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

L.F. Peng [a*], M.Y. Mao [a, b], M.W. Fu [b**], X.M. Lai [a]

[a] *State Key Laboratory of Mechanical System and Vibration, Shanghai Jiao Tong University, Shanghai 200240, People's Republic of China*

[b] *Department of Mechanical Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong*

* Corresponding authors.

* Tel.: +8602134206303. E-mail address: penglinfa@sjtu.edu.cn (L.F. Peng).

** Tel.: +85227665527. E-mail address: mmmwfu@polyu.edu.hk (M.W. Fu).

Abstract

Grain size effect on the friction behavior 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 realize 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 behaviors in metal forming processes and further helps the optimization of the surface quality of the metal-deformed products.

Keywords: Friction, grain size, adhesion, ploughing, metal forming

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 minimization 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 behaviors of different engineering materials.

For brittle polycrystalline materials, the grain size effects on friction and wear behaviors 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 behavior 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 ℃. They claimed the largest grain size exhibits a slightly higher friction coefficient and observed the transgranular cracks in the largest-grain-size material. These studies have made it clear that the grain size effect on friction and wear behaviors 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 recrystallization 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 behavior of material in scratching is generally characterized 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] modeled 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 plowing components. The adhesion component is proportional to real contact area, while the plowing 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 behaviors 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 behavior of Al and Al-7Si alloys suggested that the wear behavior 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 behavior 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 behaviors of nanocrystalline materials. The dry sliding tribological behavior of the nanocrystalline copper with an average grain size of 10 nm and the coarse grain copper with an average grain size of 70μm 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 behaviors.

Based on the studies mentioned above, the grain size effect on the friction and wear behaviors 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 minimize 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.

2 Physical experiments

Pin-on-disc friction test was conducted in this study, and the friction pair was designed to be composed of a copper pillar and a 42CrMo steel disc. The geometries of the friction pair are shown in Fig. 1.Considering copper is much softer than steel, two kinds of surface pairs, viz., SC-RS pair (smooth copper-rough steel) and RC-SS pair (rough copper-smooth steel), were designed to study the adhesive and plough frictions separately.

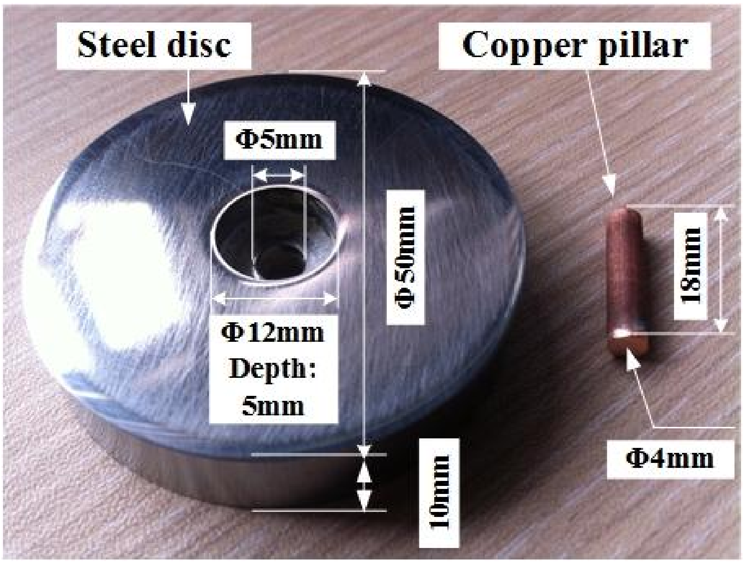
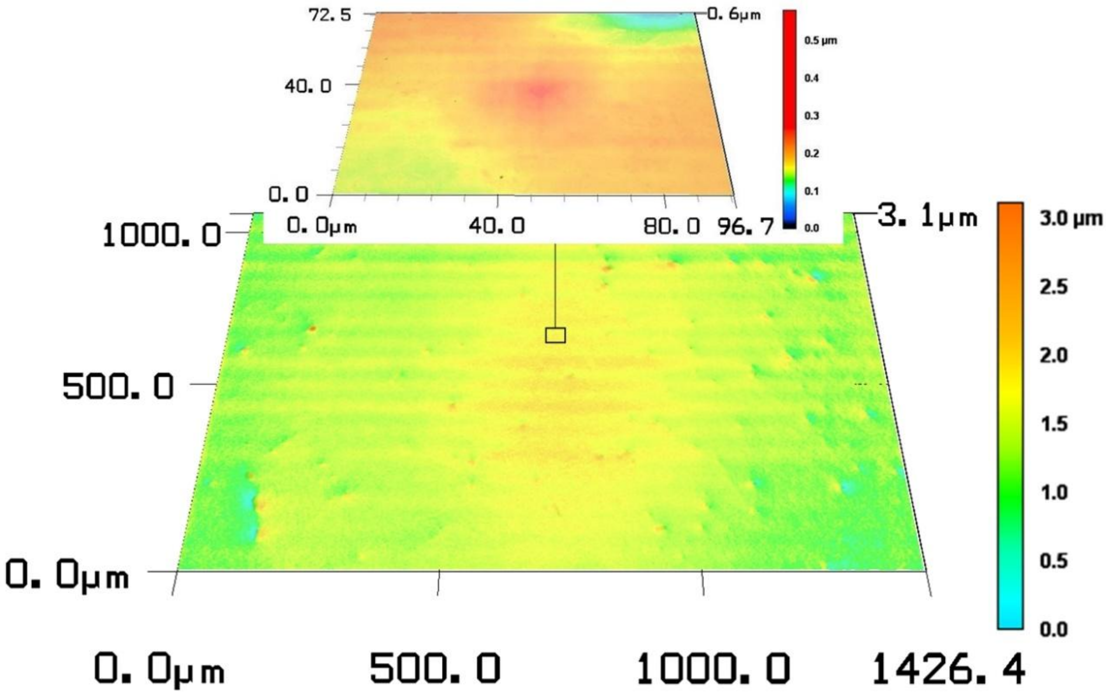


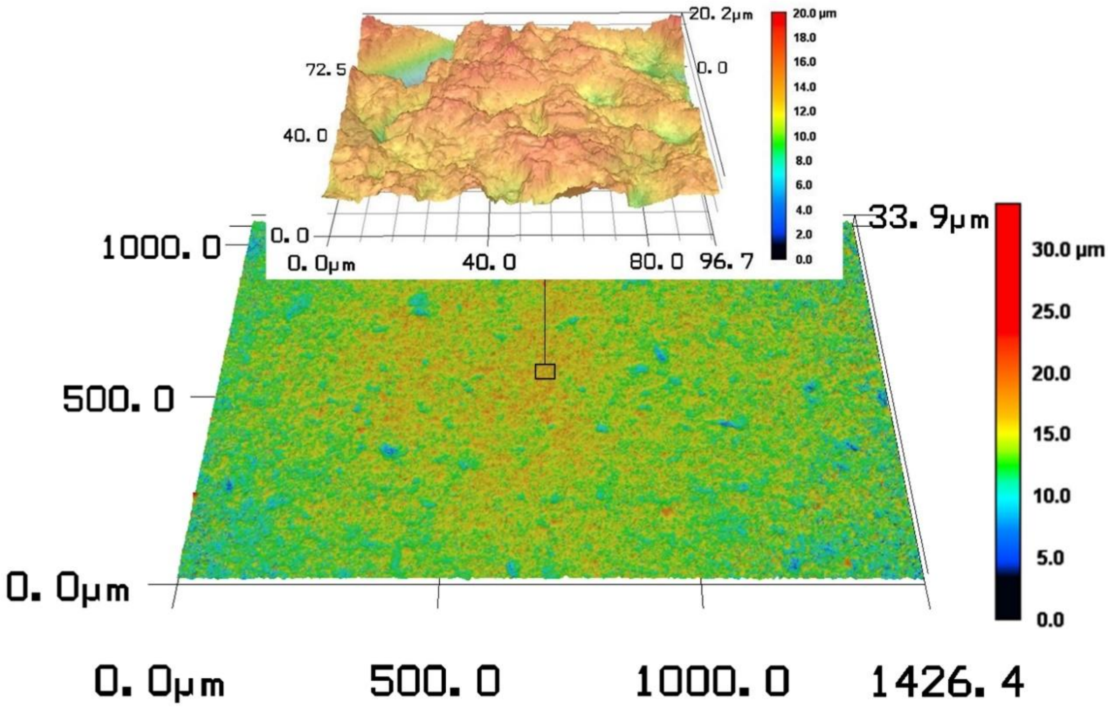
Fig. 1. Geometry of samples

2.1 Preparation of steel disc

The steel disc was machined to the round shape and the detailed geometrical dimensions are presented in Fig. 1. The surface hardness $H_s = 4900\text{MPa}$ is measured by micro-hardness test setting and the testing load is 0.2 kgf. Samples with the smooth and rough surfaces were fabricated. The smooth steel samples were polished with the roughness of $R_a = 0.05\mu\text{m}$. And the rough samples with the surface roughness of $R_a = 1.74\mu\text{m}$ were obtained using the sand-blasting method with 80# sands. The roughness of surfaces were measured by a Digital Scanning Laser Microscope, as shown in Fig. 2.



(a) Smooth steel surface



(b) Rough steel surface

Fig. 2. Smooth and rough surfaces of steel disc

2.2 Preparation of copper pillars

Different grain sized copper pillars were prepared by the vacuum heat treatment to investigate the grain size effect on friction behavior. Three different heat treatment process are used in this study to obtained three grain sizes [27]. To avoid the surface oxidation of the samples, argon gas were employed as the protective gas. After annealing, the metallographic examination was done after the specimen was etched in a solution of 5 g of FeCl3, 15 ml of HCl and 85 ml of H_2O for 15 s, and the grain sizes were measured according to ASTM [5]. Fig. 3 shows the microstructures of the copper samples used in the experiment. Fig.2 a) is the microstructure of the original material. Fig. 3b), c), d) show the microstructures of the copper samples with an average grain size of 4μm (heat treatment at 220℃ for 1hour), 12μm (heat treatment at 600℃ for 1 hour) and 130μm (heat treatment at 900℃ for 2 hours). They are named fine, medium and coarse grains in this study.

