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THE EFFECT OF TEMPERATURE AND STRAIN RATE ON THE ABRASIVE WEAR OF METALS

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Abstract: *The work reported in this paper derives its value from the fact that the development of metallic materials are alloys with high resistance to wear depending to a certain degree on devising a successful method of defining their wear resistance and its relation to speed and temperature. It deals with the effect of temperature and strain rate on the abrasive wear rate.*

Abrasion wear tests were carried out using pins of different ductile metals abraded by different grades of SiC abrasive papers, using a conventional pin-on-disk apparatus. The tests were carried out at different surface temperatures, sliding speeds, and constant load.

The effect of grit size on the removal rate was measured at different surface temperatures and sliding speeds. The abrasive wear rate increased rapidly with the grit diameter size of the SiC abrasive particles up to a certain grit diameter, above which the wear rate increased slowly and then remained constant. This occurred at a critical grit diameter of about 115 μm. Sliding speed and temperature variations had no effect on the value of the critical grit diameter for all the tested metals and alloys investigated. Increasing the sliding speed within a low range caused a slight decrease in wear rate, which is attributed to the effect of strain rate on the mechanical properties of the abraded metals, at a constant temperature. Increasing the surface temperature within a low range of strain rate caused slight increase in wear rate which may be attributed to the softening of metals and, thus, changing their mechanical properties.

In general, an increase in strain rate is equivalent to a decrease in temperature, from the point of view of metal removal rate.

Keywords: *abrasive wear, grit size, temperature effect, strain rate effect.*

1. INTRODUCTION

1.1 Mechanism of Abrasive Wear

Abrasive wear occurs in direct physical sliding contact situations between two surfaces, and results when one of the surfaces is considerably harder than the other. The harder surface asperities press into the softer surface with plastic flow of the softer surface occurring around the asperities. When tangential motion is imposed the harder surface will move, ploughing and removing the softer material.

Abrasive wear may be due to various mechanisms which cause surface destruction such as cutting, scratching and single or multiple plastic deformations.

Adhesion also plays a role in the abrasion process [1]. Very frequently when grits are in contact with various metals in the clean state, metals adhere to the grit surfaces; adhesive transfer as a result of adhesive grits, occurs with transfer of the metal to the abrasive grits. When this happens on a very large scale with very chemically active metals, the cutting surfaces become charged with metal. At this point, the cutting surface must be cleaned in order to renew the effectiveness of the cutting or polishing.

Abrasive wear as a useful form of wear is very largely found in material finishing operations. The two-body type of abrasive wear is achieved by files, abrasive paper, abrasive cloth, and abrasive wheels, whereas the three-body type of wear is found in lapping and polishing processes.

1.2 Validity of simple model for abrasive wear

A simple model for abrasive wear has been proposed by Rabinowicz [2]. He assumed one surface to consist of an array of hard conical asperities all with the same semi-angle θ. The second surface, being flat is the softer one. By considering a single asperity, under load P the abrasive cone penetrates the softer surface of hardness H to a depth z. From Fig. (1) it is observed that:

$$z = r \tan \theta \quad (1)$$

$$H = P / \pi r^2 \quad (2)$$

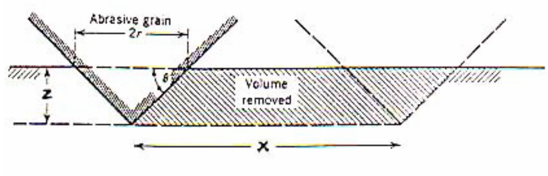

Figure 1. Abrasive wear model

The volume V of the surface material removed during a horizontal motion x of the cone is a prism of base area rz and height x. Thus:

$$V = r\,z\,x = r^2\,x \tan \theta \quad (3)$$

Substituting equation (2) into equation (3) gives:

$$V = \frac{Px \tan \theta}{\pi \cdot H} \quad (4)$$

In practice usually the abrasive cones have different angles, and thus a statistical average value tan $\bar{\theta}$ may be selected to represent a given abrasive surface. By replacing (tan $\bar{\theta}/\pi$) by (K_a) the previous equation becomes:

$$V = K_a \frac{Px}{H} \quad (5)$$

where K_a is a dimensionless abrasive wear coefficient.

