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Effect of Abrasive Particle Size on Abrasive Wear Resistance in Automotive Steels

Ibrahim Sevim

Additional information is available at the end of the chapter

<http://dx.doi.org/10.5772/55914>

1. Introduction

Machine parts are subject to the following wear types: Abrasive, adhesive, fatigue and corrosive. In abrasive wear, chipping of harder material a micrometer scale occurs as result of rubbing the soft member. The wear is formed as result of cutting, hitting, and scratching. Abrasion takes places at the solid-solid, particle-solid, solid-liquid interface [1].

If one of the surfaces which are in touch is rough and hard, it chips the other surface due to relative motion or touching forces. The wear is called two-body abrasive wear. If there are free abrasive particles between the two bodies, the wear is called three-body abrasive wear. The free abrasive particles may be external material dust or the remains of chipping. Usually, the wear starts as a two-body abrasive or adhesive wear and then becomes a three-body wear as dust form between the two surfaces due to external particles, chipping remains, or oxide particles. In three-body abrasive wear, wear rate increases as diameter of abrasive particles increases. Gouging, high stress abrasion and low stress abrasion are types of three-body abrasive wear [1-3].

In gouging, surface wear is formed using large abrasive particles. A gouging mechanism is common in ground leveling machines and excavation and digging machines. In these machines, wear occurs on moving, digging, and excavating members. High-stress abrasion occurs when the sharp edged small abrasive particles, which are formed by the crushed particles under excessive loads, scratch the surface. Ball-bearing grinders are mostly subject to high-stress abrasion [2]. These grinders are predominately used to crush the metallic ores and minerals. High-stress abrasion contributes to the significant portion of the wear in grinders. Low-stress abrasion takes place when there is no crushing or grinding in the abrasive particles and one of the surfaces is subject to wear [3].

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, and cone) are adapted to abrasive wear cases with abrasive particle more than one based on some assumptions. The abrasive particle is generally modeled as a cone shape [4]. Rabinowicz [5] has aimed at a simple expression for the volume of material removed during two-body abrasion by a conical abrasive particle;

$$\frac{V}{L} = \left(\frac{2 \tan \alpha}{\pi} \right) \left(\frac{F_N}{H} \right) \quad (1)$$

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

The equation (1), for linear wear density can be written as follows [1];

$$W = k \frac{P}{H} \quad (2)$$

Where; W : linear wear density, k : wear coefficient, P : pressure applied on surface, H : 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 behavior cannot be derived from (2). The zone corresponding this is called zone II. The zones II and I are shown in Figure 1 [1, 4]. (2) is similar to the Archard's adhesive wear expression.

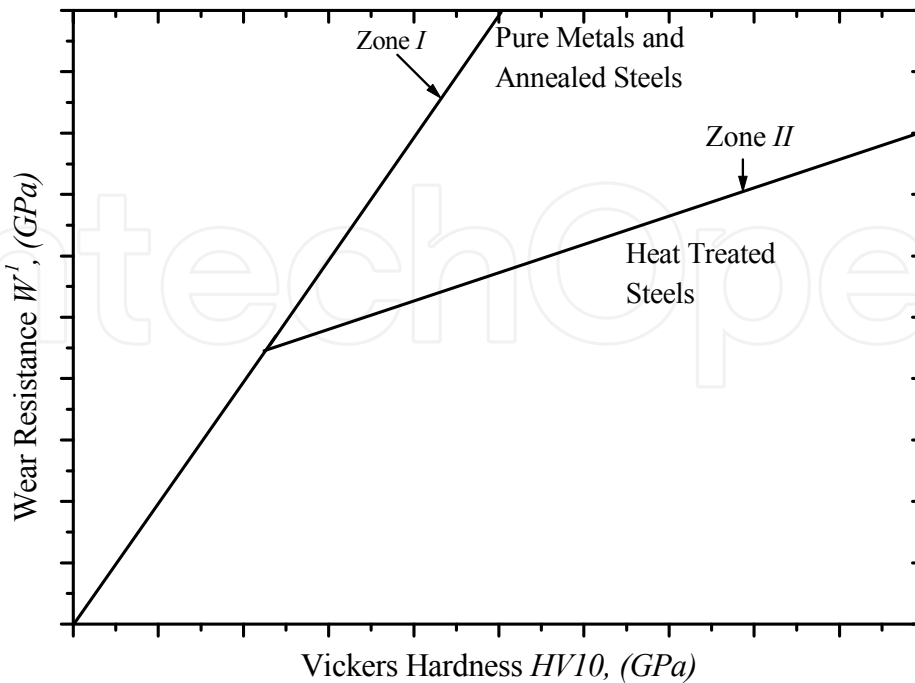


Figure 1. Relationship between wear resistance and hardness [1, 4].

Generally, (2) does not agree with the experimental results. The main reasons for this incompatibility are the changes of wear coefficient k depending 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 behavior 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 braking 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 $80\text{ }\mu\text{m}$ 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 grit 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 plowing 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 become 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 dependency of abrasive particle size. Many researchers have examined the abrasive particle size effect in the zone *II* [14, 15]. Rabinowich [14] determined empirically the following abrasive wear rate expression for the zone *II* using only one type of abrasive particle size

$$W = k \frac{P}{\frac{1}{3}H + \frac{2}{3}H_0} \quad (3)$$

where H is the hardness of alloy, H_0 is the hardness of the alloy in the fully soft condition and P is the pressure applied to the surface.

