Effect of Two Different Energy Inputs for Laser Cladding of Stellite 6 on P91 and P22 Steel Substrates

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Abstract

Stellite 6 was deposited by laser cladding of two different chromium-bearing steel substrates (P91 and P22). The chemical compositions, microstructures and surface roughnesses of these coatings were characterized by atomic absorption spectroscopy, optical microscopy, scanning electron microscopy and atomic force 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 P22 steel substrate. Further, the Stellite coating on P22 steel was significantly harder than that deposited on the P91 steel. The wear test results showed that the weight loss for the coating on P22 steel was significantly lower than for the P91 steel substrate. The surface topography data showed that the surface roughness for the coating on P22 steel was much lower than for the P91 steel substrate. It is concluded that the residual C content for the deposit on P22 was higher, mainly because the lower concentration of strong carbide formers, compared to P91, reduced the extent of carbon loss in the deposit.

Keywords: Laser cladding, Stellite 6 coating, friction and wear, HAZ, surface roughness, P91 steel, P22 steel

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1. Introduction

Vilar (1999) reported that Stellite 6 is a very versatile material for hardfacing of various component parts for applications requiring wear resistance. The microstructure of Stellite 6 contains hard M₇C₃ carbides in interdendritic regions of the fcc matrix phase in both as-cast and as welded conditions (Jeng et al., 1991). Stellite alloys also contain a hard Laves phase in a softer matrix of eutectic or solid solution, which is useful for unlubricated wear conditions (Steen, 2003).

High temperature strength and high temperature corrosion resistance are the main properties required for applications in a material for the power plant industry. Heat resistant steels, such as P22 (2.25Cr – 1Mo), are extensively used for high temperature applications, and are generally classified as ferritic steels. Research on the development of high-strength ferritic steels has produced new alloys able to operate in the supercritical range. These steels show good weldability and fracture toughness and improved resistance to sliding wear (Polar, 2009).

P91 steel is an important steam generator material for thermal and nuclear power plants. P91 steel (9Cr - 1Mo) displays three distinct temperature regimes for the variations of tensile strength, average work hardening rate and ductility. It has the advantages of low thermal expansion, high thermal conductivity, good steam corrosion resistance and excellent creep resistance (El-Azim et al., 2013 and Samuel and Choudhary, 2011).

Steen (1986) and Bruck (1987) 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 bonding between the substrate and the clad layer. Laser clad layers can be produced that are defect-free and result in low dilution and a small heat affected zone in the substrate (Monson and Steen, 1990 and Hirose and Kobayashi, 2005).

The purpose of this study was to evaluate the sliding wear characteristics of Stellite 6 coating materials produced by laser cladding of P91 steel and P22 steel substrates. The sliding wear tests were carried out on a flat sample in an unlubricated (dry) condition using a reciprocating wear tester with a tool steel ball. The surface roughness of the coatings was evaluated in each sample using an atomic force spectroscopy.

2. Experimental Method

2.1. Laser Cladding Deposition

The laser cladding process for the P91 steel and P22 steel substrates with Stellite 6 was carried out by a laser company in Sydney, Australia, using 1 kW and 1.8 kW energy input. The initial coating thickness as received was about 0.35 mm for both steels and both energy inputs. Table 1 shows the nominal compositions of the P91 steel, the P22 steel and the Stellite 6 alloy.

2.2. Characterisation of Stellite Coated Samples

The Stellite 6 coatings were sectioned perpendicular to the coated surface using an automatic cutting machine with an alumina cut-off wheel operating at 3000 rpm and a cutting rate of 0.050 mm/s. The cut samples were then mounted in Poly Fast bakelite resin.

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.

