction factor and temperature as well as strain rate for the lubricants under study have been obtained. Some practical recommendations were given.

Key words: Al-Mg alloy, Al-Cu-Mg alloy, ring test, FEM, friction model, friction factor, lubricant

1. INTRODUCTION

Hot-die forging of the aluminium alloys can be performed with the help of several types of metal-forming machines, namely hydraulic press, mechanical press, screw press etc. Applying one of these machines allows production of the forgings of different shape including the near-net shape forgings. The lubricant's composition can be one of the technological parameters which have a strong influence the quality of a forging made of an Al-alloy. The choice of a lubricant for forging is the major task, especially in case of deformation of aluminium alloys. The efficiency of the lubricant can be estimated by at least three criteria: 1) the lubricant should have good tribological properties; 2) the lubricant should have good heat-shielding properties; 3) the lubricant should produce little or no smoke.

Each of the mentioned criteria equally contributes to the quality and perfection of the lubricant for metal forming. The research on the tribological properties is the most sophisticated problem in comparison with the other two criteria.

The tribological properties of the lubricant for hot-die forging can be determined with the help of one of the known experimental techniques: ring-compression test, forward rod–backward cup extrusion test, double-cup extrusion test, the conic dies test, etc. [1]. The aim of these methods is to determine the proportionality coefficient in a friction

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model, which can be used for estimation of the interfacial friction during forging. It is known three basic friction laws, namely Coulomb's law, constant friction law [6] and the general friction model [7]. Among the common techniques, the ring-compression test is the most simple, reliable and widely used method for the quantitative estimation of the interfacial friction during bulk metal formation. It was pioneered by Kunogi [2] and Male & Cocroft [4].

To sum up, the aim of the present paper is the research on the effect of temperature of the Al-alloys under study, i.e. Al-Mg and Al-Cu-Mg alloys, as well as the strain rate on the value of friction factor.

2. EXPERIMENTAL PROCEDURE

Two lubricants with different chemical composition were used for physical investigation of friction with the help of ring-compression test. Both lubricants contain colloidal graphite particles but the first lubricant is based on industrial oil while the second one is based on synthetic oil. The heat-shielding properties of the lubricants were investigated and the results were published in 2007 [5].

The behaviour of the lubricants was estimated in case of hot deformation of AMg6 and D16T aluminium alloys. These alloys correspond approximately to A95456 and AA2024 alloys correspondingly. The chemical composition of the alloys is given in table 1. The bold type in table 1 indicates the amount of the major alloying elements, which the investigated alloys contain. The major alloying elements for AA2024 alloy are copper and magnesium; for A95456 alloy the major alloying element is magnesium.

Table 1. *Chemical composition of alloys under study.*

Al-alloy	Percentage, %								
	Al	**Cu**	Si	Mn	**Mg**	Ti	Zn	Fe	Cr
A95456	base	0.04	0.16	0.63	6.80	0.1	0.2	0.22	-
AA2024	base	3.98	0.27	0.50	1.39	0.05	0.02	0.26	0.003

To investigate physically the effect of friction, the ring specimens were cut from the bars of aluminium alloys under study. The sizes of the ring samples were as follows: inner diameter = 20 mm; outer diameter = 40 mm; height = 14 mm. The ring samples were heated to temperatures of 200°C, 350°C, 430°C, 450°C, and 470°C in the electric furnace. Two regimes of forging were modeling. The first one is the isothermal hot forging with the help of a hydraulic press. The second regime is the hot-die forging with the help of a screw press and a hydraulic press as well. In case of the isothermal forging, deformation of the heated samples was carried out on flat dies that were warmed up with induction installation while for hot-die forging the flat dies were warmed up to the temperature of 120°C. Samples were compressed with lubrication mentioned above.

For the hydraulic press with maximum load of 2.5MN, die velocity was constant at $V \approx 2$ mm/s. But for the screw press with nominal load of 10 MN and maximum load of 16 MN, die velocity was also constant and equal to 400 mm/s. These values of die velocity correspond to the initial strain rate of 0.14 s^{-1} and 28.6 s^{-1}, accordingly. Moreover, the values of strain rate belong to the strain rate interval (10^0-10^2 s^{-1}) within that the hot-die forging is usually carried out.

The values of height h^{exp} and inner diameter d^{exp} were determined after compression of the ring samples. The inner diameter was measured in three locations along the height of the rings. Finally, the value of the inner diameter was determined as $d^{exp}=(d_{top}+d_{mid}+d_{bot})/3$, where d_{top}, d_{mid} and d_{bot} = inner diameter at the top, middle and bottom along the height of the ring, accordingly.

