Hindawi Publishing Corporation
Advances in Tribology
Volume 2009, Article ID 648075, 4 pages
doi:10.1155/2009/648075

Research Article

Deformation of SS 304 LN during Scratch Test and Influence on Evolution of Coefficient of Friction

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Received 18 June 2009; Revised 22 September 2009; Accepted 24 September 2009

Recommended by João Paulo Davim

An AISI 304 LN nuclear grade forged, metallographically polished specimen was subjected to progressive load scratch tests using a spheroconical indenter at three different scratch speeds 1, 3, and 27 mm/min. The present study attempts to address the evolution of coefficient of friction with scratch speed invoking its correlation with scratch induced deformation in the specimen. At higher scratch speeds, plastic deformation rates were higher which caused friction coefficient to be of higher magnitude. This was correlated with dynamically obtained high resolution optical images that revealed deformation driven microstructural alterations. These alterations significantly influenced the evolution of friction coefficient which was intimately related to plasticity of the surface.

1. Introduction

The scratch test is a routinely used technique to measure the adhesive strength of coatings at the interface, but obtained results depend on many extrinsic and intrinsic parameters [1]. Scratch hardness, abrasion resistance and wear of bulk materials can also be evaluated using scratch test [2, 3]. The mechanical properties extracted during scratch test involve indentation of the material moving relative to the indenter. The normal indentation force can be kept constant or can be increased progressively. But, results obtained from the scratch test depend on a number of parameters like scratch speed, scratch length, loading rate, surface roughness and material properties [1]. These factors also influence the evolution of coefficient of friction during scratch test [4]. The friction is intimately related to both adhesion and wear which require an understanding of highly nonequilibrium processes occurring at the molecular level to determine what happens at the macroscopic level [5]. The hydrodynamic analysis [6] suggests that the enhancement in plasticity is controlled by the flow induced deformation occurring over the contact interfaces and also explains indentation induced local surface deformation. The tangential force record during scratch test provides a valuable and simple method for identifying the transitions in deformation modes [7]. The ratio between plastic and elastic deformation during a scratch test carried out with a Berkovich indenter is related to the ratio of elastic modulus to hardness of the specimen [8]. It is inferred from various studies [1, 3, 8–10] that the role of friction in material characterization via indentation test is still a challenging field of research in applied mechanics. Generally, scratch studies have been carried out to determine the adhesive strength of thin films [1]. There are reports in which scratch test has been used to induce deformation in thin films to understand the failure mechanisms [11, 12]. Less attention has been paid towards the study of deformation and evolution of coefficient of friction in case of bulk materials during progressive load scratch test. Therefore, it will be interesting to study the scratch induced deformation in bulk materials and its effect on the coefficient of friction which can be useful for cutting applications.

The present paper attempts to provide a comprehensive and precise picture on the effect of scratch speed on evolution of coefficient of friction during scratch test of stainless steel AISI 304 LN. Eventually, the resulting deformation and wear have been correlated with coefficient of friction.

2. Experimental

AISI 304 LN is chosen for scratch study due to its use in several technological applications. The scratch tests were performed on a mechanically polished AISI 304 LN specimen using a Revetest scratch tester (CSM Instruments, Switzerland). The surface roughness was measured to be 30 nm. A spheroconical diamond indenter with tip radius 200 μm was used as the scratching body. Normal load was applied progressively (in linear manner) from 1 N to 15 N and scratch length was kept constant at 3 mm for all the scratches. Scratches were conducted at three different scratch speeds, that is, 1, 3, and 27 mm/min. The tests were carried out in dry and unlubricated conditions. Frictional force and indenter penetration into the material were measured during each scratch test. After each test, residual scratch tracks were analysed through an optical microscope for observing the mechanical deformation in the material.

