

## Abrasive Wear of Digger Tooth Steel

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### Abstract

The influence of silicon carbide SiC abrasive particles of 20, 30, 40, 50 and 60  $\mu\text{m}$  size on carburized digger tooth steel was studied. Four types of steel, with different hardness, were tested at two constant linear sliding speeds and under various loads of 10, 20, 30, 40 and 50N. Tests were carried out for sliding time of 0.5, 1.0, 1.5, 2.0 and 2.5min. Experimental results showed that there was consistent reduction in abrasive wear as the hardness of the materials was increased. It was found that wear increased with the increase of applied load, linear sliding speed and sliding time. Also, it was noticed that the wear increased with increase in abrasive particle size, and the most effective size was 40  $\mu\text{m}$ . SEM observations of the worn surface showed that the cutting and ploughing were the dominant abrasive wear mechanisms.

**Keywords:** Abrasive Wear, Wear Resistance, Carburized Digger Tooth Steel.

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### 1. INTRODUCTION

Wear processes in metals have been classified into many types depending on the mechanism responsible for removal of material from the surface. Experiments have revealed that wear is a very complex process. Wear predictions, even through flawed, can be used in a number of ways besides estimating the wear rate. First, an equation for wear indicates the relative influence of various parameters, such as load, hardness, linear sliding speed, and surface roughness that

suggest changes in wear that might result, if the sliding system is changed. Second, component of the wear is also important in the failure analysis or in the study of any worn component of a system. Quantitative analysis of wear starts with the concept that while a sliding system may be losing material in more than one way, another mechanism will dominate the overall wear rate [1].

The failure of components in service can be often attributed to wear, erosion or corrosion-enhanced wear and erosion. The phenomenon contributing to failure under all these conditions is complex and often specific to the particular application. Material properties determining resistance to wear and erosion are correspondingly complex, making it difficult to predict the service behavior of a particular material. Generally, high hardness, rapid work hardening, and good oxidation and corrosion resistance can all contribute to wear and erosion resistance. Common materials currently used in severe wear and erosion applications include cobalt-based alloys, high manganese stainless steels, and other chromium containing alloys [2]. Under different testing conditions, all results showed that there was a decreasing trend in wear with increasing hardness of hard metals [3]. In experiments testing wear mechanisms, once equilibrium surface conditions have been established, the wear rate is normally independent of the area of contact. The wear rate is therefore proportional to the load for only a small number of variations, but there is still a small deviation between wear rate and load that forms a direct proportionality. Published literatures concluded that wear rate is proportional to the load and independent of pressure unless the area of contact was equivalent to one third of materials' hardness [4]. The most widely used quantitative relationship among abrasive wear rate, material properties, load and sliding speed, at the interface of two bodies loaded against each other in relative motion, was formulated [5]. Also, it was reported that wear rates of some materials vary linearly with the applied load and independent of pressure over a wide range. It was shown that there is an inverse relationship between wear rates and hardness. Wear is quantified by weight or volume loss per unit of time or per sliding distance. These simple results are marked in contrast to the majority of wear experiments reported in literature. They suggest that wear is dependent on a large number of variables and there is no general agreement about how the wear depends on such variables as applied load, linear sliding speed, and apparent area of contact. Generally, the abrasive wear of alloy steel is characterized by two modes, designated severe wear and mild wear. This has been recognized by many investigators for a long time [6]. It has been found that, at the constant linear sliding speed used, in the load range, where equilibrium mild wear operates, the sliding distance for initiation of mild wear decreases logarithmically with the load. The slope of this decrement is termed the running-in coefficient and is a quantitative measure of the running-in behavior of the steel. The presence of 3% Cr markedly decreases the running-in coefficient, i.e. increases the sliding distance required for the initiation of mild wear at a given load [7].

Hard metals could be an ideal solution for wear resistance. At present, hardened steel or some technical ceramic materials, in bulk or as a surface coating, are often used. The main purpose of these materials is to extend the life time of existing devices and/ or components by decreasing their wear rate. A significant disadvantage of these materials is their relatively high friction coefficient in dry contact conditions (heat development and energy loss). Moreover, their high hardness renders them intrinsically difficult to shape and to finish using conventional methods [8]. High chromium content white cast irons have generally good wear resistance and toughness properties. These types of cast irons are generally used in slurry pumps, brick dies, and several mine drilling equipment. Rock chromium content cast iron materials have higher toughness than have low chromium ones [9]. Investigations of the wear behavior of white cast irons under different compositions were conducted against SiC and Al<sub>2</sub>O<sub>3</sub> abrasive paper, and the results showed that the wear rate was affected by the composition of white cast iron [10]. White cast iron containing copper under erosive wear testing has been devised, and the results showed that a linear relationship has been established between the percentage of copper and the amount of erosion. Relative erosion is directly dependent on the carbide volume, carbide particle size and also the angle of impact [7]. The results of wear test of hard boron carbide B<sub>4</sub>C thin films, and the data obtained from pin-on-disc tests show that the abrasiveness of a contact is proportional to the number of asperities in the contact and the effect of increasing the load is to enlarge the initial

apparent contact region, and the dependence of the wear rate on load follows relationships that are similar to Hertzain relationships [11].

