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Effect of grain size on the adhesive and ploughing friction behaviours of polycrystalline metals in forming process

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ABSTRACT

Grain size effect on the friction behaviour of polycrystalline metals in metal forming processes has become one of the most critical issues as the interfacial friction is the most dominating factor which affects the surface quality of the metal-deformed products. Although attentions have been paid to the experimental observation of grain size effect on friction coefficient, the understanding is still quite superficial, and robust conclusions are not yet obtained. To have an in-depth understanding of grain size effect, adhesion and ploughing are studied separately using pin-on-disc friction tests in this research. Different roughness and grain sizes of testing samples are designed for the friction pairs in the experiments to realise both the adhesion-dominated and ploughing-dominated frictions. The experimental results show that with the increase of grain size, the friction coefficient increases in adhesive friction and decreases in ploughing friction. Different mechanisms of the grain size effect on adhesive and ploughing frictions are found by theoretical analysis to account for this phenomenon. For adhesive friction, the transformation from elastic deformation to plastic deformation is the main mechanism. While for ploughing friction, the main mechanism is the transformation from intergranular fracture to transgranular fracture. This work advances the understanding of friction behaviours in metal forming processes and further helps the optimisation of the surface quality of the metal-deformed products.

1. Introduction

Tool-workpiece interfacial friction is one of the most important influencing factors in metal forming processes and has a significant effect on forming energy, forming limitation, and the surface quality of the metal-deformed products [1,2]. The study on determination of friction coefficient on tool-workpiece interface is thus a crucial issue for precision forming of metal-deformed products [3]. Recently, the trend towards the minimisation of products has made the friction issue to be more critical and of concern, since the interfacial effect is thought to be much greater in micro forming than that in macro forming [4–7].

Previous studies show that the tool-workpiece interfacial friction in metal forming processes depends much on the mechanical properties of workpiece, among which the shear strength and surface hardness may be the main factors [8–10]. As the grain size has a significant effect on the mechanical properties of materials [11], a lot of attentions have been paid to the investigation of grain size effect on the friction and wear behaviours of different engineering materials.

For brittle polycrystalline materials, the grain size effects on friction and wear behaviours are significant. The experiments [12,13] have revealed that the decrease of grain size of ceramic is helpful in improving its wear property. The numerical analysis of Rice et al. [14] indicated that the grain size dependence of wear is substantially higher than the typical grain size dependence of hardness, but is less than the grain size dependence of fracture. Detailed observations of the wear surfaces of alumina [15,16] suggested that the dominant process material removal is grain dislodgment and intergranular cracks induced by an accumulation of plastic strains. More recently, Radgy et al. [17] studied the grain size effects on the tribology behaviour of Ti_3SiC_2 using pin-on-disc test, and reported the wear resistance increases with grain size. The attributed grain size effect to the change of fracture modes with delamination, crack bridging and grain buckling were found with coarse grained materials, but only grain pullout and fracture were observed with fine grained material. Similarly, Senda et al. [18] studied the sliding friction and wear of three different grain-sized alumina from room temperature to 1000 °C. They claimed the largest grain size exhibits a slightly higher friction coefficient and observed the transgranular cracks in the largest-grain-size

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material. These studies have made it clear that the grain size effect on friction and wear behaviours of brittle materials is attributed to the fracture of materials.

For ductile materials, however, the grain size effect is more complex, due to phenomena such as transfer of material from one contact surface to another [19], mechanical alloy-forming process [20], mechanical twinning [21], and dynamic recrystallisation involved. For the wear of ductile materials, scratching tests with single conical or pyramid asperity are widely used to study the material removal mechanisms [22,23]. It is suggested that the behaviour of material in scratching is generally characterised by scratching hardness, which is a function of the included angle of the tool, the microstructure of the material and the lubrication between tool and material [24]. On the other hand, the friction mechanism of metals is also studied by many. To name a few, Bowden et al. [25] suggested that the frictional resistance between unlubricated metals is caused by the shearing of metallic junction formed by adhesion at the points of contact, and to the work of ploughing the surface irregularities of the harder metal through the softer one. Based on the explanations of Bowden [25], Wilson et al. [8] modelled the friction stress of metals under different lubricated conditions, and claimed the friction stress at the tooling-workpiece interface can be decomposed into an adhesion and a ploughing components. The adhesion component is proportional to real contact area, while the ploughing component to the mean slope of the tooling asperities. Actually, the surface deformation with adhesion and ploughing are quite different. In adhesion, surface is deformed by shear force, but in ploughing, surface is compressed to failure.

