Investigations on high temperature wear and metallurgical characteristics of Stellite 6 GTA (Gas Tungsten Arc) weld claddings

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Abstract
Stellite 6, a cobalt based superalloy was deposited on mild steel AISI 1020 using Gas tungsten arc welding (GTAW) process. The claddings were overlaid in four conditions viz. single layer cladding, double layer cladding, single layer cladding with remelting and double layer cladding with remelting, where remelting of the topmost layer was carried out using autogeneous GTA arc itself. The chemical composition, microstructure, wear mechanism and phase composition of the substrate and coatings were characterized by spectroscopy, optical microscopy, scanning electron microscopy, energy dispersive spectroscopy and x-ray diffraction. The hardness and wear characteristics of different cladded samples were measured using microhardness tester and pin on disc high temperature tribometer respectively. The results show that remelting of Stellite 6 clad layers resulted into microstructural modification that increased their hardness significantly which consequentially improved their wear performance. Oxidative layer formation that occurred at 300°C reduced frictional resistance which resulted into better wear performance of Stellite 6 clad pins. Further, a critical clad thickness was established based upon the wear performance of these claddings and it was observed that 5 mm Stellite clad thickness was sufficient enough to impart uniform wear behavior to these claddings when subjected to high temperature two body abrasive wear applications.

1. Introduction

Hardfacing of worn out machine components is an industrially proven, efficient and economical technique in comparison to replacing the same worn out components. It also helps in reusing or utilizing the available resources as much as possible. The relative motion between two or more interacting surfaces always deteriorate the surface layers in contact and this deterioration rate depends upon the extent of severity of working conditions especially in heavy industries. The wear of these mating surfaces can be reduced up to a larger extent by laying a layer of harder material over both the surfaces before subjecting them to working conditions thus resulting into enhanced life of machine components.

Commonly known hardfacing superalloys comprise of Fe-based, Ni-based, Co-based etc Stellite 6, which is a Co-based superalloy, is one the most used hardfacing material of Stellite superalloy family in heavy industries. It is exclusively recommended to be used for hardfacing of components that are exposed to high temperature [1–4]. The capability of Stellite 6 to impart high temperature wear resistance is attributed to the cobalt matrix having dispersed interdendritic hard carbide phase in it which maintains high hardness up to a temperature of 500 °C and even above it also. Besides that, it provides high resistance to corrosion, oxidation and wear at high temperatures as well as in unlubricated condition. As a result, it is widely used in valves industries, power plants, nuclear reactors etc Literature review indicates that this material because of its industrial importance has caught the attention of various researchers. Stellite superalloy hardfacing over various industrially active substrate materials has been reported to be carried out using various weld overlaying processes like GTAW, GMAW, Plasma transferred arc etc [5–12]. Laser welding for hardfacing using Stellite 6 has also been applied covering a
range of aspects including parametric optimization, wear characterization of clads etc [13–17]. Supersonic laser deposition has also been used for Stellite 6 surfacing [18–20]. Formation of oxide layer on the Stellite 6 coating surface and serving as a special lubricant during the wear test at high temperature and the formation of compact layers (glazes) resulting from the agglomeration of wear debris has been reported for this alloy [21, 22]. The quality of cladding is largely dependent upon the term ‘dilution’ that is the most important aspect of any cladding or hardfacing procedure by welding. It is defined as the ratio of the cross-sectional area of weld metal below the original surface to the total area of the weld bead measured on the cross-section of the weld deposit. Different welding processes conventionally used have the range of dilution as GTAW (25%–30%), GMAW-spray transfer (24%–40%), GMAW-dip transfer (15%–30%), SMAW (24%–40%), SAW (30%–60%). It is always attempted to achieve minimal dilution assuring good bond integrity with the base metal.

Despite of so many studies on Stellite 6, its data base needs to be strengthened further by exploring the role of using gas tungsten welding arc for re-melting and improving its hardness, different ranges of wear conditions where it can serve satisfactorily, the role of oxidative layer formation and establishing critical thickness for consistent wear performance so as to save this alloy from unnecessarily thicker clads than the required ones. So in view of covering these research gaps the present work was undertaken where different clad samples were prepared by using GTAW process for overlaying of Stellite 6 as single layered as well as double layered multipass claddings which were also subjected to surface remelting using GTAW process in the autogenous mode. The effectiveness of remelting technique as well as influence of clad thickness on the wear behaviour of Stellite 6 claddings are reported.