The aim of this work is to investigate the role of abrasive particles size and other factors on the wear properties of carburized digger tooth steel. There are a number of different types of wear testing methods. Low stress or scratching abrasion is probably the most predominate in the mining industry. A quantitative method of measuring a materials resistance to this scratching type abrasion is the pin-on-disc apparatus, (ASTM G99-05, 2006). This test characterizes materials removed in terms of weight loss under a controlled set of laboratory conditions. Correlation to actual field conditions which may be influenced by other wear parameters, such as the amount of impact, corrosion, galling, etc. is required.

## 2. EXPERIMENTAL WORK

Pins of 8mm diameter and 80mm length for wear test were prepared by machining them from digger tooth steel. The composition of the digger tooth steel used for this study is listed in Table 1. All pins were case hardened under pack carburizing conditions given in Table 2.

C%	Si%	Mn%	Mo%	Ni%	Al%	P%	S%	HRC
0.40-0.42	0.40	0.90-0.95	0.25	0.20	0.04	0.03	0.02	45

**TABLE 1:** Composition of the Digger Tooth Steel.

Group No.	Holding time, h	Cooling medium	Heating temperature, °C	HRC
1	16	Air	980	64
2	12	Air	850	58
3	10	Air	750	52

**TABLE 2:** Carburizing Conditions of Test Pins.

The carburized pins were heated to 850°C for 30min then water-hardened. Abrasive wear tests were carried out at room temperature on a pin-on-disc apparatus shown in Figure 1. The steel disc,  $\phi$  230mm, was covered with abrasive papers of different SiC particles size of 20-30-40-50-60  $\mu$  m. Pins were pressed on the disc with different normal loads of 10-20-30-40-50N. Wear data were collected after 0.5, 1.0, 1.5, 2.0, and 2.5min. Wear tests were carried out at two different linear sliding speeds of 1.5 and 2.5m/s. Abrasive wear was determined from the change in the weight using  $1.00 \times 10^{-4}$ g precision digital scale. For each wear test a new pin has been used in a new sliding position. Microscopic views of the test pins were taken, also worn surfaces of pins were examined using scanning electron microscope.

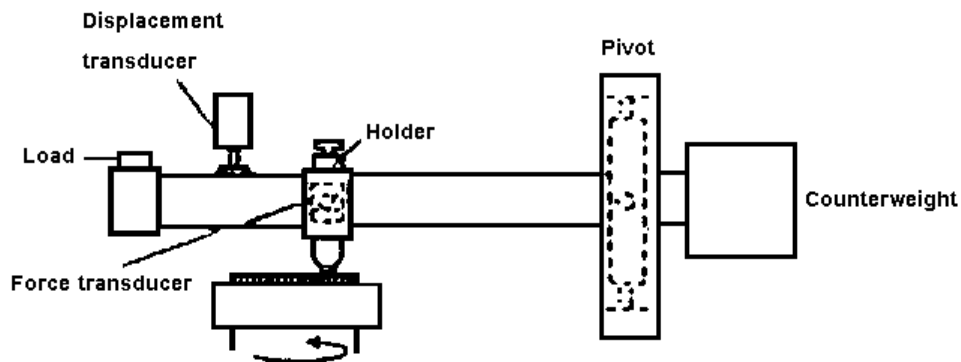


FIGURE 1: Schematic Diagram of a Typical Pin-on-Disc Tester.

### 3. RESULTS AND DISCUSSIONS

#### Effect of Sliding Time On The Total Weight Loss

The relationship between total weight loss TWL and sliding time for the specimens used in the tests is shown in Figures 2-6. The specimens used in these tests were all subjected to the same load (10N), linear sliding speed (1.5m/s), and abraded against SiC papers with different particle size (20-60  $\mu\text{m}$ ). These plots showed that the total weight loss increased as the sliding time increased. This increase in total weight loss was sharper until sliding time of 2.0min, and then the relationship behaved as steady state, especially for the SiC particles size of 50-60  $\mu\text{m}$ . This trend may be due to the increase in temperature of the worn surface and the work hardening effects. Thus, the specimen hardened to 64HRC will exhibit better wear resistance comparing with the same specimen hardened to 45HRC [12].