Khruschov [15] has studied experimentally the zone *I* in a stationary abrasive particle size using the non-heat treated steels and he found the relative wear resistance –hardness relationship for metals as follows;

$$\varepsilon = bH \quad (4)$$

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

Furthermore the following relationship has been determined to be in zone *II*, between the relative wear resistances of heat-treated steels and hardness;

$$\varepsilon = (\varepsilon_0 - C_0 H_0) + C_1 H \quad (5)$$

where ε_0 and H_0 are the relative wear resistance and hardness of annealed steel, and C_0 and C_1 are constants.

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 (for example erosive wear) [15-18].

The focus of this study is to investigate the effect of abrasive particle size on abrasive wear resistance in zone *I*, *II* 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*, *II* and to develop the equations of empirical relative wear resistance connected to abrasive particle size.

2. Experimental procedure

The steels AISI 1010, 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 prepared from non-heat treated and heat-treated steels. The heat treatment conditions are given in Table 2. The samples were ground with abrasive papers grading from 80 to 800 meshes and then polished with 0.3 μm diamonds. The hardness were measured by the Vickers hardness method in load of 98.0865 N (HV10). The average of measurements and the standard deviations were calculated. The average hardness values and standard derivations are given in Table 2. Wear experiment was carried out on the pin-abrasion testing machine shown in Figure 2; tambour diameter $D=118$ mm, tambour rotation $n=1000$ rpm and abrasive wear set-up rate $V=6.18$ ms⁻¹. In wear experiments, the 180, 125, 85, 70 and 50 μm alumina (Al_2O_3) abrasive paper in sizes 100x1150 mm were used. For wear experiments, the apparatus in Figure 3 was mounted on the pin-abrasion testing machine. In order to fix the samples within apparatus in Figure 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 specimen were replaced.

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 1. The chemical compositions of experiment sample (wt. %) [19, 20]

Materials	Heat Treatment	Vickers hardness <i>HV10 (MPa)</i>
AISI1010	–	1648±10
AISI1030	–	1716±20
AISI1040	–	1961±29
AISI1050	–	2175±34
50CrV4	–	2549±49
AISI1010	Water quenched from 900-925 °C	2255±54
AISI1030	Water quenched from 830-850 °C	5609±20
AISI1040	Water quenched from 820-850 °C	6276±15
AISI1050	Water quenched from 810-840 °C	6570±0
50CrV4	Water quenched from 830-850 °C	8895±0
AISI1010	Water quenched from 900-925 °C + 2 hours refrigerated at –25 °C	2256±10
AISI1030	Water quenched from 830-850 °C + 2 hours refrigerated at –25 °C	6767±25
AISI1040	Water quenched from 820-850 °C + 2 hours refrigerated at –25 °C	7100±39
AISI1050	Water quenched from 810-840 °C + 2 hours refrigerated at –25 °C	7875±20
50CrV4	Water quenched from 830-850 °C + 2 hours refrigerated at –25 °C	8895±0
AISI1010	Water quenched from 900-925 °C + tempered at 250 °C	1873±25
AISI1030	Water quenched from 830-850 °C + tempered at 250 °C	5551±34
AISI1040	Water quenched from 820-850 °C + tempered at 250 °C	5943±17

Materials	Heat Treatment	Vickers hardness <i>HV10 (MPa)</i>
AISI1050	Water quenched from 810-840 °C + tempered at 250 °C	6139±37
50CrV4	Water quenched from 830-850 °C + tempered at 250 °C	6845±25
AISI1030	Water quenched from 830-850 °C + tempered at 350 °C	4511±83
AISI1040	Water quenched from 820-850 °C + tempered at 350 °C	4884±26
AISI1050	Water quenched from 810-840 °C + tempered at 350 °C	5198±49
50CrV4	Water quenched from 830-850 °C + tempered at 350 °C	5492±29
AISI1030	Water quenched from 830-850 °C + tempered at 450 °C	3118±26
AISI1040	Water quenched from 820-850 °C + tempered at 450 °C	4550±49
AISI1050	Water quenched from 810-840 °C + tempered at 450 °C	4737±20
50CrV4	Water quenched from 830-850 °C + tempered at 450 °C	4805±39
AISI1030	Water quenched from 830-850 °C + tempered at 550 °C	3030±55
AISI1040	Water quenched from 820-850 °C + tempered at 550 °C	3324±29
AISI1050	Water quenched from 810-840 °C + tempered at 550 °C	3589±35
50CrV4	Water quenched from 830-850 °C + tempered at 550 °C	3727±64
AISI1030	Water quenched from 830-850 °C + tempered at 650 °C	1973±10
AISI1040	Water quenched from 820-850 °C + tempered at 650 °C	2059±25
AISI1050	Water quenched from 810-840 °C + tempered at 650 °C	2256±39
50CrV4	Water quenched from 830-850 °C + tempered at 650 °C	2902±34

Table 2. Heat treatment and hardness values [19, 20]



Figure 2. The pin-abrasion testing machine [19, 20]

