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"Effect of surface treatment on the adhesive wear of low carbon steel"

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Abstract :
Wear is one of the problems that occur in the moving parts either by rolling or sliding. This work includes experimental study on the wear of low carbon steel. Three surface treatments were chosen these are cyaniding, solid carburizing and hard chrome plating. The wear test was made under dry contact condition for the treated and the untreated surfaces. A constant load and speed were used for two types of motion: sliding-rolling and pure rolling. An Amsler machine was used. The high carbon steel was chosen for making the upper specimen and the low carbon steel was chosen for making the lower specimen. The high carbon steel was hardened while the other was surface treated (carburizing, cyaniding). The hard chrome plating was also used to increase the surface hardness. It was noticed that increasing of surface hardness reduced the wear amount produced, and the cyaniding gave the highest resistance to wear whereas the hard chrome plating gave the lowest one, and the wear under pure rolling condition was small .It was found that the wear rate of treated surfaces is high in the first stage of the test then the rate decreases until it reaches a steady state and for both motions.[v]

Key words: “ Wearing , surface , treatment , hardening , steel “.

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I. Introduction:

Wear, along with fatigue and corrosion, is one of the common industrial problems that often lead to the replacement of affected parts. Wear can also be defined as the degradation of surfaces due to use. The amount of wear that occurs in materials largely depends on the properties of the materials used and the nature of the interacting surfaces. It is impossible to completely prevent wear, as it typically occurs whenever there is a load accompanied by motion, which can be either sliding, rolling, or a combination of both. The occurrence of this phenomenon costs industries vast amounts of money, as in some factories the annual cost of replacing worn parts is very high. This has encouraged researchers to study the phenomenon, understand its causes and mechanisms, particularly under dry wear conditions (i.e., without lubrication), as results in such conditions are more evident.

Many studies and research have been conducted on this phenomenon to find solutions to minimize it, whether by selecting suitable materials and alloys or by applying surface treatments such as surface hardening methods and coating techniques. The application of such treatments provides two benefits simultaneously: high surface hardness while maintaining core ductility, which improves wear resistance and the ability to withstand high stresses. Given the importance of this phenomenon, this research aims to improve the wear resistance of low-carbon steel through surface treatments, including surface hardening methods like nitriding and carburizing, as well as hard chrome plating. The tests were conducted under dry conditions using two motion types: sliding-rolling and pure rolling, as these two movements are important in several engineering applications such as cylindrical bearings, ball bearings, and gears .[ii]

II. Material and experimental work

Low-carbon steel designated (CK15) according to the German specification (DIN) was selected for surface treatments, including solid carburizing, cyaniding, and hard chrome plating, to manufacture the lower test sample. Steel designated (CK60) according to the German specification (DIN) was selected for full hardening and tempering to be used as the upper test sample[iv]. Their chemical compositions are given in Table 1.

The raw materials for the two types of steel mentioned above were machined to a diameter of 45 mm to produce test samples according to the required dimensions based on the specifications of the Emsler testing machine[iii]. Figure 1 shows the dimensions of the samples used in the wear test. The above-mentioned surface treatments were then applied to the CK15 steel to increase surface hardness, while the CK60 steel was subjected to hardening.

The solid carburizing process involved preparing four test samples by placing them inside a steel box with a lid designed for this purpose. The samples were surrounded by carburizing material, which consisted of solid granules made of coal and barium carbonate. The box was then sealed, and its lid was coated with clay to prevent gas leakage from the chemical reactions inside. The box was placed in an electric furnace, which was heated to 915°C for three hours. This treatment resulted in chemical reactions that decomposed carbon monoxide on the surface, allowing atomic carbon to diffuse into the steel surface. Once the steel samples' surfaces were saturated with carbon, surface hardening was performed by heating the samples to 840°C for 20 minutes, followed by direct water quenching. The samples were then tempered at 200°C for one hour.

The cyaniding process involved placing four steel samples in a crucible filled with the required material for this process, which consisted of solid balls commercially known as CE Constant 80 A, made of sodium cyanide and barium chloride. The crucible was inserted into a furnace to saturate the steel surface with nitrogen and carbon. The furnace was heated to 900°C until the solid balls melted into a liquid state, and the samples were left for 1.5 hours to saturate their surfaces with cyaniding material. Afterward, the samples were removed from the furnace and immediately quenched in water to achieve high surface hardness.[x]

Table 1: Chemical composition of the steel used in manufacturing the test samples.