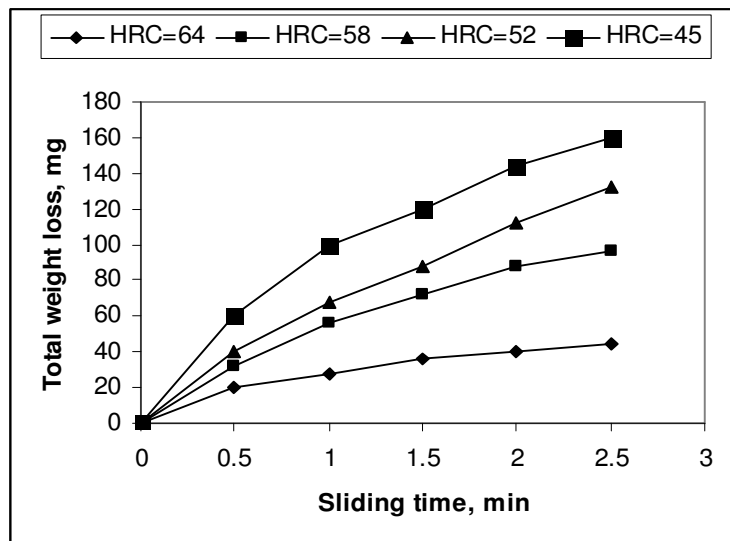


FIGURE 2: Effect of Sliding Time on the Total Weight Loss for Load = 10 N, Linear Sliding Speed = 1.5 m /s and SiC Particles Size = 20  $\mu\text{m}$ .

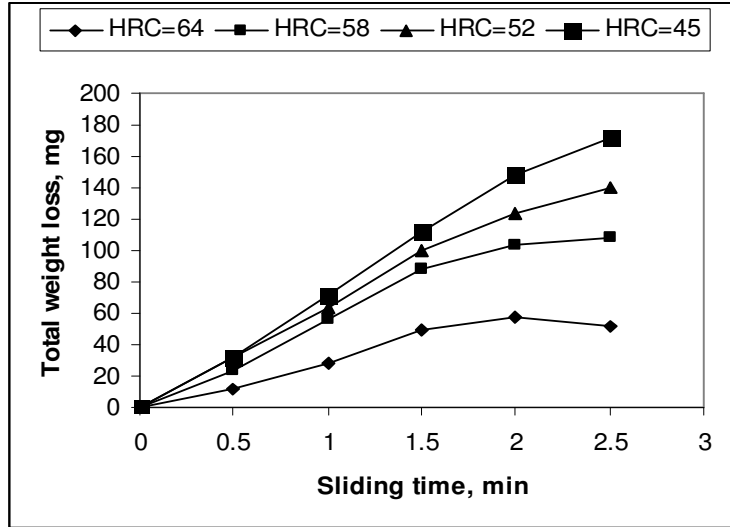


FIGURE 3: Effect of Sliding Time on the Total Weight Loss for Load = 10 N, Linear Sliding Speed = 1.5 m /s and SiC Particles Size = 30  $\mu$  m.

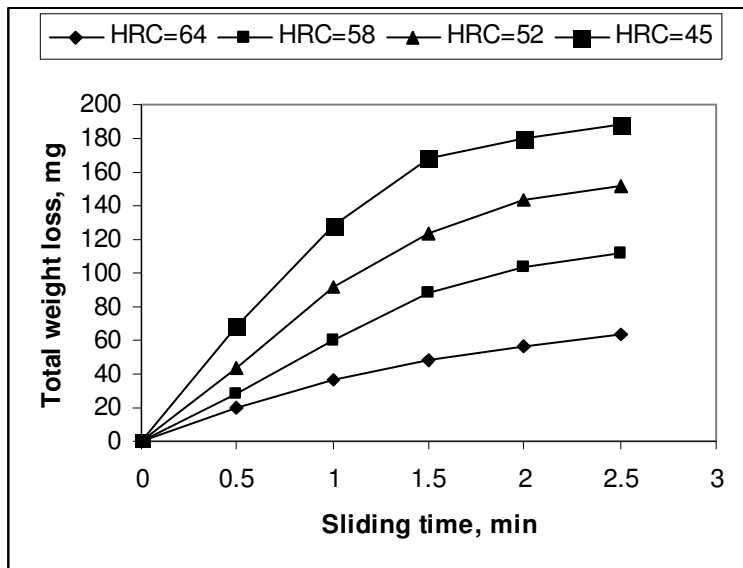
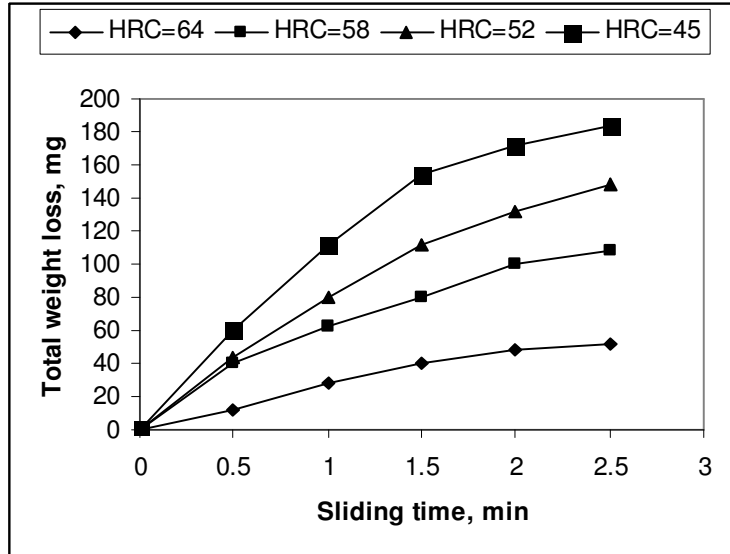