2. Experimentation

Four cylindrical pieces used as substrate material, each having 50 mm length were cut from a long 50 mm diameter cylindrical bar of AISI 1020. The surfaces of the substrate were cleaned to make them free from any source of contamination like oil, dirt, oxide, scale etc using emery paper followed by chemical cleaning that involved using acetone before cladding. Stellite 6 claddings were deposited on these substrate work pieces so as to get specimen combinations as single layer cladding (C1), single layer cladding with remelting (C2), double layer cladding (C3) and double layer cladding with remelting (C4) using gas tungsten arc welding (GTAW) process and one of the representative cladded workpiece (C3) is shown in figure 1. A bead overlap of around 25% was used while depositing the subsequent pass of the clad layers. This helped in reducing dilution and hence maintaining good clad quality. The chemical compositions of the substrate AISI 1020 and the solid filler gas tungsten arc electrode Stellite 6 are shown in table 1. The second clad layers were overlaid using the same set of parametric combinations and an interpass temperature of around 150 °C was maintained while depositing the second pass of clad material. After laying down first layer clads and second layer clads, the top surfaces of these clad layers were remelting using GTAW process itself. Table 2 represents the cladding/parametric conditions used in the present work.
**2.1. Metallurgical characterization of Stellite 6 clads**

Different Stellite 6 clads were subjected to microhardness evaluation, microstructural, XRD and EDS examination. Different specimens for microstructural studies were extracted from their respective cladded samples. The cross sections of these specimens that contained different zones of clads viz. clad metal, HAZ and unaffected base metal were polished successively using emery papers of varying grit sizes starting from coarse (150 no.) to finer (3000 no.). The etchant Aqua regia (HCl:HNO3 in the ratio of 3:1) was applied manually with a cotton swab for 20 to 25 s and then cleaned under running water. The etched specimens were then dried using acetone and were viewed under the optical metallurgical microscope. Different photomicrographs of interest were captured and analyzed.

The same polished specimens were used for microhardness evaluation using a load of 0.5 kg with a dwell time of 20 s and ten readings covering all major zones were taken across the clad layers of each specimen. The pins for wear testing were extracted using wire cut-EDM which were further machined accurately to achieve cylindrical pins with dimensions of 8 mm and 32 mm length from each cladded sample as shown in figure 2. Further different surfaces were subjected to XRD and EDS examination to understand the influence of different phase formations under different testing conditions.

**2.2. Wear testing of Stellite 6 clads**

A high temperature and computerized tribometer wear tester, with a pin-on-disc testing arrangement and coupled with a dedicated software, was used for wear testing of different pins. A number of trial runs were carried out to find and establish the final wear testing conditions. The finally used wear testing parameters and conditions are shown in table 3. Wear testing involved three sets of experiments having three phases. The first two sets used for establishing the wear testing parameters and investigating the effects of varying parameters on wear resistance of Stellite 6 claddings. The third phase of wear testing was solely aimed at finding the critical thickness of clad layer beyond which clad layer thickness would become insignificant i.e. uniform wear performance would be achieved.

**3. Results and discussions**

**3.1. Microstructural results of Stellite 6 claddings**

Different microstructures were captured using a dedicated metallurgical software coupled with a digital camera mounted on the inverted metallurgical optical microscope and the same are presented in figure 3. As can be seen in figure 3(a), epitaxial solidification pattern was observed near the fusion boundary zone (FBZ) which exhibited competitive growth towards the weld center. Figure 3(b) shows the clad metal that consisted of dendrites of Co solid solution having f.c.c. structure (light region) and interdendrites formed from the eutectic comprising of Co and Cr with carbides having h.c.p. structure (dark region). The intermetallics (Co, Cr & W) reacted with carbon to form M7C3 (Cr) and M2C (W) and these were the carbides which were found to be responsible for increase in hardness, abrasion and consequently wear resistance of Stellite clads. Figure 3(c) shows the clad metal of the second layer as well as the HAZ formation within the previously deposited clad layer which was observed to experience microstructural grain coarsening. A clear demarcation was seen between the top and the bottom.
Figure 2. Pins prepared from the cladded plates for wear testing.

