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Identification of a friction model for the bearing channel of hot aluminium extrusion dies by using ball-on-disc tests

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ABSTRACT

A physically-based friction model is developed based on the ball-on-disc test results. The model is verified by using double action extrusion tests. Good agreements between the FE predictions and experiments have been obtained, in terms of the extrudate length and steady-state extrusion load, indicating that ball-on-disc test is an effect way of characterizing the friction for the bearing channel of hot extrusion dies. The nature of friction in the bearing channel can be summarized as a pressure dependant process: formation of isolated adhesive junctions, adhesive junctions growth and coalescence of adhesive junctions.

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1. Introduction

Extrusion is a process in which a cast billet of solid metal is converted into a continuous length of generally uniform cross-section by forcing it to flow through a shaped die opening. Generally, the extrusion process is a hot working operation, in which the metal billet is heated to a proper temperature, at which a relatively high ductility and low flow stress can be achieved. FE simulation of the extrusion processes is widely used in both scientific research and industrial practice. The selection of friction models and the assignment of friction coefficients or factors for the FE simulations of extrusion processes remain an essential issue, because the accuracy of the simulation results is strongly affected by the flow stress of workpiece material (thermo-viscoplastic behavior at elevated temperatures) and the assignment of boundary conditions, e.g., friction boundary conditions. The uncertainty of flow stress is low when the constitutive equations determined from thermo-mechanical testing are implemented. However, unreliable FE simulation results could be obtained if the friction boundary conditions are not assigned appropriately.

In the past years, efforts have been made to study the tribological phenomenon of the extrusion process and some friction testing techniques have been developed, which can be classified as three different categories, namely, field tests; simulative tests (or physical simulation tests) and tribological tests.

In general, field test is to estimate the friction coefficient or factor by using extrusion friction tests. Based on the material flow response to the friction force, some novel extrusion friction tests have been developed, including double backward extrusion [1], combined forward rod-backward can extrusion [2] and combined forward conical/straight can-backward straight can extrusion [3]. These tests were designed with highlighted friction sensitivity indicated by extrudate lengths, and the lubricants can be evaluated and the global friction coefficient or factor on the workpiece/tooling interface can be determined quantitatively with the aid of FE simulations. On the other hand, the friction coefficients/factors over the container wall can be estimated based on the friction effects on the extrusion load [4,5]. Table 1 shows a summary of the friction test results obtained from extrusion friction tests. For the friction at extrudate/bearing interface, extrusion friction test [6–8] was used to characterize the friction in this region. A transition from full sticking to sliding was experimentally observed and the friction stress was therefore determined from the lengths of sticking and sliding zones [6,7,9].

Field tests are normally time consuming, expensive and difficult to control. In most of the field tests, the local contact conditions vary significantly throughout the whole operating cycle. Therefore, there is a need for simplified friction testing techniques, in which more stable contact conditions can be achieved. As such, simulative friction tests have been proposed and conducted. The block on cylinder tests [10,11] were developed to simulate the contact between the workpiece and extrusion die, and the wear mechanisms in the bearing channel region were studied. The results revealed that adhesive wear and abrasive wear were dominant wear patterns of the extrusion dies. In the meanwhile, high values of friction coefficients ($1<\mu<1.5$) were observed and this was attributed to a high degree

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Table 1
Friction test results obtained from extrusion friction tests.

Extrusion test	Work piece material	Tool material	Billet temperature (°C)	Die temperature (°C)	Lub(*s*)	Friction coef./factor
1992 Buschhausen et al. [1]	AISI 1006		25	25	Lub	m=0.08–0.2
1997 Nakamura et al. [2]	6061	High speed steel	–	–	*Ca*-Al	$\mu \approx 0.3$–0.4
					VG26	$\mu \approx 0.5$
					MoS_2	$\mu \approx 0.5$–0.6
1998 Nakamura et al. [3]	6061	High speed steel, cemented carbide	-	–	VG2	μ_d=0.017–0.05
						μ_{LP}=0.37–0.42
					VG26	μ_d=0.005–0.048
						μ_{LP}=0.15–0.19
					VG1000	μ_d=0.001–0.039
						μ_{LP}=0.15–0.28
					MoS_2	μ_d=0.088–0.105
						μ_{LP}=0.07–0.18
2002 Bakhshi-Jooybari [4]	CP Al	H13	25	25	No Lub.	m=0.84
	Steel		900	900	Graphite	–
2003 Flitta et al. [5]	AA2024 Al-Cu ally	–	300–450	250–400	No Lub.	m=0.654–0.92