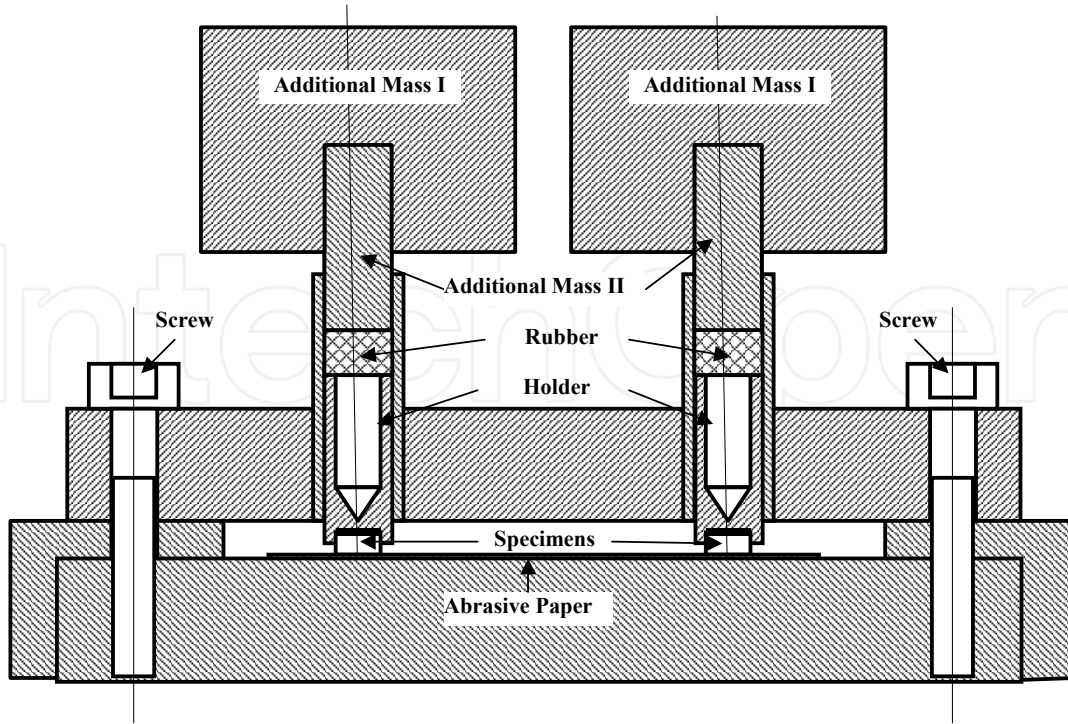


Figure 3. Apparatus for abrasive wear experiments [19, 20]

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 adhesive were 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 mass of the sample were measured gravimetrically with 10^{-4} mg sensitivity. Then, they were assembled into the apparatus (Figure 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 damp out the vibrations. Additional masses were fixed on the copper bars that were on top the rubber dampers. Abrasive wear experiments have been performed on each sample for 10 seconds under 0.13 MPa pressure and the experiment were repeated 5 times under the same conditions on each sample. At each repetition, the mass of the sample were determined gravimetrically and recorded. The wear volumes, V , were determined from the measured mass losses using the specific mass of the samples. The linear wear rates, W , were computed using the following equation

$$W = \frac{V}{LA} \quad (6)$$

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

3. Results and discussion

In this section, we use the abrasive wear expressions and definitions given in nomenclature section. In particular, we define the pressure wear resistance, W_p^{-1} as:

$$W_p^{-1} = \frac{P}{W} \quad (7)$$

where P is the applied pressure to the experiment sample, and W is the linear wear rate defined in (7).

3.1. For non-heat treated steels

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

$$W_p^{-1} = C_2 H \quad (8)$$

where $C_2 = k^{-1}$, and k is the wear coefficient.

Rewriting (8) in terms of wear coefficient, the following expression for pressure wear resistance is obtained

$$W_p^{-1} = \frac{H}{k} \quad (9)$$

In Table 3, the coefficients C_2 , k and R are given for non-heat-treated steels. The variation of wear coefficients k (Table 3) with abrasive particle size d for non-heat treated steels is seen in Figure 5.

