International Journal of Scientific and Technological Research
ISSN 2422-8702 (Online)
Vol 4, No.3, 2018
www.iiste.org

Analysis of Two Body Abrasive Wear on Machine Parts Due To Single Wear Particle

Ibrahim Sevim (Corresponding author)
Karamanoglu Mehmetbey University, Campus of Yunus Emre, Faculty of Engineering,
Department of Mechanical Engineering, 70100, Karaman/Turkey,
E-mail: isevim@kmu.edu.tr

Omer Uctu
Gaziantep University, Naci Topcuoglu Vocational School 2. Organize San.
Baspinar Sehitkamil/Gaziantep, Turkey,
E-mail: omeructu@outlook.com

Burak Sahin
Gaziantep University, Faculty of Engineering,
Department of Mechanical Engineering, Gaziantep/Turkey,
E-mail:buraksahin@gantep.edu.tr

Abstract

The multi-particle abrasive wear mechanism includes the mechanisms of plastic deformation, micro cutting and brittle fracture depending on the material subject to the wear. The plastic deformation wear occurs through the fatigue removal of the material around the groove formed by abrasive particles. In the micro cutting wear, the abrasive particle removes chips from the material thorough cutting. The micro crack (brittle fracture) wear occurs on ceramic type materials. In these materials, the wear volume is larger than the volume of the grove formed by the abrasive particles. In this study, the abrasive wear mechanisms on both ductile and brittle materials are analyzed.

Keywords: Abrasive wear, wear grove, ductile and brittle materials

1. Introduction

Wear is a failure mechanism consisting of breakage from material surface or fracture at micro or smaller scale. The presence of unintentional relative movement between materials' surfaces is enough to define a mechanism as wear. Adhesion, abrasion, fatigue and tribochemical can be classified as wear failure types but the most effective one for machines and machine elements is abrasion (abrasive wear) [1].The harder of two contacting surfaces cause to wear on the softer one at micro or smaller scale due to inclusion on surfaces under the effects of loading and movement. This is defined as abrasive wear. When one of two contacting surfaces is rougher than other one, it causes material removal from smoother surface because of relative motion between them and contact pressure. This mechanism is main reason of wear and called as "two body abrasive wear" [1-3].
The wear of machine elements in large size is an example of two body abrasive wear so it should be inspected in laboratory conditions. Each asperity on two bodies which make relative movement is designed as an abrasive particle. These designed particles are multi-particle abrasives [2,3].

Multi-particle abrasive wear mechanism consists of plastic deformation, micro cutting and brittle fracture depending on wearing part [4]. The main principle of wear occurs after plastic deformation is: A groove forms due to abrasive grain movement and wear takes place because of removal of material which gets out from that groove. In the micro cutting wear, the abrasive particle removes chips from the material through cutting and no asperity occurs due to plastic deformation at the edges of groove. The wear due to fracture after micro crack (brittle fracture) occurs in ceramics and similar "brittle materials" which have low fracture toughness. For these kinds of materials, the volume of wearing part is greater than volume of groove created by abrasive particles [4, 5].

In this study, wear mechanisms on ductile and brittle materials are investigated.

2. Abrasive wear mechanisms

Grooves are scratches on softer surface or wear scar due to abrasive particle entering into between rough hard and soft surfaces under the effects of pressure and relative movement.

In this study, grooves by ideal and simplified abrasive particle were examined. Cross sectional area of the groove due to cone shape abrasive particle is given in following equation:

$S = \frac{1}{2} 2rh$ and length of groove (Figure 1);

$$\overline{\delta V} = S.L \tag{1}$$

$\overline{\delta V}$ is the volume of groove on the surface.