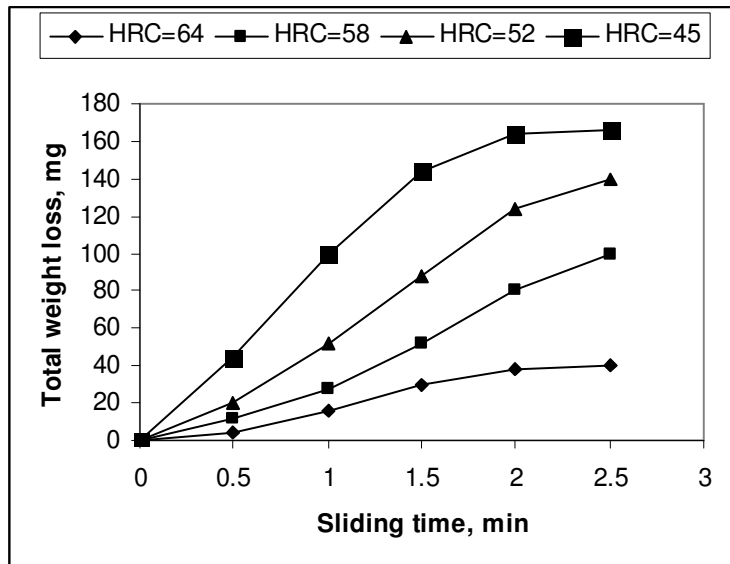
FIGURE 4: Effect of Sliding Time on the Total Weight Loss for Load = 10 N, Linear Sliding Speed = 1.5m /s and SiC Particles Size = 40  $\mu$  m.



**FIGURE 5:** Effect of Sliding Time on the Total Weight Loss for Load = 10 N, Linear Sliding Speed = 1.5m /s and SiC Particles Size = 50 μ m.

**Effect Of Abrasive Articles Size On The Total Weight Loss**

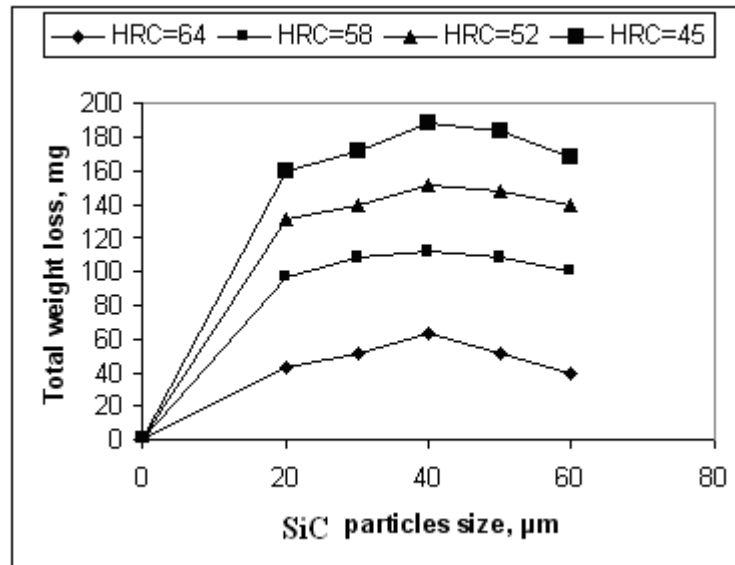
This means that the specimen with 64HRC is more abrasive wear resistant than that with the total weight loss for four specimens with different hardness as a function of SiC particles size is shown in Figure 6. The specimens were subjected to the same load (10N), sliding speed (1.5m/s), and abraded against SiC papers with different particles size (20-60 μ m) for 2.5min sliding time.



**FIGURE 6:** Effect of Sliding Time on the Total Weight Loss for Load = 10 N, Linear Sliding Speed = 1.5 m/s and SiC Particles Size = 60 μ m.

