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Improvement of Wear Property of Carbon Steel by Vanadium Carbide Surface Layer

Xiaowei. Pan

Abstract**—**Carbon steels are widely used in manufacturing of simple constructions and machine elements. The main limitations of these materials are their low hardness, poor friction and poor wear properties. For that reason, many attempts have been made to improve their hardness and other mechanical properties. One of the challenges is to find ways to improve the surface property of cheap steels in order to enhance its usage properties and ultimately extend the service life in an economic way. Due to its high hardness, vanadium carbides are often applied to the surface of carbon steels through coating processed and thermal diffusion processes.

Samples of high carbon steels are treated using the molten slag process to form vanadium-based alloy layer on the surface of steel. After treatment using the mentioned molten slag process, the anti-wearing property of high carbon steel is improved by 15.6 times. The surface-alloy layers on high carbon steel are found in the form of vanadium carbide with a composition of $VC_{0.8}$. The hardness of the alloy layer is 2200Hv, 3.4 times higher than that of high carbon steel.

Keywords**—**steel surface treatment, vanadium carbide, surface alloying

I. Introduction

It is well known that the surfaces of metal parts usually undertake most of the stresses and the failure of many metal parts is due to the failure of its surface, see in Fig.1. It frequently happens, when the metal parts are used under the conditions of pressing; hinging; joining; wearing; oxidizing and chemical corrosion. South Africa is one of the important players in the industries of mining, mineral processing, rail transportation, petrochemical and energy generation. Many metal parts are deployed under the conditions that require better properties, such as anti-wearing, anti-corrosion and anti-oxidization. In most applications, those metal parts are often made from steels with high alloys, such as high chromium steals, high nickel steels, high manganese steels. Steels with high alloys require more difficult processes to make and needs to add more expensive alloys. It will be rational, economic, and effective, if some metal parts can be made from low cost carbon steels with a layer of desirable and expensive high alloys. Therefore it is important to find ways to improve the surface properties, in order to achieve a better usage of metal parts with longer lifespan, and less cost.

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Fig. 1 Illustration of new and failed steel bearings, due to the damaged on the surface

Carbon steels are widely used in manufacturing of simple constructions and machine elements [1]. The main limitations of these materials are their low hardness, poor friction and poor wear properties. For that reason, several attempts have been made to improve their hardness and other mechanical properties [2]-[4]. Due to its high hardness, vanadium carbides are often applied to the surface of carbon steels through coating processed [5]-[8] and thermal diffusion processes [9]-[13].

II. Metal Surface Alloying In Molten Slag

Metal surface alloying in molten slag is a process of metal surface treatment [10]. When kept in molten slag, the surface of a metal part will react with certain alloy element existing in the slag in the form of solid-liquid reaction, where chemical reactions and diffusion occur. As a result of the solid-liquid reactions, an alloy layer with designed mechanical properties will be formed on the metal surface. After the surface treatment, a metal part will perform much better because of the improved mechanical properties on the surface. The metal surface alloying in molten slag consists of the following processes:

- Choose chemical composition of the slag
- Melt the slag in a crucible or a furnace under a non oxygen atmosphere
- Add reduction agent in the molten slag
- Insert metal part in the molten slag
- Maintain at a designed temperature for a certain time
- Take out the metal part, cool and clean

Various chemical compositions can be selected for the slag. In general the following factors should be considered when choosing a slag composition:

- Usage properties of a metal part
- Mechanical properties of an alloying layer on the surface of metal part
- Maximum temperature and time to treat a metal part
- Slag melting temperature (liquidus temperature)
- Chemical stability to maintain alloy elements activated in the molten slag
- Less volatility to prevent air pollution
- Easy to re-use or easy to dispose the slag
- Availability and economic

III. Experimental Condition

In the experiment, a slag with vanadium oxide (V2O3) was selected and its chemical composition can be seen in Table I. Metal parts were made from inexpensive high carbon steel and its chemical composition can be seen in Table II. The main process factors are summarized in the following:

- Slag with vanadium oxide
- Metal materials: high carbon tool steel
- Treatment temperature: 1000 ^{o}C
- Reducing agent: silicon powder
- Treatment time: 2 hours
- Ceramic crucible in an electric heating furnace

Table I
Chemical Composition Of Slag (%)

Slag No	B2O3	SiO2	CaO	V2O3
A	30-50	20-30	5-10	5-10

Table II
Main Chemical Composition Of High Carbon Tool Steel (%)

Element	Silicon	Manganese	Iron	Carbon
%	3.16	1.86	93.80	1.20

IV. Result And Discussion

A. Mechanical Wearing Test

The wearing test was conducted using Charpy V-notch impact test machine with rotating speed of 580 rpm, loading of 125 kg. Standard samples were made from carbon steel, with and without the surface alloying treatment in molten slag. The wearing test was carried out in atmosphere without lubrication. At time interval of 30 minutes, 45 minutes, and 60 minutes, the test samples were removed from the test machine, cleaned with alcohol, dried in an oven, and then weighed. Using the loss of weight, the wearing property can be evaluated accordingly. With surface alloying treatment, the anti-wearing ability of carbon steel is improved by 15.6 times, see in Fig. 2. Similar results have been reported for high carbon steel and medium carbon steel **[3]**.