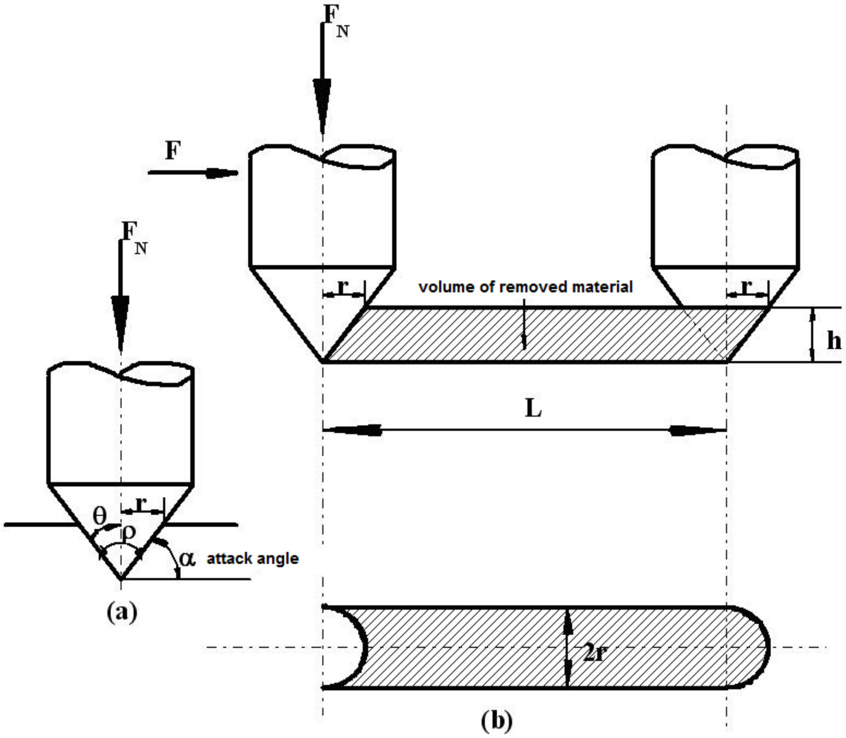


Figure 1. Modeling of an abrasive particle as cone shape [1-11].

The material corresponding to this volume of groove does not break away from the surface [1-3]. An amount of f_{ab}, groove volume leaves as wear part. Volume of removed portion as wear part δV is;

$$\delta V = f_{ab}.\overline{\delta V} \tag{2}$$

The ratio of volume of wearing material to volume of groove is given below:

$$f_{ab} = \frac{\delta V}{\overline{\delta V}} \tag{3}$$

The aim of abrasive wear laws based on Eq. 2 is to define f_{ab} by depending on properties.

There are three different wear mechanisms in the systems supposed to abrasive wear [1-3];

1. Ideal microploughing
2. Microcutting wear
3. Fracture Wear due to micro cracks

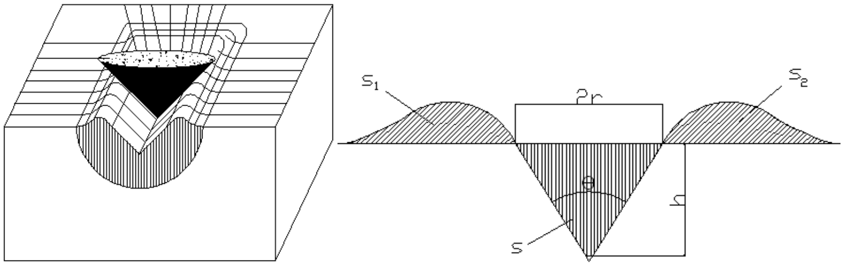
2.1. IdealMicroploughing

Abrasive particle end forms groove through plastic deformation in very ductile materials and removed materials accumulate at two sides of groove. This kind of abrasion is very similar to plowing, so it is called as microploughing. Volume of groove is equal to volume of accumulated material at both sides of groove because total volume is constant during plastic deformation. As understood from Figure 2:

$S.L = (S_1 + S_2).L$, and

$$f_{ab} = \frac{\delta V}{\overline{\delta V}} = \frac{(S - S_1 + S_2)}{S} = 0 \tag{4}$$

As it is seen from Eq.4, no particle breaks off from surface through this mechanism, but surface is supposed to deformation.



(a) **(b)**

Figure 2. Groove formation through ploughing: a) Formation of ploughing groove b) Volume of ploughing groove [1-11].

Ideal ploughing conditions in practical occurs for wear through single abrasive particle end when attack angle, α , is below a critical value [1-3]. Attack angle (α) is defined as angle between front side of abrasive end and wearing surface (Figure 1). As attack angle is above critical value, it is possible to remove material from surface by micro cutting. In researches conducted, it is seen that passing from microploughing to micro cutting in this critical attack angle value is not sudden [1].When total volume of groove formed in surface leaves as wearing volume, there is a gradual transition (f_{ab}=1) (Figure 3).