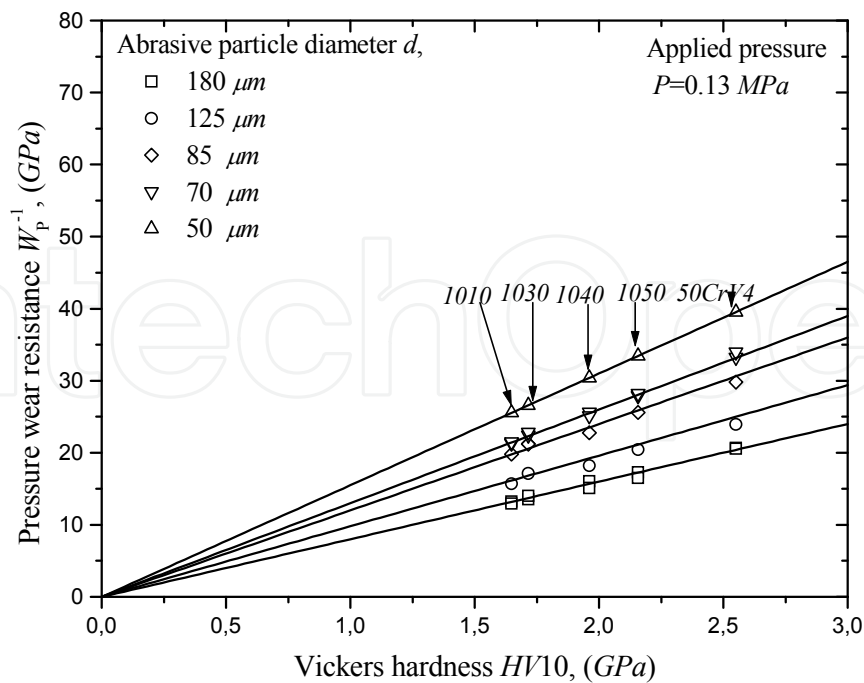


Figure 4. Non-heat-treated steels pressure wear resistance versus Vickers hardness (Parameter: Abrasive particle size) [19]

Materials	Abrasive particle size d , (μm)	C_2	Wear coefficient $k=1/C_2$	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

Table 3. Coefficient C_2 and wear coefficient k [19]

As seen in Figure 5, the dependence of wear coefficient k on the abrasive particle size d is consistent with previous works [5, 6, 10, 15, 16]. However, the results in Figure 5 shows that although wear coefficient k increases initially fast with increasing abrasive particle size d , the wear coefficient does not reach to 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 Figure 5.

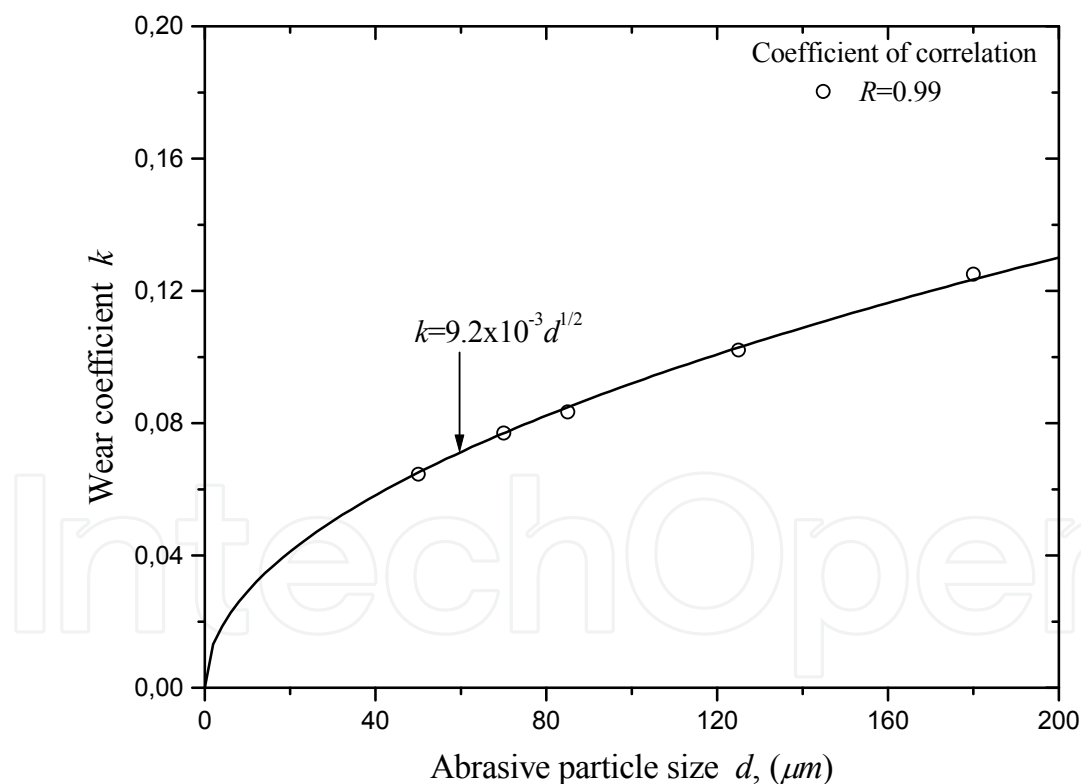


Figure 5. Variations of wear coefficient k of non-heat treated steels versus abrasive particle size [19]

From Figure 5, the relation between wear coefficient k and particle size d for zone I is given by

$$k = 9.2\sqrt{d} \quad (10)$$

where d is abrasive particle size.

If (10) is substituted in (9), the pressure wear resistance expression for zone I becomes

$$\left(W_P^{-1}\right)_{ZoneI} = \frac{H}{9.2\sqrt{d}} \quad (11)$$

and the wear resistance is

$$\left(W^{-1}\right)_{ZoneI} = \frac{1}{9.2\sqrt{d}} \frac{H}{P} \quad (12)$$

The previous works [3, 5, 6] states that the wear coefficient k and/or the wear rate W are dependent on the particle size d for pure metals and non-heat treated steels, but they did not give the mathematical expressions for this. In this study situation, the equation (12) 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. (12) is valid for ideal microcutting, according to Zum Garh [3].

3.2. For heat treated steels

The variation of pressure wear resistance of the heat-treated steels (water quenched, water quenched+ refrigerated at -25°C , water quenched + tempered) with hardness is given in Figure 6. According to Figure 6, the general expression of pressure wear resistance in terms of hardness for heat-treated steels can be written as follows;

$$\left(W_P^{-1}\right)_{ZoneII} = C_3 + C_4 \quad (13)$$

where C_3 and C_4 are constants.