Table 3. Parameters used for wear testing of Stellite 6 cladded pins.

| Testing parameters         | Value                   |
|-----------------------------|-------------------------|
| Load                        | 4.5 kgf                 |
| Disc RPM                    | 350                     |
| Wear track diameter         | 90 mm                   |
| Pin sliding distance        | 3000 m                  |
| Test duration               | 30 min                  |
| Testing temperatures        | Room temperature and 300 °C |

Figure 3. Optical micrograph (200X) of Stellite 6 double layer weld cladding with remelting, C4 (a)-Near fusion boundary layer; (b)-Weld zone of first clad layer; (c)-composite zone between first and second clad layer; (d)-weld zone of the second clad layer; (e)-top region of the second clad layer that was remelted.
layer of Stellite 6 cladding as there formed an intermediate HAZ in between these two layers which resulted into dendrite coarsening because of slower cooling rate due to heat received from the second clad pass. The difference in the grain size between first layer and second layer (top layer) were clearly distinguishable from figures 3(b) and (d) respectively as the top layer of the clad was directly exposed to the surroundings which led to faster cooling rate as compared to bottom layer of the clad. That’s why the grains of the bottom layer of clad were comparatively coarser than grains of the top layer of Stellite 6 cladding. And finally the dark carbide region was observed at the remelted region of the top layer with very fine eutectic islands of Co as shown in figure 3(e).

3.2. Microhardness results

The microhardness measured near the fusion boundary zone for single layer cladded specimen (C1) was 207 HV and single layer cladded and remelting specimen (C2) was 215 HV. Similarly, the hardness measured for double layer cladded specimen (C3) and double layer cladded and remelted specimen (C4) was 265 HV and 280 HV respectively as shown in figure 4.

The microhardness measured for Stellite 6 overlays at a distance of 4 mm from fusion boundary zone was 355 HV for single layer cladding (C1), 363 HV for single layer cladding with remelting (C2), 373 HV for double layer cladding (C3) and 388 HV for double layer cladding with remelting (C4). The microhardness was measured for double layer cladded (C3) and double layer cladded and remelted (C4) specimen at 7 mm away from fusion boundary layer which contained full filler chemistry and was found to be 480 HV and 515 HV respectively. This 35 HV increase in hardness was found to be the highest increase among all the other clad layers. This indicated that moving towards the richer chemistry of Stellite 6, the remelting technique proved to be more beneficial for enhancing the microhardness of the clad layer. So finally lesser dilution and remelting of the top region of the clad layer were observed to be the key factors in improving the microhardness of Stellite 6 claddings.

3.3. Pin on disc wear testing results of Stellite 6 claddings

In the first phase of wear test, the single layer Stellite 6 cladded pins were tested at three different temperatures i.e. room temperature, 150 °C and 300 °C with 3.5 kg load and 350 rpm. The wear testing parameters and results of first phase of wear testing of Stellite 6 claddings are tabulated in table 4. After performing the test, the wear loss was recorded to be 70 mg, 62 mg and 34 mg for room temperature, 150 °C and 300 °C testing conditions respectively. The results showed that only 8 mg less wear loss was recorded at 150 °C as compared to the room temperature testing while a significantly low i.e. 36 mg or 51.4% lesser wear loss was recorded in case of testing temperature of 300 °C. The computer generated results for both room temperature and 300 °C testing are shown in figures 5(a) and (b), which show wear, coefficient of friction and the frictional force generated corresponding to each wear testing experiment. The calculated wear loss of pins at different testing temperatures are plotted graphically in figure 6. Reduced wear rate indicated by automatic recording of low COF is also reported for reinforced friction stir welded joints [23].

The wear loss in the cladded sample tested at high temperature was observed to be less in comparison to the sample tested at room temperature because at high temperatures, oxides such as Cr₂O₃, Cr₃O₄, CoCr₂O₄ had probably formed on the contact surface area between pins and the rotating disc against which the pins were abraded. Due to the formation of these oxide films over the contact surfaces, these got entrapped in between the two contacting surfaces and formed a protective layer over Stellite 6. This protective layer of oxide film over
Table 4. Wear testing parameters and results of first phase of wear testing of Stellite 6 claddings (first set of experiments).

| S. no. | Specimen | Temp (°C) | Load (kg) | Rp m  | Track diameter (mm) | Time (min) | Coefficient of friction (μ) | Wear loss (mg) | Remarks/Observations |
|--------|----------|-----------|-----------|--------|---------------------|------------|-----------------------------|----------------|----------------------|
| 1      | F1       | RT        | 3.5       | 350    | 90                  | 30         | 0.365                       | 70             | μ, coefficient of friction (COF) as well as wear was found to be maximum because of absence of oxidative layer in between pin and disc surface under wear. |
| 2      | F2       | 150       | 3.5       | 350    | 90                  | 30         | 0.344                       | 62             | Effect of oxidelayer was again not observed at this temperature. |
| 3      | F3       | 300       | 3.5       | 350    | 90                  | 30         | 0.299                       | 34             | Formation of oxidative layer was observed at high temperature due to which μ as well as wear rate decreased. |
Stellite 6 provided lubrication between the two mating surfaces while being tested at high temperature which consequently reduced the wear. Such type of oxide layer formation resulting into lubrication tendencies has been reported as ‘glazing layer’ and is illustrated in figure 7.