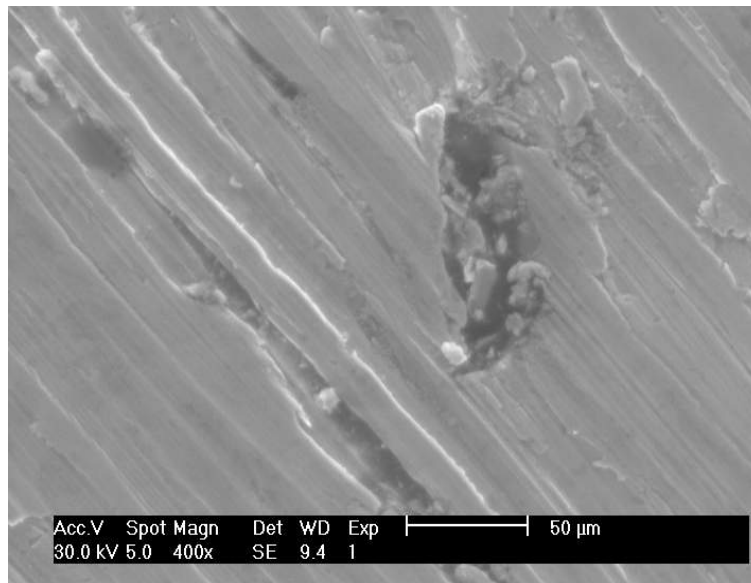
Figure 7 shows that the specimen with 45HRC is the most worn one, while the specimen with 60HRC is the least worn one, and the total weight loss has been increased with increasing in SiC particles size. It is considered that the total weight loss for all specimens is maximum when they are abraded by SiC of 40 μ m size, which is the critical size, and then the effect of SiC particles

size has been decreased due to the change in their mechanical action from cutting to scratching and deformation [13].

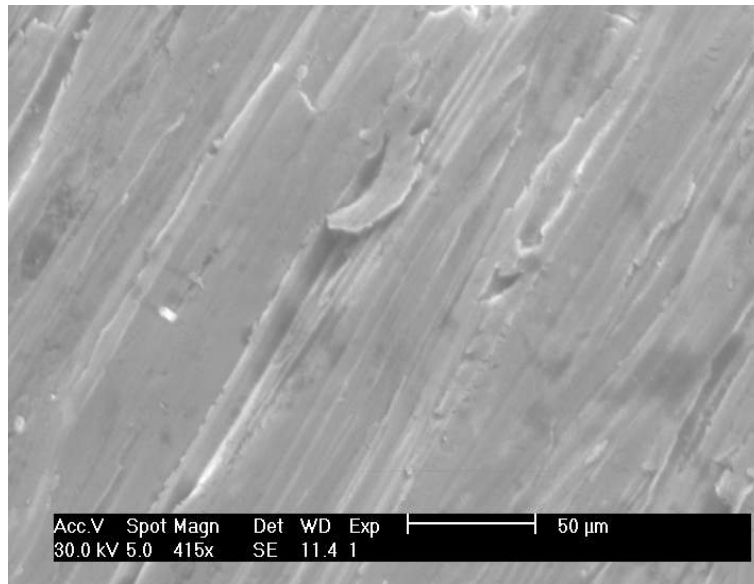


**FIGURE 7:** Effect of SiC Particles Size on the Total Weight Loss for Load = 10 N, Linear Sliding Speed = 1.5m/s and Sliding Time = 2.5 min.

Figures 8 and 9 show the worn surfaces of the specimens of 64HRC abraded under the same abrasive wear conditions (load =10N, sliding speed=1.5m/s and sliding time=2.5min).