C_3 and C_4 constants and coefficient of correlation R are given in Table 4 for heat-treated steels. (3) shows how the pressure wear resistance in zone II changes with the hardness. Let us define C_3 and C_4 as follows:

$$C_3 = \frac{2}{3k} H_0 \quad (14)$$

$$C_4 = \frac{1}{3k} \quad (15)$$

where H_0 is defined in (3) as the hardness of annealed alloyed steel.

If we substitute for C_3 and C_4 in (13), we obtain (3). According to (3), since the values of H and H_0 are dependent on abrasive particle size d , both coefficients in (13) are dependent on abrasive particle size d . But our results (Table 4) show that C_4 coefficient is not dependent on

abrasive particle size d . The variation of C_3 coefficient is plotted versus abrasive particle size d (Figure 7). Since C_4 coefficient is not dependent on abrasive particle size it is understood that the abrasive particle size for heat-treated steels does not change the slope in zone II (Figure 6). The abrasive particle size affects the slopes in zone I and II (Figure 8). If C_3 coefficient in (13) replaced with the value from Figure 7 and C_4 coefficient from Table 4, the pressure wear resistance expression in zone II for the heat-treated steels becomes;

$$\left(W_p^{-1}\right)_{ZoneII} = \frac{1.4}{d} + 2.6H \quad (16)$$

and the wear resistance becomes

$$\left(W^{-1}\right)_{ZoneII} = \frac{1}{P} \left(\frac{1.4}{d} + 2.6H \right) \quad (17)$$

Materials	Abrasive particle size $d, (\mu m)$	C_3	C_4	Coefficient of Correlation R
Heat treated steels	180	7750	2.6	0.98
	125	11700	2.6	0.98
	85	16600	2.6	0.97
	70	18200	2.6	0.96
	50	28800	2.6	0.99

Table 4. Coefficients C_3 and C_4 [20]

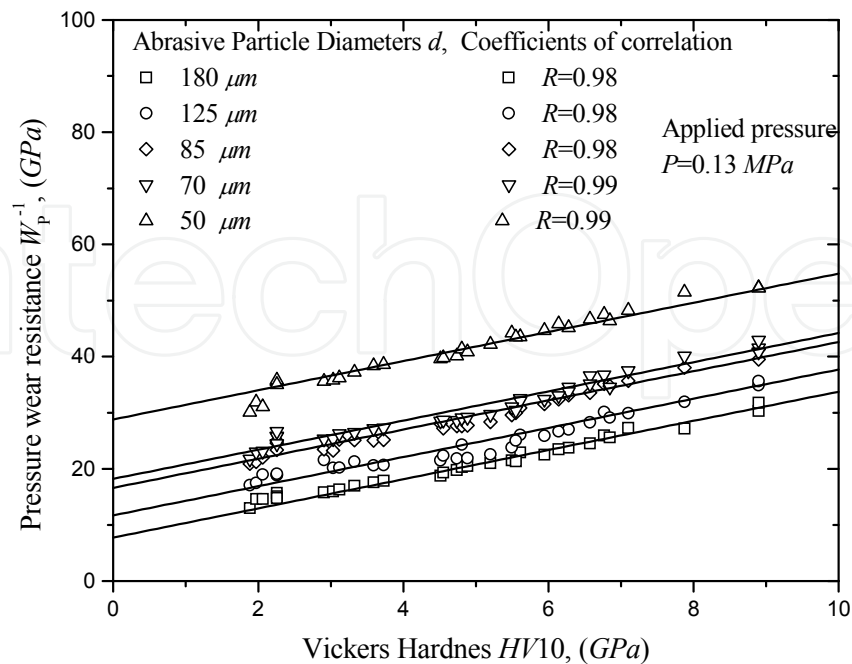


Figure 6. Heat-treated steels pressure wear resistance versus Vickers hardness (Parameter: Abrasive particle size) [20]

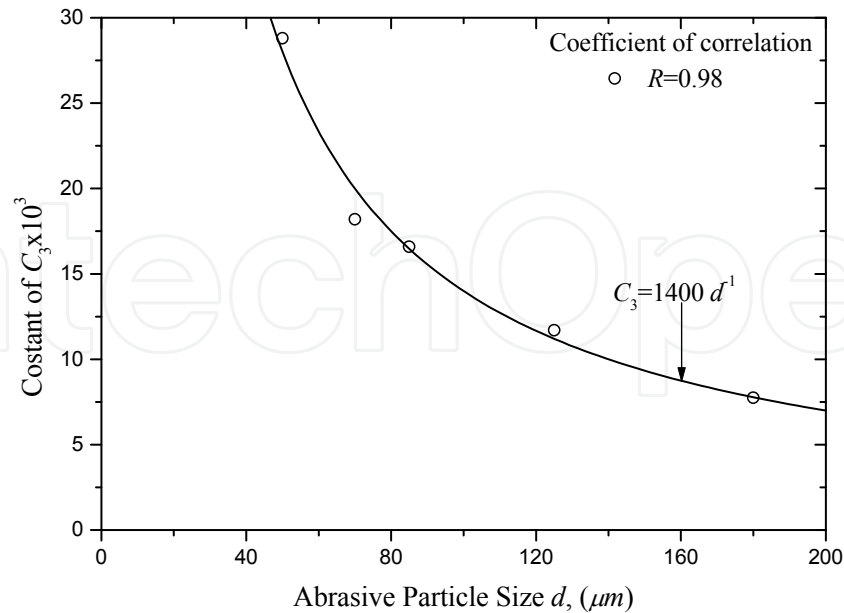


Figure 7. Constant C_3 of heat-treated steels versus abrasive particle size d [20]

