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Laser cladding of Stellite 6 on stainless steel to enhance solid particle erosion and cavitation resistance

Raghuvir Singh *, Damodar Kumar, S.K. Mishra, S.K. Tiwari

CSIR National Metallurgical Laboratory, Jamshedpur 831007, India

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ABSTRACT

Laser cladding of Stellite 6 on stainless steel 13Cr–4Ni has been performed to study the performance of clad on solid particle erosion (SPE) and cavitation erosion at varied energy densities (from 32 to 52 J/mm^2). Results are also compared with the AISI 304 stainless steel. The cladding geometry, dilution, microstructure and variation in microhardness were also investigated with laser energy inputs. The performance of cladded surfaces was studied for solid particle erosion and cavitation erosion resistance in 3.5% NaCl solution according to ASTM standard G76-07 and ASTM G32-07 methods respectively. Results indicated that clad dilution was 3–6% (geometrically) and 4.48% (compositionally) at 32 J/mm^2 that increased further with laser energy density. This accompanied compositional changes in the clad such that the Fe and Ni contents increased and Co, Cr, and W were observed to reduce with variation of laser energy density from 32 to 52 J/mm^2. The highest hardness (705 Hv) of the clad was obtained at 32 J/mm^2 which reduced further by enhancing the laser energy density. Stellite 6 cladding has significantly enhanced the solid particle erosion resistance of stainless steel. Cladding at 32 J/mm^2 showed SPE and cavitation resistance than the cladding performed at higher laser energy densities. Cavitation erosion resistance of the stainless steel in 3.5% sodium chloride solution was enhanced by >90% by laser cladding. Lower corrosion current density of 13Cr–4Ni is observed after laser cladding which further increased with laser energy density. The erosion resistance obtained can be explained on the basis of dimensionless parameter related to kinetic energy. Cavitation resistance appears related to elastic recovery after cladding.

1. Introduction

Stellite 6 is a useful hardfacing alloy in which chromium provides corrosion resistance while carbides add strength to the alloy. Molybdenum (Mo) and tungsten (W) are solid solution hardening elements and also contribute to the strength of Stellite 6 via precipitation hardening by formation of carbides and intermetallic phases such as Co (Mo, W). Studies performed on deposition (overlaying) of Stellite coatings using various methods such as oxyacetylene, TIG, Nd:YAG and CO$_2$ laser on stainless steels indicate better performance of laser applied Stellite coatings than by the other techniques [1,2].

Work carried out on the laser cladding of Stellite 6 so far has been focused on two important aspects (i) evolution of microstructure, hardness, and wear resistance of clad [3–13] and ii) effects of laser processing parameters on the clad geometry, fissure and on microstructures [13–18]. Villar showed increase in hardness of Stellite clad which was attributed to the hard dispersed phases like M$_7$C$_3$, M$_{23}$C$_6$ and Co$_3$W and dislocation–dislocation interactions to its overall strength [3]. Pizurova et al. investigated the microstructure and phases which evolved in the cobalt rich coating prepared by laser cladding on low carbon steel [4]. Frenk et al. investigated the solidification characteristics, the type, size and the fraction of phases in laser cladded Stellite 6 by changing the laser scan speed [5,6]. Hosson et al carried out a detailed TEM investigation and assigned three different mechanisms namely solid solution hardening by tungsten and chromium, dislocation–dislocation interactions, and impenetrable particle hardening as a result of metal-carbides and CoW precipitates for the observed high hardness of Stellite cladding [7]. The hardness of the alloy was shown dependent on the microstructure and size of the dendrites. Several studies were performed on Stellite cladding with addition of WC to achieve better wear resistance in some extreme situations [8,9]. Gassmann studied laser cladding of Stellite 6 with the addition of (WC + W$_2$C)/Co–Cr–C and (WC + WC)/Ni–B–Si to enhance abrasive wear resistance while Zhong et al. looked into the variations in microstructure with addition of WC contents from 0 to 100% [8–10]. It was clearly pointed out that the Stellite with 0 to 36% WC produced dendrites and interdendritic eutectics in which WC was completely melted. Re-solidified structure contained α-Co, σ-CoCr and carbides such as M$_7$C$_3$. Further increases in WC > 36% (up to 100%), however, revealed various faceted dendrites (in block, flower, butterfly, star shapes). Microstructure contained re-solidified WC, Co and various Co–W–C, Fe–W–C complex carbides [9]. Stellite deposition by plasma transferred arc method on AISI 1045 carbon steel showed enhanced