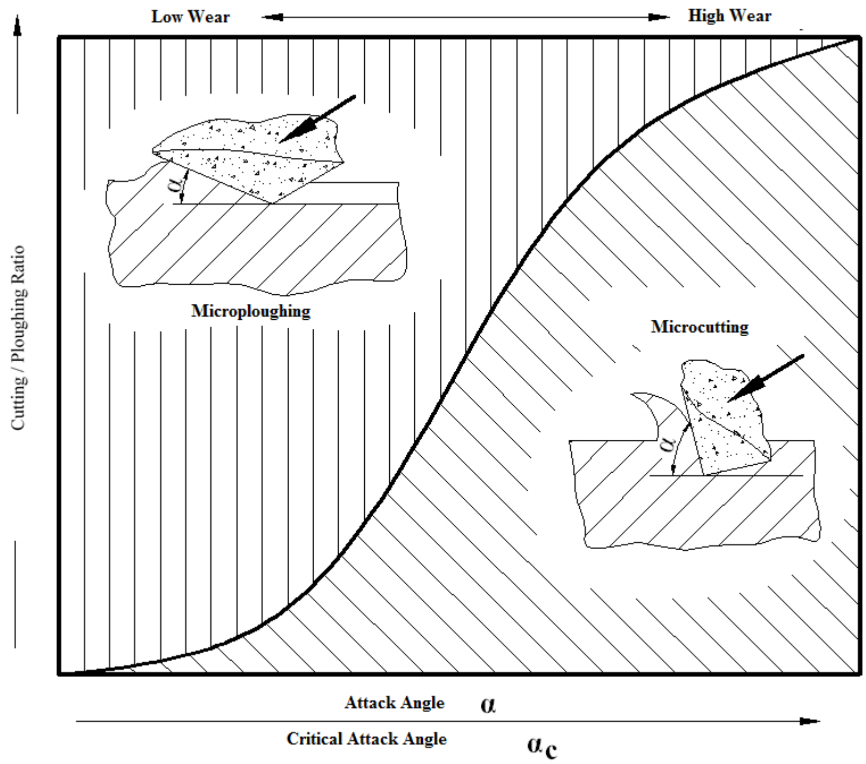


Figure 3. The change of ratio of attack angle to critical attack angle based on ratio of micro cutting to micro ploughing [1-11].

Practically, the passing of more than one abrasive particle through a wearing surface one after another is possible. When this is the case, asperities formed at sides of groove due to plastic deformation removes from surface as wearing particles due to repetitive short life fatigue. Following wearing particles in micro ploughing conditions cause to this (Figure 4). Namely; in this case, even attack angle of each particle is lower than critical attack angle value (α<αc); $0 \langle f_{ab} \langle 1$ is valid for multi-particle wear. Therefore, under conditions of micro ploughing through multi particle wear, minimum value of f_{ab} is different than zero and is equal to 0,25 [1].

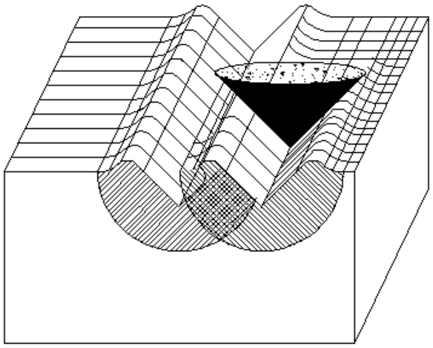


Figure 4. Wear due to short life pitting [1-11].

2. 2. Microcutting Wear

Secondary abrasive mechanism is ideal microcutting. (Figure 5). Abrasive particle end removes groove on wearing surface by cutting and there is no tip occurrence at sides of groove under plastic deformation.

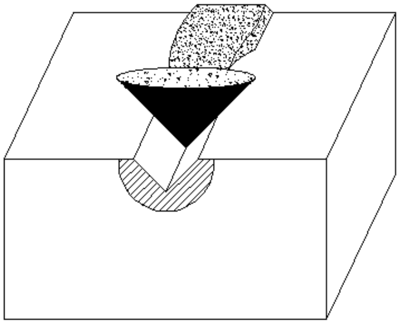


Figure 5. Microcuttingwear [1-11].

f_{ab} is equal to unity and volumetric wear rate is obtained in following form [1]. Abrasive end is modeled as conical form as shown in Figure 1. Hardness of wearing surface is calculated in Eq. 6 based on half tip angle of cone shape abrasive particle, θ and applied normal load on the conical particle, F_N.

$$H = \frac{F_N}{\pi.r^2} \tag{5}$$

Wear volume per unit distance of sliding can be expressed as $\frac{V}{L}$ where wear volume and distance of sliding are V and L respectively [4, 5].

$$V = S.L = \left(\frac{2r.h}{2}\right).L = r^2.L.\cot\theta \tag{6}$$

h: depth of removed material,

θ: half tip angle of cone shape abrasive particle (Figure 1)

When r^2 is putted into place from Eq. 5;

$$\frac{V}{L} = \frac{F_N}{H}.\frac{\cot\theta}{\pi} \tag{7}$$

The volume of removed chip in unit sliding distance, i.e, volumetric wear rate, w_V is obtained below:

$$w_V = \frac{V}{L} = \frac{F_N}{H}.\frac{\cot\theta}{\pi} \tag{8}$$

$\frac{\cot\theta}{\pi}$ is a geometrical parameter related to abrasive.

