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GENERALIZED APPROACH TO THE CHOICE OF LUBRICANT FOR HOT ISOTHERMAL FORGING OF ALUMINIUM ALLOYS

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Abstract

The present paper is a generalization of the results which were obtained for the last four years (Petrov et al., 2003, 2004, 2005, 2006). It implies the investigations of interfacial friction in hot isothermal deformation of such non-ferrous material as Al-Mn (AA3003), Al-Mg (A95456), Al-Cu-Mg (AA2024) and Al-Cu-Mg-Fe-Ni (A92618) aluminium alloys. Two completely different types of lubricant were used for the research on. Wide range of temperatures was observed. Moreover, the hydraulic press was used for the deformation of the samples of aluminium alloys under study. The tribological properties of lubricants were determined with the help of ring upsetting technique. The sets of calibration curves were drawn. Each set of calibration curves corresponds to the definite type of aluminium alloy as well as definite conditions of deformation. Some practical recommendations were given.

Key words: aluminum alloy, Al-Mn alloy, Al-Mg alloy, Al-Cu-Mg alloy, Al-Cu-Mg-Fe-Ni alloy, calibration curve, finite-element method, friction factor, isothermal deformation, numerical simulation, oil-based lubricant, water-base lubricant, thermal stability of lubricant

1. INTRODUCTION

Isothermal forging is a technological process of hot bulk forging which is related to definite temperatures of dies and workpiece heating. Usually, isothermal forging is performed with the help of low-velocity forging equipment like hydraulic presses. So that the maximum value of die velocity is not more than 5 mm/s. To avoid die chilling the dies are heated up to approximately the same temperature as the workpiece. In this range, conventional die materials for hot bulk forging cannot undergo the significant loss of strength or hardness. So, special tool materials should be applied for dies production.

It is known two types of hot isothermal massive forging. These are low-temperature and high-temperature isothermal forging. Low-temperature forging technique is usually applied for forming of non-ferrous material when a temperature of deformation is less than 500-550°C. In the second case, the isothermal forging is useful for deformation of such material as copper-based alloys and titanium alloys.

The development of any technological process of bulk forging and namely isothermal one requires the solution of the following tasks: 1) choose the forging method or forming process (forging with/without flash); 2) design a forging part in accordance with a machined part; 3) determine the necessary amount of forging operations; 4) determine the size and shape of workpiece; 5) design forging dies; 6) choose the suitable press-forging equipment and lubrication; 7) try out experimentally the developed technology and if necessary make some modifications.

In most cases, the application of forging in isothermal conditions means the production of a near net shape forging. Design of near net shape forging part according to a machined one can be carried out with the help of some recommendations which are

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based on practical experience of forging. One of the technological parameters which has a strong influence the quality of a near net shape forging is the type of the lubricant.

The choice of a lubricant for isothermal forging is a major task, especially in case of aluminium alloys deformation. The isothermal forging of Al-alloys belongs to the forging processes in which the slight increase in contact friction affects on the material flow as well as the quality of the forgings and gives rise to increase in deformation load. The efficiency of any lubricant can be estimated by at least three criteria: 1) the lubricant should have good tribological properties and ensure the forging part quality as well as the required production rate; 2) the lubricant should have good heat-shielding properties; 3) the lubricant should be environmentally safe and produce little or no smoke. So that, some set of laboratory tests should be carried out.

The tribological properties of a lubricant for metal forming can be determined with the help of one of the known experimental techniques (Grudev et al., 1982). The aim of these methods is to determine the proportionality coefficient in a friction model, which can be used for estimation of the interfacial friction during forming. It is known three basic friction laws, namely Coulomb's law, constant friction law (Siebel, 1930) and the general friction model (Wanheim, 1973). Among the common techniques, the ring-compression test is the most simple and widely used method for the quantitative estimation of the interfacial friction during bulk metal formation which was developed by Kunogi (1954) and Male & Cocroft (1964-65).

The heat-shielding properties or thermal stability influence both the efficiency of the lubrication and the formation of the insulating lubricant layer at the deformed material interface. The thermal-stability index relates to the mass loss of the lubricant sample heated to the investigated temperature and can be research on with the help of special equipment, namely derivatograph.

The environmentally safeness of a lubricant can be detected by means of tests which should be carried out in industry. In this case, the level of airborne contaminants and smoke are detected when the defined part is forged at elevated temperature.

Each of the mentioned criteria equally contributes to the quality and perfection of the lubricant for metal forming. But the laboriousness of their investigation is completely different. In spite of the choice of simplest technique of friction estimation, the research on the tribological properties is the most sophisticated task in comparison to the other two criteria.

