Dilution and Wear Evaluation for Stellite 6 Deposited on a Martensitic Stainless Steel Substrate by Laser Cladding

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Abstract—**Stellite 6 was deposited by laser cladding on a martensitic stainless steel substrate with laser powers of 1 kW (MSS-1) and 1.8 kW (MSS-1.8). The chemical compositions and microstructures of these coatings were characterized by atomic absorption spectroscopy, optical microscopy and scanning electron microscopy. The microhardness of the coatings was measured and the wear mechanism of the coatings was examined using a pin-on-plate (reciprocating) wear testing machine. The results showed less cracking and pore development for Stellite 6 coatings applied to the MSS substrate with the lower laser power (MSS-1). Further, the Stellite coating for MSS-1 was significantly harder than that obtained for MSS-1.8. The wear test results showed that the weight loss for MSS-1 was much lower than for MSS-1.8. The measurements of dilution and coating C content showed that MSS-1 possesses lower dilution and higher coating C content than MSS-1.8. It is concluded that the lower hardness of the coating for MSS-1.8, together with the softer underlying substrate structure, markedly reduced the wear resistance of the Stellite 6 coating and the lower hardness of the coating for MSS-1.8 was due to higher level of dilution and lower coating C content. C content martensitic/bainitic steel substrates showed significantly high coating wear resistance.**

Keywords—**Dilution, Martensitic Stainless Steel, Stellite 6 Coating and Wear**

I. INTRODUCTION

Stellite 6 is a very versatile material that is used for hardfacing of various component parts for applications requiring wear resistance [1]. The microstructure of Stellite 6 contains hard M_7C_3 carbides in interdendritic regions in both as-cast and as welded conditions [2]. Stellite alloys also contain a hard Laves phase in a softer matrix of eutectic or solid solution, which is useful for unlubricated wear conditions [3].

Martensitic stainless steels are similar to carbon steels, having a structure similar to the ferritic steels. Their structures are body-centered tetragonal (bct) and they are classed as a hard ferromagnetic group. The main alloying element is chromium, typically 12 to 15%, molybdenum (0.2-1%). Due the addition of carbon, they can be hardened and strengthened by heat treatment. Increasing the carbon content increases the strength and hardness. Optimum corrosion resistance is attained in the heat treated i.e. hardened and tempered condition. Martensitic stainless steels can be developed with nitrogen and nickel additions. These steels have improved toughness, weldability and corrosion resistance. These steels are suitable for application where the material is subjected to both corrosion and wear [4], [5]. However, the martensitic stainless steel has not been extensively studied for the development on wear resistance of laser cladding using Stellite 6 powder as well as calculating dilution on weld deposit.

Surface alloying is usually done by advanced techniques such as laser cladding due to significant advantages like fast processing speed, relative cleanliness, a very high heating/cooling rate (105 K/s) and high solidification velocity (up to a maximum of 30 m/s) [6]. As a result, the process has a low energy input and causes less distortion of the component than hand or arc welding. Steen and Bruck [7] have reviewed laser cladding processes. In the coaxial laser cladding process, metal powder is injected through a nozzle, which is coaxial with the laser beam. The powder absorbs laser energy and become partially melted before reaching the substrate. Part of the laser energy is also absorbed by the substrate to cause surface melting, forming a strong metallurgical bond between the substrate and the clad layer. Laser clad layers can be produced that are defect-free and low dilution [8].

The purpose of this study was to evaluate the sliding wear characteristics of Stellite 6 coating materials produced by laser cladding of a martensitic stainless steel substrate with low (1 kW) and high (1.8 kW) laser powers. The sliding wear tests were carried out on flat samples in an unlubricated (dry) condition using a reciprocating wear tester with a tool steel ball. This paper also discussed on dilution measurements and estimation of coating C content of weld deposit and the role of C content in forming Cr_7C_3 particles to harden the deposit and contribute the increase wear resistance.