When $C = \frac{\cot \theta}{\pi}$ is written and under ideal conditions f_{ab} is unity, and:

$$w_V = C.\frac{F_N}{H} \tag{9}$$

This is valid for ideal microcutting. Generally, a portion of groove volume (f_{ab}) is removed as wearing chips [6]. In this case, Eq. 8 can be written in following form:

$$w_V = f_{ab}.C.\frac{F_N}{H} \tag{10}$$

By writing $f_{ab}.C = k$, Eq. 9 is obtained below:

$$w_V = k.\frac{F_N}{H} \tag{11}$$

From this equation, law of abrasive wear resembles Archard’s Adhesive Law. Due to $k = f_{ab}.C$ in Eq. 10, in ideal microploughing conditions $f_{ab} = 0$ and $k = 0$ so $w_V = 0$ is obtained. In ideal microcutting conditions, $f_{ab} = 1$ and $k = C$ thus $w_V = C.\frac{F_N}{H}$ is obtained. In cases of both of cutting and ploughing, the condition of $0 \langle f_{ab} \langle 1$ is valid, and Eq. 11 is obtained.

2. 3. Fracture wear due to micro cracks

Fracture wear due to micro cracks occurs in ceramics and similar “brittle materials” which have low fracture toughness. Volume of wear in these kinds of materials is greater than volume of groove which abrasive particle created on wearing surface. In this case, $f$ab is grater or equal to unity. Crack formation around groove and reach of these cracks to wearing material surface cause to big particle rupture from surface (Figure 6).

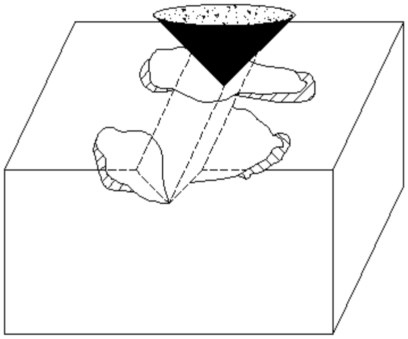


Figure 6. Fracture wear due to micro cracks [1-11].

If sharp tipped abrasive particle is pressed on the surface, main cracks at bottom surface and side cracks occur when load decreases [8]. Different kinds of cracks under load and no-load condition are presented in Figure 7.

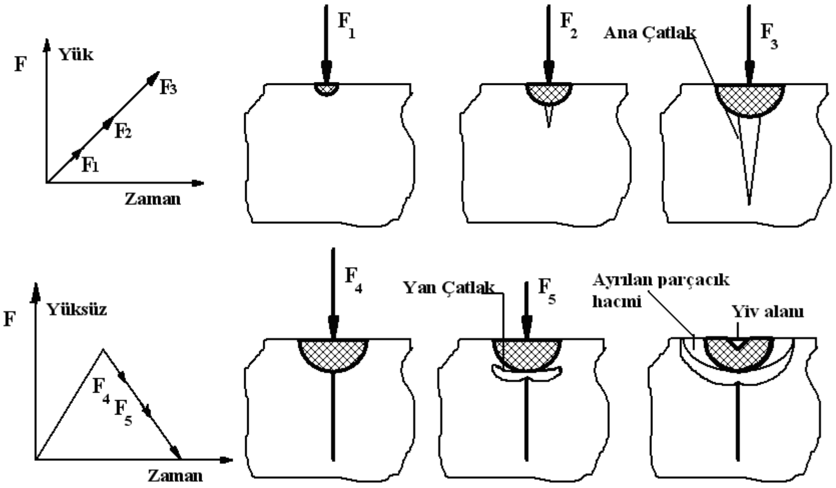


Figure 7. Main and side cracks formation under the effect of sharp tipped abrasive end in brittle materials [1-11].