3. Results and Discussion

In Figure 1(a), it is shown that the ratio of residual depth (R_d) to total penetration depth (P_d), that is, plastic factor (P_f), is higher for higher scratch speeds (v_s). The plastic factor provides a scale of plastic deformation in the material. P_f is related to elastic recovery (E_f) in accordance with the following equation:

$$E_f = \frac{(P_d - R_d)}{P_d} = 1 - \frac{R_d}{P_d} = 1 - P_f; \quad E_f + P_f = 1. \quad (1)$$

Equation (1) shows a simple relation that larger plastic deformation is accompanied with reduced elastic recovery. The growth values of P_f are 0.17, 0.26, and 0.6 for scratch speeds 1, 3, and 27 mm/min, respectively.

Figure 1(a) depicts that the increase of v_s from 1 to 3 mm/min has marginal effect on P_f. However, the average value of P_f grows significantly to 0.6 for 27 mm/min which is nearly 4 and 2 times higher than the value obtained for speeds 1 mm/min and 3 mm/min, respectively. In Figure 1(b), it is shown that for all v_s, friction force linearly increases with progressive normal load indicating plastic deformation of the material. The loading rate is higher for higher scratch speed leading to faster energy dissipation in the material. Similar behavior is observed for coefficient of friction (μ) with progressive normal load as shown in Figure 1(c). For scratch speeds 1, 3, and 27 mm/min, the average values of μ obtained are 0.3, 0.4, and 0.9, respectively. The coefficient of friction μ is nearly constant for lower scratch speeds but for higher scratch speeds, μ relatively increases with progressive normal load. Also, μ is found to be the same at low loads for all the three scratch speeds. But the load, at which μ shows a deviation, decreases with increase in scratch speed. This can be explained on the basis of higher rate of dissipation of energy at higher scratch speed as same

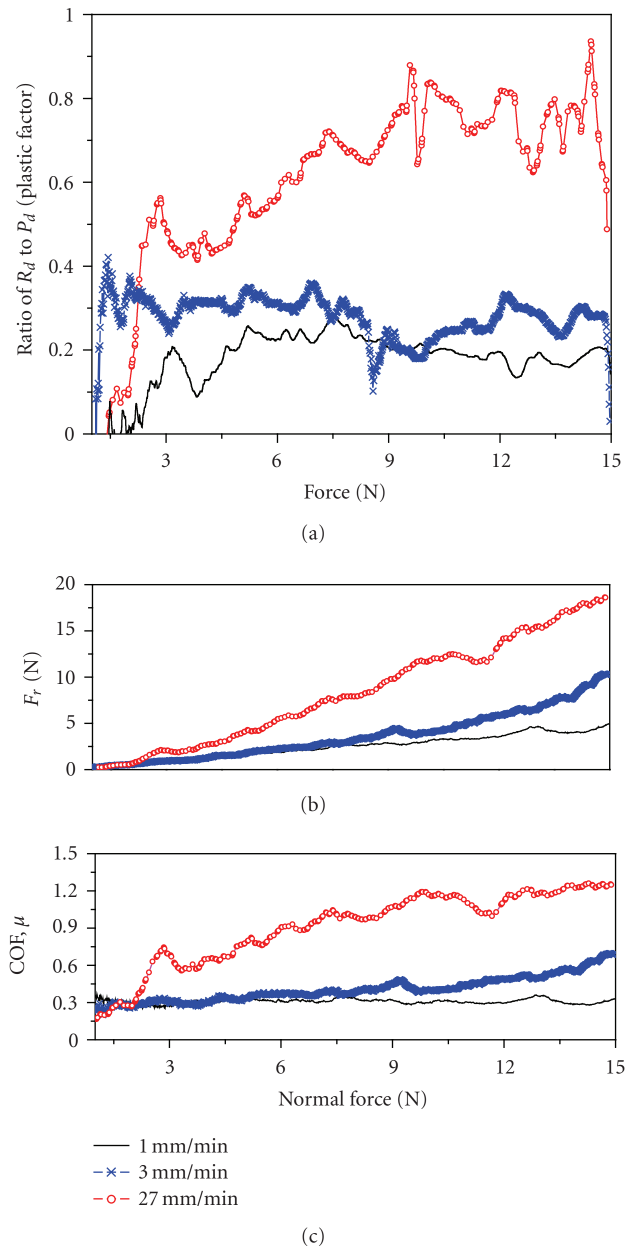

Figure 1: (a) The ratio of residual depth to penetration depth for progressive load ranging between 1 N to 15 N at three different values of scratch speed v_s = 1, 3, and 27 mm/min, (b) frictional force with progressive normal force acting on to the material SS AISI 304, and (c) the evolution of coefficient of friction μ for scratch speed v_s = 1, 3, and 27 mm/min.

load is applied in lesser time leading to higher strain rate imposed on the material. This also leads to an increase in μ at higher loads. The sudden jump in μ at highest speed could indicate towards the change in wear mode which is discussed later.