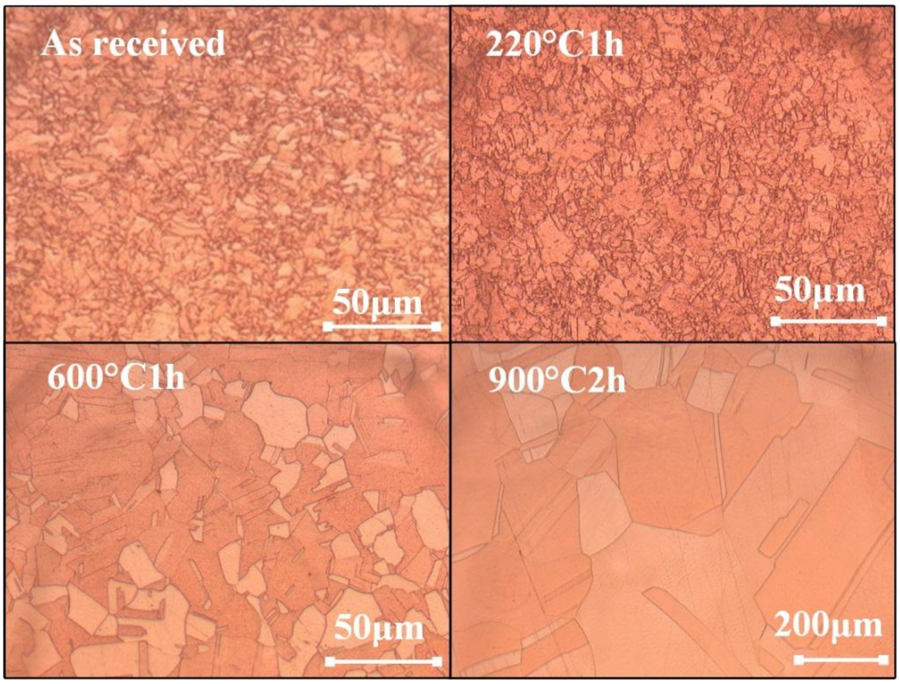


Fig. 3. Microstructures of the copper samples

The surface hardness was measured by micro-hardness test. The test load was set as 0.2kgf, and the hardness of the samples is presented in Fig. 4. The trend that the surface hardness decreases with the increase of grain size is observed. With the increase of grain size, the fraction of grain boundary in the material decreases, thus leads to the decrease of the average surface hardness of materials [34].

Different from those samples with small grain, when the grain size of samples is large enough (the samples treated at 600 and 900℃), its effect on hardness is not significant. Since the thickness of grain boundary is extremely small compared with the grain interiors, and the decrease of fraction of grain boundary slows down with the increase of grains [35].

The elastic modulus of copper sample surfaces are measured by nano-indentation tests [36], as presented in Fig. 4. All the samples are tested with the highest load of 5mN and dwell for 2 seconds.

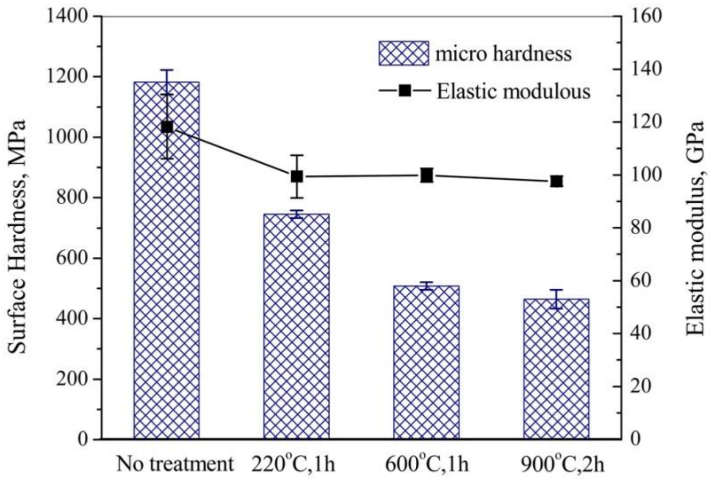


Fig. 4. Micro-hardness and elastic modulus of the copper samples

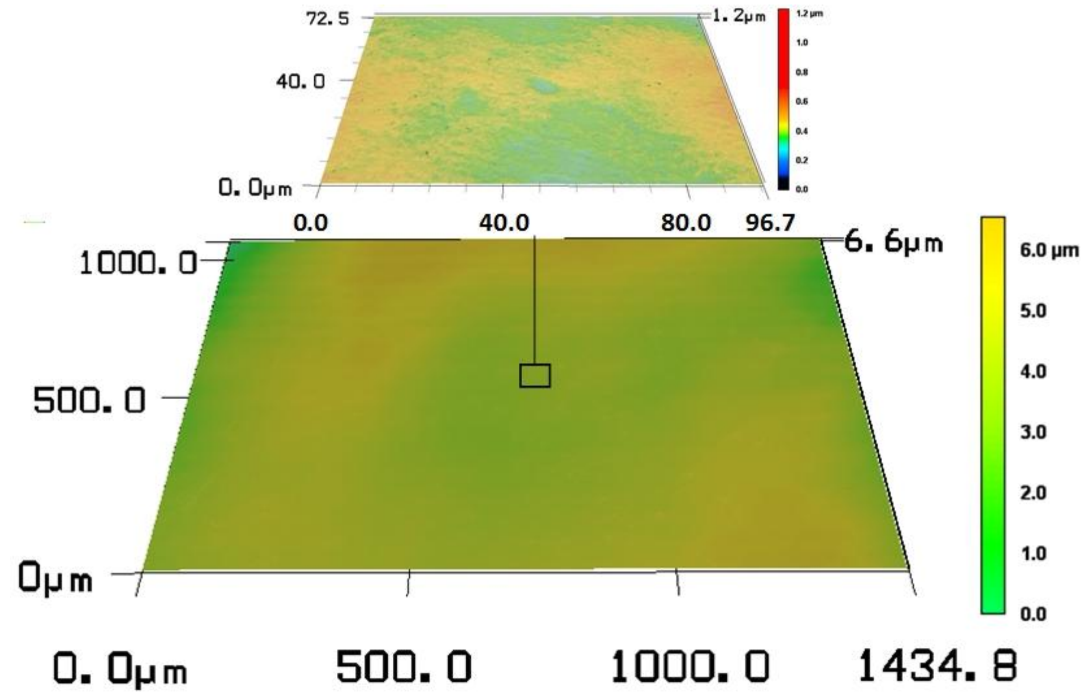
In preparing the surface of the copper sample, electrochemical method [37, 38] instead of mechanical method is employed to avoid the hardening of the material caused by surface deformation. All the samples are first polished to a smooth level ($R_a = 0.02\mu m$) using electrolytic polish method with the parameters listed in Table.1. (step 1). The rough surfaces are the obtained using the parameters in Table.1. (step 2).The surface roughness for different grain sizes are measured using a Digital Scanning Laser Microscope and illustrated in Table.2. and Fig. 5. It is clear that a unique surface roughness is obtained for copper samples with different grain sizes in both the smooth and rough cases.

Table.1. Parameters of the copper surface preparation process

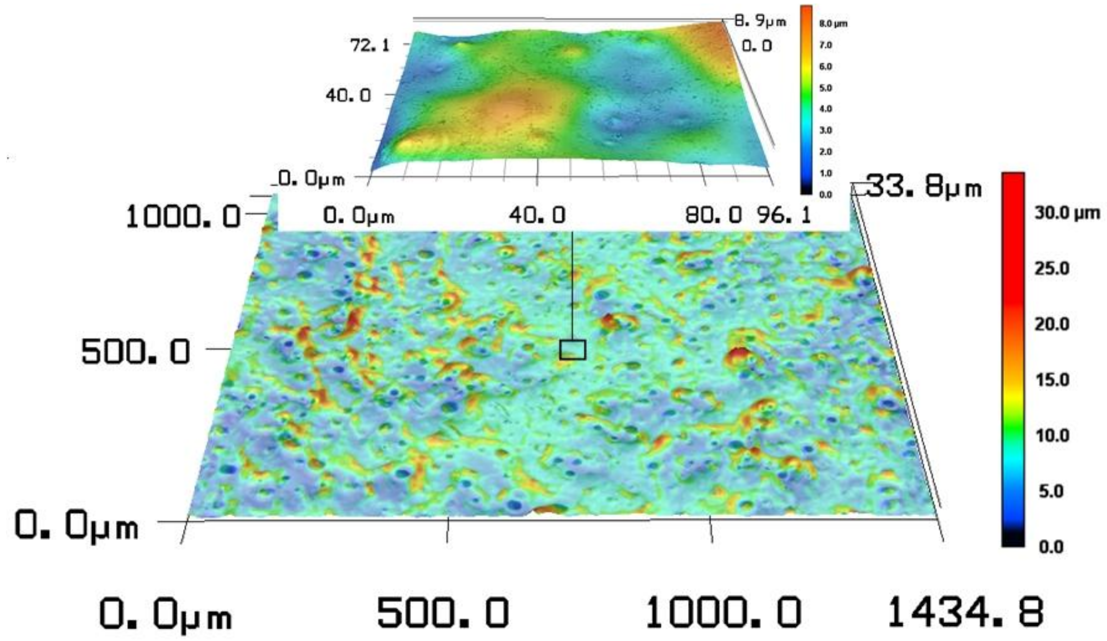
Process	Electrolyte	Electrode spacing(mm)	Current(mA)	Time(min)
Step 1 (smoothening)	80% phosphoric acid solution	80	55±5	8
Step 2 (roughening)	80% phosphoric acid solution	80	155±5	8

Table.2. Surface roughness of the copper samples

Ra(μm)	Fine grain	Medium grain	Coarse grain
Smooth	0.027±0.007	0.026±0.008	0.025±0.004
Rough	3.287±0.182	3.133±0.021	2.761±0.663



a) Smooth surface of copper pin



b) The asperity of rough surface of copper pin

Fig. 5. Smooth and rough surfaces of the copper samples measured with Digital Scanning Laser Microscope

2.3 Friction test

As shown in Fig. 6, the test apparatus is a MFT-5000 type Universal Tribometer. Two different load cells are installed in the machine to measure the normal and friction loads. For the low normal load from 1 to 100 N, a sensitive load cell with the resolution of 5 mN is used. For the medium to high normal loads ranging from 50 to 5000 N, another load cell with the resolution of 250 mN is used. The friction is measured with an accurate piezoelectric sensor, which can be operated in two different regimes, one from 0 to 20 N with the resolution of 10 mN and the other from 0 N to 200 N with the resolution of 50 mN. The equipment is connected to a PC to record the real time data of the normal and friction loads.

