EFFECT OF ABRASIVE PARTICLE SIZE ON WEAR RESISTANCE IN NON-HEAT-TREATED STEELS

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The effects of abrasive particle size on wear resistance have been studied extensively. But, none of these studies is completely satisfactory for finding the relation between the abrasive particle sizes and wear rate. The abrasive wear resistance of non-heat-treated steels has been determined by using a pin-abrasion machine having five abrasive papers ground on a small pin of the test materials. The mass loss of test material during abrasive wear was determined gravimetrically. The results for the non-heat-treated steels show that there is a parabolic relation between the wear coefficient and abrasive particle size. This agrees with similar findings in the literature. There is a linear relationship between the abrasive wear resistance and hardness, depending on abrasive particle size. However, the relative wear resistance and hardness are related linearly for non-heat-treated steels, and this relationship does not depend on abrasive particle size.

From the findings, the empirical mathematical wear resistance model as a function of abrasive particle size is derived. Additionally, the empirical equations of the relative wear resistance of these steels as a function of abrasive particle diameter are formulated.

Key words: abrasive wear resistance, wear coefficient, abrasive particle size, relative wear resistance

1. Introduction

Abrasive wear experiments have been made with substances containing one or more abrasive. Abrasive statements, which are obtained through single abrasive end patterns (i.e. sphere, pyramid, cone) are adapted to abrasive wear cases with abrasive particle more than one based on some assumptions. The abrasive particle is generally modelled as a cone [1]. Rabinowicz [2] derived a simple expression for

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the volume of material removed during two-body abrasion by a conical abrasive particle:

$$\frac{V}{L} = \left(\frac{2\tan\alpha}{\pi}\right)\left(\frac{F_{\mathrm{N}}}{H}\right), \tag{1}$$

where V is the volume loss due to wear, L is the sliding distance, F_{N} is the normal load on the conical particle, H is the hardness of wearing surface and α is the attack angle of the abrasive particle.

For linear wear intensity, Eq. (1) can be written as follows [1, 3]:

$$W = k\frac{P}{H}, \tag{2}$$

where W is linear wear intensity, k is wear coefficient, P is pressure applied on surface and H is hardness of abraded material.

For pure metals and annealed steels, the wear resistance versus hardness is a line passing through the origin. The linear zone is called zone I throughout the paper. The abrasive wear resistance versus hardness graph of the heat-treated steels is a line not passing through the origin [3]. This behaviour cannot be derived from Eq. (2). The zone corresponding to this is called zone II. The zones II and I are shown in Fig. 1 [1, 4]. Equation (2) is similar to the Archard's adhesive wear expression. Generally, Eq. (2) does not agree with the experimental results. The main reason for this incompatibility are the changes of wear coefficient k depending

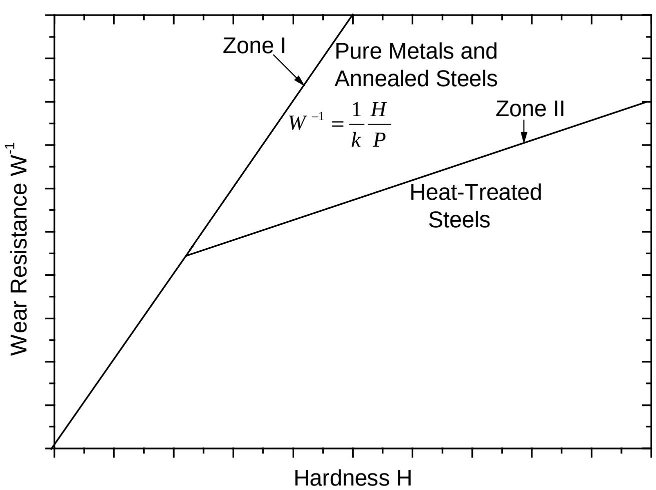

Fig. 1. Relationships between wear resistance and hardness [1, 4].