Similarly in the second phase of wear testing, the cladded pins were tested at two temperatures i.e. room temperature and 300 °C with three different loadings conditions i.e. 3.5 kg, 4.5 kg and 7 kg keeping a constant disc speed of 350 rpm. The wear loss recorded for 4.5 kg loading condition was 155 mg and 103 mg when wear testing was performed at room temperature and 300 °C respectively. It was observed that the effect of oxide layer in case of high temperature wear testing of Stellite 6 cladded pins at 4.5 kg loading was present. But for the pins tested at a high loading condition of 7 kg at room temperature and 300 °C, the wear loss measured was 332 mg and 323 mg respectively. From this phase of work, it was concluded that the oxide layers between the mating surfaces could not sustain themselves during wear test at such a high loading condition. As a result of this, similar wear loss of cladded pins resulted when tested for wear at room temperature. All the data related to the second
phase of wear testing is mentioned in table 5 with specific remarks/observations given corresponding to each pin tested.

During the third phase of wear testing, the double layer cladded Stellite 6 pins were prepared by maintaining clad thicknesses of 3 mm, 4 mm, 5 mm and 6 mm in a set of two pins for each clad thickness. These pins were subjected to pin on disc wear testing at two temperatures i.e. room temperature and 300 °C. The load applied during the test was 4.5 kg keeping 350 rpm as the disc speed for 30 min at 90 mm wear track diameter of the disc. The results obtained from this phase of work are tabulated in table 6. It was observed that for 3 mm clad thickness, the wear loss calculated in case of room temperature testing was 199.80 mg as compared to 139.00 mg wear loss when tested at 300 °C. When 4 mm clad thickness pins were tested, the wear loss at room temperature was measured 155 mg whereas when tested at 300 °C, the wear loss was 103 mg. Testing of 5 mm clad thickness pins resulted in 127.4 mg wear loss during room temperature testing and same clad thickness resulted in 88.90 mg of wear loss when tested at 300 °C. Similar results were found for 6 mm clad thickness where wear loss was measured to be 125.60 mg and 84.80 mg when tested at room temperature and 300 °C respectively. The dilution of different layers of Stellite 6 was observed to have a considerable influence on their wear resistance.

Figure 6. Graph showing wear loss of Stellite 6 weld cladding (mg) during pin on disc testing.

Figure 7. Picture of the disc used for wear testing showing different wear tracks.
Table 5. Wear testing parameters and results of second phase of work related to wear testing (second set of experiment).

| S. no | Specimen | Temp (°C) | Load (kg) | Rpm | Track diameter (mm) | Time (min) | Coefficient of friction ($\mu$) | Wear loss (mg) | Remarks/Observations |
|-------|-----------|-----------|-----------|-----|--------------------|------------|-----------------------------|----------------|----------------------|
| 1     | S1        | RT        | 3.5       | 350 | 90                | 30         | 0.365                       | 70             | $\mu$ was high at room temperature as well as wear was also high because of absence of oxidative layer in between pin and disc. |
| 2     | S2        | 300       | 3.5       | 350 | 90                | 30         | 0.299                       | 34             | Formation of oxidative layer at high temperature induces a lubricating effect and COF and hence wear rate decreases |
| 3     | S3        | RT        | 4.5       | 350 | 90                | 30         | 0.392                       | 155            | Wear rate increased with increase in loading and COF also increased. |
| 4     | S4        | 300       | 4.5       | 350 | 90                | 30         | 0.338                       | 103            | Oxide layer was present and also found to be effective. |
| 5     | S5        | RT        | 7         | 350 | 90                | 30         | 0.431                       | 332            | No oxide layer was present |
| 6     | S6        | 300       | 7         | 350 | 90                | 30         | 0.436                       | 323            | No oxide layer was present |
As per the wear tests performed on various thicknesses of cladded layer, it was observed that, for 4 mm clad thickness, the wear was 29% less that for 3 mm clad thickness. Further for 5 mm clad thickness, the wear was found to be 20% less than that for 4 mm clad thickness. The wear loss for 5 mm and 6 mm clad thickness was found to be almost the same. From these results, it could be concluded that 5 mm clad thickness of Stellite 6 cladding was sufficient enough to impart good wear resistance characteristics to the substrate material and cladding beyond this thickness may not be of much significance in terms of wear performance of these claddings.