High stresses occur in materials at first contact point under load of F1. As a result, there is plastic deformation at around of abrasive end. When critical load value of F2 applied on sharp tipped abrasive end is exceeded, main cracks form in brittle materials. If load is increased to load of F3, main cracks moves by growing. When value is decreased to load of F4, main cracks close by coming together. In the case of decreasing load more, i.e when load is lower than F5, it is difficult for main cracks closing because of earlier plastic deformation occurrence at these regions. Side cracks at bottom surface of material and these moves into material surface. During load decrease, the reason of side cracks and move is residual stress because of plastic regions (dashed regions shown in Figure 7). Increase or decrease of load occurs when moving abrasive particle approaches, reaches to a point on material surface and move away from that point [8]. Wear rate in micro crack can be calculated by taking dimensions given in Figure 8 into consideration.

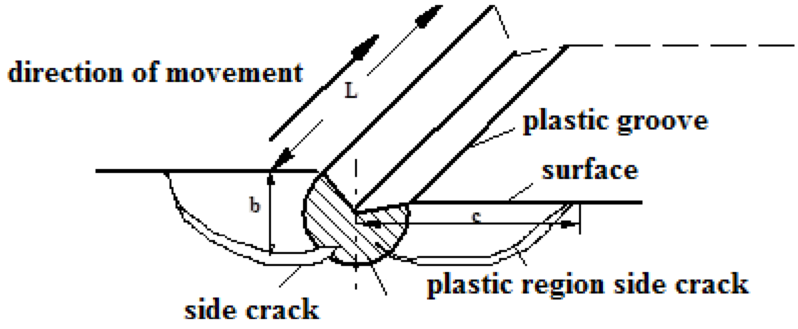


Figure 8. Wear in brittle materials due to extension of side cracks under plastic groove [1-11].

Side crack length is calculated in Eq. 12[7-118];

$$c=\alpha_1.\frac{(E/H)^{3/5}.F_N{}^{5/8}}{K_{IC}{}^{1/2}.H^{1/8}} \tag{12}$$

Where

FN: Normal load on particle,

E: Elastic modulus of material,

H: Hardness of wearing material,

K_{IC}: Fracture toughness of wearing material

α1: constant which is dependent on particle shape and independent on material?

Width of crack,b is calculated in following equation:

$$b=\alpha_2.\left(\frac{E}{H}\right)^{2/5}.\left(\frac{F_N}{H}\right)^{1/2} \tag{13}$$

Here, α2 is another geometrical constant. In this case, volume of removed material from side cracks at bottom surface of material by abrasive particle (Figure 8) is estimated by Eq. 14.

$$V=2.b.c.\mathrm{L} \tag{14}$$

When expressions in Eq 11 and 12 are putted into Eq.13, volumetric wear rate, w_V for brittle materials are expressed in following form[4, 5];

$$w_V=\frac{V}{L}=\alpha_3.\left(\frac{E}{H}\right).\frac{F_N{}^{9/8}}{H^{5/8}.K_{IC}{}^{1/2}} \tag{15}$$

Here; $\alpha_3=2.\alpha_1.\alpha_2$ and it is a constant which is independent from material.

Evans and Wilshaw[5] found out that crack propagation in materials are related to end of abrasive particle and ratio of wearing material hardness to fracture toughness. They stated that occurrence of main and side cracks are independent of geometry of wearing particle tip (Figure 7). They claimed that side cracks are the significant factors in material removing in abrasive wear. Volumetric wear rate, w_V for brittle materials is given in following equation [9];

$$w_V=\frac{V}{L}=\alpha_4.\frac{F_N{}^{5/4}}{K_{IC}{}^{3/4}.H^{1/2}} \tag{16}$$

Here, α4 is a material independent property.

Eq. 16 and 17 are similar because there is no significant difference between ratio of E/H for brittle materials. From expressions, wear rate in brittle materials is proportional to (H) and (FN) whereas inversely proportional to (KIC).

Mathia and Lamy[11] showed that transition from abrasive wear in ductile materials to brittle materials starts with occurrence of side cracks. Side cracks form chips. These researchers stated that fracture toughness to hardness ratio is an important factor in estimation of material characteristics in terms of ductility and brittleness. Side cracks occur when normal load on abrasive particle exceeds a critical load value of F*. This critical value, F* changes with fracture toughness (Kc) and hardness (H). So:

$$F^{*} \propto \left(\frac{K_C}{H}\right)^3 .K_C \qquad (17)$$

Here, K_C is generally taken as Mod I, plane shape change fracture toughness, K_{IC}.