The above derivation is appropriate to two-body abrasive wear. In the case of three body abrasion, the same form of equation will hold, but K_a will be lower, since in this case many of the particles will tend to roll rather than slide. Rabinowicz[3] stated representative values of the wear coefficient K_a with the range about (0.02-0.2) for two-body abrasive wear and about (10^{-3}-10^{-2}) for three-body abrasive wear. Although this equation is based on a simple model, it does express some of the basic observations of two-body abrasive wear. The volume of material removed is generally directly proportional to the load, to the distance travelled and is in general inversely proportional to the hardness of the surface of annealed metals. This particular prediction of the model, though apparently satisfied in the case of annealed pure metals, is hardly followed in the case of quenched and tempered carbon steels or age-hardened aluminium and copper based alloys [4-6].

Larsen-Badse [7] attempted to overcome the limitations of this simple model by proposing that the wear rate is dependent not only on the bulk hardness, but also on its strain-hardening capacity. However, this postulate has not been incorporated in a quantitative fashion in an abrasive wear model.

Another approach which takes into account many of the important material parameters which influence abrasion is that due to Athins [8]. He suggested that the abrasive wear rates should be correlated with the elastic modulus, the material fracture toughness, the yield strength and some other parameters.

1.3 Effect of Temperature and Strain Rate on Mechanical Properties of Metals

Experimental data for various metals are available for the flow stress as a function of strain rate and temperature. However, these results are usually confined to relatively small strains. There is little, if any information on the effect of high strain rates and elevated temperature for the large strains expected in abrasion.

When a material is deformed elastically, the energy required for the operation is stored in the material as strain energy and no heat is generated. However, when the material is deformed plastically, there is a generation, movement and interlocking of dislocations. The greater the degree of deformation the large number of dislocations produced, and because of their mutual interaction and obstruction, larger stresses are required to enforce their movement and hence causing further plastic flow; broadly this explains work hardening.

Above a certain slightly indefinite temperature, the recrystallization temperature T_r, a metal may be worked and after a certain small strain, it becomes no harder as the amount of strain imposed is increased. The yield stress during, say compression, would remain constant [9]. A balance would have been established between the tendency to work-harden and the tendency to soften, these two competing tendencies are concurrent. The concurrency first seriously occurs over a narrow range of temperature near T_r. Below this range, as has been remarked, the material hardens during straining, but above it the yield stress is constant, therefore, highly strain rate dependent.

There is little information on the effect of high strain rates and elevated temperature for the large strains expected in abrasion. For example, Moore [10] observed that in two-body abrasive wear the shear strain γ near the surface was 4.3. Larsen-Badse [7] estimated the shear strain in two-body abrasive wear to be about 8.3. Information is available for copper for large strains applied at modest strain rates to specimens originally at ambient temperature. An attempt shall be made to apply this and other information to make qualitative predictions for the flow stress in abrasion.

Lindholm et al [11] carried out torsion tests in which shear strain up to 7 was reached. He showed the shear stress-strain curves at different strain rates for pure copper initially at room temperature. He found that at high strain rates the strain hardening tends to decrease at large strains. The cause of the gradual loss in strain-hardening capacity is attributed to the retention of the heat generated by plastic work.

During plastic deformation, most of the energy used for the operation is converted into heat. If a large strain is developed at a high strain rate, then the plastic deformation is virtually adiabatic and there will be a significant temperature rise in the deforming region. An estimate of the adiabatic temperature rise during plastic deformation is given by

$$\rho \, c\Delta T = \alpha \int_0^{\gamma} \tau \;\, d\gamma \qquad (6)$$

where ΔT is temperature rise, α is a material constant, ρ is the density, γ is the shear strain, c is the specific heat and τ is the shear stress.