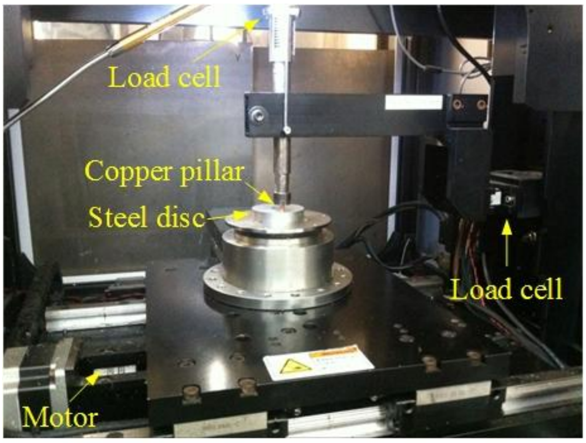


Fig. 6. Friction testing facility

To ensure the comparability of testing results for different samples, the parameters of the friction tests are set to be the same. Specifically, the testing radius and rotation speed are set to be 16 mm and 5 r/min, and the accelerating time and testing time are set as 0.1 s and 0.6 s, respectively. As this study is focused on the friction behavior at the inception of sliding, the low testing speed and short testing time are chosen to prevent the over abrasion of surface asperities and the increase of temperature. During the test, the normal and tangential loads are recorded every one micro-second.

To reduce the influence of contact area caused by normal load, the testing normal loads are normalized by yield stress as:

$$F^* = \frac{F}{\sigma_0 A} \tag{1}$$

where, F* is the normalized normal load. F is the normal load. σ_0 is the initial yield stress of copper. A is the nominal contact area. The grain size effect on friction is measured under the same normalized normal load. Two pairs of contacting surfaces are assembled to investigate the adhesive and ploughing frictions separately. The design of experiments are shown in Table.3.

Table.3. Design of the friction tests

Process	Steel surface Ra(μm)	Copper surface Ra(μm)	Copper grain size(μm)	Normalized normal loads(F*)
Adhesive friction	0.05	3.2 ± 0.18	4.3 ± 0.18	0.03,0.05,0.07
		3.1 ± 0.02	11.4 ± 1.3	
		2.8 ± 0.66	132.2 ± 17.7	

Ploughing friction	1.74	0.027 ± 0.007	4.3 ± 0.18	0.005,0.008,0.011
		0.026 ± 0.008	11.4 ± 1.3	
		0.025 ± 0.004	132.2 ± 17.7	

3 Results and discussion

3.1 Experimental Results

3.1.1 Surface morphology

The surface morphologies of the copper samples after adhesive friction test under different normal loads are shown in Fig. 7. The asperities with a larger height are flattened by the smooth steel surface. More asperities are flattened under higher normalized normal load. Previous studies have confirmed this observation [8, 9, 39, 40]. They claimed that the asperities of softer material are deformed by the normal load and merged through the plastic flow caused by friction force [8, 40, 41].

Moreover, small tracks of ploughing are observed on the flattened surfaces. This is caused by the small asperities on the smooth steel surfaces. With the increase of normal load, more copper asperities are flattened, and the ploughing tracks become deeper and longer.

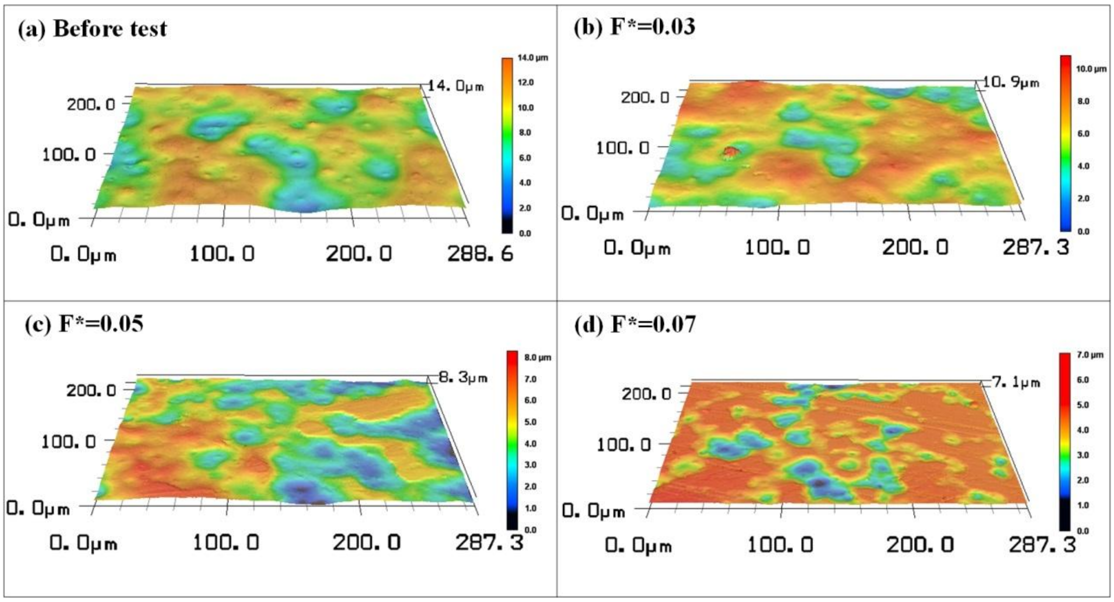


Fig. 7. Surface morphology of the rough copper samples after adhesive friction test

Fig. 8 shows the derivation of the copper surfaces in ploughing friction tests under different normal loads. Obviously, the copper surface is ploughed by the hard steel asperities, and the surface roughness increases significantly after the test. Moreover, the increase of normal load has a positive effect on the increase of surface roughness.

According to Wilson's theory, the surface of the soft material is roughened by the ploughing of hard material, and the increased roughness is thought to be the sum of sink-in and pile-up [8].

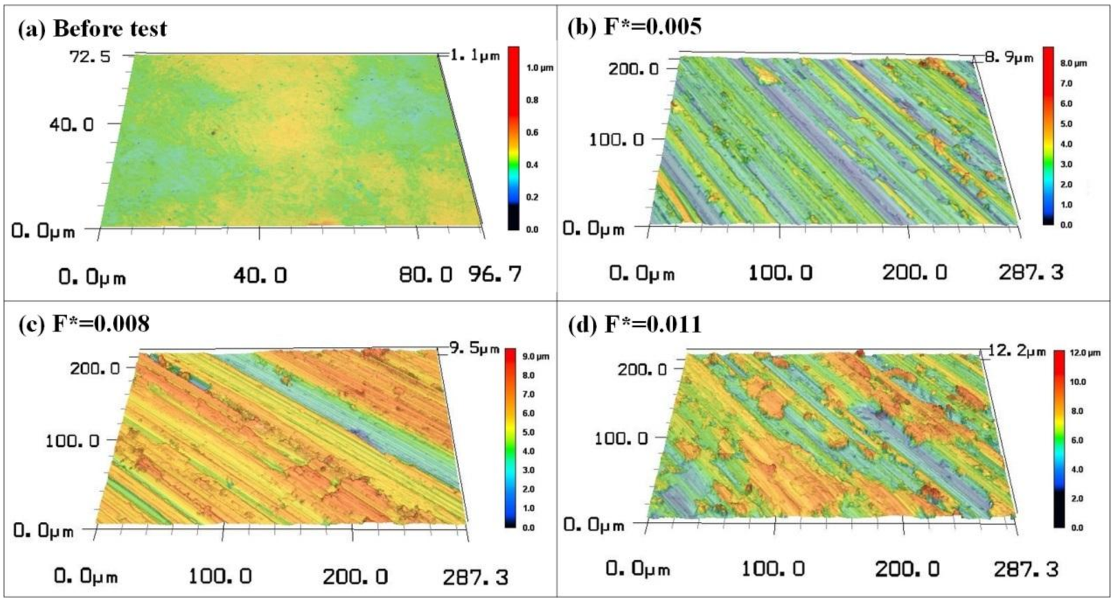
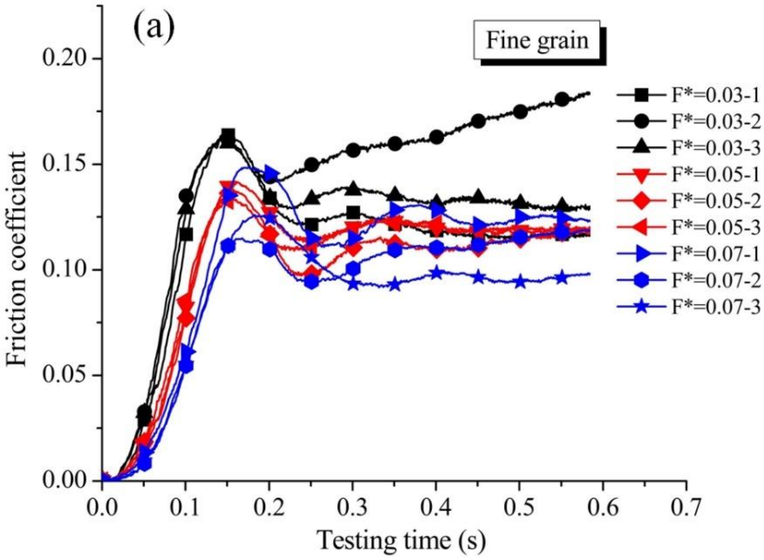