Metal type	%C	%Si	%Mn	%P	%S
CK15	0.14	0.40	0.38	0.029	0.03
CK	0.62	0.41	0.73	0.031	0.032

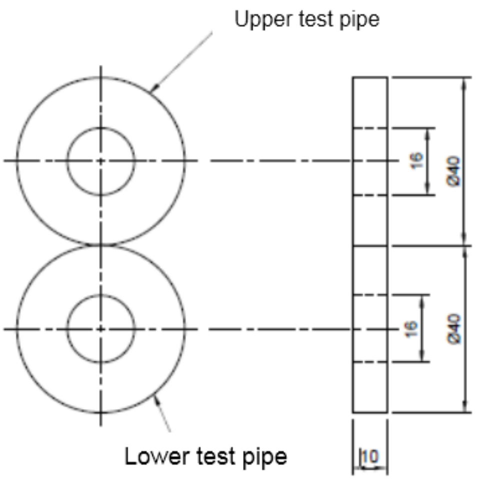

Figure (1): Dimensions of the wear test samples (in millimeters)

This process is considered one of the more sensitive industrial procedures due to the hazardous nature of the materials used, which are toxic. Therefore, industrial safety precautions were taken, such as using gloves, masks, etc., in addition to ensuring good ventilation to expel the hazardous fumes released during the process. Following that, the tempering of the samples was conducted at 200°C for one hour.

As for the chrome plating process, it is worth noting that chrome is one of the most important and widely used metals in electroplating, alongside nickel. There are two main types of chrome plating: the first is used to enhance the external appearance of the steel surface (decorative), and the second is hard chrome plating, which provides properties such as wear resistance and heat resistance by depositing chrome directly onto the surface. This method was employed in the research, using a setup consisting of a plating tank, a power supply, lead electrodes, an electric heater, and a plating solution. The plating tank, which has a 70-liter capacity, was prepared by washing it and adding chromic acid at a concentration of 300 g/liter of distilled water and sulfuric acid at a concentration of 3 g/liter of distilled water. The plating solution was heated to a temperature of 45–50°C. The steel samples to be plated were connected to the power supply as the negative electrode, and the lead electrodes were connected as the positive electrode.[vi] The samples were submerged in the solution, and a current of 15 amps was applied for 50 minutes. The amount of current and duration of the process depend on both the surface area and the desired thickness of the coating layer.

Regarding the hardening of CK60 steel, the samples were heated to 820°C for 20 minutes, then quenched directly in water. Following this, tempering was carried out at 200°C for one hour. Table 2 details the surface treatments and heat treatments applied to the test samples. The hardness test was conducted using the Vickers hardness test method on all samples before and after the treatments to determine the changes in surface properties. A Vickers hardness tester[vii] (Karl Kolb) was used for this purpose, and the test results are shown in Table 2.

Next, a wear test was performed on all the samples using the Amsler testing machine. This machine is equipped with a two-speed electric motor. When the motor is turned on, two disks (the test samples) rotate against each other under a load. By adjusting the speed difference between the two disks, a rolling-sliding motion with a 10% sliding component can be achieved, or pure rolling motion can be obtained when the disks rotate at equal speeds. For the test, the samples were first cleaned with alcohol, dried, and weighed using a precision balance (Mattler Ae 160). The samples were then mounted on the machine and run for two hours before stopping the machine. The samples were then disassembled, cleaned chemically with a special solution, dried, and re-weighed to determine the weight loss due to wear. In this research, the wear resistance of surface-treated samples was studied under constant load and speed, using both rolling-sliding and pure rolling motion without lubrication. Table 3 shows the conditions used in the wear test.

Table (2): Types of treatments applied to the samples:

Metal type	Heat Treatment		Hardness
	Carburizing	Carburizing to (915) °C for (3) hrs. + Heating to (840) °C for (20) min	600Hv
CK 15		+ Cooling in water +Tempering to (200) °C for (1) hr.	
	Cyaniding	Cyaniding to (900) °C for (1.5) hrs. + Cooling in water +Tempering to (200) °C for (1)hrs.	680 HV
	Hard chrome plating	Heating the solution to (45-50) °C Current:15 (A) for (50) min.	560 Hv
CK 60	Hardening	Heating to (820) °C for (20) min. + cooling in water. +Tempering to (200) °C for (1) hr	755Hv