To sum up, the aim of the present paper is linked to the investigation of interfacial friction in terms of friction factor values and farther generalization of the obtained data which can be applied in industry in order to optimize the new or/and being technological processes of metal forming.

2. EXPERIMENTAL PROCEDURE

Two lubricants were chosen for the investigation. In particular, one of the lubricants under study is based on industrial oil (IO+G) while the other is based on synthetic oil (SO+G). Both lubricants contain colloidal graphite particles as lubricant's components. In both cases, the size of colloidal graphite particles was less than 15 μm. The behaviour of the lubricants was estimated in case of hot isothermal deformation of several aluminium alloys which have different chemical composition. The chemical composition of alloys under study is given in Table 1. The bold type in Table 1 indicates the amount of the basic impurities, which the investigated alloys contain.

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

Element	Percentage, %			
	AA3003	A95456	AA2024	A92618
Al	**base**	**base**	**base**	**base**
Cu	0.05	0.04	**3.98**	**2.12**
Si	0.24	0.16	0.27	0.20
Mn	**1.12**	0.63	0.50	0.03
Mg	-	**6.80**	**1.39**	**1.56**
Ti	-	0.1	0.05	0.05
Zn	0.007	0.2	0.02	0.06
Fe	0.24	0.22	0.26	**1.0**
Ni	-	-	-	**0.80**
Cr	-	-	0.003	-

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, 300°C, 350°C, 390°C, 430°C, and 450°C in the electric furnace. Deformation of the heated samples was carried out on flat dies that were warmed up with induction installation. Samples were compressed with lubrication. Die velocity was constant at $V \approx 2$ mm/s (hydraulic press = 2.5 MN), which corresponded to an initial strain rate of 0.14 s^{-1}. This strain rate value belongs to the strain rate interval (10^{-4}-10^{-1} s^{-1}) within that the isothermal 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 ring deformation 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 experiment within the range of 200–450°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 within the investigated range and the deformation condition was isothermal, as observed in the experiments. This meant that the tools and the sample were at an equal temperature during the initial stage of deformation. Owing to the heat effect of plastic deformation, the sample temperature had increased by the end of deformation, whilst the temperature of the tools remained the same.

The results of FE simulation allowed us to obtain the necessary data for the temperature dependence of the friction factor construction. The general form of this dependence is given below:

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

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

The values of the coefficients in equation (2) for the investigated alloys are calculated with the help of least-squares method and given in Table 2.

***Table 2.** Coefficients of temperature dependence for factor k_n.*

Coefficients	Type of aluminium alloy				
	A95456	A92618		AA3003	AA2024
		$200 \leq T_o \leq 390$	$390 < T_o \leq 470$		
Lubricant type – SO+G					
A_0	0.155	-0.157	2,427	0.20	0.25
A_1, 1/°C	8.80×10^{-4}	2.58×10^{-3}	-9.59×10^{-3}	1.81×10^{-4}	7.30×10^{-4}
A_2, 1/(°C)^2	-2.05×10^{-6}	-4.21×10^{-6}	10.0×10^{-6}	-4.95×10^{-7}	-2.10×10^{-6}
Lubricant type – IO+G					
A_0	0.16	0.196		0.20	0.38
A_1, 1/°C	3.70×10^{-4}	6.10×10^{-4}		4.77×10^{-4}	-6.70×10^{-4}
A_2, 1/(°C)^2	-1.01×10^{-6}	-1.6×10^{-6}		-10.90×10^{-7}	4.10×10^{-7}

***Table 3.** Values of friction factor k_n*

Temperature, °C	Type of aluminium alloy				
	A95456	A92618		AA3003	AA2024
		$200 \leq T_o \leq 390$	$390 < T_o \leq 470$		
Lubricant type – SO+G					
200	0.249	0.191		0.216	0.312
300	0.235	0.238		0.21	0.28
390	0.186	0.209		0.195	0.215
430	0.154		0.152	0.186	0.176
450	0.136		0.137	0.181	0.153
470	0.116		0.129	0.176	0.129
Lubricant type – IO+G					
200	0.194	0.254		0.252	0.262
300	0.180	0.235		0.245	0.216
390	0.151	0.191		0.220	0.181
430	0.132	0.162		0.204	0.168
450	0.122	0.147		0.194	0.162
470	0.111	0.129		0.183	0.156

To determine the unknown coefficients in equation (2) the true value of friction factor k_n can be calculated. Those values are presented in Table 3. Using the calculated values of friction factor for different compositions as well as temperatures, the effect of the basic impurities on the frictional properties of the investigated lubricants is shown as a 3D surface in figure 1.