3.4. SEM results of worn out Stellite 6 pins

The differences in the amount of wear as well as worn out surface morphologies were observed for both the pins. From figure 8(a) it was observed that the wear was severe at room temperature testing as compared to wear observed in figure 8(b) which exhibited relatively less severity of wear when tested at 300 °C. Figure 9 shows the SEM fractographs of the wear surface of both pins at a higher magnification of 1000X which show that the type of wear in case of room temperature testing was of delamination type involving erosion, abrasive wear and pits formation while for specimen tested at 300 °C only abrasive wear was observed to be the main cause of wear.

In general the strain experienced by the Stellite 6 surface during the sliding wear has also been reported to increase its surface hardness without having microcutting of the surface.

Further the Co phase in the Stellite 6 has a face centred cubic crystal structure, which is consistent with ductility and high strength of the worn cladded surface [24]. So finally, oxidative layer formation supported the wear mechanism as observed at 300 °C testing temperature. While comparing the results obtained from EDS, it was clearly observed that oxygen was present on the worn out surface of pin tested at 300 °C as 3.71 weight % as shown in figure 10 whereas there was no evidence of presence of oxygen on the pin surface tested at room temperature. This increase in oxygen in case of high temperature wear was at the expense of loss of carbon as it was approximately 8.09% during room temperature wear testing but the carbon remained only 3.57% when the pin was tested at 300 °C. Presence of Fe at the worn out surface was attributed to wear of disc. It was observed that the amount of Fe in case of room temperature wear was 26% which reduced to 16% when compared to high temperature wear which was attributable to the presence of lubrication action provided by the oxide layer formation during high temperature testing.

| Pin no. | Temperature | Clad thickness | Wear loss (mg) |
|---------|-------------|----------------|----------------|
| T1      | Room temperature | 6 mm  | 125.60       |
| T2      | 5 mm       | 127.40       |
| T3      | 4 mm       | 155.00       |
| T4      | 3 mm       | 199.80       |
| T5      | 300 °C     | 6 mm  | 84.80        |
| T6      | 5 mm       | 88.90        |
| T7      | 4 mm       | 103.00       |
| T8      | 3 mm       | 139.90       |

Figure 8. SEM images at 250X magnification of wear surface of pins tested on (a) room temperature (b) 300 °C.

Table 6. Wear testing results of the third and the final phase of work related to wear testing.
3.5. XRD results of Stellite 6 cladded worn out pins

XRD results of the claddings are shown in figure 11 which indicate that the phase composition of these claddings mainly contained Co, Cr7C3, Co8W6C, CrCo and W2C. The chromium-rich carbides Cr7C3 formed during GTA cladding had stable face-center-cubic structure that contributed to high microhardness and good abrasive wear resistance of the claddings. The XRD spectrum (figure 11(b)) of the pin tested at 300 °C showed the presence of oxides like Cr2O3, CoCr2O4. The confirmation of the presence of these oxides during high testing temperature wear condition thus could be evidenced through these XRD studies.
4. Conclusions

1. Remelting technique using autogenous GTAW process in the present work showed that remelting of the top layer of Stellite 6 improved the microhardness of Stellite 6 claddings.

2. The wear loss recorded for Stellite 6 cladded pin at 300 °C testing temperature was 34 mg in comparison to 70 mg wear loss for the same clad pin but tested at room temperature, which indicated a 51.4% less wear loss in case of high temperature testing.

3. EDS and XRD results of the worn out pins indicated the presence of various oxides on the surface of the pins tested at 300 °C thus indicating the presence of oxidative layer which was responsible for low frictional resistance and hence better high temperature wear performance of Stellite 6 clads.

4. Among different clad thicknesses, thickness of 5 mm was established to be the critical clad thickness, as beyond this value the wear performance of Stellite 6 claddings did not vary much.

5. Finally it could be concluded from the present work that double layer cladding procedures using GTAW process and then followed by remelting of the top layer of the Stellite 6 clad pass can help in enhancing the microhardness and consequently its wear performance at high temperatures.

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