2.3. 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.
Table 1. Nominal compositions (wt%) of the P91, P22 and Stellite 6 alloy

| (%)     | Stellite 6 | P91   | P22   |
|---------|------------|-------|-------|
| Co      | 60         |       |       |
| Cr      | 27         | 9.08  | 2.25  |
| Fe      | 2.5        |       |       |
| W       | 5          |       |       |
| Ni      | 2.5        | 0.08  |       |
| C       | 1          | 0.09  | 0.11  |
| Si      | 1          | 0.45  | 0.34  |
| Mn      | 1          | 0.46  | 0.58  |
| P       |            |       | 0.01  |
| S       |            |       | 0.01  |
| Mo      | 0.96       | 0.93  |       |
| V       | 0.19       |       |       |
| Nb      | 0.08       |       |       |

The specimens for wear testing were 5 mm thick, 37 mm long and 20 mm wide. The flat specimens were ground starting with 80 grit silicon carbide paper then progressing to 220 grit paper before diamond polishing on 9 μm and 3 μm diamond pads. The flat specimens were rinsed in water, then alcohol, before drying.

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 details of the various tests conducted are listed in Table 2.

Table 2. Details of the various tests conducted

| Test No | Flat samples | Applied load (kg) |
|---------|--------------|-------------------|
| #1      | P22-1        | 2                 |
| #2      | P91-1        | 2                 |
| #3      | P22-1.8      | 2                 |
| #4      | P91-1.8      | 2                 |
| #5      | P22-1        | 5                 |
| #6      | P91-1        | 5                 |
| #7      | P22-1.8      | 5                 |
| #8      | P91-1.8      | 5                 |

P22: P22 substrate; P91: P91 substrate; The number suffix indicates a laser energy of 1 kW or 1.8 kW.
2.4. Examination of Wear Damage and Surface Topography

In order to study the effect of laser heat input and the applied load during wear testing on the wear track, the surfaces of the samples from Tests # 1-8 were examined after testing using a S440 scanning electron microscope (SEM) operating at 20 kV and using Atomic Force Microscopy (Veeco) with scan size of 50 μ and scan rate of 1 Hz.

3. Results

3.1. Coating compositions

The compositions of the Stellite 6 coatings were determined by AAS (Atomic Absorption Spectroscopy), see Table 3. Table 3 indicates that the two chemical analyses of the coatings obtained for the two energy inputs of 1 kW and 1.8 kW were similar for each substrate and moreover, the differences in compositions of the coatings on the two substrates were also minor. The coating on P91 was richer in Fe and V and slightly lower in Co, Ni and Cr than that formed on P22 substrate. The carbon contents of the deposits were not measured but would be significantly lower than the nominal 1% (Table 1) because of dilution by the low C substrates.

Table 3. Measured compositions (wt%) of the Stellite 6 coatings

| (%)  | P22-1  | P22-1.8 | P91-1  | P91-1.8 |
|------|--------|---------|--------|---------|
| P    | 0.27   | 0.24    | 0.23   | 0.25    |
| Mn   | 0.34   | 0.39    | 0.33   | 0.40    |
| Si   | 0.66   | 0.53    | 0.57   | 0.59    |
| Ni   | 2.45   | 2.05    | 2.40   | 2.00    |
| Cr   | 29.75  | 28.75   | 29.25  | 28.40   |
| Mo   | 0.26   | 0.092   | 0.23   | 0.13    |
| Cu   | 0.013  | 0.028   | 0.011  | 0.039   |
| Nb   | 0.01   | <0.01   | 0.02   | <0.01   |
| Ti   | 0.03   | 0.02    | 0.02   | 0.02    |
| V    | 0.019  | 0.008   | 0.028  | 0.024   |
| Fe   | 4.3    | 6.3     | 6.2    | 8.2     |
| W    | 4.0    | 4.2     | 4.1    | 3.9     |
| Co   | 55.1   | 54.8    | 54.0   | 53.1    |

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

SEM micrographs showing the coating structures of the P91-1, P91-1.8, P22-1 and P22-1.8 samples are presented in Figs. 1. (a-d), respectively. The coatings on P91 steel and P22 steel substrates had a cellular-dendritic appearance. The higher heat input of 1.8 kW produced a coarser cellular-dendritic structure for both substrates.