The numerical simulation also allowed us to construct calibration curves which are the keypoint of the determination of friction factor on the basis of ring-compression test. Figure 2 illustrates some charts of calibration curves. These charts were constructed for alloy AA2024 and A95456 correspondingly and are valid in case of those alloys isothermal forming at the temperature of 450°C.

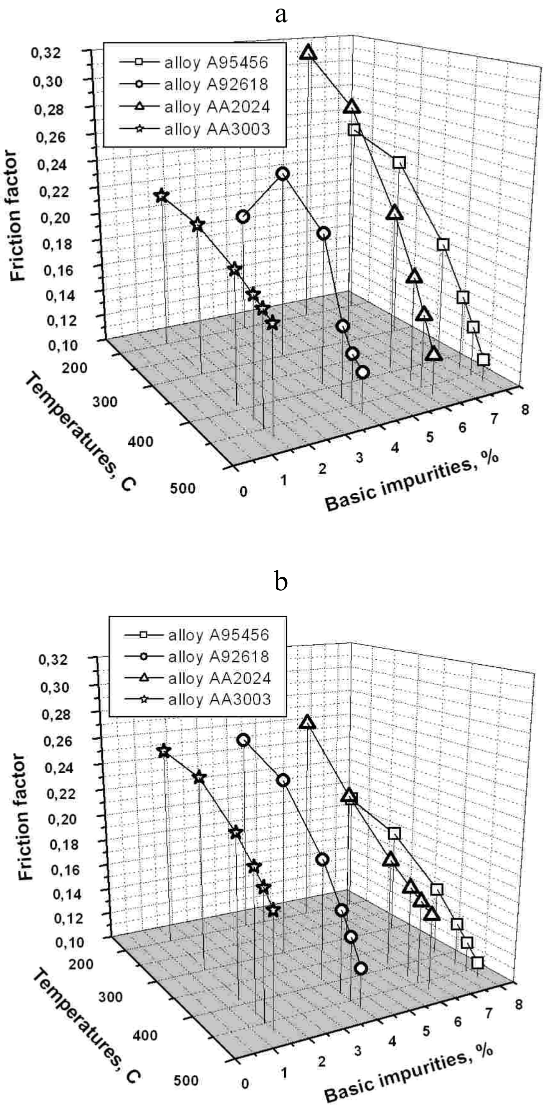

Fig. 1. Friction factor response surface as a function of basic impurities and forging temperature: a – for lubricant SO+G; b – for lubricant IO+G.

Figure 2 also represents the experimental data (circle points) which were obtained with the lubricant IO+G at a temperature of T_o = 450°C. The results of the FEM were similar to the experimental results only at the final point of the curve, which corresponded to a friction factor value of 0.158 (see figure 2a). In turn, the final point corresponded to a reduction in height of about 50%. A discrepancy between the FEM results and the experimental results was observed at smaller height reduction values (figure 2). These results illustrate that the friction factor was not constant within the height reduction range of 0–50%.

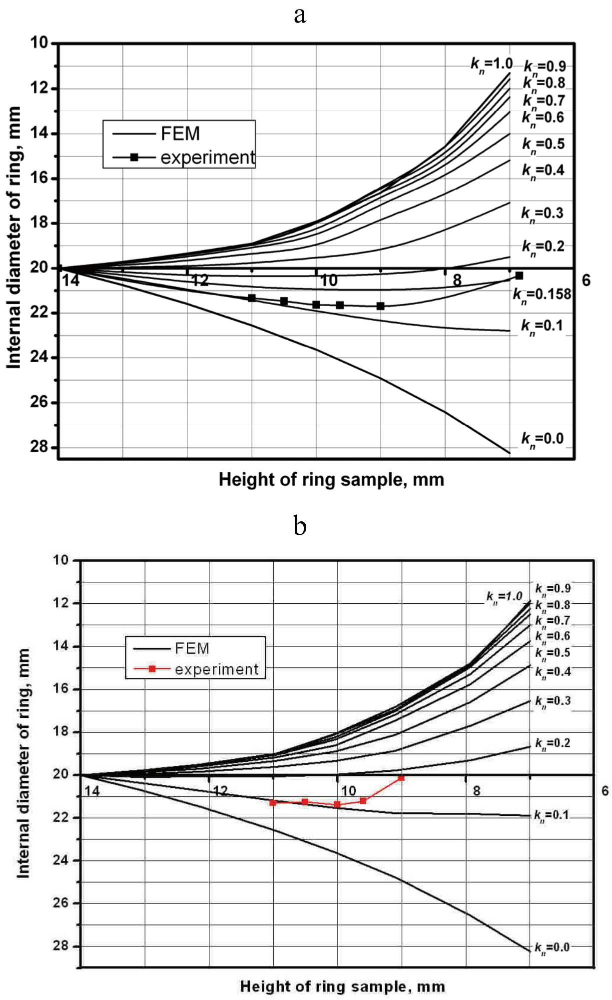

Fig. 2. Calibration curves for temperature T_o = 450°C: a - for alloy AA2024; b - for alloy A95456.