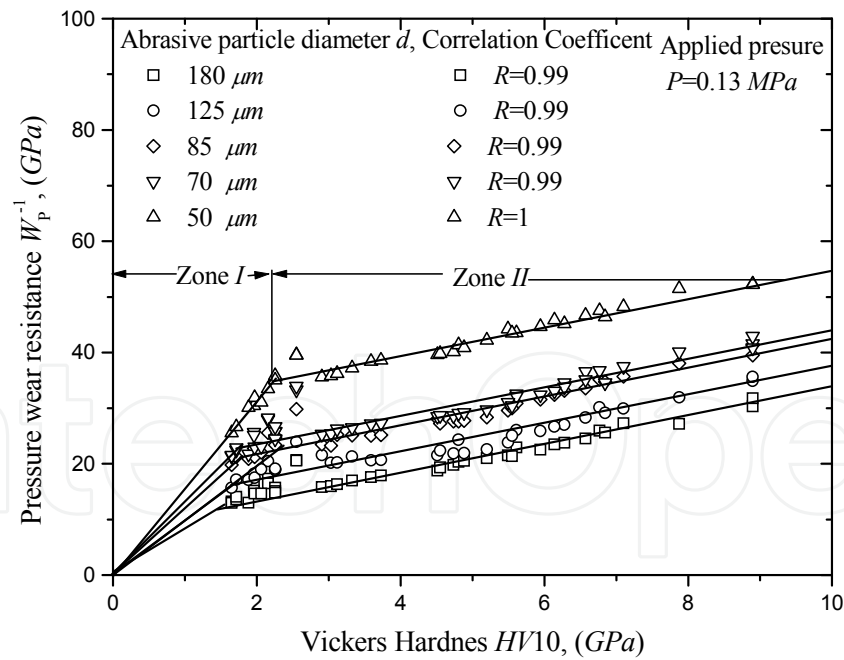


Figure 8. Non-heat treated and heat treated steels pressure wear resistance versus Vickers hardness (Parameter: Abrasive particle size) [19, 20]

In previous works, the abrasive wear resistances of heat-treated steels were found to be different than that of non-heat treated steels. Researchers concluded that this difference was

due to the heat-treatment of the material [14, 15, 16]. After heat-treatment the hardness of the material changes. According to the abrasive wear mechanism of heat-treated steels, abrasive particle cuts more chips than wear groove volume [1-3]. Abrasive particle produces chip via micro cutting and micro cracking mechanisms. It was concluded that the difference in the wear resistance of heat-treated and non-heat treated steels arises from micro cracking mechanism in heat-treated steels during abrasive wear.

The variations of the pressure wear resistances of non-heat-treated and heat-treated steels with the hardness are shown in Figure 8. As seen in Figure 8, the pressure wear resistances of non-heat-treated and heat-treated steels are dependent on abrasive particle size.

3.3. Relative wear resistance for non heat treated

From Figure 9, the dependence of the relative wear resistance on hardness for non-heat treated steels can be expressed as

$$e = 6 \times 10^{-4} H \quad (18)$$

The relative wear resistance of non-heat-treated steels does not depend on abrasive particle size. This result is supported with the results calculated by equation (4) which was proposed by Khrushchov [15].

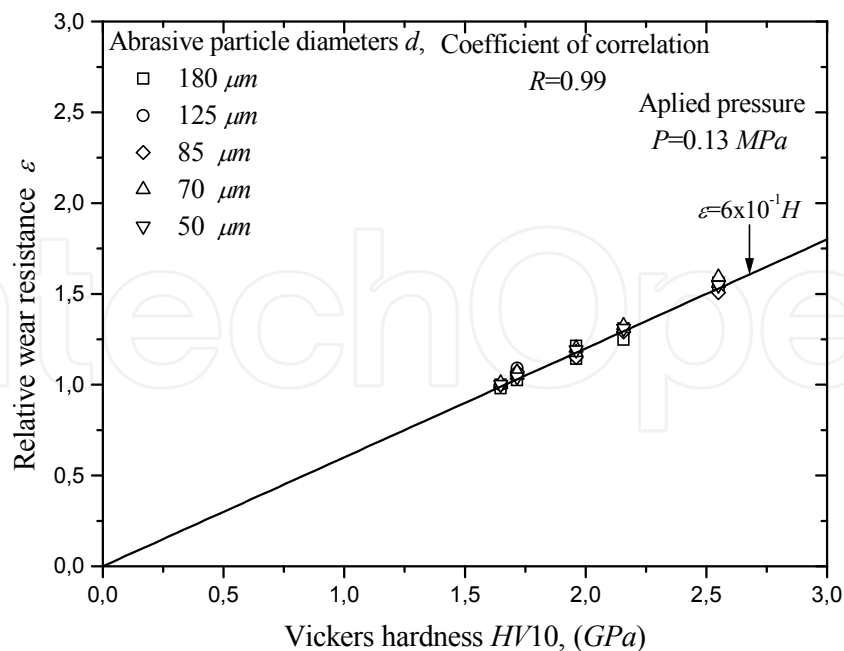


Figure 9. Non-heat-treated steels relative rear resistance versus Vickers hardness (Parameter: Abrasive particle size) [19]