The anti-wearing property is one of the most important factors to determinate its performance of a metal part. The anti-wearing property of a metal part is mainly affected by its surface hardness, structure, and its environmental condition of usage. Research has shown that a metal surface alloyed with vanadium can tremendously increase its anti-wear property [8]-[9]. Therefore our research is mainly focused on the effect of surface alloy of vanadium on the anti-wearing of carbon steel. High carbon steel is chosen to be treated in molten slag with vanadium oxide as alloy element.

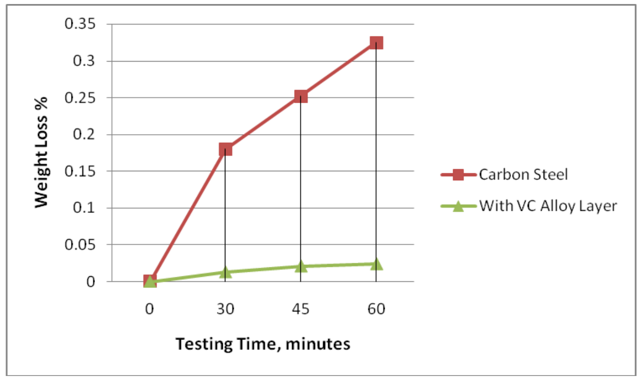

Fig. 2 Mechanical wearing test of high carbon steel, with and without VC surface alloying in molten slag, showing 15.6 times of improvement after treated

B. Alloy Layer Morphology

A layer of vanadium alloy on the surface of high carbon steel can be seen in Fig. 1 with a magnification of 250 times. The alloy layer is bright in color and has an even thickness, see in Fig. 3.

The sample was treated in a solution of nitric acid and alcohol for 10 second. The chemical composition was analyzed using scanning electron microscope, not including carbon due to the limitation of the equipment. The result shows that the alloy layer has contents of silicon, calcium, vanadium, manganese and iron. The main content is vanadium, seen in Fig. 4.

C. Alloy Layer Hardness

The hardness test is carried out using Reichert-Jung, high-temperature microscope, with loading of 20 pound, loading time of 3 second and loading speed of 3 pound/second. The test result of micro hardness shows that the alloy layer has a hardness of 2200 HV and 510 HV for the base of high carbon steel, see in Fig. 5. Comparing with the base steel, the hardness of the alloy layer increases by 3.4 times.

It is reported [12] that a layer of vanadium carbide was prepared on steel surface in a salt bath, and the micro-hardness of 3050-3200 HV was measured. Other similar results are reported as well that the hardness of VC alloy layer is 3100 to 3800 HV **[3]**, which is much higher than the result of our test. The other existing elements in our alloy layer, such as silicon and iron, may contribute to the result of lower hardness

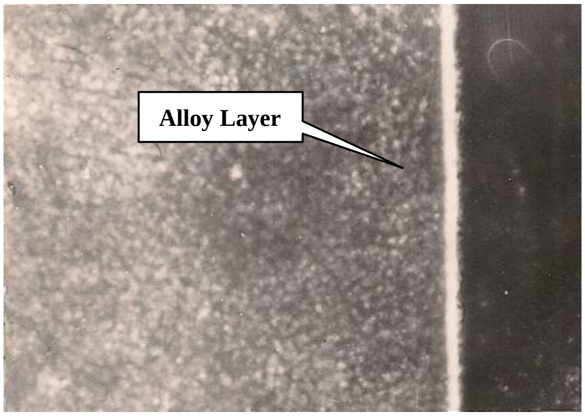

Fig. 3 Layer of vanadium alloy on the surface of high carbon steel, etched in a solution of nitric acid and alcohol in 10 second, x250