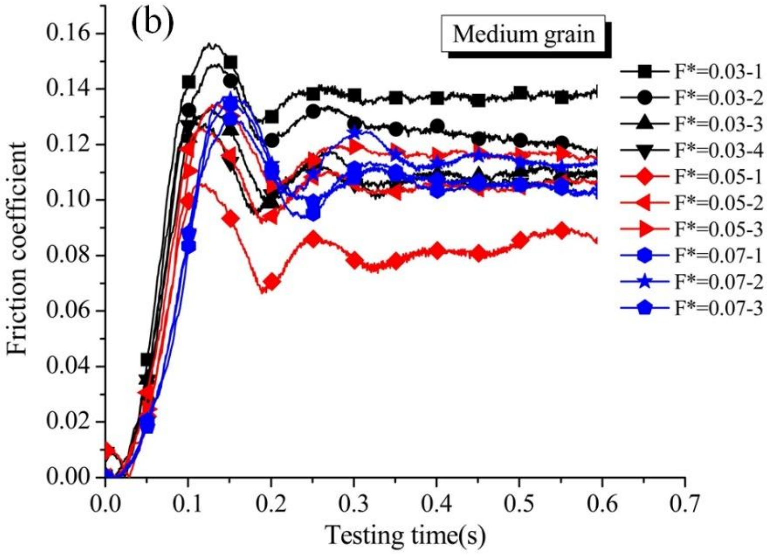
Fig. 8. Surface morphology of the smooth copper samples after plough friction test

3.1.2 Friction coefficient

The friction coefficient μ as a function of time t for different grain sizes and the normalized normal loads is presented in Fig. 9 and Fig. 10. The friction coefficient is obtained based on the normal and tangential loads measured by load cells. For the adhesive friction tests (as shown in Fig. 9), the friction coefficient is first increased from 0 to a peak value, and then decreased to a stable value rapidly. Obviously, the peak value is the static friction coefficient and the stable value is the dynamic one. However, the dynamic friction coefficient is not really stable. An increasing tendency of the dynamic friction coefficient with the test time is observed for most of the samples. The reason may be the abrasion of copper asperities and the elevation of temperature. The abrasion makes the increase of the real contact area and the wear particles between copper and steel surfaces result in a third body abrasive friction [42]. Furthermore, the elevated temperature makes the welding junction much easier to be formed, which also contributes to the increase of friction coefficient.

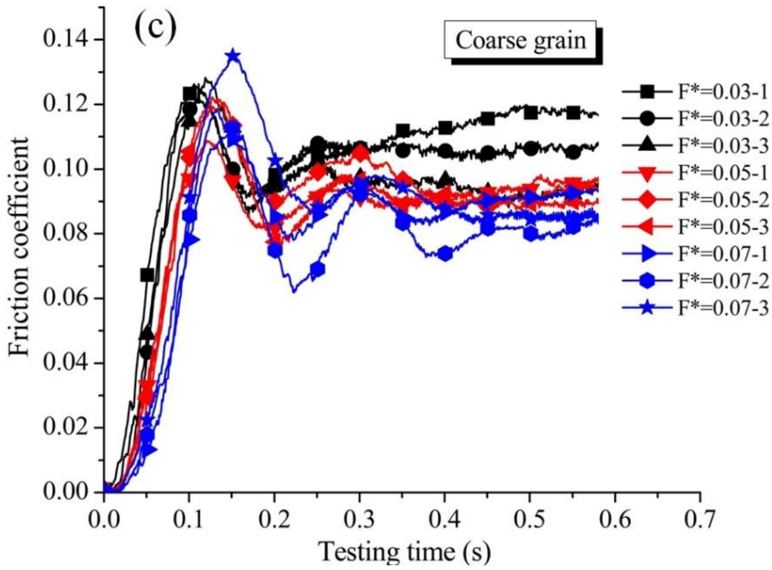


(a) Samples with fine grains



(c)

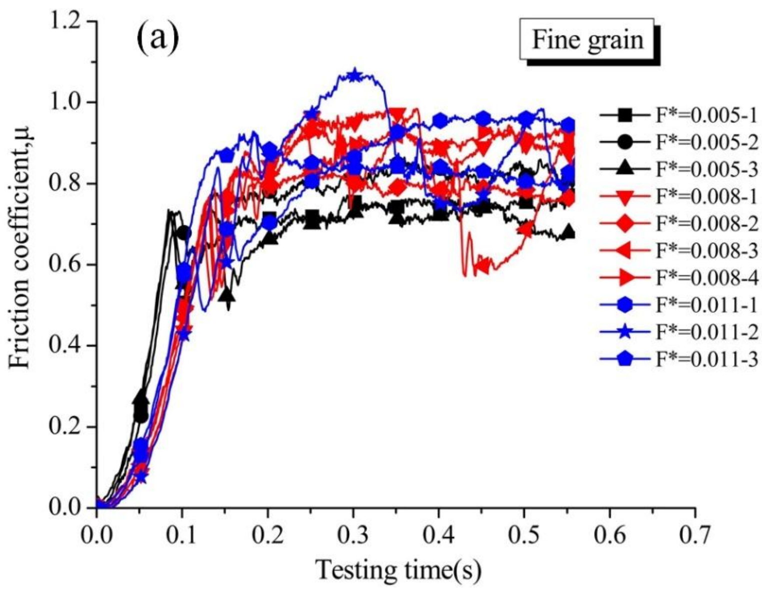
(b) Samples with medium grains



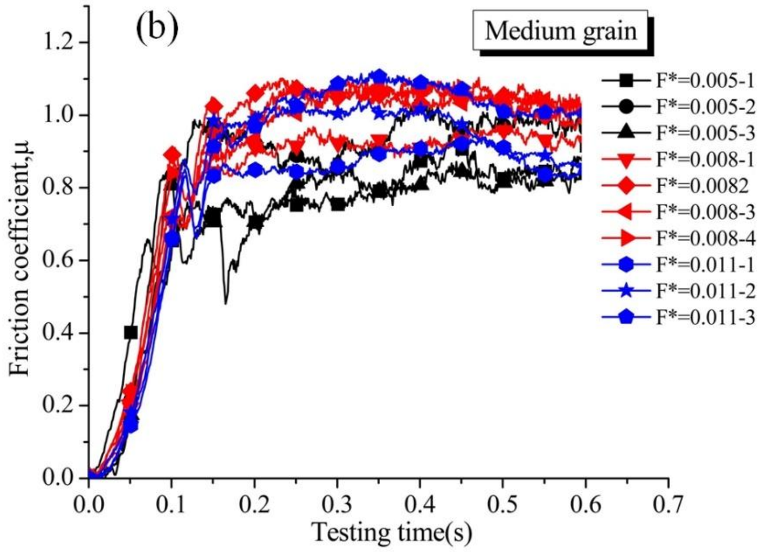
(c) Samples with coarse grains

Fig. 9. Variation of friction coefficient with time for different normal pressures and grain sizes in the adhesive friction test

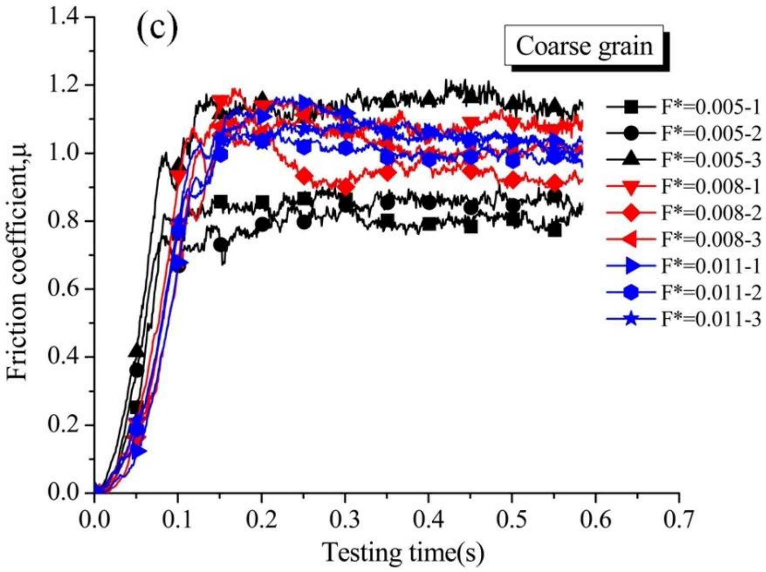
For the ploughing friction test, the shape of friction coefficient-test time curve is more complicated. A nearly linear increasing curve followed by an oscillating curve is observed for most of the samples as shown in Fig. 10. The linear part is considered to be the static friction, and the oscillating part represents the friction coefficient when the steel disc is rotating. The maximum static friction coefficient is the linear limit of the curves. It is probably smaller than the dynamic coefficient in ploughing friction tests, since the pile-up of material increases the contact area of the steel asperity and the copper surface during the process. And Bellemare et al. [43] claimed that the pile-up height in frictional sliding is as three times high as the one obtained through normal indentation. Meanwhile, the abrasion in the ploughing friction test is much stronger than that in the adhesive friction test. The third body abrasion friction is thus more significant than that in the adhesive friction test.