on abrasive grit size [5, 6]. In literature, there are many investigations about the effect of the abrasive grit size on abrasive wear rate in zone I. Avient et al. [7] have examined the abrasive behaviour of many materials and realized that the clogging of the interstices between the finer abrasive grains by wear debris is responsible for the grit size effect. This decreases the number of abrasive grains, which contact the surface and remove material, thus decreasing the abrasive wear rate. Mulhearn and Samuel [8] studied samples of silicon carbide (SiC) abrasive papers. They believe that the mechanical properties of coarse and of fine abrasive grains are different, and that the fine grains have a needle-like shape and contain many cracks, thus breaking up more readily. In this way, abrasive wear rate becomes zero, because small grains are flattened. Rabinowich and Mutis [9] have aimed an account of the size effect using adhesive wear particles. Using a surface energy criterion, they theoretically show that the critical abrasive particle size is a function of the adhesive particle size of the material being worn away. Sin et al. [5] have used the critical depth of penetration to explain the effect of grit size on abrasive wear loss and have found that there was not a critical abrasive particle size for a specific material. They also showed that the constant wear rate starts at 80 μm abrasive particle size for all metals used in the experiments. The elastic contact hypothesis was first suggested by Larsen-Badse [10] who measured the size and number of grooves formed on polished copper specimens abraded by SiC abrasive papers and estimated the real contact area. He postulated that many fine grits have elastic interaction with the surface. It was also suggested that the fraction of the load carried by particle in elastic contact increased with decreasing grit size since it is unlikely that the abrasive grits gradually become more angular with increased size. Moore and Douthwaite [11] have tried to explain the size effect by plastic deformation concept below worn surfaces. They estimated the equivalent plastic strain and the flow stress as a function of depth below worn surface and calculated the work done in deforming the material below the groove and energy absorbed in ploughing the surface. They concluded that the energy expended in plastic deformation of material to form the grooves and deform the surface account for almost all the external work done for all grit sizes in abrasion and that wear volume is dependent on the grit size probably because the deterioration and pick up of abrasive particles becomes more intense at small grit sizes. Hutchings [12] has stated that the size effect is due to the variation of shape changing rate dependent to abrasive particle size. However, Misra and Finnie [13] have found that the shape-changing rate has only changed the wear resistance, and has no effect on the dependence of abrasive particle size. Khruschov [14] has studied experimentally the zone I in a stationary abrasive particle size using the pure metals and annealed steels and he found the relative wear resistance – hardness relationship for metals as follows:

$$\varepsilon = bH, \qquad (3)$$

where ε is the relative wear resistance, b is a constant coefficient and H is the initial hardness.

There are numerous explanations in the literature to explain the abrasive grit size effect. However, most of them have been insufficient since they have not been able to explain the grit size effect encountered in all abrasive wear mechanisms (e.g. erosive wear) [15].

The aim of this article is to investigate the effect of abrasive particle size on abrasive wear resistance in zone I and to develop the equations of empirical abrasive wear resistance connected to abrasive particle size. Moreover, to search for the effects of relative wear resistance in zone I and to develop the equations of empirical relative wear resistance connected to abrasive particle size.

2. Experimental procedure

The steels AISI 010, 1030, 1040, 1050 and 50CrV4 were used in the study. The chemical compositions of these samples are given in Table 1. The specimens were in the form of cylinders of 9 mm diameter and 3 mm height. The samples were ground with abrasive papers grading from 80 to 800 meshes and then polished with 0.3 μm diamonds. The hardness was measured by the Vickers hardness method in load of 98.0865 N (HV 10). The average of measurements and the standard deviations were calculated. The average hardness values and standard deviations are given in Table 2. Wear experiment was carried out on the pin-abrasion testing machine shown in Fig. 2; tambour diameter $D = 118$ mm, tambour rotation $n = 1000$ rpm and abrasive wear set-up rate $V = 6.18$ m$\cdot$s^{-1}. In wear experiments, the 180, 125, 85, 70 and 50 μm alumina (Al_2O_3) abrasive paper in sizes 100 $\times$ 1150 mm was used. For wear experiments, the apparatus in Fig. 3 was mounted on the pin-abrasion testing machine. In order to fix the samples within apparatus in Fig. 3, the cylindrical copper bars of 50 mm in length and 20 mm in diameter have been used. In order to prepare the specimens for abrasive wear test, holes of 9 mm in diameter and 1.5 mm in depth were milled on one end of the copper bars through which the specimens were replaced. On the other end, a hole of 14 mm in diameter and 25 mm in depth was drilled in order to balance the sample. An