3.3. Microhardness Testing of Coating Cross-Sections

Microhardness profiles for the two Stellite 6 weld samples are shown in Figs. 2 and 3. For the P22 steel substrate, Fig. 2, the average coating hardness was about 600 HV for 1 kW and about 500 HV for 1.8 kW heat input. However, the higher heat input resulted in a wider HAZ and a lower average heat affected zone (HAZ) hardness. The HAZ hardness was lower than the coating, but higher than the substrate.
The coating on P91 steel substrate showed a lower coating hardness of about 550 HV for 1.0 kW and about 500 HV for 1.8 kW, Fig. 3. The HAZ hardness was generally lower than that of the coating, but higher than the substrate. The hardness of the unaffected substrate was about 225 HV, compared to 250 HV for the P22 steel.

![SEM micrographs](image)

**Fig. 1.** SEM micrographs of cross-sections of the Stellite 6 layers deposited on (a) P91 (1 kW), (b) P91 (1.8 kW), (c) P22 (1 kW), (d) P22 (1.8 kW).

### 3.4. Wear Testing

Tests # 1-4 were conducted using an applied load of 2 kg. It was found that the deposit on P22 wore substantially less, with only a shallow wear track, while the deposit on P91 showed significant wear with the deep grooves. Figs. 4.(a) and 4. (b) are optical micrographs compare the typical wear tracks for a 2 kg load on deposits produced at 1 kW: P91-1, Fig. 4. (a) and P22-1, Fig. 4. (b).

The effect of a higher load (5 kg), tests# 5-8, on deposits produced at 1 kW is illustrated by the optical micrographs in Fig. 5. (a) for P91-1 and in Fig. 5. (b) for P22-1.
3.5. Mass Losses

Graphs showing the wear rate were prepared from the weight loss measurements for the Stellite coated samples. It can be seen in Figs. 6 (Tests # 1-4) and 7 (Tests # 5-8) that the wear rate increased with load and was higher for P91 samples.
3.6. 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 and atomic force microscopy to establish the nature of wear.

SEM micrographs of the worn surfaces of the P91-1, P91-1.8, P22-1 and P22-1.8 samples are shown in Figs. 8 and 9. The worn surface of P22-1, Fig. 8. (b) appears to be smooth compared to the P91-1 surface which is more porous and shows greater surface roughness, Fig. 8. (a). The worn surface of P22-1.8, Fig. 8. (d), appears to be relatively rough but is still smoother compared to the surface of P91-1.8 which is rougher and more porous, Fig 8. (c). The effect of a higher load (5 kg) at 1 kW heat input is illustrated by Fig. 9. (a) (P91-1) and Fig. 9. (b) (P22-1).

AFM micrographs of surface roughness on the P91-1, P91-1.8, P22-1 and P22-1.8 samples are shown in Figs. 10 and 11. The surface roughness at lower heat input (1 kW) of P22-1, Fig. 10. (b) has Ra of 50.860 nm, while P91-1 has a value of 74.284 nm, Fig. 10. (a). For the higher heat input (1.8 kW) of P22-1.8, Fig. 11. (b) gives a roughness Ra of 58.860 nm, while for P91-1.8 it is 89.237 nm, Fig. 11. (a).
4. Discussion

The comparative tests conducted for laser clad P22 steel and P91 steel substrates showed that the wear rate was lower for P22 coated samples for both heat inputs (1.0 kW and 1.8 kW).

The amount of wear (mass loss) on the Stellite coated samples was greater for the tests conducted using P91 coated samples than for those using P22 coated samples, as shown in Figs. 6-7.

For deposits made at 1 kW, the weight loss increased in an approximately linear way with increasing test load up to 5 kg, but for the higher heat input the rate of weight loss strongly increased with increasing load. For both heat inputs, the weight loss was significantly lower for the P22 substrate. A higher carbon content of 0.11%C for the P22 substrate compared to 0.09%C for the P91 substrate is indicated in Table 1. The carbon loss from the Stellite deposit would therefore be expected to be lower for the P22 substrate, and therefore a higher amount of hard carbide would be present and this would impart better wear resistance (Kusmoko and Crosky, 2014).