(a) Samples with fine grains



(b) Samples with medium grains



(c) Samples with coarse grains

Fig. 10. Variation of friction coefficient with time for different normal pressures and grain sizes in the plough friction test

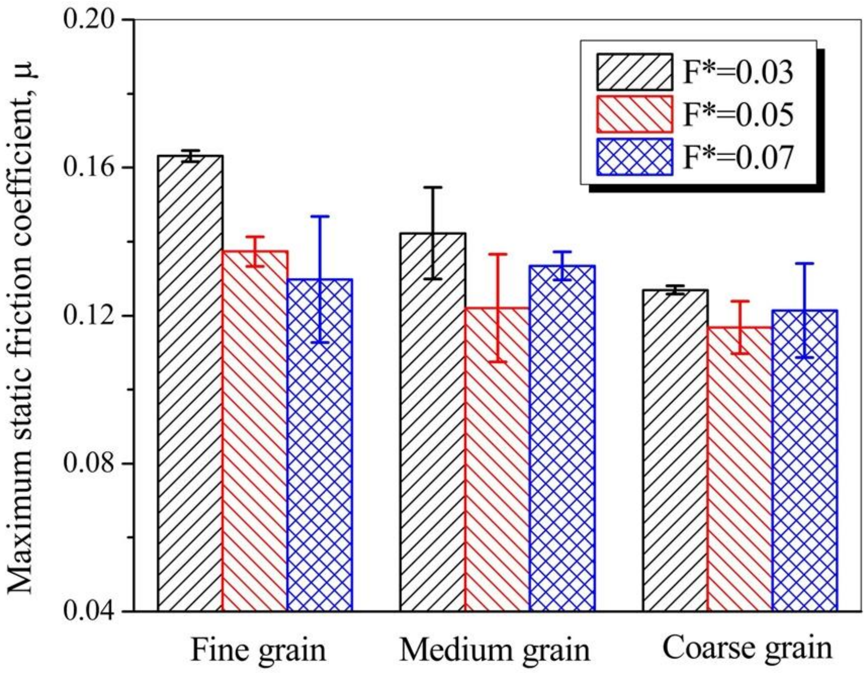
3.2 Adhesive friction behavior

3.2.1 The effect of grain size

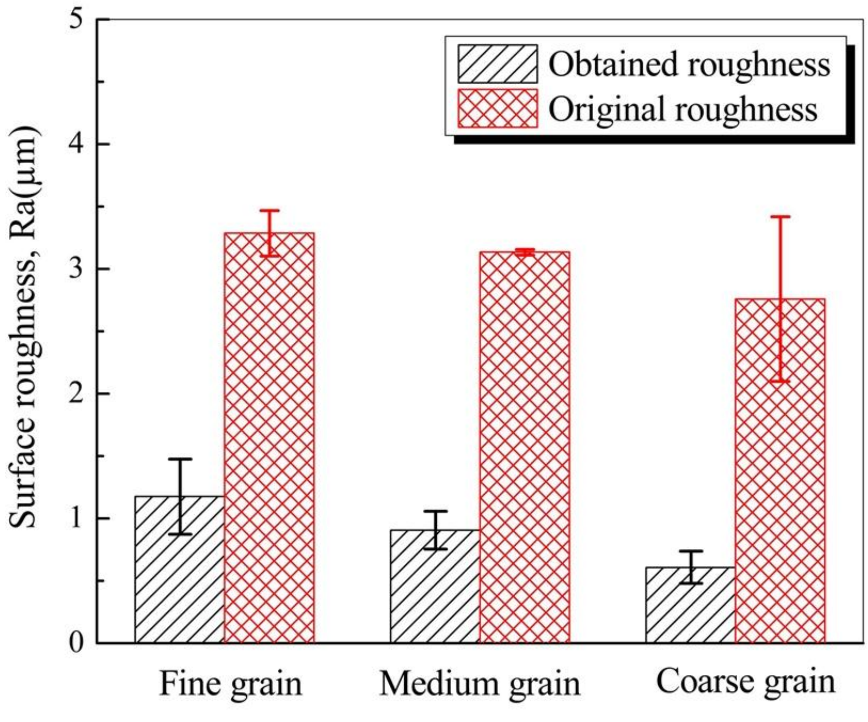
The maximum static friction coefficient, μ, measured in adhesion test under the normalized normal load of 0.03, 0.05, and 0.07 for the samples with different grain sizes is given in Fig. 11 (a). It is clear that friction coefficient decreases with the increase of grain size. When the normalized normal load is 0.03, the average coefficient of the samples with coarse grains is 0.127. Compared with the coefficient values of 0.163 and 0.142 for the samples with fine and medium grains, a significant decrease of 28.3% and 11.8% is observed, respectively.

Furthermore, the grain size effect on adhesive friction decreases with the increase of the normalized normal load. When F*=0.05, there is a 16% decrease of the average coefficient from the fine grain to coarse grain. The decrease, however, is much larger, with about 28.5% when F*=0.03. On the other hand, the standard error bars of the results when F*=0.05 for different samples are over lapped, and this is not observed in the results when F*=0.03.

The results obtained when F*=0.07, on the other hand, do not match the grain size effect occurring under other normal loads. Since the medium-grained samples possess a larger friction coefficient than fine-grained samples under the normalized normal load of 0.07. Moreover, for the samples with medium and coarse grains, the friction coefficient under the normalized normal load of 0.07 is higher than that obtained under the normalized normal load of 0.05. This goes against the understanding of the adhesive friction that the friction coefficient decreases with the increase of normal load. These deregulations may be attributed to the effect of the tiny asperities on the smooth steel surface plowing the deformed rough copper surfaces. As is shown in Fig. 7, the plowing tracks are clearly observed on the samples tested under the normalized normal load of 0.07, but those tracks are not obvious on the samples tested under the normalized normal loads of 0.05 and 0.03. This indicates that the ploughing friction comes into effect when the normalized normal load is increased to 0.07. Actually, when the normal load is small, large soft asperities on the surface of workpiece are deformed and flattened by the smooth rigid surface to support the applied normal load. With the increase of normal load, the ratio of the real contact area to the nominal contact area is increased close to 1. When no more contact area is able to be added through the deformation of workpiece-asperity to support the increased normal load, the indentation of the rigid tool-asperity into the workpiece at the contact interface becomes a main mechanism to generate the friction in the contacting process. And the ploughing effect thus becomes more significant under high normal load. Under this normal load, the grain size effect on the friction coefficient is not the same as that in adhesive friction.



(a) Maximum static friction coefficient



(b) Deviation of surface roughness

Fig. 11. Effect of grain size on the maximum static friction coefficient and the deviation of surface roughness in adhesive friction tests

The obtained roughness of the samples after adhesion test under the normalized normal load of 0.05 is compared with the original roughness shown in Fig. 11 (b). It is found that the average value of the obtained roughness decreases with the increase of grain size. A decrease of 48% in the roughness is found between the fine grained samples and the coarse ones. The fine grained samples have the highest surface roughness (SR) of 1.18 μm, while the coarse grained samples get the SR of 0.61 μm. Compared with the original roughness, the SR with more than 2 μm decrease is observed. This is due to the flattening of asperities by the smooth steel surface. The grain size effect on the surface roughness is attributed to the proportion of the elastic deformation in the total flattening deformation. More elastic deformation means more recovery after unloading, and the rougher of the end surface. The surfaces of the fine grained samples are more elastic than the coarse ones, which will be discussed later. However, the grain size effect on roughness evolution is not so obvious since the small difference in the average value of the original roughness of the fine and coarse grained samples also contributes to the difference in the final roughness.

3.2.2 Theoretical analysis

The gain size effect on adhesive friction behavior is due to the plastic deformation of surface asperities. According to Nolle and Richardson [44] the reduction in friction coefficient is attributed to the increase of plastic deformation of asperities. In the adhesive friction, the steel surface could be simplified to a rigid flat plane and the copper could be represented by a deformable rough surface, depending on the difference of the hardness and surface roughness between tool and workpiece [45]. When the normal load is applied, the asperities on the workpiece surfaces are deformed by the rigid tool. In fact, both elastic and plastic deformations exist on the workpiece surface since the height of asperity is not uniform. To identify whether the surface is likely to deform plastically or not, Greenwood and Williamson [46] proposed the plasticity index, Ψ, and further developed by Chang et al. [47] with the following formulation.

$$\psi = \frac{4E}{3\pi K_c H}\left(\frac{\sigma}{R}\right)^{\frac{1}{2}}\left(1-\frac{3.717\times10^{-4}}{(\eta\sigma R)^2}\right)^{\frac{1}{4}} \quad (2)$$

where K_c, E and H are the material-related parameters, representing the maximum contact pressure factor, Hertz elastic modulus and the hardness of softer material in the contacting mates, respectively. The formulations of K_c and E are given by

$$K_c = 0.454 + 0.41\nu \quad (3)$$

$$E = \frac{E_s}{1-\upsilon^2} \quad (4)$$

where E_s and ν are the elastic modulus and poison's ratio of the softer material. R and η in Eq. are the roughness-related parameters representing the average radius and the density of the asperity summits. The detailed representations are given by [48]

$$R = \frac{3\sqrt{\pi}}{\sigma''} \quad (5)$$

$$\eta = \frac{(\sigma''/\sigma')^2}{6\pi\sqrt{3}} \tag{6}$$

σ, σ' and σ'' are root mean square (RMS) height, RMS slope and RMS curvature of the surface. All these parameters can be obtained based on the surface profile y(x) [47], which can be measured by the digital laser microscope. In this experiment, the values of the dimensionless parameters are obtained as $\eta\sigma R = 0.223$, $\sigma/R = 4 \times 10^{-4}$. Assuming the surfaces of copper samples are similar, the plasticity indexes of the copper samples with different grain sizes are obtained by substituting the surface parameters and mechanical parameters into Eq.. The results are shown in Fig. 12. It is obvious that the plasticity index increases with grain size, since the ratio E/H of the sample increases with grain size.