II. EXPERIMENTAL METHODS

A. *Laser Cladding Deposition*

The laser cladding process of martensitic stainless steel substrates with Stellite 6 was carried out by commercial coating manufacturing companies using 1 kW and 1.8 kW laser power. The initial coating thickness as received was about 0.35 mm for both laser powers.

Table 1 shows the nominal compositions of the martensitic stainless steel and the Stellite 6 alloy. The composition corresponds closely to that of a 410 martensitic stainless steel.

B. Characterisation of Stellite Coated Samples

The microhardness measurements were made at intervals of 0.05 mm through the coating thickness using a Leco M-400-H1 hardness testing machine with a load of 300 g. The samples were then etched in a mixed acid solution to reveal the microstructure of the Stellite 6 coating. Subsequently, coatings were studied using a Leica DMRM optical microscope.

TABLE 1
Nominal compositions (wt%) of the martensitic stainless steel and Stellite 6 alloy [3]

(%)	Co	Cr	Fe	W	Ni	C	Si	Mn
S 6	60	27	2.5	5	2.5	1	1	1
MSS		12.93	Bal		0.28	0.13	0.43	0.74
(%)	P	S	Mo	V	Al	Ti	Nb	B
S 6								
MSS	0.022	0.005	0.17	0.03	0.02			

C. Wear Testing

Wear testing was carried out using a pin-on-plate (reciprocating) mode with a 6 mm tool steel ball as the pin. A ball was fixed in a collet and during operation, the ball remained stationary while the flat specimen moved in a linear, back and forth sliding motion, under a prescribed set of conditions.

Since the aim of the work was to examine the wear of Stellite 6 coating materials, it was necessary to grind and polish the flat specimens (coatings) to the required surface finish for the wear test. The coatings were about 0.3 – 0.4 mm thick and approximately 0.05 mm of the coating was removed.

Prior to carrying out the wear tests, the test specimens were weighed to an accuracy of 0.0001 g. The flat specimen was then screwed firmly in place on the base of the wear tester. After the test was complete, wear debris was removed from the sample, which was then washed in alcohol, dried, and reweighed.

The tool steel ball was also washed in alcohol, dried and weighed to an accuracy of 0.0001 g at the start of each test and at the same time as the flat specimen. The ball was re-weighed after testing but, as the weight of the steel ball did not change significantly, it was not considered in assessing the wear damage.

The test speed, number of cycles and test duration were held constant: 50 rpm, 10,000 cycles and 200 minutes. The various tests conducted are: Test# 1, MSS-1 with applied load of 2 kg; Test# 2, MSS-1.8 with applied load of 2 kg; Test# 3, MSS-1 with applied load of 5 kg; Test# 4, MSS-1.8 with applied load of 5 kg.

D. Examination of Wear Surface

In order to study the effect of laser power and the applied load during wear testing on the wear track, the surfaces of the samples from Tests# 1-4 were examined after testing using a S440 scanning electron microscope (SEM) operating at 20 kV.

E. Measurements of Dilution and Estimation of Coating C Content

A measured compositions of Stellite 6 coatings has been conducted using Atomic Absorption Spectroscopy to determine the chemical analyses present using two different laser power (1 kW and 1.8 kW). However, the C content was not detected. Therefore it was necessary to estimate the C content by calculating dilution. The method of calculation is shown in Fig. 1.

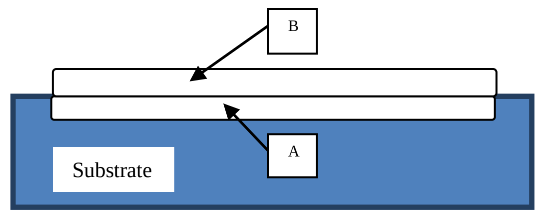


Fig.1. Schematic diagram showing the clad layer, which consists of two parts: added Stellite 6 alloy (region B) and melted base plate (region A). The dilution D of the Stellite alloy is given by A/(A+B) [9].