3. NUMERICAL SIMULATION

To determine the true value of the friction factor, the several trials of finite-element (FE) simulation of material flow during the ring specimen compression were carried out. To identify the true value of the friction factor k_n, the following criterion was used

$$\delta = d^{exp} - d^{fem} \leq 0.05\,, \qquad (1)$$

where d^{exp} and d^{fem} = the inner (or outer) diameter of the ring sample obtained experimentally and by FEM, respectively.

The variable parameter in the simulation was the friction factor. The simulation was carried out for the same forging temperatures as in the experiment within the range of 200–470°C. QForm-2D (QuantorForm Ltd., Russia) commercial code was used for FE simulation. Here, we assumed that the contact friction was constant at the defined temperature of deformation. Levanov's friction model [3] was implemented by the QFORM simulation software. Levanov's friction model can be considered as a combination of Coulomb's friction law and constant friction law. It gives almost the same results as Coulomb's friction law for low value of contact pressure σ_n. In case of high contact pressure, Levanov's friction model and constant friction law allow us to obtain approximately the same values of friction shear stress. The numerical simulation takes into consideration two regimes of ring samples' compression as it was mentioned above.

The results of FE simulation allowed us to obtain the necessary data for the construction of the relationship between the friction factor value and the temperature of deformation as well as the strain rate value. The general form of the temperature dependence of the friction factor is:

$$k_n = A_o + A_1 \times T_o + A_2 \times T_o^2 , \qquad (2)$$

where A_o, A_1 and A_2 = coefficients, and T_o = the temperature of the deformable material.

Table 2. *Coefficients of the equation (2) (isothermal forging).*

Coefficients	Type of aluminium alloy	
	A95456	AA2024
Lubricant type – SO+G		
A_0	0.155	0.26
A_1, 1/°C	0.00088	0.00021
A_2, 1/(°C)^2	-2.05×10^{-6}	-8.2×10^{-7}
Lubricant type – IO+G		
A_0	0.16	0.375
A_1, 1/°C	0.00037	-0.00065
A_2, 1/(°C)^2	-1.01×10^{-6}	4.0×10^{-7}

Table 2 contains the values of coefficients in equation (2) and these coefficients are valid in case of the isothermal forging of A95456 and AA2024 alloys within the temperature range of 200-470°C and at constant strain rate of 0.14 s^{-1}.

The influence of temperature on friction factor in case of isothermal hot forging with hydraulic press is shown in figure 1.

In case of the hot-die forging with the help of the screw press and the hydraulic press, the values of the coefficients in equation (2) were also calculated. Their values are given in table 3.

Figure 2 illustrates the effect of temperature of deformable alloys on the friction factor value for the second regime of forging, i.e. for hot-die forging. To estimate the coupling effect of temperature T and strain rate $\dot{\varepsilon}$ on friction factor the data shown in figure 2 have to be rearranged. Table 4 contains the data which illustrate the combined influence of strain rate and temperature of forging on friction factor value.

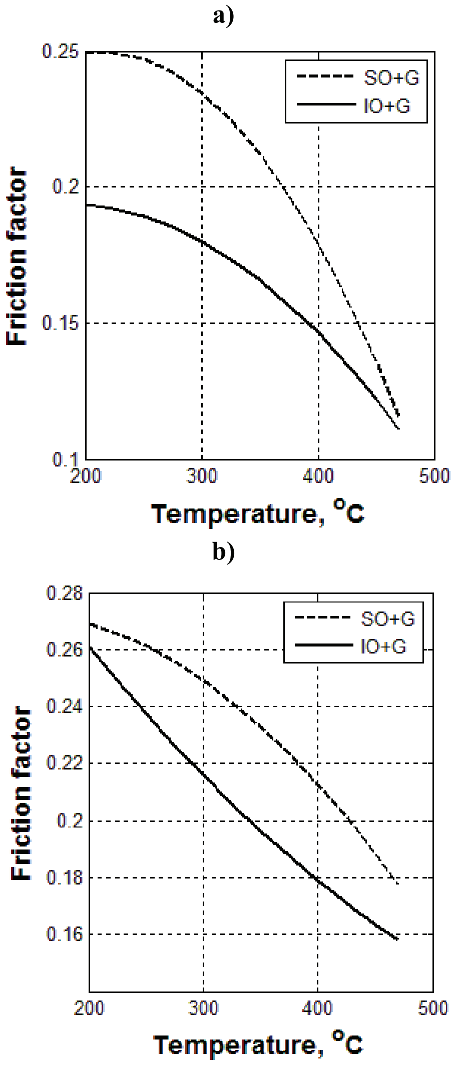

Fig. 1. *Friction factor versus temperature (isothermal forging): a – A95456 alloy; b – AA2024 alloy.*