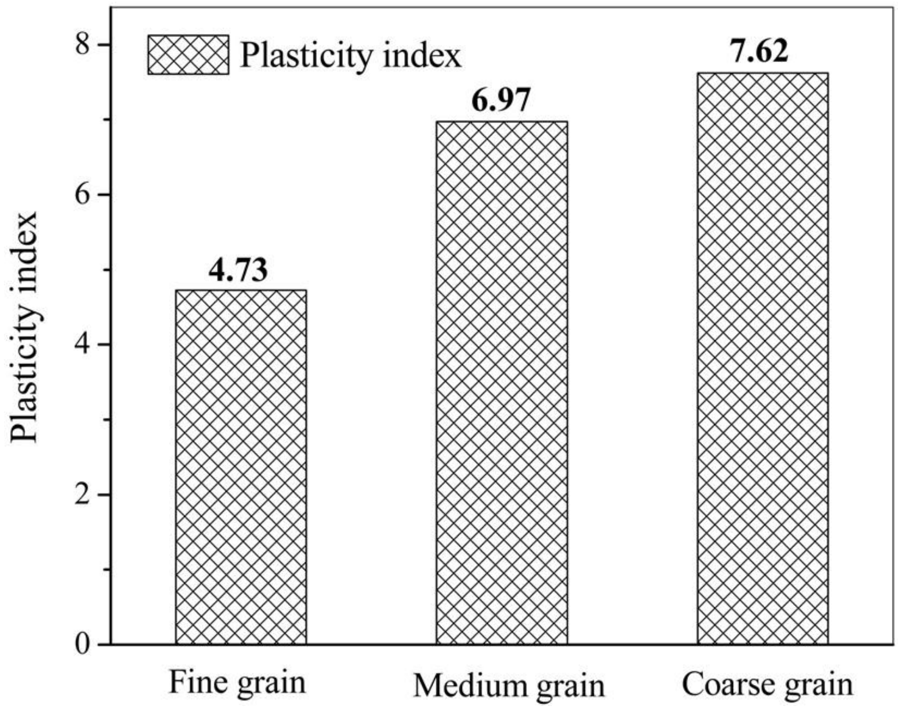


Fig. 12. Plasticity index of specimens

According to Kogut and Etsion [49], for the surfaces with $0.6 < \psi < 8$, both elastic and plastic deformation occur during the contact. And friction coefficient decreases with the increase of plasticity index [50-53]. The adhesive friction behavior is modeled in our previous study considering the material hardening and junction growth [54]. Assuming the hardening exponential n=0, the friction coefficients as a function of normalized normal load is calculated and compared with the experimental results, as shown in Fig. 13.

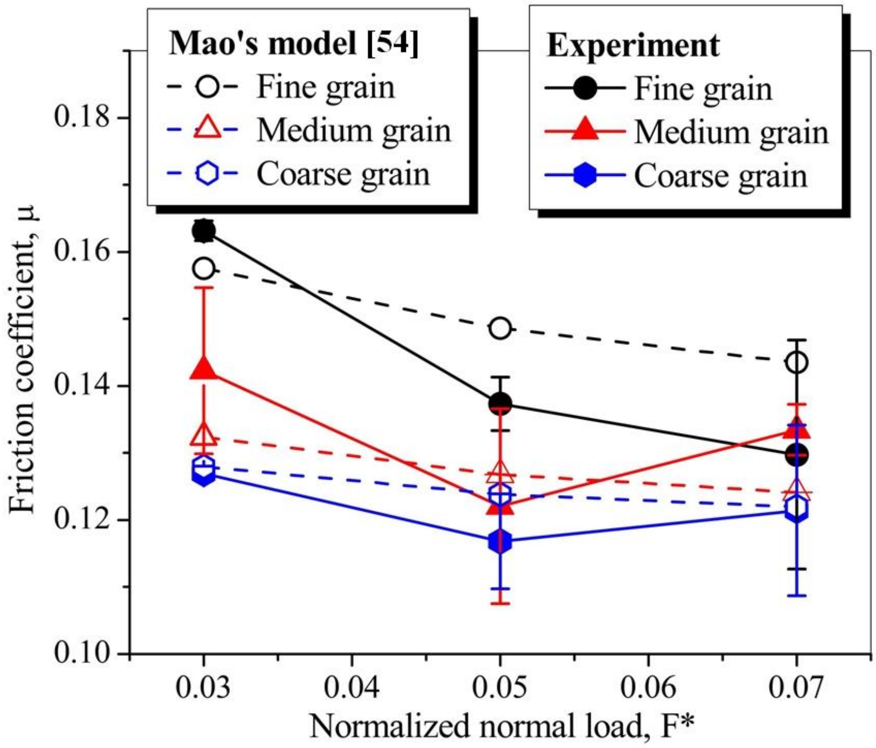


Fig. 13. Comparison of the friction coefficients predicted by model with the experiment

According to Fig. 13, the predicted results reveal the same tendency as the experimental results. The friction coefficient decreases with the increase of both grain size and normalized normal load. Although a difference is observed between the predicted values and the measured ones, the predicted error is acceptable, since most of the predicted values are located within the error bar. And the discrepancy of the model and experiment may be caused by the measurement errors of the test facility.

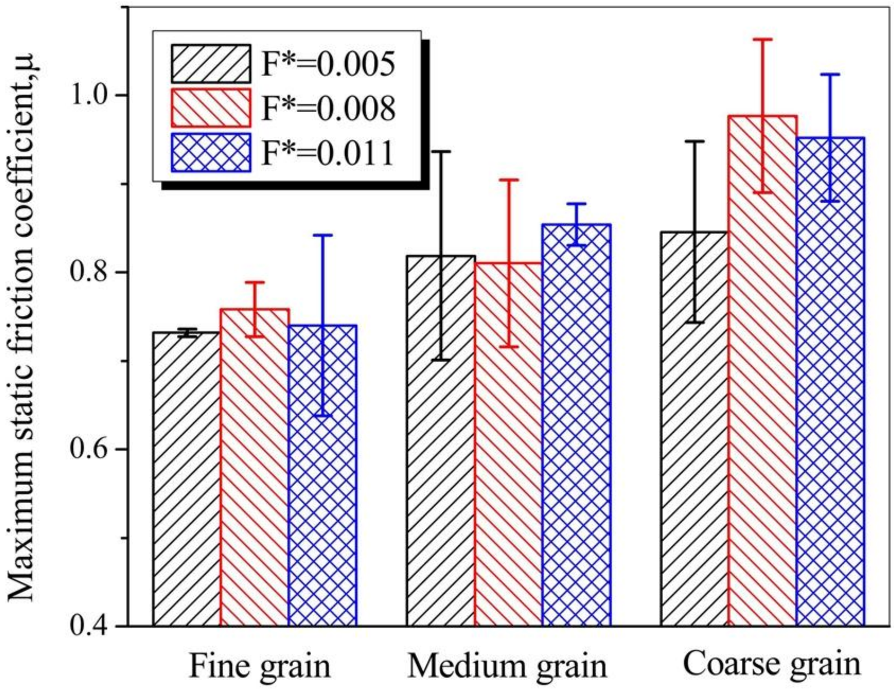
The theoretical model reveals that the grain size effect on the coefficient value of adhesive friction is attributed to the fact that the samples with a larger grain size have a higher ratio of E/H, which causes a higher value of plasticity index of the contact surface and makes the deformation more plastic. The friction coefficient thus decreases with grain size. When the normal load increases, all the samples tend to deform plastically, the discrepancy between different grained sized samples gets smaller. That is why the grain size effect decreases with the normal load. On the other hand, the plasticity of the surface also affects the ending surface. Since the samples with a lower plasticity index have more elastic recovery. As the surfaces are flattened by the rigid tool, the recovery after unloading is thus beneficial to the roughening of the ending surfaces.

3.3 Ploughing friction behavior

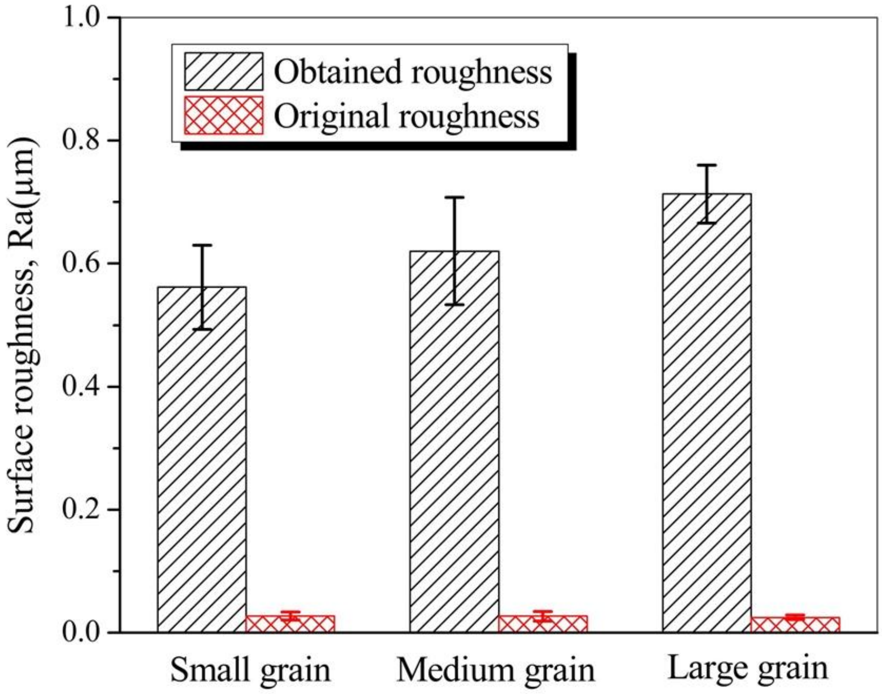
3.3.1 Effect of grain size

The grain size effect on the maximum static friction coefficient of ploughing tests is shown in Fig. 14. The maximum static friction coefficient is defined as the linear limit of the friction coefficient-test time curve as shown in Fig. 10. Opposite to that observed in adhesive friction test, the samples with larger grain size possess the higher average values of μ under all the normal loads in the ploughing friction tests. And no significant relation is found between the grain size effect and the normalized normal load. Comparing the average friction coefficients of the samples with fine and coarse grains, a 14% increase is observed in the case of F*=0.005. The ratio increases to about 22% when F* is raised to 0.008 and 0.011. Additionally, the values of μ in ploughing friction tests are much higher than those measured in the adhesive friction tests. And the difference between the samples with fine and coarse grains in friction coefficient is much greater than that in the adhesive friction tests.