Johnson et al [12] obtained the following expression relating shear stress, shear strain, shear strain rate and temperature for the stress-strain curves given in reference [11].

$$\tau = \mathrm{K_T}\ (0.069 + 0.106\ \gamma^{0.32})\left\{1.0 + 0.027\ \mathrm{Ln}\left(\frac{\dot{\gamma}}{\dot{\gamma}_0}\right)\right\} \mathrm{x}10^3 \qquad (7)$$

where τ (MPa) is the shear stress, γ is the shear strain, $\dot{\gamma}_o$=1 (s^{-1}) is the shear strain rate and K_T is a factor used to adjust the stress for temperature effects.

Johnson's et al results are for a material initially at ambient temperature. An attempt to use them to deduce stress-strain curves for higher initial temperatures was made by Soemantri et al [13] by substituting equation (6) into equation (7) and integrating over a range of γ leads to

$$\Delta T = \frac{\alpha K_T}{\rho c}\,(0.069\ \gamma + \frac{0.106}{1.320}\ \gamma^{1.32})\left\{1.0 + 0.027\ \mathrm{Ln}\left(\frac{\dot{\gamma}}{\dot{\gamma}_0}\right)\right\} \mathrm{x}10^3 \qquad (8)$$

They predicted shear stress-shear strain curves for pure copper at different initial temperatures and shear strain rates.

The effect of very high strain rates on mechanical properties can be found in reference [14]. For the relationship between the strain rate and the flow stress at different temperatures, it was found that the effect of strain rate becomes pronounced only when the strain rates exceeded 10^4 s^{-1}. In this range the curves appear to be that flow stress becomes insensitive to the change in temperature. A similar behaviour can be found in reference [15], where at approximately the same range of the shear strain rate, the shear stress becomes insensitive to the change of the shear strain.

For the effect of the strain rate and temperature together [16], it was shown that an increase in strain rate is equivalent to a decrease in temperature. It was also seen that the hardness of copper and aluminium decrease with increasing homologous temperature (T_h) defined as the test temperature divided by the melting temperature; both in Kelvins

2. EXPERIMENTAL

One of the configurations for the study of a friction and wear is the pin-on-disc apparatus which was employed in the present work. The principle of operation of the apparatus consists of loading a vertical stationary pin against a horizontal rotating disk holding the abrasive paper. Some modifications were made on the apparatus to facilitate the heating of the specimen to the required surface temperature. Other standard devices were used to measure the test parameters and also for calibrations.

The motion is transmitted to the disc holding the abrasive paper by a motor through the following parts:

a. Electrical motor drive, induction type, three phase, 380 V, 50 Hz, 15 h.p. and maximum speed of 2930 rpm.
b. Five speed gear box.
c. Two universal joints connecting the gear box to the bevel gear.
d. Bevel gear with a speed reduction of 1:3.33
e. Steel disc of 225 mm diameter for supporting the abrasive paper fixed to the output shaft of the bevel gear.

The pin-on-disc arrangement is supported on a substantially rigid steel table (190 x 65 cm) with four (120 cm) high legs. The steel table, motor, gear box and bevel gear are firmly fastened to a concrete foundation which helped to damp out the vibration that may be induced during operation. The motion is transmitted from the motor to the steel disc through a belt drive system, gear box, universal joints, bevel gear and its output shaft. The bevel gear output shaft, which is at 90^o with the input shaft, is positioned vertically through the steel table and is supported by a ball-bearing fastened to the steel table. The steel disc is coupled to the end of the output shaft by four bolts and chuck nuts. It rotates in a horizontal plane parallel to the steel table. The abrasive paper is firmly fixed between the steel disc and steel annular ring fastened by three bolts to a horizontal guard to avoid tearing or slipping of the abrasive paper.

2.1 Heating and Temperature Measurement

A steel plate of (30 x 30 cm) was fixed on the table to hold the heating arrangement which consists of supporting shaft, a heating drum holder, and a heating drum. The heating drum used is one phase, 250 V, 50 Hz, 0.375 kW, and maximum operating temperature of 900 °C. The heating drum holder enables the heating drum to rotate and to change the horizontal distance between the drum and the supporting shaft by using two positioning bolts.