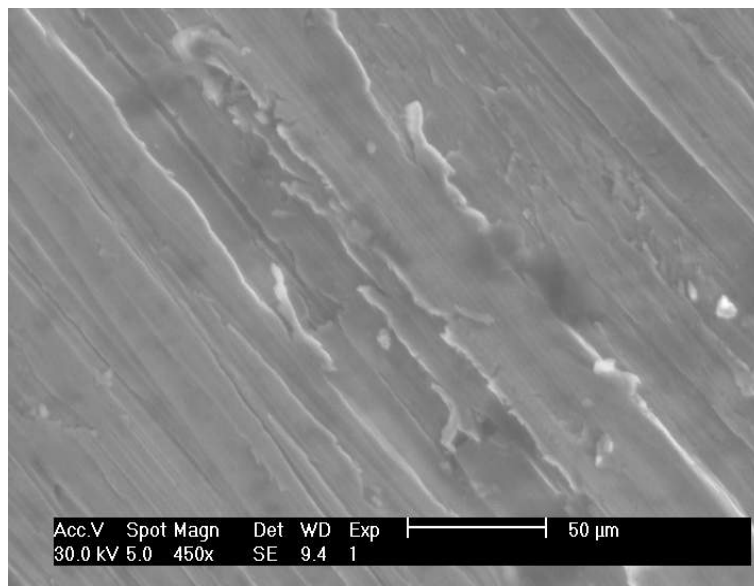


**FIGURE 8:** SEM Micrograph of Worn Surface of 64HRC Specimen Exposed to Abrasive Wear with 40 µm SiC.



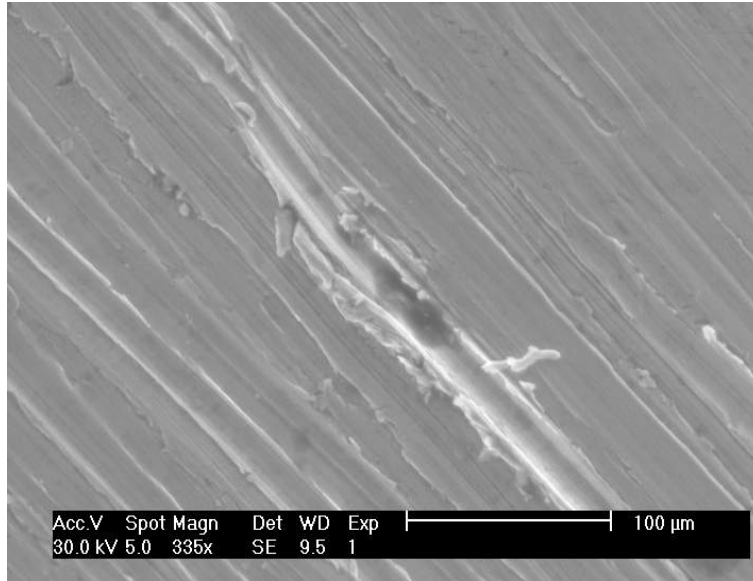
**FIGURE 9:** SEM Micrograph of Worn Surface of 64HRC Specimen Exposed to Abrasive Wear with 60  $\mu$  m SiC.

Figures 10 and 11 show the SEM micrographs of worn surfaces of digger tooth steel before case hardening (45HRC) and after case hardening (64HRC) abraded under the same abrasive wear conditions (applied load =50N, linear sliding speed =2.5m/s, and sliding time =2.5min). It is clear from Figs. 10 and 11 that the surface damage before case hardening is more than that after case hardening 45HRC.



**FIGURE10:** SEM Micrograph of Worn Surface of 45 HRC Specimen Exposed to Abrasive Wear with 40  $\mu$  m SiC Particles, 50 N load, and 2.5m/s Linear Sliding Speed.

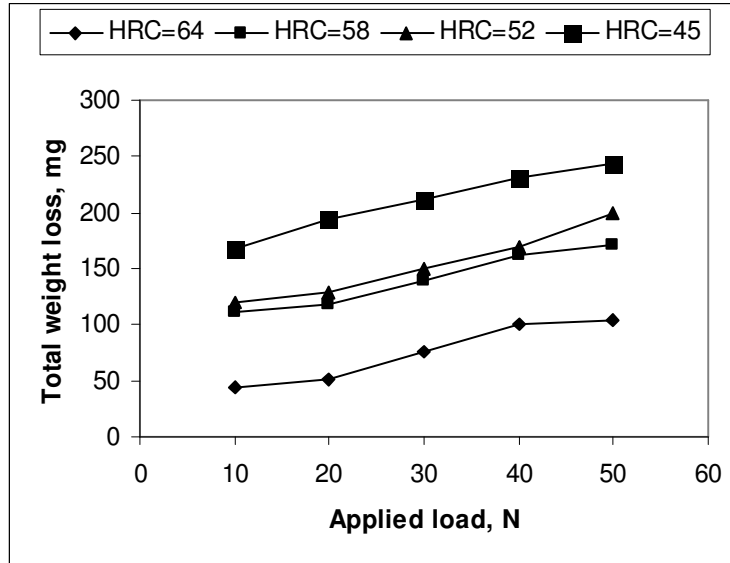




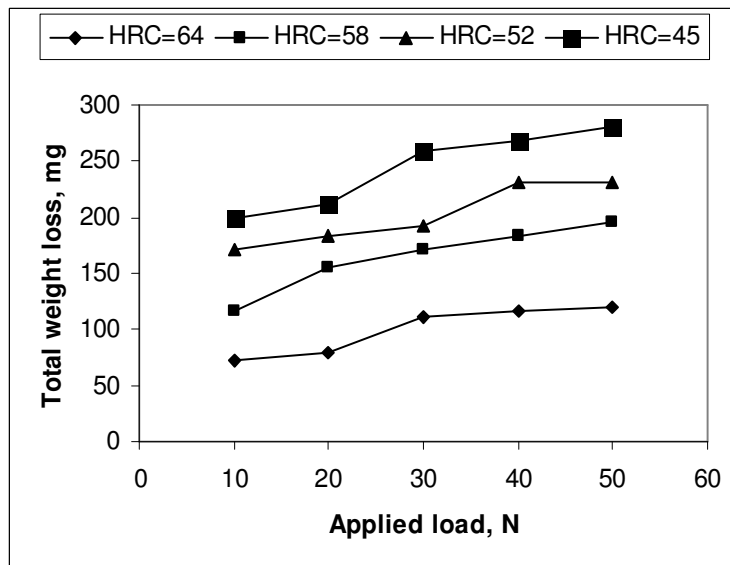
**FIGURE11:** SEM Micrograph of Worn Surface of 64 HRC Specimen Exposed to Abrasive Wear with 40  $\mu$  m SiC Particles, 50 N Load, and 2.5m/s Linear Sliding Speed.