3.4. Relative wear resistance for heat treated steels

The variation of pressure wear resistance of the heat-treated steels (water quenched, water quenched+ refrigerated at $-25\text{ }^{\circ}\text{C}$, water quenched + tempered) with hardness has been shown in Figure 10. As seen in Figure 10, the relative wear resistance in steel shows different slopes depending on abrasive particle size. The relative wear resistance equations in zone II for the heat-treated steels can be written in general as follows;

$$\varepsilon = A_0 + B_0 H \quad (19)$$

where A_0 and B_0 are constant coefficients.

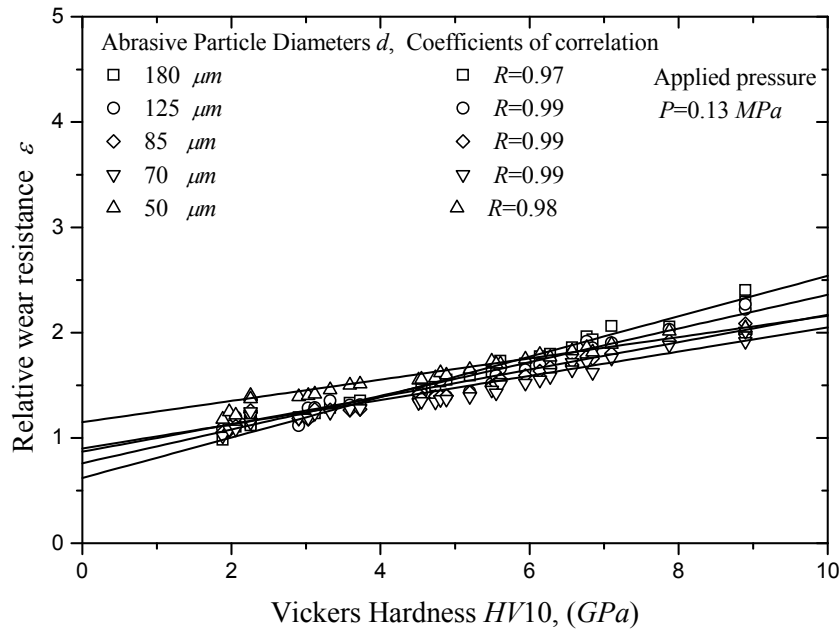


Figure 10. Heat-treated steels relative wear resistance versus Vickers hardness (Parameter: Abrasive particle size) [19, 20]

The experimental results for A_0 and B_0 constants, and coefficient of correlation R are given in Table 5 for heat-treated steels. (5) shows how the relative wear resistance in zone II changes with the hardness. Let us define A_0 and B_0 as follows;

$$A_0 = (\varepsilon_0 - C_0 H_0) \quad (20)$$

$$B_0 = C_1 \quad (21)$$

The variation of A_0 and B_0 constants are plotted versus abrasive particle size d (Figure 11). The following equation are obtained using least square approximation method,

$$A_0 = \frac{8 \times 10^{-3}}{\sqrt{d}} \quad (22)$$

$$B_0 = 1.42 \times 10^{-3} \sqrt{d} \quad (23)$$

Materials	Abrasive particle size d , (μm)	A_0	$B_0 \cdot 10^{-5}$
Heat treated steels	180	0.62	19.2
	125	0.76	16
	85	0.87	13
	70	0.9	11.5
	50	1.158	10.1

Table 5. Coefficients A_0 and B_0 [20]

If A_0 and B_0 constants in (19) replaced with the expressions given in (22) and (23), the relative wear resistance expression in zone II for the heat-treated steels becomes;

$$\varepsilon = \frac{8 \times 10^{-3}}{\sqrt{d}} + 1.42 \times 10^{-3} \sqrt{d} H \quad (24)$$

The hardness H , of abraded material versus the relative wear resistances ε , of the non-heat-treated and heat-treated steels are shown graphically in Figure 12. As seen in Figure 12 and (18), the relative wear resistance ε , is independent on abrasive particle size d in zone I while it is dependent on d in zone II (see (24)).