Furthermore, similar grain size effect is reported in the prior arts, although adhesive and ploughing friction tests are not separated. Senda et al. [18] studied the effect of grain size on the sliding wear and friction of alumina at elevated temperature and concluded the friction coefficient increases slightly with the increase of grain size. And Mori et al. [27] reported the average value of static friction coefficients is 0.46 for brass samples with small grains and 0.52 for large grain-sized samples. The reason why the grain size effect on friction coefficient is not so significant may be attributed to the counteraction of adhesive and ploughing frictions, since grain size reveals opposite effects on friction coefficient. The friction process dominated by ploughing friction is believed to reveal a slight increase tendency with grain size, and those dominated by adhesive friction, a decrease tendency.



(a) Maximum static friction coefficient



(b) Deviation of surface roughness

Fig. 14. Effect of grain size on maximum static friction coefficient and deviation of surface roughness in plough friction test

The surface roughness after ploughing test of F*=0.008 is presented in Fig. 14 (a). Compared with the original roughness, a more than 0.6 μm increase of roughness is obtained after the test. The roughening of the surface is mainly caused by the steel asperity plowing the copper surface. An increasing tendency of the roughness with the grain size is observed. As the original roughness of the samples has only a little difference of 0.002 μm, the increased difference between the surface roughness of the samples with different grain sizes is attributed to the grain size effect.

The grain size effect on the surface morphology is shown in Fig. 14 (b), where the copper surfaces with different grain sizes as well as the steel surface after the ploughing test of F*=0.008 are presented. The ploughing tracks and damages on the copper surfaces shown in Fig. 15 (b-d) are caused by asperities on the steel surface in Fig. 15 (a). Furthermore, by comparing Fig. 15 (b-d), a significant difference is easily found between the ploughing tracks of the samples with fine and coarse grains. For the samples with fine grains, the edges of the tracks appear to be blurry. But for the samples with coarse grains, the much clearer and more continuous edges of the tracks are formed. As the material damage is significant in ploughing process, a transformation of the damage mechanism is believed to be the reason for the difference in the surface morphology. A similar mechanism transformation is reported by Senda et al. [18]. They found the transgranular cracks in the wear surface of large-grained specimens, and the intergranular cracks in the fine grained samples.

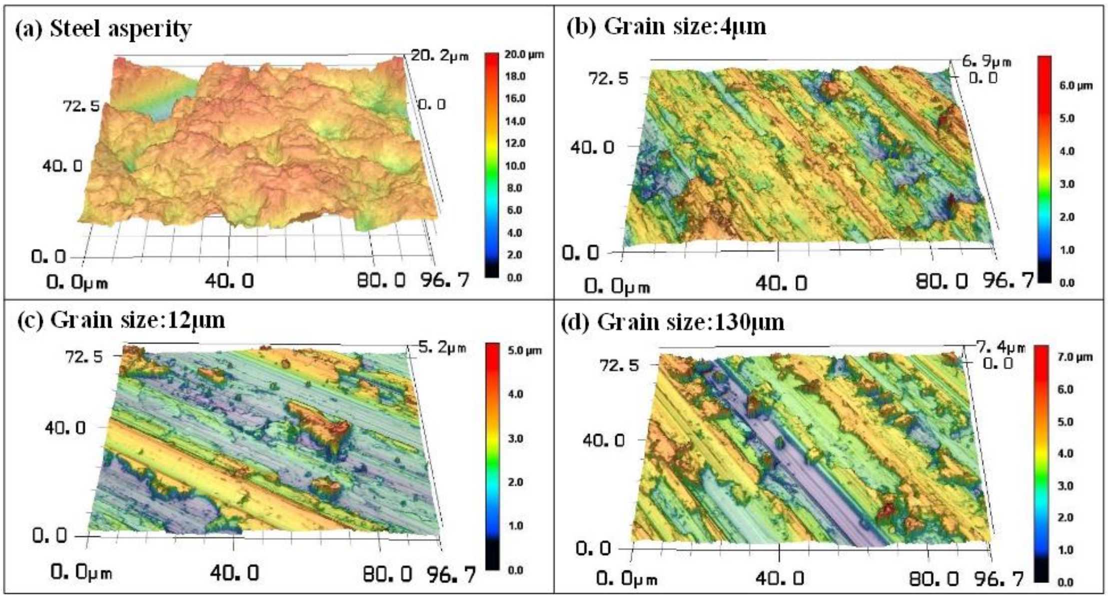


Fig. 15. Comparison of the surface topography after ploughing test

3.3.2 Theoretical analysis

To identify the mechanism of grain size effect on ploughing friction, theoretical analysis based on elastic-plastic deformation and fracture mechanics is conducted in this section.

The friction force is resulted from the force of steel asperity plowing the copper surface in ploughing process. According to contact mechanics, the steel asperity is assumed to be a rigid conical indenter and the copper surface is assumed to be a deformable flat. The friction coefficient for ideal rigid-plastic material is given as [55]

$$\mu_p = \frac{2}{\pi}\cot\theta \qquad (7)$$

where θ is the semi-angle of the indenter.

According to Eq., the ploughing friction coefficient only depends on the surface profiles of the rigid surface. However, recent studies have revealed that the mechanical property of the deformable material is another important factor that affects the friction coefficient. Bressan et al. [56] found that the coefficient of friction decreases when elasticity becomes more predominant and becomes zero when elastic deformation is the only deformation. Bucaille et al. [57] attributed this phenomenon to the elastic recovery, and adopted the rheological factor to measure the ratio between the deformation imposed by indenter and the part of the elastic deformation. The rheological factor is given by [57]:

$$X = \frac{E}{\sigma_0}\cot\theta \qquad (8)$$

When X is closed to 10, the deformation is mainly elastic, and if X>100, the deformation is mainly plastic.

By substituting the mechanical properties of the specimens used in this experiment into Eq. (9), it is found that for a common semi-angle smaller than 80 ^{o} , the rheological factors of the specimens used in this experiment are usually larger than 100. This means that elastic deformation is not the main reason for the grain size effect in ploughing of metals.

As material damage and abrasion are observed on the surfaces of the specimens (shown in Fig. 8), the fracture behaviors of copper is considered to be a main reason for grain size effect on ploughing behavior.

As is mentioned above, two modes of fracture, transgranular and intergranular fracture [58] are both available in friction process. When the indented depth is smaller than the grain size, ploughing only happens within the surface grains. The ploughing force mainly comes from the transgranular fracture of surface grains. However, if the indented depth is much larger than the grain size, the intergranular fracture becomes more dominating than the transgranular fracture, since it is easier for micro voids to generate and propagate at grain boundaries than inside the grains [59], and the stress needed to cause intergranular is thus smaller [60].

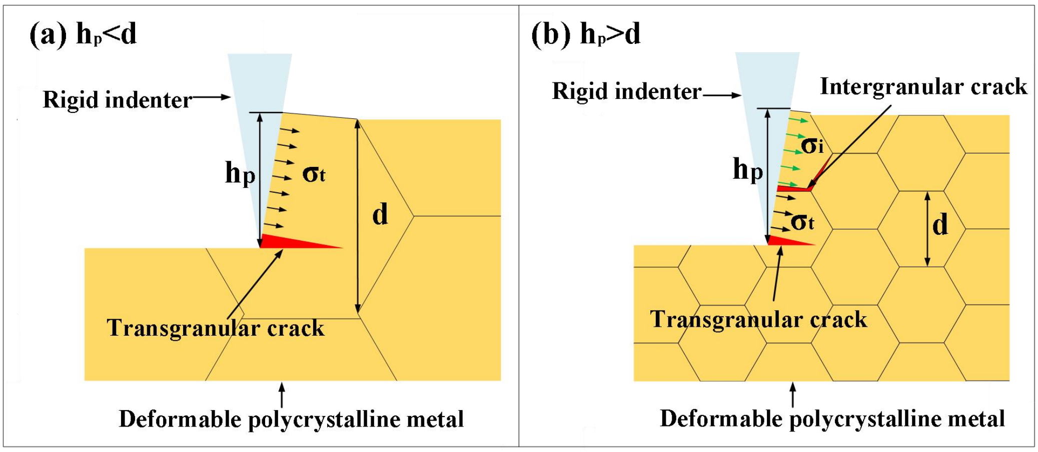


Fig. 16. Grain size effect on ploughing friction of polycrystalline metals

Fig. 16 shows the mechanism of grain size effect on ploughing friction for polycrystalline metals. With a given normalized normal load, the indented depth, hp, of the samples is almost the same. And its average value is around 6.5 μm according to Fig. 15 (b-d). For the samples with coarse grains, the grain size (d=132 μm) is much larger than the indented depth. Thus the damage only happens in the surface grains and the fracture mode should be transgranular fracture. For the samples with fine grains, as the grain size (d=4 μm) is smaller than the indented depth, intergranular fracture is dominating in the ploughing process. And for the samples with medium grains, both the two modes of fracture is effective, since the grain size (d=10 μm) is a little larger than the indented depth. With the increase of grain size, the fracture mode is transformed from intergranular fracture to transgraular fracture. Actually, the observations in Fig. 15 confirm this transformation. Since for intergranular fracture, cracks propagate along grain boundaries, and the fracture surface is always uneven. While, for transgranular fracture, cracks propagate within the grain, and fracture surface is smoother. That may be the reason for the difference in surface morphologies shown in Fig. 15.

To model the ploughing friction, σ_i and σ_t (shown in Fig. 16) are assumed to represent the intergranular and transgranular fracture strength, respectively. The average ploughing stress is obtained as:

$$\sigma_p = \lambda\sigma_t + (1-\lambda)\sigma_i \tag{9}$$

where λ is the proportion of the transgranular fracture. Apparently, λ is a function of grain size, d, and the indenting depth, h_p. For the cone-shaped rigid asperity, the maximum value of λ is

$$\lambda = \begin{cases} \dfrac{d^2}{h_p^{\,2}} & d \le h_p \\ 1 & d > h_p \end{cases} \tag{10}$$

Obviously, for a given indenting depth, λ increases with grain size.