Table 1. The chemical compositions of experiment sample [wt.%]

Alloys	C [%]	Si [%]	Mn [%]	P [%]	S [%]	Cr [%]	Mo [%]	Ni [%]	Al [%]	Cu [%]	Ti [%]	V [%]
1010	0.107	0.11	0.413	0.019	0.025	–	0.003	–	0.032	0.031	0.002	–
1030	0.328	0.069	0.673	0.015	0.019	–	0.001	–	–	0.037	0.002	0.005
1040	0.402	0.247	0.82	0.012	0.028	0.025	0.001	0.003	0.014	0.032	0.001	0.003
1050	0.506	0.252	0.654	0.014	0.006	0.251	0.002	–	0.006	0.017	0.002	0.006
50CrV4	0.523	0.394	0.915	0.021	0.027	0.917	0.025	0.034	–	0.183	–	0.095

Table 2. Hardness values

	Vickers hardness HV 10 [MPa]				
Steels	AISI 1010	AISI 1030	AISI 1040	AISI 1050	50CrV4
Non-heat-treated steels	1648 ± 10	1716 ± 20	1961 ± 29	2157 ± 34	2549 ± 49

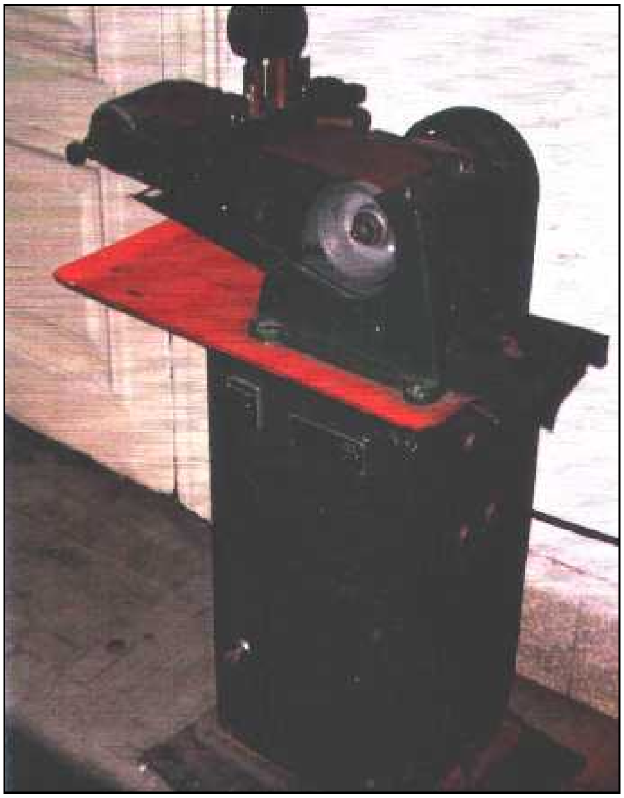

Fig. 2. The pin-abrasion testing machine.

adhesive was applied to the samples and then the samples were attached into the holes milled on copper bars. Prior to the experiment, the samples were cleaned with alcohol and the masses of the samples were measured gravimetrically with 10^{-4} mg sensitivity. Then, they were assembled into the apparatus (Fig. 3) mounted on the pin-abrasion testing machine. Hard rubber dampers of 20 mm diameter and 10 mm thickness were put on the experiment sample to dampen out the vibrations. Additional masses were fixed on the copper bars that were on top of the rubber dampers. Abrasive wear experiments have been performed on each sample for 10