Table 3. *Coefficients of the equation (2) (massive hot forging).*

Coefficients	Type of aluminium alloy			
	A95456		AA2024	
	Screw press (28.6 s^{-1})	HydPress, closedieforging (0.14 s^{-1})	Screw press (28.6 s^{-1})	HydPress, closedie-forging (0.14 s^{-1})
Lubricant type – SO+G				
A_0	0.32	-0.1224	0.1004	0.05984
A_1, 1/°C	0.00113	0.001454	0.0008661	0.00128
A_2, 1/(°C)^2	-2.53×10^{-6}	-1.552×10^{-6}	-8.297×10^{-7}	-2.065×10^{-6}
Lubricant type – IO+G				
A_0	0.387	0.2522	-0.05654	0.3798
A_1, 1/°C	0.00037	-5.247×10^{-4}	0.001789	-0.000858
A_2, 1/(°C)^2	-1.65×10^{-6}	3.81×10^{-7}	-2.857×10^{-6}	5.681×10^{-7}

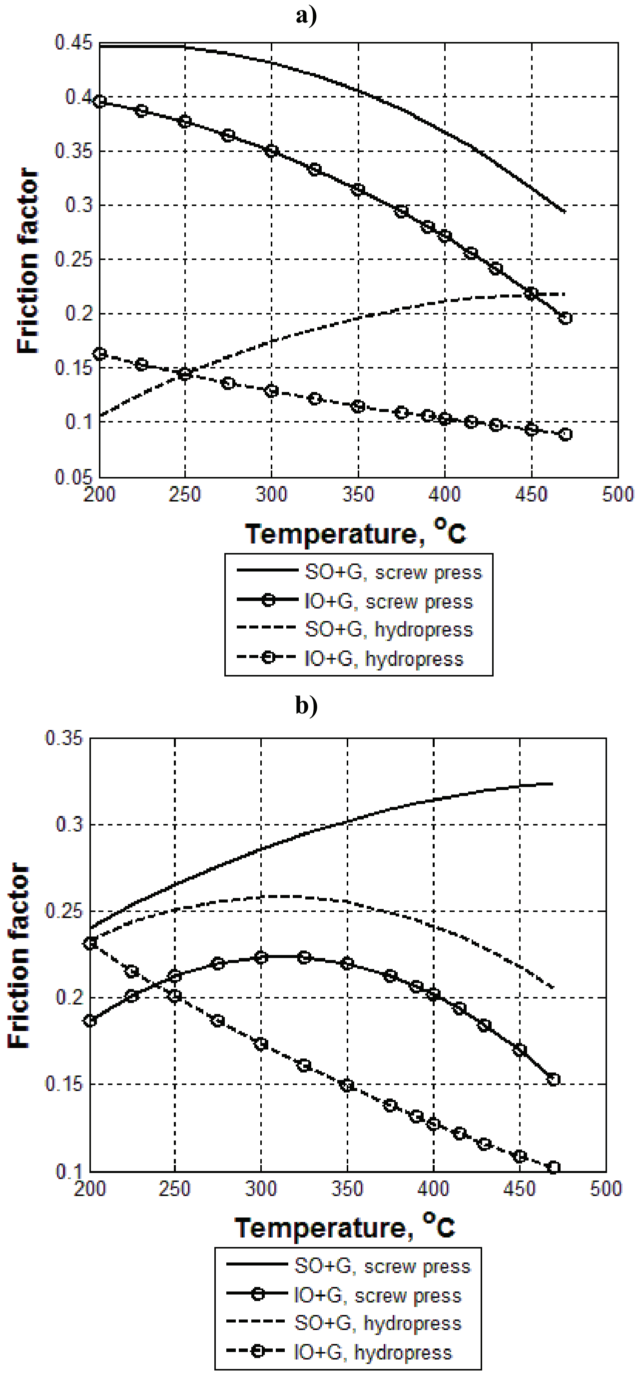

Fig. 2. Friction factor versus temperature (hot-die forging): a – A95456 alloy; b – AA2024 alloy.