![Fig. 8. SEM micrographs of worn surfaces after testing at a load of 2 kg of (a) P91-1, (b) P22-1, (c) P91-1.8, (d) P22-1.8.](image)

The higher wear rate for the P91 Stellite coated samples is also consistent with their lower average surface hardness of approximately 550 HV compared with 600 HV for the P22 Stellite coated samples for 1.0 kW heat input, as shown in Figs. 2 and 3. However, the average hardness (~ 500 HV) for the deposit produced on P22 at 1.8 kW is only slightly higher than that on P91. Acceleration of the wear rate is therefore likely for Stellite coated P91 as the wear grooves penetrate the coating.
For heat input of 1kW, the surface roughness for the P22 Stellite coated samples was lower than for the P91 Stellite coated sample, as shown in Fig. 10. (a-b), while for the higher heat input, again the surface roughness for the P22 Stellite coated sample was lower than for the P91 coated sample, Fig. 11. (a-b). It is likely that the higher average surface hardness for the P22 Stellite coated sample, resulted in the formation of thick, brittle oxide which is continuously generated by the high flash temperatures at the asperity contacts. Oxide fragments break away to produce wear debris but the oxide is continuously replenished so that direct metal-to-metal contact is prevented. In contrast, deeper tearing occurred at the softer surface of the deposit on P91 steel giving more wear (Lim et al., 1987).

The difference in wear behaviour for the two substrates is also likely to be due partly to differences in the Stellite coating compositions, microstructures, hardnesses and surface roughnesses.

As Table 3 indicates, the Stellite composition was significantly modified by the substrate. This change occurred by melting of the substrate and mixing with the deposited alloy (dilution). The coating produced on the P22 substrate showed higher Cr, Fe, Mo, V and Nb contents than those of the nominal Stellite 6 composition given in Table 1, while the Co, Ni, Mn, Si and W contents were reduced. The coating on P91 also showed significant pick-up of Cr, Fe, Mo, V and Nb and the loss of Co, Ni, Mn, Si and W. There was no marked difference in the compositions of the two deposits, except that the V pick-up was higher for the deposit on the P91 substrate. Overall the compositional differences shown in Table 3 do not appear to be significant enough to contribute to the higher wear rate measured for the deposit on P91. However, because of the low C contents of the P22 and P91 substrates, C loss by dilution and diffusion out of the coating is expected to be significant. The nominal Stellite composition does not list Mo, so any measured in the deposits came from the ~1% in the substrates (Kusmoko et al., 2014). The coating C content would be expected to be high enough to promote the formation of Cr$_7$C$_3$ particles and to harden the deposit. The deposit on P22 was 50 points higher than for the coating on P91 (Figs. 2 and 3) and this difference would be expected to substantially increase wear resistance (Bowden and Tabor, 1964). The higher nominal C content of the P22 substrate could result in a higher residual C content in the Stellite deposit. However, there is another possible reason for the higher hardness and wear resistance of the deposit on P22. This is that there was a lower extent of carbon partitioning into the substrate, compared with P91 which contains higher concentrations of strong carbide formers (Cr, V and Nb). The segregation of C to these elements and possible carbide formation would serve to steepen the C gradient and promote migration and loss of C from the deposit (Qiu et al., 2012).

![Fig. 9. SEM micrographs of worn surfaces after testing at a load of 5 kg of (a) P91-1, (b) P22-1.](image-url)
5. Summary and Conclusions

The present study compared the wear behaviour of Stellite 6 under reciprocating wear conditions as laser clad deposits on two different steel substrates: P22 steel and P91 steel. The measured coating compositions were not markedly different in the two cases. However, the coating hardnesses were substantially different. The coating on P22 steel had a hardness of approximately 600 HV, while the coating on P91 steel had a hardness of approximately 550 HV for the lower heat input (1 kW). The tests were carried out unlubricated, using loads of 2 and 5 kg and a speed of 50 rpm for 10000 revolutions. The rate of weight loss and the total weight loss were higher for the higher load and also for the higher heat input.

The results showed that the wear rate was lower for P22 coated samples at both heat inputs, with less cracking and pore development in the Stellite 6 coatings. The AFM results also indicated that the surface roughness was lower for P22 coated samples at both heat inputs. It is suggested that these observations are due to different diluted...
C contents in the two deposits. The lower concentration of strong carbide formers in the P22 substrate, relative to P91, is proposed to reduce carbon loss from the deposit.

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