Table (3): Conditions used in the wear test

100N	Load applied
DRY	Inspection type
1430 R.PM	Engine revolution
1148 R.PM	Number of r.p.m for lower axis
1148 rpm for pure rolling motion 1040 rpm for sliding & rolling motion	Number of r.p.m for upper axis
25-30°C	Temperature

III. Result and discussion :

In this research, the effect of surface treatments such as carburizing, cyaniding, and hard chrome plating on the wear resistance of low-carbon steel was studied. Dry wear tests were conducted on both treated and untreated surfaces under constant load and speed, using two types of motion: sliding-rolling and pure rolling. The wear curve for each test was plotted, showing the relationship between test duration and weight loss. From Figure 2, it is evident that the untreated samples experienced a significant increase in wear from the start of the test, and this increase continued with longer test durations, consistent with Archard's theory[ix] .

As is well known, even the smoothest surfaces are microscopically rough . The ongoing increase in wear can be explained by the substantial removal of surface asperity peaks in untreated samples due to their low hardness and, consequently, lower yield strength. This leads to plastic deformation of the asperities, which are then removed by shearing.

When examining the effect of different types of motion (rolling-sliding and pure rolling) on surface wear (Figure 2), it is noticeable that the amount of wear is lower in the case of pure rolling compared to rolling-sliding. This is because, in pure rolling, the two test specimens rotate at equal speeds, reducing the number of asperities in contact. As the motion continues, plastic deformation and adhesion of the contacting asperities occur, followed by tearing and removal of the less hard asperities . Therefore, wear is lower in pure rolling compared to rolling-sliding, which is true for both treated and untreated surfaces.

The behavior of low-carbon steel aligns with Yamada's findings , which indicate that mild carbon steel exhibits continuous wear as the test duration increases. The amount of wear primarily depends on the nature and area of contact between surfaces, which in turn is influenced by the distribution and size of surface asperities[ii] . The applied load is supported by some asperity peaks, leading to the formation of microscopic adhesion points, which contribute to the real contact area being smaller than the apparent contact area . If the applied load is large and the material has a low yield strength, plastic deformation of the contact area will occur , as the localized stress at the asperities is high, leading to plastic deformation and subsequent removal of the asperity peaks, thereby increasing wear.

Saturating the steel surface with nitrogen and carbon through the cyaniding process had the greatest effect in reducing wear, while surface carburizing (carbon saturation only) had a lesser effect compared to cyaniding. The increase in hardness was greater for cyanided surfaces than for carburized ones. In carburizing, the carbon content at the surface increases, enhancing the steel's hardenability. In cyaniding, both carbon and nitrogen contribute to the surface hardness, with nitrogen increasing hardness by dissolving in ferrite and forming iron nitrides.

The third treatment, hard chrome plating, also reduced wear, but to a lesser extent than the aforementioned surface hardening techniques. Figure 3 shows the wear curves for treated and untreated surfaces, demonstrating the significant effectiveness of the treatments in reducing wear compared to untreated surfaces under rolling-sliding motion conditions.

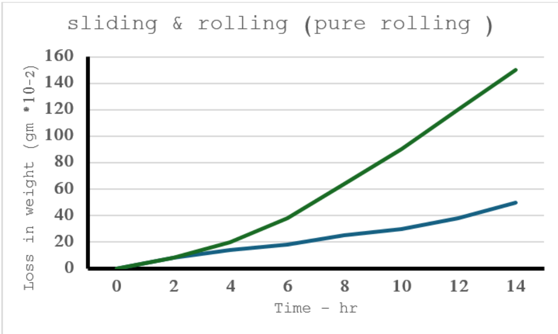

Figure (2): The relationship between wear and test duration for untreated surfaces under two types of motion.

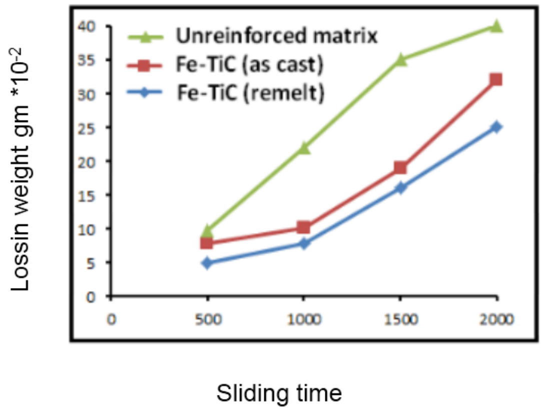

Figure (3): The relationship between wear and test duration for treated and untreated surfaces under sliding-rolling conditions.