The specimen holder arrangement consists of a thin elastic beam with a rectangular cross-section of (3 x 25 mm) and a length of (65 mm). The beam was firmly fixed at one end to the supporting shaft and the other end was simply supported. A slider was used to hold the test specimen that allowed it to slide along the steel beam. The slider consists of a steel shaft with one end holding the test specimen and the other to protrude into the heating drum. The slider position may be adjusted in order to give the required speed. The heat was transmitted from the heating drum through the slider and hence to the test specimen by conduction. Although this kind of heating is slow because heat loss from the heating drum and the specimen holder to the surroundings. However, it provided a good stability in the temperature of the specimen. To measure the surface temperature of the test specimen, a digital thermocouple was used. The sensor was placed horizontally on the specimen surface facing the abrasive paper.

2.2 Sliding Speed Measurement

The rotational speed of the disc was adjusted by the driving pulley on the motor, the driven pulley and the gear shift lever on the gear box. For the rotational speed of (51 rpm), the slider position was varied along the radius of the disc and a linear sliding speed in the range of (120-375 mm/s) was obtained between the test specimen and the abrasive paper.

To maintain almost identical abrasive conditions throughout, the number of revolutions for all the tests ought to be the same. The duration of a test was kept constant at (60 sec.).

3. EXPERIMENTAL PROCEDURE

The abrasive wear tests were performed on four types of common metals which are low carbon steel, copper, brass and aluminium. The wear test specimens were made cylindrical of (5 mm) diameter and (50 mm) in length. They were abraded on (SiC) abrasive papers with grit size of (68, 81, 115, 220, 450μm) and the applied load used was (15 N).

For each grit size of the abrasive paper used in the tests, the specimen was first run-in for a sliding distance of a few meters in order to ensure the steady state conditions in the abraded surface. The weight loss in the test specimen was measured at surface temperature of (ambient, 50, 100, 150, 200°C) and for sliding speeds of (150, 200, 250, 300, 350 mm/s). Special care was taken to prevent heat build-up in the specimen due to frictional heating.

The average of three consecutive abrasion test measurements were taken for each value of surface temperature and sliding speed. From the weight loss, density of the abraded metals, and the sliding distance, the volumetric metal removal rate could be obtained as volume removed per meter of sliding distance. The weight loss was measured using a twin-scale balance with an accuracy of (± 0.1 mg). The specimen was weighed before and after each abrasion test.

4. RESULTS AND DISCUSSION

To study the influence on surface temperature on metals tested in two-body abrasive wear graphs were plotted to show the following relationships:-

a. The volumetric removal rate versus the abrasive grit size at different temperature, Figs. (2a & 2b).
b. The volumetric removal rate versus the temperature at different sliding speeds, Figs. (3a & 3b).
c. The volumetric removal rate versus grit size at different sliding speeds, Figs. (4a & 4b).

The four metals tested for the influence of strain rate and temperature resulted in a large number of graphs and in this paper only some typical plots will be shown.

5. CONCLUSIONS

From the results presented, the following conclusions may be drawn:

a. The abrasive wear rate of metal increases rapidly with the grit size of the SiC abrasive particle up to a critical diameter, above which the wear rate remains constant. This critical grit diameter was found to be almost close to 115 μm.

b. Sliding speed and surface temperature variations have no effect on the value of the critical grit diameter for all the metals investigated.
c. Increasing the sliding speed within a low range causes a slight increase in wear rate. It is attributed to the effect of strain rate on the mechanical properties of the abraded metals. This is true only when the metal temperature remains constant during abrasion.
d. Increasing the surface temperature within a low range of strain rate causes slight increase in wear rate. This may be attributed to the effect of softening the metals and thus changing their mechanical properties.
e. An increase in strain rate is generally equivalent to a decrease in temperature from the point of view of metal removal rate.