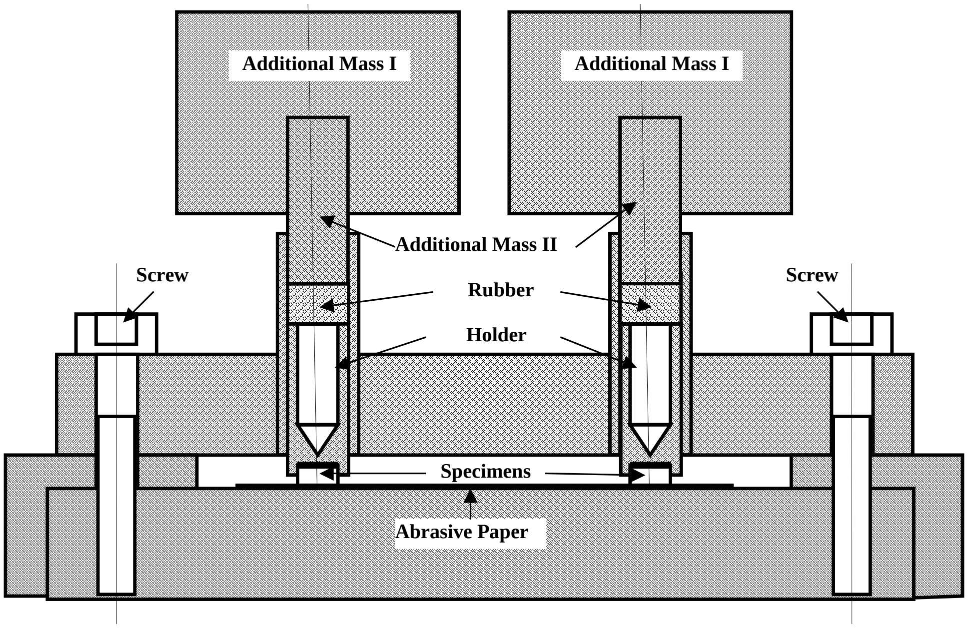

Fig. 3. Apparatus for abrasive wear experiments.

seconds under 0.13 MPa pressure and the experiment was repeated 5 times under the same conditions on each sample. At each repetition, the mass of the samples was determined gravimetrically and recorded. The wear volume, V, was determined from the measured mass losses using the density of the samples. The linear wear rates, W, were computed using the following equation:

$$W = \frac{V}{LA}, \tag{4}$$

where L is the sliding distance of the experiment sample and A is the wear surface area of the sample.

Relative wear resistances of the studied materials were calculated dividing their wear resistance value by the wear resistance of the mildest AISI 1010 steel. Wear resistance and the relative wear resistance of the studied materials are given in Table 3.

3. Results and discussion

In this section, we define the pressure wear resistance, W_{P}^{-1}, as

$$W_{\mathrm{P}}^{-1} = \frac{P}{W}, \tag{5}$$

Table 3. Abrasive wear resistance and relative wear resistance of the studied steels

	Abrasive particle size d [μm]	Materials				
		AISI 1010	AISI 1030	AISI 1040	AISI 1050	50CrV4
Abrasive wear resistance [W^{-1}]	180	101626.01	104231.81	123380.62	133191.26	158277.93
	125	120918.98	131734.94	140016.8	156372.16	183992.64
	85	152276.53	163238.65	175162.02	196695.51	229410.41
	70	163853.84	175407.82	192901.23	216966.8	260824.2
	50	196502.25	204582.65	233808.74	257201.64	304043.78
Relative wear resistance [ε]	180	1	1.02564	1.21407	1.3106	1.55745
	125	1	1.08945	1.15794	1.2932	1.52162
	85	1	1.07199	1.15029	1.2917	1.50654
	70	1	1.07051	1.17728	1.32415	1.59181
	50	1	1.04112	1.18985	1.3089	1.54728

where P is the applied pressure to the experiment sample, and W is the linear wear rate defined in Eq. (4).