Figure (4) illustrates the relationship between wear and test duration for treated and untreated surfaces under pure rolling conditions. When comparing the performance of surfaces treated with the three methods under the influence of different types of motion (sliding-rolling, pure rolling), it is important to note that both motion types can occur in some components, such as gear teeth. It was observed that the amount of wear is greater when there is sliding in addition to rolling due to the interaction of a larger number of surface asperities, resulting in greater shearing of the microscopic adhesion areas compared to pure rolling, where the speed of both test specimens is equal.

To study the effect of hardness on wear rates of surfaces, it is well known that hardness is closely related to yield strength. The term "hardening" of metals typically refers to increasing their resistance to failure caused by loads exceeding the elastic limit. Wear resistance can be improved by increasing the material's hardness. However, traditional hardening methods often reduce ductility and impact strength. When combining high surface hardness with a high ductility in the core, it allows for resistance to high stresses and severe wear conditions. This method is applied in many components such as gears, cams, piston rings, and cylindrical bearings.

It is noticeable that surfaces with the highest hardness exhibited the lowest wear regardless of the type of motion. This agrees with research by Archard, which found that wear volume is inversely proportional to material hardness. Figures (5) and (6) show the effect of hardness on the amount of wear for each surface.

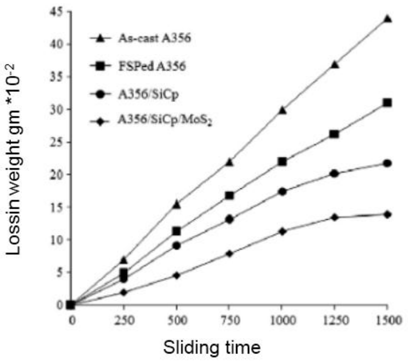

Figure (4): The relationship between wear and test duration for treated and untreated surfaces under pure rolling conditions.

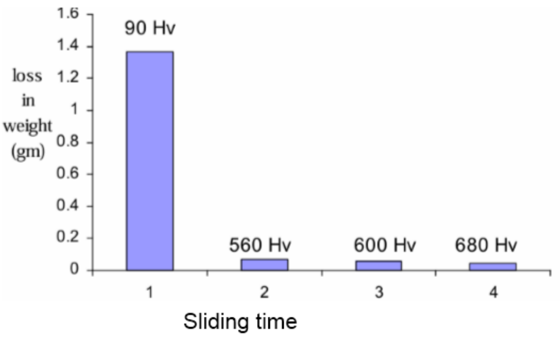

Figure (5): Weight loss versus surface hardness during sliding-rolling motion for the surfaces:
1 - untreated, 2 - chrome-plated, 3 - carburized, 4 - cyanided.

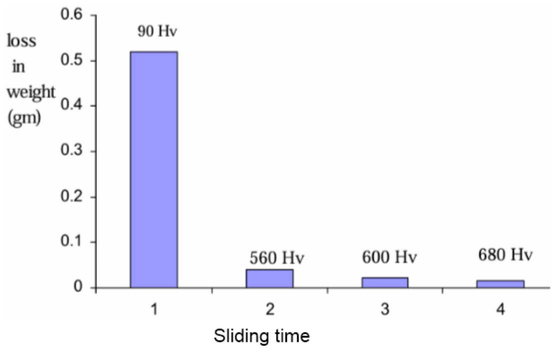

Figure (6): Weight loss versus surface hardness during pure rolling motion for the surfaces:
- untreated, 2 - chrome-plated, 3 - carburized, 4 - cyanided.

IV. Conclusions:

Based on the results obtained from this research, the main conclusions can be summarized as follows:

1. The amount of wear on the surfaces generally increases with the duration of the test under dry wear conditions and for both types of motion: sliding-rolling and pure rolling.
2. A significant amount of wear was observed on the untreated low-carbon steel surfaces for both types of motion.
3. The amount of wear on the surfaces treated by cyaniding, carburizing, and hard chrome plating decreases due to the increased surface hardness for both types of motion.
4. Among the three treated surfaces, the lowest amount of wear was observed on the cyanided surface, while the chrome-plated surface exhibited the highest amount of wear.
5. The amount of wear for all treated and untreated surfaces is greater when the motion type used is sliding-rolling.

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