Combining $\dot{\varepsilon}$ and T, the effect of these parameters on friction factor value can be described by the following equation:

$$k_n = B_0 + B_1 \times T + B_2 \times \dot{\varepsilon} + B_3 \times \dot{\varepsilon} \times T\,, \quad (3)$$

where B_o, B_1, B_2, B_3 = coefficients, $\dot{\varepsilon}$ = strain rate, T = temperature.

The coefficients of the equation (3) are presented in table 5. Figure 3 shows the relations $k_n = f(\dot{\varepsilon}, T)$ for both Al-alloys under study.

Table 4. *Friction factor versus strain rate and temperature (hot-die forging).*

Strain rate, s^{-1}	Friction factor						
	200	300	350	390	430	450	470
A95456 alloy: Lubricant type – SO+G							
0.14	0.1063	0.1741	0.1964	0.2086	0.2159	0.2176	0.2181
28.6	0.4481	0.4343	0.4084	0.3786	0.3407	0.3187	0.2947
A95456 alloy: Lubricant type – IO+G							
0.14	0.1625	0.1291	0.1152	0.1055	0.097	0.0932	0.0898
28.6	0.4095	0.3273	0.2899	0.2618	0.2352	0.2225	0.2101
AA2024 alloy: Lubricant type – SO+G							
0.14	0,2332	0,258	0,2549	0,245	0,2284	0,2177	0,2053
28.6	0,2404	0,2856	0,3019	0,312	0,3194	0,3221	0,3242
AA2024 alloy: Lubricant type – IO+G							
0.14	0,2309	0,1735	0,1491	0,1316	0,1159	0,1087	0,1020
28.6	0,187	0,2230	0,2196	0,2066	0,1845	0,17	0,1532

Table 5. *Coefficients of the equation (3)*

Coefficients	Type of aluminium alloy			
	A95456		AA2024	
	Lubricant type – SO+G	Lubricant type – IO+G	Lubricant type – SO+G	Lubricant type – IO+G
B_0	0.0330	0.2049	0.2702	0.3086
B_1, 1/°C	4.2386×10^{-4}	-2.5113×10^{-4}	-9.8003×10^{-5}	-4.4658×10^{-4}
B_2, s	0.0195	0.0121	-0.0029	-0.0023
B_3, s/°C	-3.5122×10^{-5}	-1.6988×10^{-5}	1.4169×10^{-5}	1.0633×10^{-5}

4. CONCLUSIONS

This paper presents a new approach to the modelling of interfacial friction in forming processes of Al-Mg and Al-Cu-Mg alloys by introducing the relations $k_n=f(T)$ and $k_n=f(T, \dot{\varepsilon})$. It should be taken into consideration that the obtained relations are valid in the temperature range of 200-470 °C. This now enables a new type of model to be incorporated into simulation software to give a more realistic interpretation of friction effect in terms of temperature and strain rate.

Moreover, the lubricant based on industrial oil provides better tribological properties in comparison with the synthetic oil based lubricant. Independently of the type of forging process, i.e. closed die forging with screw press or hydraulic press with or without flash, the industrial oil based lubricant guarantees good quality of the forgings.