As stated above, the ratio of $(\frac{H}{K_C})$ for a material is an indication of its brittleness and low values of "brittleness index" refers high values of critical load value of F*. Thus, wear of material in question is difficult because of brittle fracture. The value of $\left(\frac{K_C}{H}\right)^2$ has length dimension, it can be accepted as a critical reference length of fracture which occurs under the effect of sharp tipped abrasive particle contact on material surface [11]

3. Results

When volumetric wear rates for ductile and brittle materials are compared, followings are obtained: the equation derived for ductile materials in literature (Eq. 11)

1. $w_V = k.\frac{F_N}{H}$ (Microploughing + Microcutting); (Eq. 11)

Following equation is suggested for brittle materials:

2. $w_V = \alpha_4 . \frac{F_N^{5/4}}{K_{IC}^{3/4} . H^{1/2}}$ Micro crack (brittle fracture) (Eq. 16)

4. Discussion

As seen in expressions;

- Whereas there is no effect of material fracture toughness on wear rate in micro ploughing and micro cutting, it affects it in microcrack wear
- There is an increased effect of applied normal load on wear rate for micro crack wear (exponential is greater than unity)
- Exponential of hardness in micro crack is lower than unity so decreasing effect of increased hardness on wear rate has been decreased.

5. Lists of Symbols

Symbol	Explanation	Unit
K_{IC}	Fracture toughness based on Mod I	(MPa $m^{1/2}$)
$\alpha_1, \alpha_2, \alpha_3, \alpha_4$,	Constants	(-)
E	Modulus of elasticity	(N/mm^2)
H	Hardness of materials	(N/mm^2)
h	Depth of wearing groove	(m)
S_1, S_2,	Surface area of side cracks occured due to plastic deformation	(m^2)
2r	Width of wearing groove	(m)
f_{ab}	The ratio of wear material to volume of groove	(-)
C	Length of side crack	(m)
B	Depth of crack	(m)
θ	Half tip angle of cone shape abrasive particle	(^{o})
α	Attack angle	(^{o})
α_C	Critical attack angle	(^{o})
δV	Volume of removed portion as wear part	(m^3)
V	Wear volume of side cracks	(m^3)
S	Distance of sliding	(m^2)
L	Length of groove	(m)
$\overline{\delta V}$	Volume of groove on the surface.	(m^3)
F_1, F_2, F_3, F_4, F_5,	Applied normal loads	(N)
F^*	Critical Normal load	(N)
F_N	Normal load	(N)
K_C	Fracture toughness	(MPa $m^{1/2}$)

References

[1] ZumGarh, K. H. (1987) “Microstructure and Wear of Materials”, Tribology series ;Vol. 10, Elsevier Science Publishes, Amsterdam

[2] Sevim, İ., (1998) "ÇeliklerinAbrasivAşınmasındaAşındırıcı Tane BüyüklüğününAşınmaDirencineEtkisi” DoktoraTezi, İ. T. Ü. Fen Bilimleri ENstitüsü, İSTANBUL

[3] Sevim, İ., Eryürek, İ. B., “MakineMalzemelerindeAşınmaveAşınmanınoluşumMekanizmaları" Yüzeyİşlemleri, Sayı:17, 2000, sayfa.104-108

[4] Hutchings, M. I., (1992) “Tribology: Friction and Wear of Engineering Materials”, Cambridge.

[5] Evans, G. A. veWilshaw, R. T., “Quasý-Static Solid Particle Damage in Brittle Solids-I. Observations, Analysis and Implications” ActaMetallurgica, Vol.24, pp.939-956, 1976.

[6] Murray, J. M., Mutton, J. P. ve Watson, D. J., Abrasive Wear Mechanisms in Steels. Journal of

Lubrication Technology January 1982, Vol: 104 pp. 9-16

[7] Mutton, P., J. ve Watson, J., D., "Some Effects of Microstructure on The Abrasion Resistance of Metals." Wear, (1977)385 -398.

[8] Lawn, B. (1993) Fracture of Brittle Solids" Second Edition, Cambridge,

[9] Moore, A. M., and King, S. F. Abrasiv Wear of Brittle Solids.Wear Vol: 60, 1980 pp. 123-140

[10] Hornbogen, E. "The role of fracture toughness in the wear of metals", Wear 33 (1975), pp. 251–259

[11] Mathia, T. G ve Lamy, B. Proc. (1985) Conf. Wear of Materials ASME, New York, p:485,