If the C content (wt%) of the base metal or substrate is given by $[C]_{BM}$ and the C content (wt%) of the Stellite is $[C]_s$, then the estimated C content of the weld deposit $[C]_{WD}$ is given as follows:

$$[C]_{WD} = D \times [C]_{BM} + (1-D) \times [C]_s. \quad (1)$$

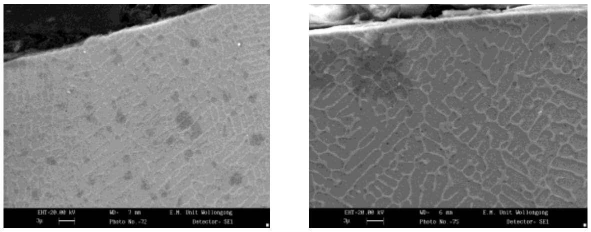
III. RESULTS

A. Coating Compositions

The compositions of the Stellite 6 coatings were determined by AAS (Atomic Absorption Spectroscopy), see Table 2. Table 2 shows that the two chemical analyses (MSS-1 and MSS-1.8) of the coatings were similar, but there were some differences in alloy content of the coatings. In particular, the coating for MSS-1 was significantly lower in Fe than for MSS-1.8.

B. Scanning Electron Microscopy (SEM) of Deposit Coating Cross-Sections

The coatings on the martensitic stainless steel substrate had a cellular-dendritic appearance. The higher laser power of 1.8 kW produced a coarser cellular-dendritic structure, see Fig. 2 (a-b).



(a) (b)

Fig.2. SEM micrographs of cross sections of the Stellite 6 layers deposited on (a) MSS-1, (b) MSS-1.8

C. Microhardness Testing of Coating Cross-Sections

Microhardness profiles for the Stellite 6 weld samples is shown in Fig. 3. For the coating deposited at 1 kW, the coating hardness was about 600 HV compared with 550 HV for 1.8 kW. A high HAZ hardness profile for the 1 kW deposit was re-hardening up to about 800 HV. The inherently high hardenability of the substrate alloy and the rapid cooling after deposition has resulted untempered martensite. A high HAZ hardness was also exhibited for the 1.8 kW deposit (up to 600 HV) despite the cooling rate being reduced by the higher laser power.The hardness of the unaffected substrate was about 300 HV.

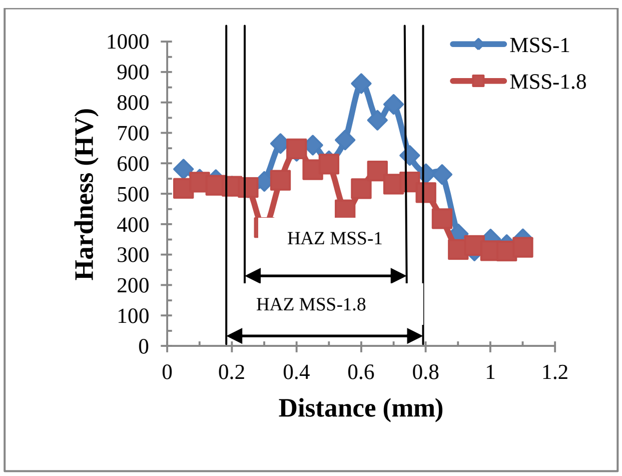


Fig.3**.** Graph of hardness profiles with distance from the coating surface for Stellite 6 deposited on martensitic stainless steel.

D. Wear Testing

Tests# 1-2 were conducted using an applied load of 2 kg. It was found that the deposit for MSS-1 wore substantially less, whereas the deposit for MSS-1.8 showed significant wear with deep grooves. The effect of a higher load (5 kg),Test# 3-4, was generally similar to that for Tests# 1-2, see Fig. 4 (a-b).

E. Mass Loss

Table3 shows the weight loss measurements for the Stellite coated samples. It can be seen in Table 3 (Tests# 1-4) that the weight loss increased with load and was higher for MSS-1.8.