The friction and surface damage between clean sliding metals is significantly affected by the deformation properties of the metals [13]. In contrast to experimental results, it can be defined that frictional force is the driving force to

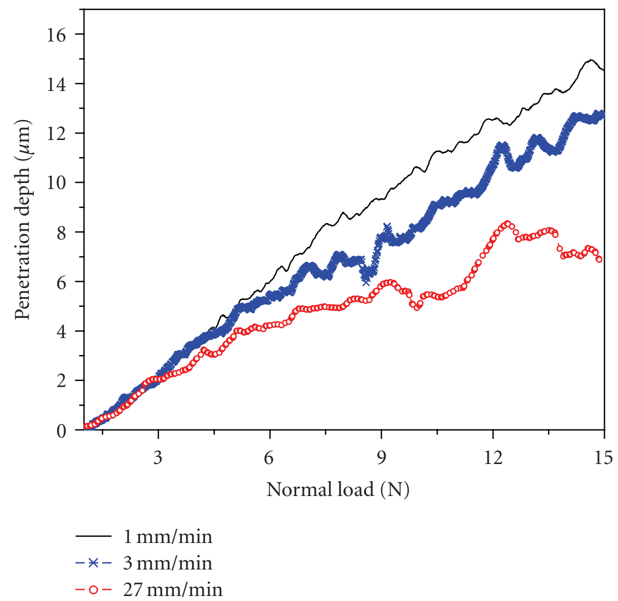

FIGURE 2: Indenter penetration depth at three different scratch speeds with increasing normal load.

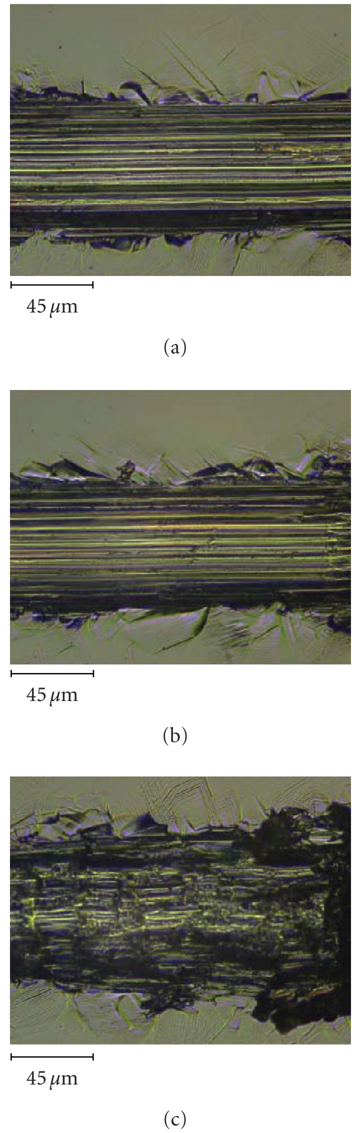

FIGURE 3: Residual scratch profiles of SS AISI 304 at scratch speed (a) 1 mm/min, (b) 3 mm/min, and (c) 27 mm/min at progressive load ranging between 1 N to 15 N for constant sliding distance of 3 mm.

detect the scale of deformation into the material. The rate of plastic energy dissipation is more in the case of higher coefficient of friction. The energy dissipation is a function of scratch speed which is proportional to the coefficient of friction by the energy loss $E = F \cdot s$ and $F = \mu N$ where F, N, and s are frictional force, normal load, and scratch distance, respectively. It has been shown that the classical law of friction $F = \mu N$ is dependent on plastic deformation of the asperities in contact on the rubbing surfaces [14] but significant rise in friction of bulk metallic glasses reveals unstable deformation via increased adhesion [15].