#### **Effect Of Load On The Total Weight Loss**

The total weight loss of the specimens as a function of applied load after 2.5min sliding time with 1.5-2.5m/s sliding speed and SiC particles size of 40  $\mu$  m is shown in Figures 12 and 13. The plots on the mentioned figures show that the total weight loss for all specimens has been increased with increasing the applied load at constant linear sliding speed. Also, the plots show that the total weight loss has been increased with increasing the linear sliding speed under constant test conditions. Transition curve has been obtained for each specimen. The transition curves show three distinct regions: mild wear, transitional wear indicating a possible change in wear mechanism, and sever wear. These regions become clearer as the HRC of the specimens increases. The transitional wear region occurs between 20-40N loads for 1.5m/s linear sliding speed, and 20-30N loads for 2.5m/s linear sliding speed. This trend is related to the temperature effect at the worn surface [3].



**FIGURE 12:** Effect of Applied Load on the Total Weight Loss under Sliding Speed =1.5m/s, Sliding Time =2.5 min and SiC Particles size =40  $\mu$  m.

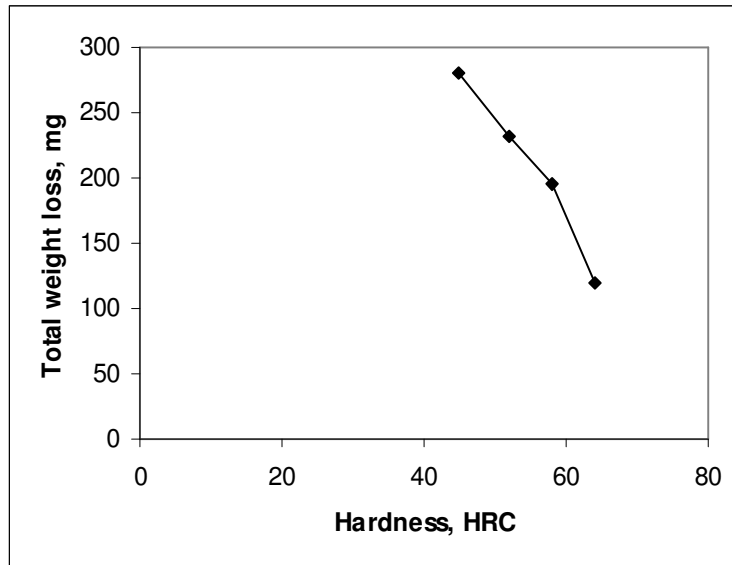


**FIGURE 13:** Effect of Applied Load on the Total Weight Loss under Sliding Speed =2.5m/s, Sliding Time =2.5min, and SiC Particles Size =40  $\mu$  m.

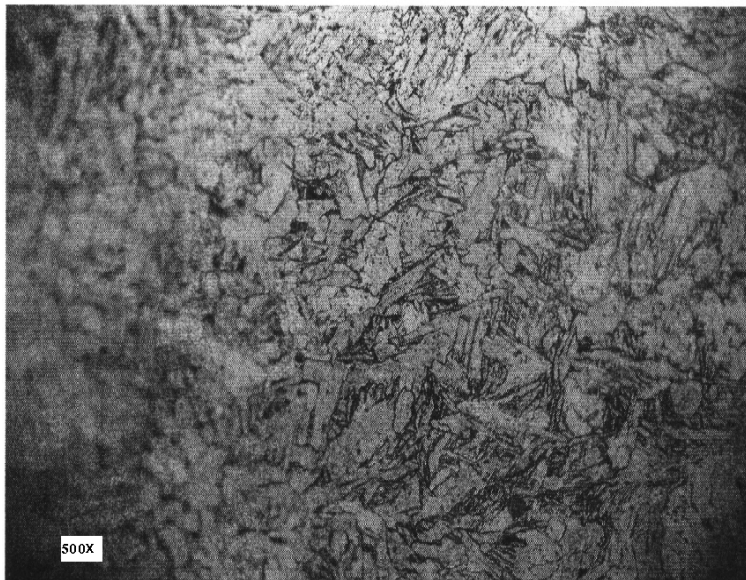
### Effect Of Specimens Hardness On The Total Weight Loss

As mentioned earlier, wear depends on a number of parameters including material hardness. The specimens used in wear tests were all subjected to the same test conditions, but due to their individual hardness, some of them, such as specimen with 64HRC, were more resistant to wear than others [11]. Figure 14 shows a trend for decreasing wear with increasing specimens' hardness and the wear in specimen of 45 HRC is twice greater than the wear in specimen of 64 HRC. The microstructure of heat treated test specimens before case hardening is shown in Figure 15. Concerning Figure 16, it shows the optical microscope photograph of steel carburized 16h to surface carbon content 0.9%, while Figure 17 shows the optical microscope photograph of water-hardening steel-case hardness was 64HRC and core hardness was 45HRC. Figures 16