F. Characterisation of Wear

In order to study the effect of load on the wear track, Stellite coated samples were examined at the completion of the wear test by scanning electron microscopy to establish the nature of wear.

The worn surface of MSS-1, Fig. 5 (a) is smooth compared to the MSS-1.8 surface which was more porous and showed greater surface roughness. The effect of a higher load (5 kg) at 1.8 kW heat input is illustrated by Fig. 5 (b)

G. Dilution Measurements and Estimation of Coating C Content

It was not possible to determine the C content of the weld deposit quantitatively by the micro-analysis methods that were available, see Sections II E and III.A, therefore to estimate the coating C content of the Stellite 6 coatings it was necessary to measure the dilution shown in Fig. 1, subsequently the coating C content was estimated. Table 4 and Table 5 show the estimation of dilution and coating C content of Stellite 6 coatings.

IV. DISCUSSION

The comparative tests conducted for laser clad martensitic stainless steel substrate showed that the weight loss was lower for coated samples deposited at a laser power of 1 kW (MSS-1). The amount of wear (mass loss) of the Stellite coated samples was greater for the tests conducted on coatings deposited with 1.8 kW than for those deposited at 1 kW, as shown in Table 3.

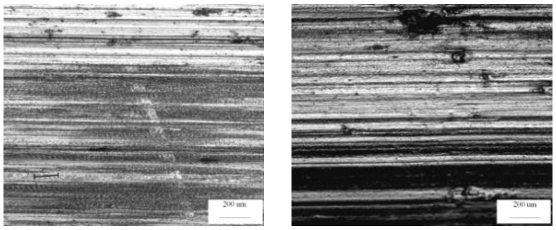
TABLE 2
Measured compositions (wt%) of the Stellite 6 coatings

(%)	MSS-1	MSS-1.8
P	0.29	0.23
Mn	0.33	0.41
Si	0.59	0.57
Ni	2.60	2.00
Cr	29.20	28.50
Mo	0.29	0.10
Cu	0.021	0.021
Nb	0.03	0.03
Ti	0.02	0.02
V	0.028	0.028
Fe	6.5	8.0
W	4.0	4.0
Co	53.1	54.8

TABLE 3
Weight loss for Stellite coatings deposited at a power input of 1 kW and 1.8 kW

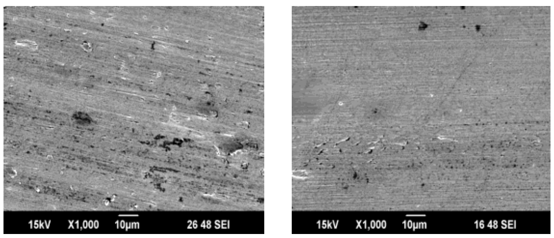
Loads (kg)	MSS-1 (g)	MSS-1.8 (g)
2	0.0028	0.00348
5	0.01298	0.02228

For deposits produced at 1 kW, the weight loss increased by a factor of about 6with increasing test load up to 5 kg, but for the higher laser power the rate of weight loss strongly increased by a factor of about 8 with increasing load. It is likely that the greater incidence of microcracks and porosity detected after wear testing of MSS-1.8 samples is due in part to the greater influence of the substrate (~ 300 HV, see Fig.3) which is relatively soft and deformable compared with the coating (~ 550 HV) [10].



(a) (b)

Fig. 4. Optical micrographs showing wear tracks at a load of (a) 2 kg for MSS-1, (b) 5 kg for MSS-1.8.



(a) (b)

Fig. 5. SEM micrograph of worn surface tested at a load of (a) 2 kg for MSS-1, (b) 5 kg for MSS-1.8.

The higher wear rate for the MSS-1.8 Stellite coated samples is also consistent with the lower surface hardness of approximately 550 HV compared with 600 HV for the MSS-1 Stellite coated samples, as shown in Fig. 3. Acceleration of the wear rate for the Stellite coating MSS-1.8 could also be due to the wear grooves penetrating the coating into the underlying HAZ which showed a variable hardness profile with values ranging from about 650 HV to as low as about 400 HV [11], [12].