Experiments were conducted to study the grain size effect on friction behaviours of ductile materials. For normal grain-sized materials, Geiger [26] used ring compression tests to study the grain size effect, and found an increase in grain size leads to an increase of friction coefficient and further the increase of the scatter of friction experiments. Mori et al. [27] claimed that the ring compression tests involved the influence of material response. Thus they presented the experimental configuration of a modified Kolsky bar apparatus and investigated the variation of friction coefficient of brass with coarse and fine grains contacting with a steel mate in the research. They concluded that the friction coefficient does not show any significant dependence on the material grain size, interface pressure, and the area of contact. Shakhvorostov et al. [28] used a single-asperity microscopic tribosystem (diamond sphere/Cu sheet) to investigate the grain size effect on the running-in related phenomenon, and found that the initial grain size has a crucial influence on wear and friction only during the first sliding interaction. Moreover, the effect of grain size on lubrication friction was studied by Moshkovich et al. [29], using a block-on-ring rig. They concluded that the transition from the elastic hybrid lubrication region to boundary lubrication region depends on the virgin grain size. And the larger the grain size, the lower the load of transition to the BL region. In addition, the studies conducted by Rao et al. [30] on the wear behaviour of Al and Al-7Si alloys suggested that the wear behaviour is not dependent on the type of grain refiner used, but depends on the grain size/dendritic arm spacing of the metal/alloy and the presence of second phase. Although the previous experiments did not draw a solid conclusion of the grain size effect on the friction behaviour of normal grain-sized ductile materials, it is sure that the grain size effect is affected by a lot of factors, such as bulk deformation of material, testing time, lubrication and second phase, etc.

Recently, a lot of experiments were conducted to study the grain size effect on the friction and wear behaviours of nanocrystalline materials. The dry sliding tribological behaviour of the nanocrystalline copper with an average grain size of 10 nm and the coarse grain copper with an average grain size of 70 μm was compared by Zhang et al. [31], using a ball-on-plate tribometer with a counterface ball of cemented tungsten carbide. Their results show that the friction coefficient of nanocrystalline layer is lower than that of the coarse-grained copper, and the discrepancy decreases with the increase of the normal load. The similar results were obtained by Han et al. [32] who used an electro-deposition technique to prepare the 20 nm grain-sized copper sample. However, the difference of friction coefficient as a function of normal load was observed, which decreases with the increase of normal load in Zhang's experiment [31] and increasing in Han's experiment [32]. Different results of grain size effect were reported by Li et al. [33], who compared the steady friction coefficient after a long testing time of nanocrystalline copper and coarse grained copper based on Han's experiment [32], and found there is no significant difference. It seems that the grain size effect on the friction of nanocrystalline materials is also inconsistent. And it should be noted, with the grain size reduced to submicro or nano scale, the processes of plastic deformation and failure which accompany the process of friction and wear can have some specific features due to a large volume fraction of grain boundaries. Thus the comparison of nanocrystalline and coarse grained materials has been done more than that of the grain size effect on friction behaviours.

Based on the studies mentioned above, the grain size effect on the friction and wear behaviours of ductile materials have been studied experimentally by a lot of researchers using different testing apparatuses and materials. Most of their results, however, are different from each other. As the mechanism of grain size effect on the friction of ductile materials is still not clear, an in-depth research is thus needed to be conducted.

According to the results obtained in prior arts, the following concerns should be taken in design of the experiments to investigate the grain size effect on friction more efficiently.

1. The material should have only one phase.
2. Sliding distance should be extremely small to minimise the change of grain size and the rise of temperature during the process.
3. Surface strain of the original samples must be avoided or to be maintained as the minimum in such a way that the influence of strain hardening can be avoided.
4. Friction mechanisms of the adhesion and ploughing should be treated separately, due to the significant different surface deformations with different friction mechanisms.

In tandem with the above, a friction test of different grain-sized pure copper pin against steel disc was conducted in this study. An extremely short testing time was set to ensure a small sliding distance. And the maximum static friction coefficients of different samples under different normal loads were measured and compared. Moreover, two types of friction processes, namely, the adhesive and ploughing frictions, were designed based on the theory of Wilson [8]. The adhesive friction refers to the deformable rough copper surface sliding on a smooth ridged steel surface, in which the friction stress is considered to be dominated by adhesion. The ploughing friction, on the other hand, refers to the ridged rough steel surface scratching the deformable smooth copper surface, in which ploughing is considered as the dominating mechanism. In preparing the frictional surfaces of copper samples, electrochemical method instead of mechanical method was employed to avoid the influence of surface strain. Finally, based on the experimental results, a theoretical analysis was further conducted to explore the mechanisms of grain size effect.