During the earlier stage of ring-sample compression, the friction factor was constant and equal to about 0.1 (see figure 2a). The major change in the friction factor value occurred after a reduction in height of 27.7%. At this height reduction, the friction factor tended to increase up to 0.158, which corresponded to the height of the ring sample at the end of its deformation (see figure 2a). In case of deformation of alloy A95456 at temperature of 450°C, there is the same tendency to friction factor change up to 50% of the height reduction.

From our point of view, this observed discrepancy could be linked to the effect of the weldability of some areas of the contact surface of the ring sample with the corresponding areas of the dies. This effect was observed at the end of the compression to a nominal height reduction of 50%. Furthermore, in order for industrialist to choose an appropriate lubricant for either alloy A95456 or AA2024 hot isothermal forging at temperature 450°C, the obtained curves can be used for estimation of tribological properties of investigated lubricant.

As was mentioned above, to choose the lubricant for hot forging it is not sufficient to define its friction factor. The lubricant should satisfy to two other criteria: good thermal stability and environmentally safeness.

The heat-shielding properties or thermal stability influence both the efficiency of the lubrication and the formation of the insulating lubricant layer at the deformed material interface, within the temperature range of 300–700°C. The thermal-stability index relates to the mass loss of the lubricant sample heated to the investigated temperature. Figure 3 shows the curve of mass loss vs. temperature for both types of lubricant. It can be seen that the lubricant SO+G had better heat-shielding properties than IO+G.

In order to verify the third criterion the set of industrial tests were carried out. Several parts were forged at elevated temperature in isothermal conditions. Both lubricants were used for forging. As a result the lubricant based on synthetic oil produce no smoke, whilst the mineral oil based lubricant produce little one.

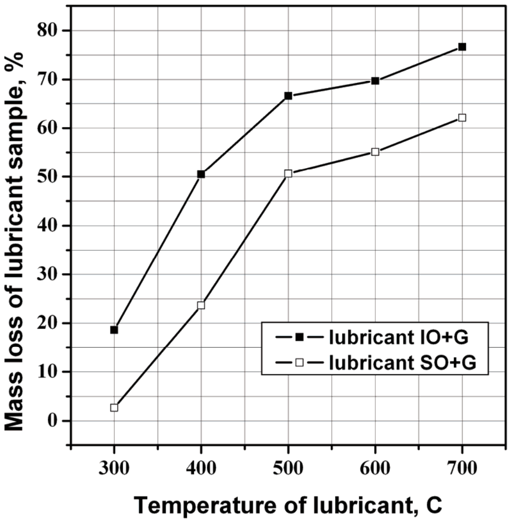

Fig. 3. Mass loss of lubricant sample vs. temperature.

4. CONCLUSION

To take into consideration each of the criteria mentioned above and corresponding results several conclusions should be done:

1) synthetic oil based lubricant has almost the same tribological properties than those for mineral oil based lubricant;
2) synthetic oil based lubricant has better thermal stability and is environmentally safe in comparison with mineral oil based lubricant;
3) despite the advantages of synthetic oil based lubricant, it guarantees good quality of the forgings in case of their production by means of closed die forging with flash technique, whilst the second lubricant is appropriate for closed die forging with/without flash.

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ANALIZA DOBORU ŚRODKA POŚLIZGOWEGO W PROCESIE KUCIA NA GORĄCO STOPÓW ALUMINIUM

Streszczenie

Uogólnienie wyników uzyskanych na przestrzeni czterech ostatnich lat (Petrov et al., 2003, 2004, 2005, 2006) z zakresu badania wpływu tarcia międzyfazowego podczas odkształcenia na gorąco jest tematem niniejszej publikacji. W pracy analizowano materiały nieżelazne na bazie aluminium: Al-Mn (AA3003), Al-Mg (A95456), Al-Cu-Mg (AA2024) i Al-Cu-Mg-Fe-Ni (A92618). Analizę prowadzono dla szerokiego zakresu temperatur i dwóch różnych smarów z wykorzystaniem prasy hydraulicznej. Własności trybologiczne wykorzystanych smarów określono bazując na wynikach spęczania pierścieni. W pracy wykreślno krzywe wzorcowe odpowiadające konkretnym warunkom odkształcenia i danemu stopowi Al. Zamieszczono również uwagi praktyczne.

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