According to the contact mechanics [61], the indenting depth depends on the mechanical properties of the deformable material and the normal load. Considering that only half of the cone is in contact when sliding initiates, the indenting depth is calculated as follows:

$$\begin{cases} F^{*} = \eta \dfrac{p}{\sigma_0} \dfrac{\pi}{2} \left(\dfrac{h_p}{\cot\theta} \right)^2 \\ \dfrac{p}{\sigma_0} = \dfrac{2}{3} \left[1 - \ln\left(\dfrac{E\cot\theta}{3\sigma_0} \right) \right] \end{cases} \tag{11}$$

where, p is the contact pressure on asperity. E and σ_0 are the young's modulus and yield stress of material. θ and η are the average semi-angle and the distribution density of rigid asperities.

Thus, the coefficient of ploughing friction is obtained in the following:

$$\mu_p = \frac{F_p}{F_N} = \frac{3\left[\lambda\sigma_t + (1-\lambda)\sigma_i\right]}{\pi\sigma_0\left[1 - \ln\left(\dfrac{E\cot\theta}{3\sigma_0}\right)\right]}\cot\theta \tag{12}$$

when $\lambda = 1$, it is effective on grain boundary, let equal Eq. equal Eq., and the following is obtained

$$\sigma_t = \frac{2}{3}\sigma_0\left[1 - \ln\left(\frac{E\cot\theta}{3\sigma_0}\right)\right] \tag{12}$$

If $\sigma_i = k\sigma_t$ $(k \in (0,1)$ is a material constant, the coefficient of ploughing friction can be written as:

$$\mu_p = \left[\lambda(1-k) + k\right]\frac{2}{\pi}\cot\theta \tag{13}$$

According to Eq., the coefficient of ploughing friction increases with λ. Hence, the coefficient of ploughing friction for coarse grained specimens is larger than the fine grained specimens.

To obtain the value of λ, the steel surface is simplified to be consisting of numerous conical asperities with the same height and semi-angle. The semi-angle of the rigid asperities is obtained by measurement of the surface profiles of the steel surface. And the value of θ is calculated by

$$\theta = \arcsin\left(\frac{\Delta x}{\int \sqrt{1 + \left(y'(x)\right)^2}\, dx} \right) \tag{14}$$

Here, y(x) is the profile of surface. Δx is the sampling length. In this experiment, the value of $\theta = 0.6$ rad is obtained. The value $\eta = 200/mm^2$ also is obtained by counting the number of the summits higher than 16 μm in Fig. 2(b).

By adopting the mechanical properties presented in Fig. 4 and the testing parameters listed in Table.3. and substituting Eq. into , parameter λ of the different grain sized specimens under different normalized normal loads is obtained (shown in Fig. 17).

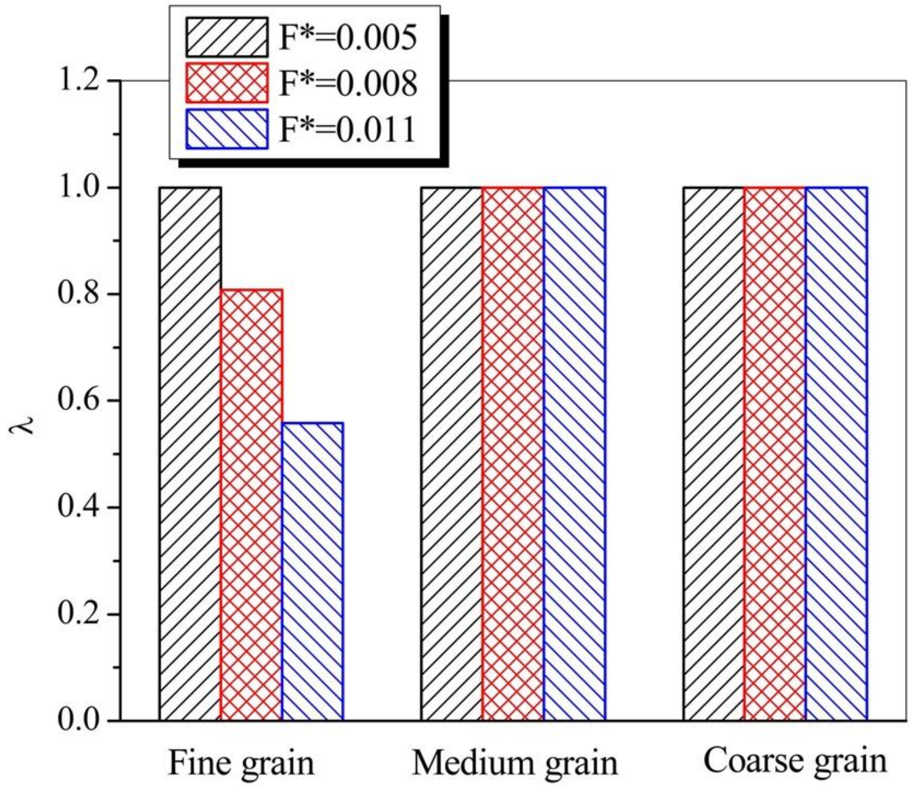


Fig. 17. The value of λ as a function of grain size and normal load

Fig. 18 presents the ploughing friction coefficient under the normalized normal load of 0.011 predicted by the present model (assuming k=0.8) as well as the Bucallie's and Gorddard's models. It is obvious that the grain size effect on the ploughing friction, which is almost neglected by the previous models, is predicted by the present model successfully. Using the present model, the predicted friction coefficient for the fine grained samples is significantly smaller than other samples, and the previous models fail to describe this phenomenon.

According to the present model, the friction coefficient of the samples with medium grains is the same as the coarse grained sample, since λ equals to 1 for both samples in testing condition. It is not consistent with the experimental results, as an increase of friction coefficient is observed in the experiment from the medium grain to coarse grains. According to the authors, this is caused by the uneven distribution of grain size in the deformable sample. In fact, small grains exist in the samples even when the average grain size is more than 100 μm . Therefore, the intergranular fracture is possible to happen even if the indenting depth is smaller than the average grain size, and as the average grain size increases, λ is close to but unable to reach 1 for polycrysitalline alloys.

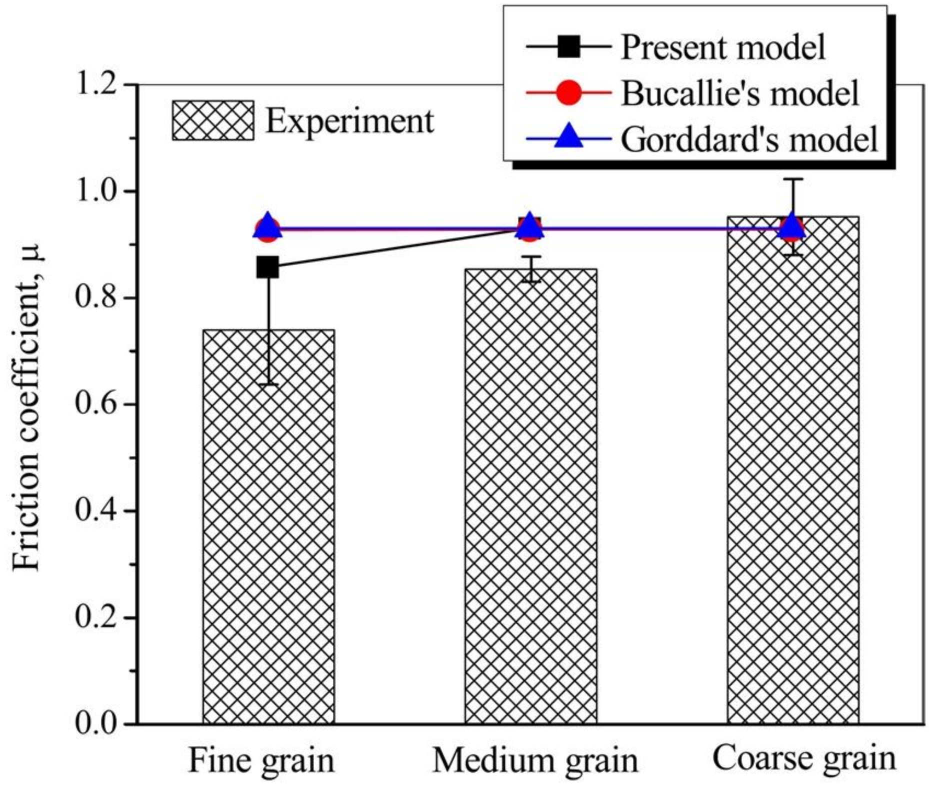


Fig. 18. The predicted ploughing friction coefficient under the normalized normal load of 0.011

This study is an experimental analysis of the mechanisms of grains size effect on friction behavior. Future works are needed in this field, such as the single-cone scratch test to find the evidence of cracks in ploughing friction, the accurate model of adhesive and ploughing friction behaviors based on the mechanisms of grain size effect, and the combination of these models to predict the friction behavior of real surfaces in metal forming process.

4 Conclusions

Adhesive and ploughing frictions are studied separately in this work to investigate the mechanism of grain size effect on the friction behavior of polycrystalline copper-steel combination using pin-on-disc friction test and theoretical analysis. The following conclusions are drawn from the research:

1. Grain size has an opposite effect on adhesive and ploughing friction behaviors. It is observed experimentally that the increase of grain size results in the decrease of coefficient of adhesive friction. But the coefficient of ploughing friction increases with grain size.
2. The main mechanism of grain size effect on adhesive friction is the increasing proportion of plastic deformation with the increase of grain size. The mechanical property that affect the friction coefficient is the ratio of $\frac{E}{H}$ or $\frac{E}{\sigma_0}$. With the

increase of normal load, the mechanism of friction is transformed from adhesion to ploughing.

3. The main mechanism of the ploughing friction is the transformation of transgranular and intergranular fracture of the softer material with the increase of grain size.

5 Acknowledgment

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