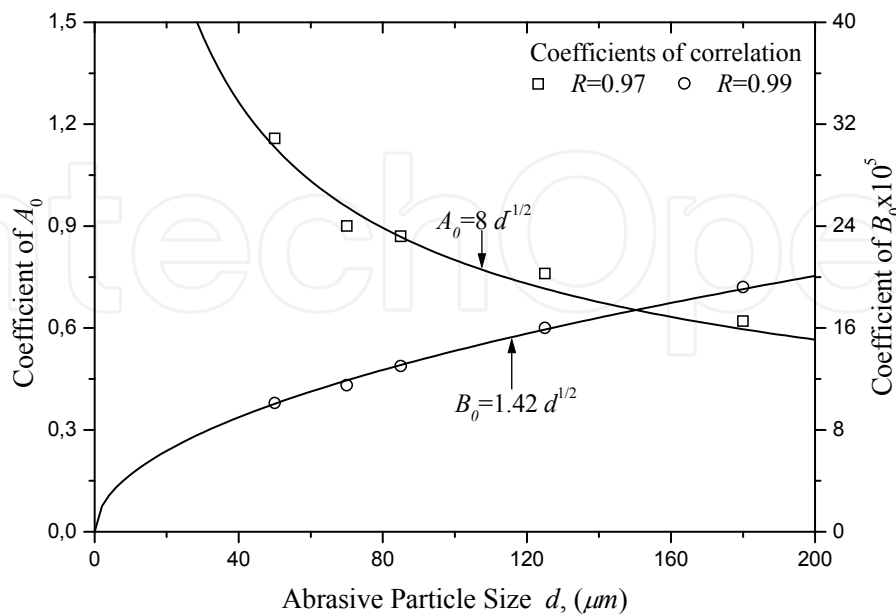


Figure 11. Coefficients A_0 and B_0 of heat-treated steels versus abrasive particle size d [19, 20]

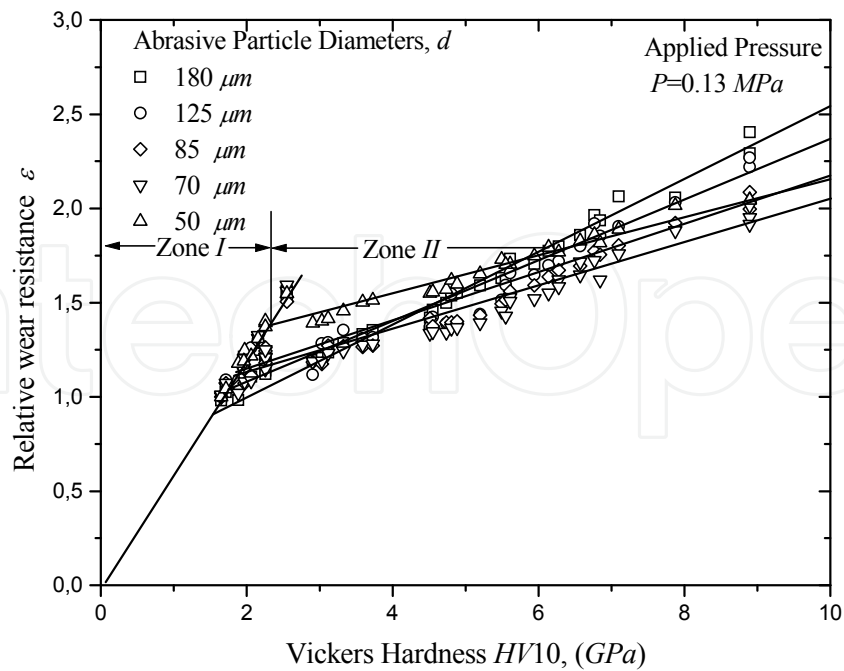


Figure 12. Non-heat treated and heat treated steels relative wear resistance versus Vickers hardness (Parameter: Abrasive particle size) [19, 20]

4. Conclusion

The results showed that the wear resistance of non-heat treated and heat-treated steels are functions 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 [18-20].

- There is a linear relationship between the abrasive wear resistance W^{-1} and hardness H , depending on abrasive particle size d , for non-heat treated steels. The relationship between wear coefficient k and abrasive particle size d is a parabolic as seen in equation (10). The wear resistance W^{-1} is inversely proportional with the square root of particle size d , for non-heat treated steels as seen in equation (12).
- The relationships for the heat-treated steels between the abrasive wear resistance and hardness H , show positive intercepts on the ordinate, depending on abrasive particle size d (equation (17)).
- The relative wear resistance ε and hardness H related linearly for non-heat treated steels as it can be seen in equation (18), abrasive particle size does not effect the relationship between hardness H and relative wear resistance ε . But, relative wear resistance ε , for the heat-treated steels is dependent on abrasive particle size d , and the relationships for the heat-treated steels show positive intercepts on the ordinate. The proportionality behavior of hardness H and relative wear resistance ε , is dependent on the terms of $\frac{1}{\sqrt{d}}$ and \sqrt{d} as given in equation (24).

- Heat-treated steels have lower resistance to wear than non heat-treated steels of the same hardness.

Nomenclature

$$W = \frac{V}{LA} = \frac{G}{\rho LA} \quad : \text{Wear Rate (Linear wear intensity)}$$

$$W^{-1} = \frac{\rho LA}{G} \quad : \text{Wear Resistance}$$

$$W_p^{-1} = P \frac{\rho LA}{G} \quad : \text{Pressure Wear Resistance (MPa)}$$

$$\varepsilon = \frac{W_n^{-1}}{W_r^{-1}} \quad : \text{Relative Wear Resistance}$$

$$W_n^{-1} \quad : \text{Wear Resistance of sample}$$

$$W_r^{-1} \quad : \text{Wear Resistance of reference material}$$

Author details

Ibrahim Sevim

Mersin University, Engineering Faculty, Department of Mechanical Engineering, Ciftlikkoy,
Mersin, Turkey

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