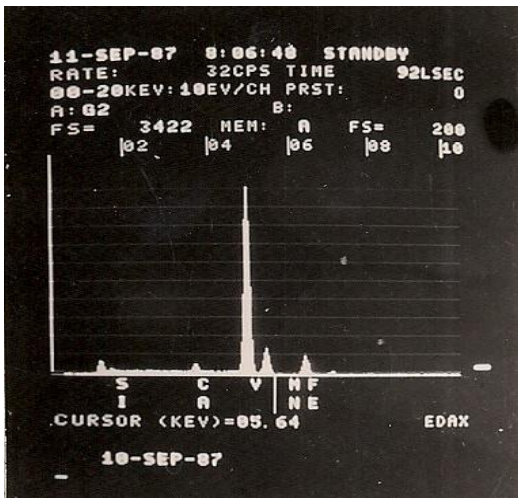

Fig. 4 Chemical composition of alloy layer by a scanning electron microscope (not including carbon content), showing a major content of vanadium and small amount of silicon, calcium, manganese and iron

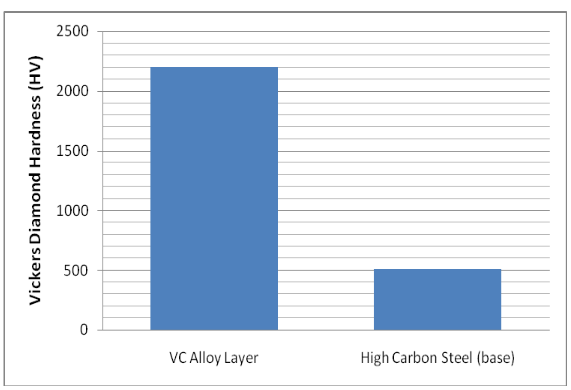

Fig. 5 Micro hardness of VC alloy layer and high carbon steel, using Reichert-Jung high-temperature microscope

It is reported [13] that the carbide layer is formed on the steel surface by dipping the steel part in a molten salt bath, where vanadium is added to as an oxide. The layer of vanadium carbide formed on the steel part is in the form of VC0.88.

D. Alloy Layer Structural Analysis

Structure analysis of the alloy layer was conducted using X-ray diffraction with a wave length of 1.7889 and the angle range of 20 to 120 degree. The diffraction result shows that the structure of the alloy layer is vanadium carbide of γ phase with a composition of VC0.8. The detail of the diffraction is listed in Table III, with comparison of the ASTM standard.

TABLE III
X-RAY DIFFRACTION WITH ASTM STANDARD

X-ray Diffraction	dA	2.08	2.41	1.47	3.74	VC0.8 (γ)
	I/I1	100	77	30	9	
ASTM Values	dA	2.08	2.40	1.47	3.70	VC0.8 (γ)
	I/I1	100	80	80	10	

E. Chemical Analysis of Alloy Layer

The analysis of chemical composition across the alloy layer was conducted using scanning electron microscope with energy dispersive spectrometer. The specimen was treated in a solution of nitric acid and alcohol for 10 second. A total of 3x6 points are selected with mark A to F, seen in Fig. 6. Column A is at the outside surface, column D is at the interface, E and F are inside the matrix of high carbon steel. The average chemical contents of silicon, manganese, vanadium, iron are listed in Table IV.

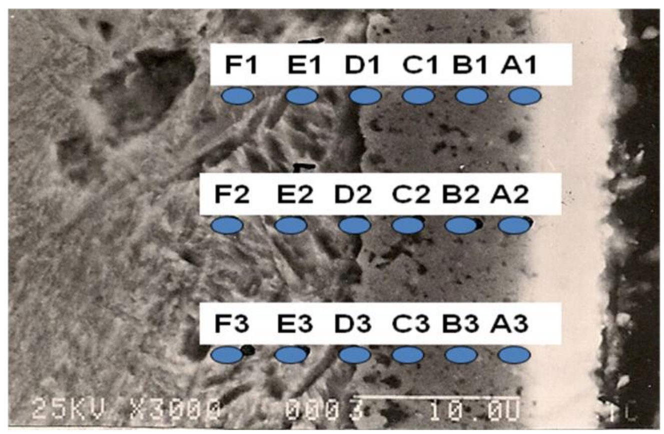

Fig. 6 Analytical positions of chemical composition using scanning electron microscope x3000, with column A at the outside surface and D at the interface of the alloy layer

TABLE IV
CHEMICAL COMPOSITION OF ALLOY LAYER AND BASE STEEL (%)

Position	A	B	C	D	E	F
Vanadium	85.84	94.74	95.77	94.80	11.71	1.80
Silicon	9.5	2.53	2.01	2.97	3.72	3.18
Manganese	0	0	0	0	1.23	1.98
Iron	4.66	2.73	2.22	2.23	83.34	93.04
Total	100	100	100	100	100	100

It is well known that carbon has very strong chemical potential to react with vanadium to form vanadium carbide. Due to the fact that the structure of the alloy layer is VC0.8 vanadium carbide determined by X-ray diffraction as mentioned early, the carbon content across the alloy layer can be calculated based on the vanadium content. The chemical composition of alloy layer, including carbon, can be seen in Table V. Other Similar results are reported as well [13].