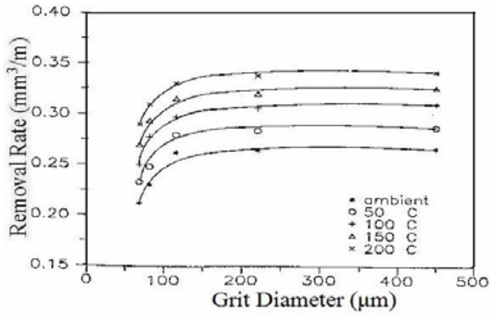

Figure 2a. Variation of abrasive grit diameter with removal rate at different temperatures for a steel.

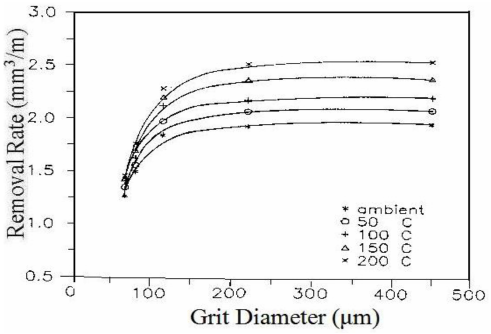

Figure 2b. Variation of abrasive grit diameter with removal rate at different temperatures for aluminium.

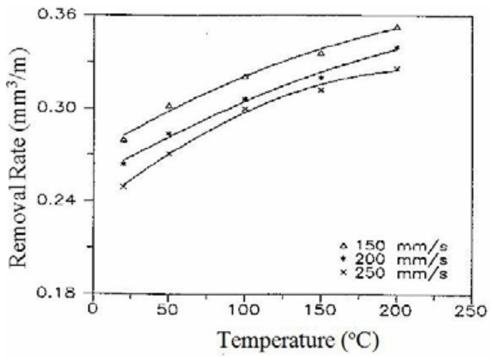

Figure 3a. Variation of temperature and removal rate at different sliding speeds for steel.

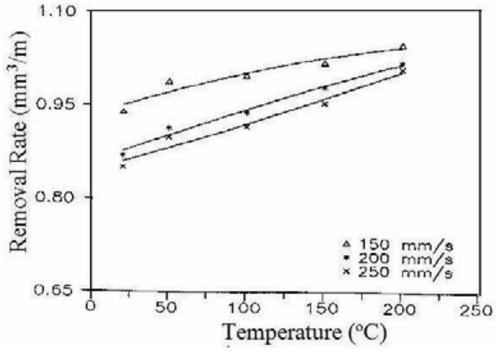

Figure 3b. Variation of temperature and removal rate at different sliding speeds for brass.

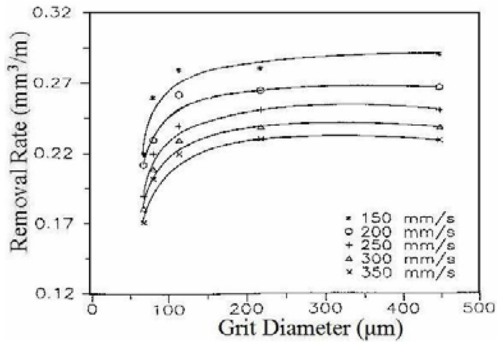

Figure 4a. Variation of abrasive grit diameter with removal rate at different sliding speeds for steel.

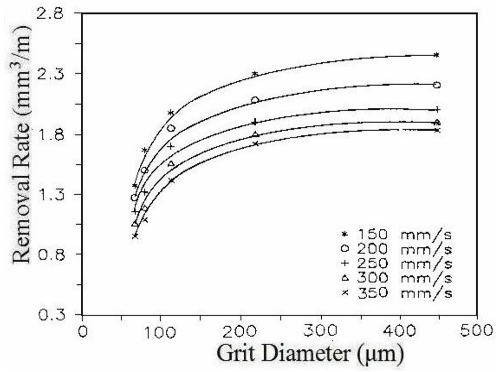

Figure 4b. Variation of abrasive grit diameter with removal rate at different sliding speeds for aluminium.

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