As Table 2 describes, the Stellite composition was modified by the substrate. This change occurred by melting of the substrate and mixingwith the deposited alloy (dilution). Compared to the Stellite 6 nominal composition (Table 1), the coatings were significantly lower in Co, Mn, Si and W due to dilution by the substrate. However, the Ni and Cr contents remained similarto those of Stellite 6, while the Mo and Fe contents were increased due to pick-up from the substrate.

The coating produced for MSS-1 showed slightly higher Cr and Mo contents than those for MSS-1.8, while the Fe and Mn contents were lower. Generally, these differences are consistent with less dilution of the coating produced at the lower laser power. For this reason, the carbon content forthe coating MSS-1 would be expected to be higher than that for MSS-1.8, therefore allowing more copious precipitation of Cr_7C_3 particles that harden the deposit [13]. Further, the faster cooling rate associated with the lower laser power is expected to result in structural refinement that contributed to the hardness of the coating.

TABLE 4
Measurements of dilution of the Stellite 6 coatings

	Area A (μm^2)	Area B (μm^2)	Dilution, D (wt%)
MSS-1	91187.745	763797.494	0.1067
MSS-1.8	294824.883	1028341.835	0.1828

TABLE 5
Estimation of C content of the Stellite 6 coatings

	$[C]_{BM}$ (wt%)	$[C]_S$ (wt%)	Dilution, D (wt%)	$[C]_{WD}$ (wt%)
MSS-1	0.13	1.00	0.1067	0.897
MSS-1.8	0.13	1.00	0.1828	0.842

The deposit on MSS-1 was about 50 HV points higher than for the coating on MSS-1.8 (Fig. 3) and this difference accounts for the substantial increase in wear resistance [14].

As discussed earlier, the higher level of dilution for MSS-1.8 Stellite coated samples, Table 4 are consistent with higher wear rate, Table 3 and lower surface hardness, Fig. 3 of approximately 550 HV compared with 600 HV for the MSS-1 Stellite coated samples suggesting that the higher laser power produced higher dilution [15].

As Table 5 indicates, the coating C content of weld deposit for the MSS-1 Stellite coated samples was higher by a factor of about 1.065 than MSS-1.8 Stellite coated samples, indicating that the higher of coating C contentof weld deposit consistent with a lower level of dilution, Table 4, hence promoting the carbide morphology of Cr_7C_3 particles and to harden the deposit, Fig. 3 thus producing higher wear resistance [16].

V. CONCLUSIONS

The recentwork compared the wear behaviour of Stellite 6 under reciprocating wear conditions as laser clad deposits on two different laser powers (1.0 kW and 1.8 kW) of martensitic stainless steel. The coating composition was slightly different in the two cases because of differential dilution by the substrate. The compositional differences combined with different cooling rates after deposition resulted in substantially different coating hardnesses. The coating on

MSS-1 had a hardness of approximately 600 HV, while the coating on MSS-1.8 had a hardness of approximately 550 HV. The tests were carried out unlubricated, using loads of 2 and 5 kg and a speed of 50 rpm for 10000 revolutions.

The results described that the rate of weight loss and the total weight loss were higher for the higher load and also for the higher laser power. The wear rate was lower for MSS-1 coated samples, with less cracking and pore development in the Stellite 6 coatings. The dilution measurement explained that the level of dilution was higher for the higher laser power and the coating C content estimation also indicated that coating C content was lower for the higher laser power.

It is concluded that the deposit obtained at 1 kW was harder because of compositional, microstructural and level of dilution differences; and also the harder coating in weld deposit of MSS-1 resulted in the higher wear resistance due to higher coating C content to form carbide (Cr_7C_3 particles) to harden the deposit than the Stellite 6 coating deposited at the higher laser power of 1.8 kW.

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