The indenter penetration measured during scratch tests for different scratch speeds is shown in Figure 2. It has been observed that scratch depth is decreasing significantly with rise in scratch speed along the length of scratch. The decrease corresponds to an increase in hardness of the material. This can be attributed to scratch induced strain hardening in the material which resists indenter penetration at higher speeds. The strain hardening also affects lateral motion of indenter during scratch causing increase in tangential force with substantial increase in scratch speed, shown in Figure 1(b). It is shown that with the change in interface shear strength between the indenter and material due to scratch speed, the wear and coefficient of friction also exhibited a change. This behavior explains the severe plastic deformation for increased scratch speed.

Figure 3 shows optical micrographs of scratch tracks revealing the extent of deformation for different scratch speeds. Figures 3(a) and 3(b) depict that in the case of lower scratch speeds, grooves parallel to the sliding direction are formed. Such features are characteristics of abrasion, in which hard asperities of the indenter counterface with the material. The abrasion was induced primarily through ploughing, in which material were piled up on either side of the scratch groove without material removal from the scratch zone. In contrast, grooves disappeared for higher scratch speed as shown in Figure 3(c). This may be explained by the shear fracture of the material at higher speed resulting in debris formation which indicated adhesive nature of wear. Also, the magnitude of damage was higher in the case of high stress abrasion (highest scratch speed) but the depth of the damage is less due to higher strain hardening, as discussed earlier. It has also been observed that progressively increasing load accelerated the plastic deformation along with scratch speed which contributed to the rise in coefficient of friction.

The correlation of coefficient of friction with the extent of deformation reveals its higher value at increased scratch speeds. Briscoe et al. have mapped deformation regimes of polymers and also found a good correlation with friction coefficient [16]. The higher value of friction force denotes larger plastic deformation (damage) with increasing scratch speed for AISI 304 LN as shown in Figure 3. At low loads, it was found that rubbing behavior was dominating where only smooth scrtach groove is seen. At higher loads, wear was found to be the dominating deformation mode where material was worn out as clear from the optical micrographs (Figure 3) of residual tracks. Same behavior has been observed by Adler and Walters where SS 304 was tested under single scratch with three different normal loads [17]. In our case, load is increasing linearly from 1 N to 15 N during a single scratch. This can help in understanding the wear behavior of SS 304 during a single experiment. The deviation in coefficient of friction, obtained at different speeds, at higher loads could be due to change in deformation mode to wear with increasing scratch speed. Interestingly, the deviation was found to take place at early stages as the speed was increasing, as shown in Figure 1(c). It is due to dependence of coefficient of friction on strain rate which increases with increase in scratch speed. Also at higher strain rates, the indenter pushes the material into more localized stress fields leading to change in deformation mode as observed in the present case [16].

It is revealed that the influence of coefficient of friction is an important aspect related to plastic deformation and consequent strain energy dissipation. Generally, as the interfacial shear strength increases the abrasive wear rate of the material decreases. However, the balance between the deformation mechanisms which control this shear strength (fracture, plasticity, deformation) changes as the substrate hardness increases due to strain induced hardening and strain energy variations during different scratch speeds.

4. Conclusions

The present results show the significant effect of plastic factor on coefficient of friction which is found to be directly linked to the deformation of the specimen material. At higher scratch speed, severe plastic deformation was observed which caused transition in wear mode from abrasive to adhesive. Higher scratch speed led to increased strain rate. The increased plastic deformation and strain hardening led to an increase in coefficient of friction with increase in scratch speed and load. It is also found that increasing scratch speed can lead to severe deformation modes at low loads due to higher strain rates. Therefore, it can be concluded that scratch speed is a determinsitic parameter in scratch test which can affect the surface and subsurface deformations.

Acknowledgments

The authors thank Dr. C. S. Sundar for his valuable reviewing and Dr. Baldev Raj for encouragement.

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