The relationship between the pressure wear resistance, W_{P}^{-1}, and hardness, H, of non-heat-treated steels is illustrated in Fig. 4. The following relationship can be deducted via curve fitting using the least square method in Fig. 4:

$$W_{\mathrm{P}}^{-1} = C_1 H, \tag{6}$$

where $C_1 = k^{-1}$, and k is the wear coefficient.

Rewriting (6) in terms of wear coefficient, the following expression for pressure wear resistance is obtained:

$$W_{\mathrm{P}}^{-1} = \frac{H}{k}. \tag{7}$$

In Table 4, the coefficients C_1, k and R are given for non-heat-treated steels. The variation of wear coefficients k (Table 4) with abrasive particle size d for non-heat-treated steels is seen in Fig. 5. As seen in Fig. 5, the dependence of wear coefficient k on the abrasive particle size d is consistent with previous works [5, 6, 10, 15]. However, the results in Fig. 5 show that although wear coefficient k increases rapidly initially with increasing abrasive particle size d, the wear coefficient does not reach a steady state value in terms of a critical particle size. Besides, as long as the abrasive particle size increases, the slope of the curve decreases as seen in Fig. 5. From Fig. 5, the relation between wear coefficient k and particle size d for zone I is given by

$$k = 9.2 \times 10^{-3}\sqrt{d}, \tag{8}$$

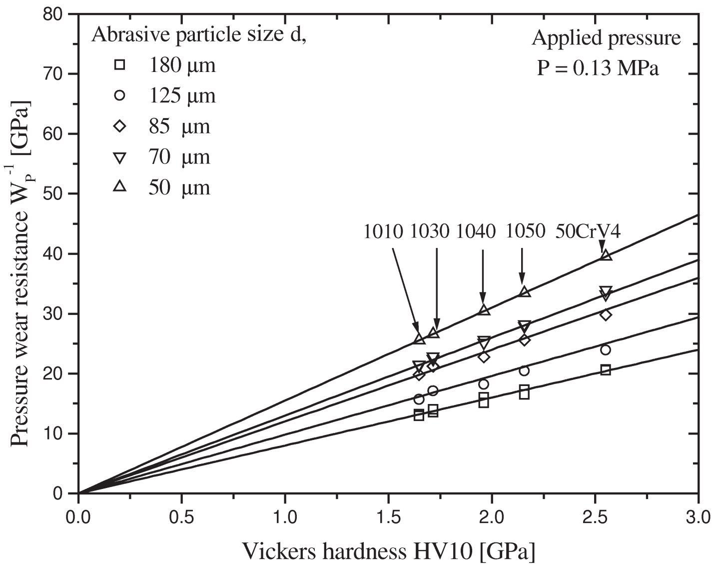

Fig. 4. Pressure wear resistance versus Vickers hardness (Parameter: Abrasive particle size).

Table 4. Coefficient C_1 and wear coefficient k

Materials	Abrasive particle size d [μm]	C_1	Wear coefficient $k = 1/C_1$	Coefficient of correlation R
Non-heat-treated steels	180	8	0.125	0.99
	125	9.8	0.111	0.99
	85	12	0.083	0.99
	70	13	0.077	0.99
	50	15.5	0.065	1

where d is abrasive particle size in μm.

If (8) is substituted in (7), the pressure wear resistance expression for zone I becomes

$$(W_{\mathrm{P}}^{-1})_{\mathrm{ZoneI}} = \frac{H}{9.2 \times 10^{-3}\sqrt{d}}, \tag{9}$$

and the wear resistance is

$$(W^{-1})_{\mathrm{ZoneI}} = \frac{1}{9.2 \times 10^{-3}\sqrt{d}} \frac{H}{P}. \tag{10}$$