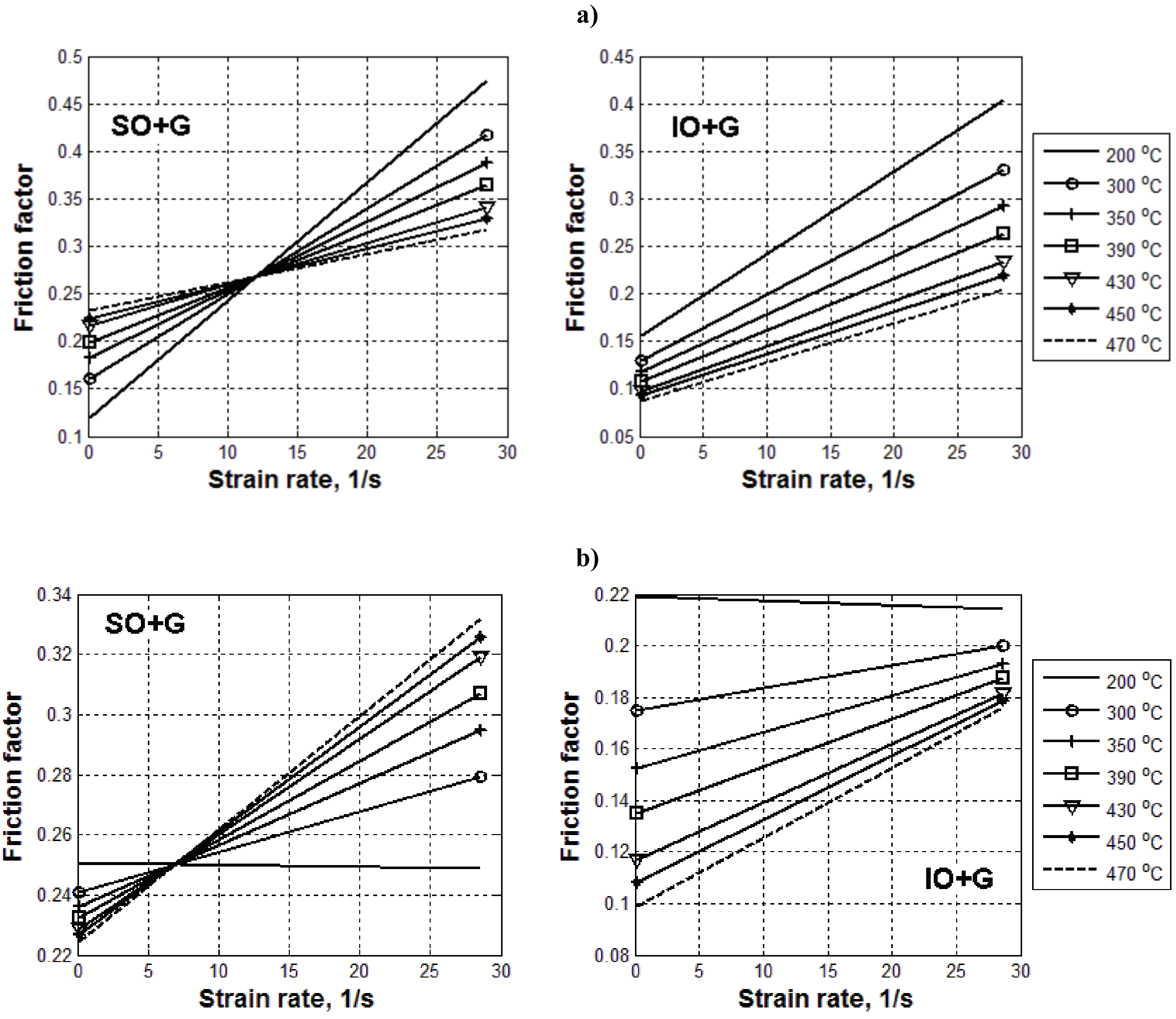

***Fig. 3.** Friction factor versus strain rate and temperature: a – A95456 alloy; b – AA2024 alloy.*

The further development of the proposed model (see equation (3)) can be linked to the verification of the equation for Al-Mn and Al-Cu-Mg-Fe-Ni aluminum alloys which are commonly used for production of parts by hot-die forging. On the other hand, the equation (3) includes only the technological parameter (T) and the parameter which characterises the deformable material state, i.e. strain rate $\dot{\varepsilon}$. In this way one more parameter which characterizes the quality of the tool interfacial surface, namely the roughness of contact surface, can be implemented into the proposed model. It will result in the establishing of the relation $k_n=f(T, \dot{\varepsilon}, R_a)$.

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WPŁYW TEMPERATURY I PRĘDKOŚCI ODKSZTAŁCENIA NA CZYNNIK TARCIA PODCZAS ODKSZTAŁCANIA NA GORĄCO STOPÓW ALUMINIUM Al-Mg I Al-Cu-Mg

Streszczenie

Tematem artykułu są badania wpływu temperatury oraz prędkości odkształcenia na własności smarów w procesie kucia matrycowego na gorąco. Współczynnik tarcia został wybrany jako jedno z kryteriów estymacji analizowanego efektu. Badania tarcia wykonano dla stopów aluminium Al-Mg oraz Al-Cu-Mg w podwyższonej temperaturze. Zachowanie się smarów analizowano w zakresie temperatur 200-470^{o}C. Przeprowadzono fizyczne oraz numeryczne symulacje. Badania doświadczalne wykonane zostały dla procesu kucia stopów aluminium na prasach hydraulicznej i śrubowej. Natomiast do analizy numerycznej wpływu temperatury i prędkości odkształcenia na współczynnik tarcia wybrano proces spęczania pierścieni symulowany przy użyciu metody elementów skończonych. Ostatecznie otrzymano zależności regresyjne pomiędzy analizowanymi parametrami, które zostały przedstawione w artykule wraz z pewnymi praktycznymi wskazówkami.

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