The calculation of carbon content is done according to the following equations:

$$V + 0.8\ C = VC_{0.8} \quad (1)$$

$$Wc = 0.8 * Mc/Mv * Wv \quad (2)$$

Where Wc and Wv is the weigh of carbon and vanadium, respectively; Mc and Mv the atomic weight of carbon and vanadium.

TABLE V
CHEMICAL COMPOSITION OF ALLOY LAYER AND STEEL BASE WITH MARKS INDICATED IN FIG 6

Element %	A	B	C	D	E	F
Vanadium	73.90	80.40	81.14	80.44	11.46	1.78
Silicon	8.18	2.15	1.70	2.52	3.64	3.15
Manganese	0.00	0.00	0.00	0.00	1.20	1.96
Iron	4.01	2.31	1.88	1.90	81.54	92.12
Carbon	13.91	15.13	15.27	15.14	2.16	0.99
Total	100	100	100	100	100	100

The distribution of vanadium, iron and carbon can be seen in Fig. 7. The vanadium content in the alloy layer reaches 80% and is almost constant. It drops from 80% to below 10% at the interface with steel base. It shows that some vanadium even enters into steel base, which is beneficial to produce strong bond between the alloy layer and steel base.

At the steel surface, vanadium reacts with carbon that dissolves in the steel base at the processing temperature. Through the formed carbide layer, carbon diffuses to the newly formed surface, where it is combined with vanadium to form vanadium carbide, thus increasing the layer thickness. At the same time, vanadium diffuses to the surface layer of the steel through the carbide layer.

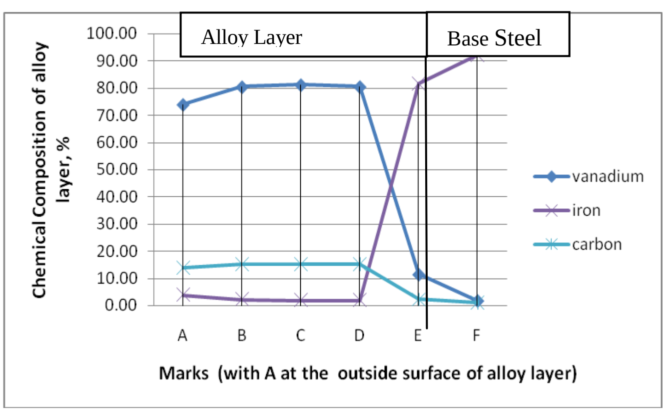

Fig. 7 Chemical composition of vanadium, iron and carbon across the alloy layer and steel base

The distribution of silicon, manganese across the alloy layer can be seen in Fig. 8. The silicon content is as high as 8% at the outside surface of the alloy layer. It reduces towards inside and reaches the same level of the steel base at the interface. No manganese was found in the alloy layer.

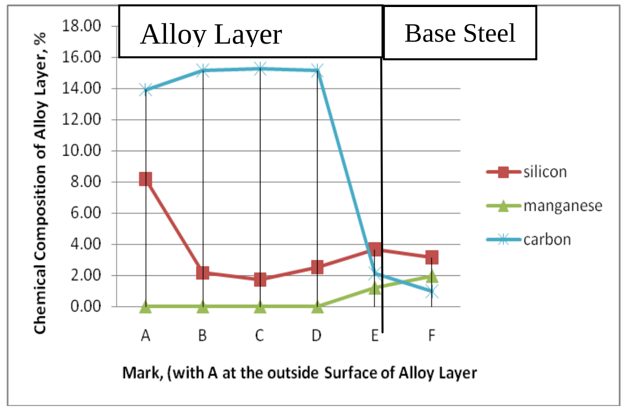

Fig. 8 Distribution of silicon, manganese and carbon across the alloy layer and steel base

V. CONCLUSION

In this paper, samples of high carbon steel are treated using the molten slag process to form vanadium-based alloy layer on the surface. Various measurements were used to conduct tests on the surface-alloying layer, including chemical composition, material structure, and micro hardness. The surface-alloy layers on high carbon steel are found in the form of vanadium carbide with composition of VC0.8. The hardness of the alloy layer is 2200Hv, 3.4 times higher than that of high carbon steel. After treated with molten slag process, the anti-wearing property of high carbon steel is improved by 15.6 times.

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