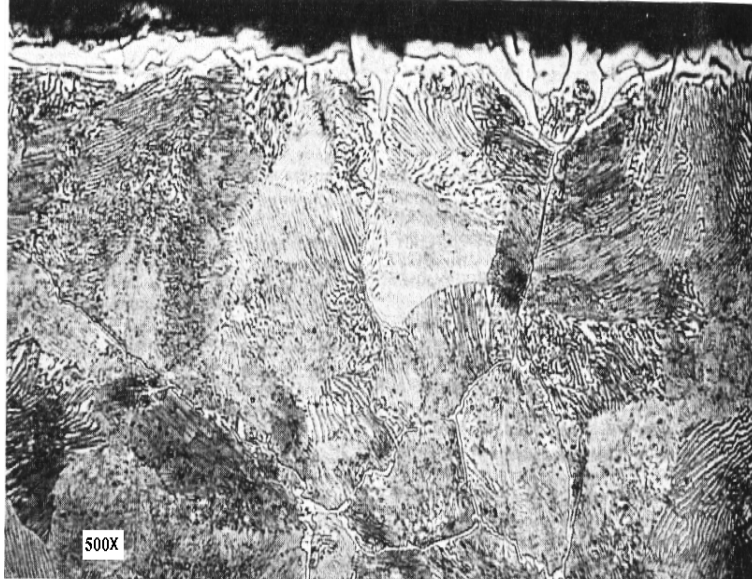
and 17 show the appearance of carbide layer on the surface, which increases the hardness, and as a result, the abrasive wear has been reduced comparing with the digger tooth steel microstructure shown in Figure 15, before case hardening.



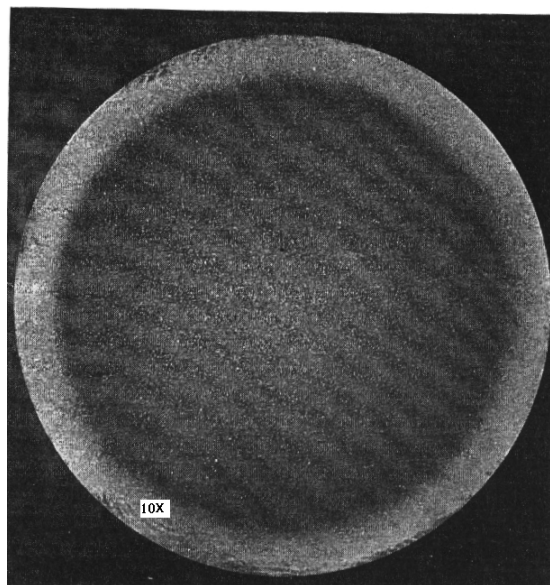
**FIGURE 14:** Effect of Hardness on the Total Weight Loss under Applied Load =50N, Sliding Time =2.5min, Linear Sliding Speed =2.5m/s, and SiC Particles Size = 40  $\mu$  m.



**FIGURE15:** Optical Microscope Photograph of Heat Treated Digger Tooth Steel before Case Hardening Showing Fine Grain of Ferrite and Pearlite.



**FIGURE16:** Optical Microscope Photograph of Steel Carburized 16h to a Surface Carbon Content 0.9% Showing Carbide Surface Layer.



**FIGURE 17:** Optical Microscope Photograph of Water-Hardening Steel. Case Hardness = 64HRC; Core Hardness=45HRC Showing Light Gray Martensitic Zone.

### **Effect Of Linear Sliding Speed On The Total Weight Loss**

Figures 12 and 13 show the effect of linear sliding speed on the total weight loss. The total weight loss in all specimens abraded under the same abrasive conditions increased as the linear sliding speed increased from 1.5m/s to 2.5m/s. This is due to the increase of the contact surfaces temperature, which leads to softening of the worn surface.

#### 4. CONCLUSION

Based on the results of this study, the following conclusions can be made:

1. The total weight loss increases with increase of abrasive particles size, and the maximum wear occurs with a critical abrasive particles size of  $40\mu\text{m}$ .
2. There is a significant reduction in wear as the hardness of materials increases.
3. Abrasion resistance of materials depends at the same time on a number of factors, such as their hardness, microstructure, applied load, sliding time, sliding speed, and other wear test conditions.
4. The total weight loss increases as the exposed time to abrasive surface, linear sliding speed, and applied load increases.
5. The transitional wear region decreases as the linear sliding speed increases.
6. As the hardness of abraded materials increases the three types of wear regions (mild, transitional, and sever) become more distinct.
7. Examination of worn surfaces shows that ploughing, cutting, and fracture are the dominant abrasive wear mechanism.

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