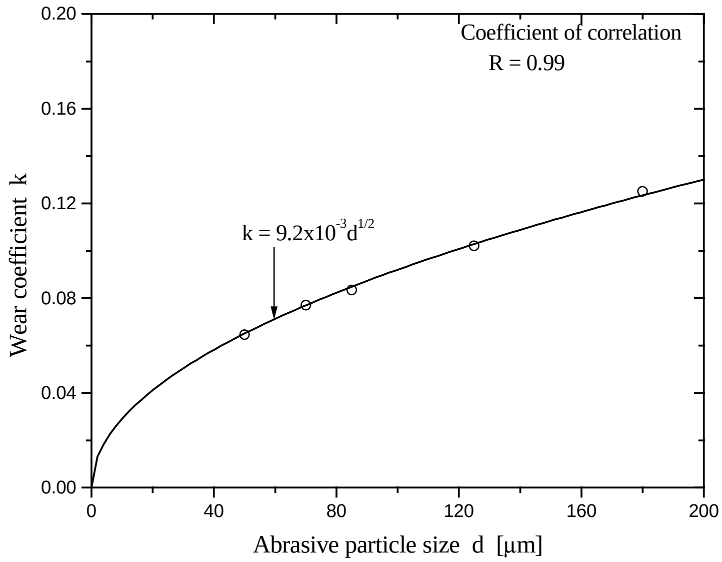

Fig. 5. Variations of wear coefficient k versus abrasive particle size d.

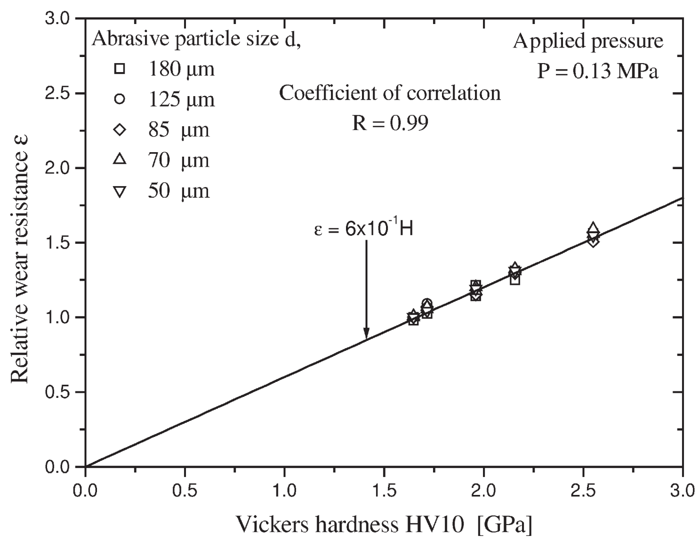

Fig 6. Relative wear resistance versus Vickers hardness (Parameter: Abrasive particle size).

The previous works [3, 5, 6] state that the wear coefficients k and/or the wear rates W are dependent on the particle size d for pure metals and non-heat-treated steels, but they do not give the mathematical expressions for this. In this study situation, the Eq. (10) was derived for the relation between the wear coefficient k and the particle size d using a curve fitting technique based on least square approximation for non-heat-treated steels. Equation (10) is valid for ideal micro-cutting, according to Zum Gahr [3].

From Fig. 6, the dependence of the relative wear resistance on hardness for non-heat-treated steels can be expressed as

$$\varepsilon = 6 \times 10^{-4} H. \tag{11}$$

The relative wear resistance of non-heat-treated steels does not depend on abrasive particle size. This result is supported by the results calculated by Eq. (3), which was proposed by Khruschov [14].

4. Conclusion

– The results showed that the wear resistance of non-heat-treated steels is a function of the abrasive particle size. From the results, an empirical mathematical wear resistance model and an empirical mathematical relative wear resistance ε, as a function of abrasive particle size d, were derived.

– The relationship between the wear coefficient k and abrasive particle size d is parabolic, as seen in Eq. (8).

The wear resistance W^{-1} is inversely proportional with the square root of particle size d for non-heat-treated steels as seen in Eq. (10).

The relative wear resistance ε and hardness H are related linearly for non--heat-treated steels as can be seen in Eq. (11), abrasive particle size does not effect the relationship between hardness H and relative wear resistance ε.

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