of aluminium to aluminium contact [11]. Most recently, a novel simulative friction test method highlighting the friction in the bearing channel of the die, double action extrusion (DAE), was developed [12]. In the DAE, an aluminium billet was pressed against two extrusion dies with different bearing lengths and two indirect extrusions took place simultaneously. The lengths of the extrudates were found to be highly friction sensitive, because the friction force for the extrudate to flow through the die with a longer bearing length was greater than that through the die with a shorter bearing length. As such, friction between the extrudate and bearing channel of the extrusion dies can be characterized, with the aid of FE simulation [12] or theoretical analysis [13]. The results obtained from the DAE tests indicate that full sticking friction occurred at the extrudate/die interface when a 15′ choke angle was applied in the extrusion dies [12,13].

In the field tests or simulative tests, it is difficult to study the effects of individual factor, such as temperature, sliding speed or contact pressure etc., on the friction. As such, tribological test is probably a sensible technique to reveal the mechanisms of friction under hot aluminium extrusion conditions. Tribological tests (pin/ball-on-disc tests) have been employed previously to identify the friction coefficients for metal cutting process [14–17]. Recently, the first attempt has been made to simulate the interactions at bearing surface by using ball/pin-on-disc tests [18]. The steady-state friction was found to be greater than 1.0 when the testing temperature was higher than 150 °C and the magnitude of friction increased with increasing temperature. The presence of a continuous transfer layer was thought to be responsible for the high magnitude of the frictional force.

Although more efforts have been made previously to simulate the extrudate/bearing interactions by using tribological tests [19,20], the fundamental understanding of the friction phenomenon in the bearing channel of hot aluminium extrusion dies is still insufficient, and the tribological test results have not been implemented into the FE simulations of hot aluminium extrusion yet. The aim of this research is to understand the fundamental of friction phenomenon in the bearing channel of hot extrusion die from a tribological point of view. Moreover, based on the ball-on-disc test results, a physically-based friction model has been developed and implemented into the simulation of hot aluminium extrusion process.

2. Selection of friction testing techniques for the friction characterization of hot aluminium extrusion processes

During a friction test, the large variety of contact conditions, such as temperature, contact pressure, sliding distance, sliding velocity and oxidation scale should be considered very carefully [21], because these factors may influence the friction coefficients considerably. In general, it is very unlikely to emulate all the contact conditions or reflect all the tribological conditions by using one single friction testing technique, because one friction testing technique is only able to reflect one specific or a few tribological conditions, i.e., the tribological conditions of a particular region of the workpiece/tooling interface. Therefore, for the friction characterization of extrusion processes, a combination of different testing methods should be used, for instance, the combination of extrusion friction tests (to determine the friction at billet/container interface) and short sliding distance ball-on-disc tests (to determine the friction in the bearing channel region).

Extrusion friction tests were developed to estimate the global friction coefficient at the billet/container interface. During the tests, high contact pressure and intensive surface enlargement can be achieved [2,3,5,22,23]. Most recent research results have shown that different contact conditions in the extrusion friction tests can be achieved by adjusting the extrusion ratio [23]: low contact pressure and surface enlargement can be achieved when low extrusion ratio is used, thus high level of friction sensitivity can be achieved. If a high extrusion ratio is used, high contact pressure and surface enlargement are obtained, which resemble the real contact condition of forging or extrusion processes, but sacrifice the fiction sensitivity. The combination of extrusion friction tests and FEM simulations is an effective way to estimate global friction at the billet and container interface.

Ball/pin-on-disc test is a widely used laboratory testing technique for the quantitative study of tribological behavior of materials. During ball-on-disc tests, high contact pressure can be achieved in a small contact area between the ball and the rotating disc. If a soft material is sliding over a harder one, severe plastic deformation may occur in the soft material, which could lead to the removal of oxide layers and the contact of pure metals. In the meanwhile, the contact pressure may drop with the increasing sliding distance. Therefore, ball-on-disc tests are favorable to the friction characterization of the regions, in which local contact pressure is high and new surface generation is severe, such as the bearing channel of hot aluminium extrusion dies. During hot aluminium extrusion, fresh aluminium is extruded from the container, and in the die bearing, a pure metal contact takes place. It is well known that the presence of chemical stable surface oxides or scale prevents the strong atomic interactions [24]. Therefore, in order to reproduce the friction conditions in the bearing channel, it is vital to choose a friction testing technique being able to remove the surface oxides. Short sliding distance ball-on-disc test is one of the best friction testing techniques over the other ones, because during the ball-on-disc tests, severe plastic deformation occurs at the ball/disc interface [14,15,18], especially

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