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* Corresponding author. Tel.: +91 657 2345078.
E-mail addresses: rsr@nmlindia.org, raghujog@yahoo.co.in (R. Singh).

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wear resistance by the addition of Mo up to 6% (by weight) due to an abrupt increase in M_6C type carbides [10]. Multilayer cladding of Stellite has been performed to produce microstructural gradient coating that revealed alternate fine and coarse microstructures which resulted in non-uniform hardness across the clad [11]. An effort has also been made to produce crack free cladding of Stellite 6 by preheating the substrate above 650 °C [12]. The effects of various parameters such as the powder feed rate, laser energy, and number of laser tracks have been investigated on the clad geometry and dilution of single track Stellite cladding. It was shown that the clad height and depth of penetration into the substrate increase with laser energy, pulse frequency, and percentage overlapping [13]. A similar study on the effect of interaction time during laser cladding demonstrated a finer microstructure with less dilution and high hardness in short interaction time as compared to longer interaction time [14].

The studies related to erosion and cavitation resistance of laser cladded Stellite 6 are relatively scarce despite the fact that alloy is well known for tribological resistance [19]. The application of Stellite 6 as such may involve huge cost and therefore laser surface cladding may be a viable option for its cost effective utilisation and benefits. Laser cladding, however, is expected to change its performance due to obvious reasons and thus justified looking into its erosion and cavitation behaviour. Underwater components such as guide vane, runner blade, labyrinth, pivot ring, pump, and compressor (component of hydroturbines) are predominantly damaged by cavitation and erosion. Such problems of cavitation and erosion in hydropower plants of South Asian countries belonging to the Himalayan regions are severe and remain a challenge to the material scientists [15]. The presence of large contents of quartz (90% or 5000–20,000 ppm) with high hardness (7 on the Mohs scale compared to 10 for the diamond) in the silt [20] accelerates synergistic damage due to corrosion assisted cavitation and solid particle erosion (SPE). Laser cladding of Stellite 6 on components of hydroturbine such as 13Cr–4Ni and AISI 304 stainless steel may be promising against cavitation and erosion. It is well documented that erosion and cavitation resistance of coatings or alloys do not necessarily rely on hardness or any single mechanical property. Mere hardness, therefore, may not predict the erosion or cavitation resistance of the clad. The wear study, on Stellite clad produced by laser, in the literature has generally been attempted by sliding wear where abrasion occurs due to external force unlike in SPE in which force is exerted by the deceleration of erodent particle and cause repetitive impacts [21–23]. During cavitation in the liquid, the surface damage occurs by stress resulted from the bubble implosion accompanied by corrosion. Little attention has been given to solid particle erosion and cavitation studies of laser cladded Stellite that may actually behave differently from Stellite alloy due to microstructural and compositional gradation along clad thickness. The present study has therefore targeted to unveil solid particle erosion and cavitation behaviour of Stellite clad fabricated at varied laser energy densities by using high power diode laser (HPDL). The clad characterization, particularly, geometry, dilution, and microstructure have also been highlighted in view of the change in laser energy density.

2. Experimental procedures

Stainless steel 13Cr–4Ni (wt.% C—0.06, Si—0.3, Mn—0.65, P—0.03, Cr—12.8, Ni—4.1) was chosen as a substrate material, as it is used for hydropower plants and suffers from severe erosion and cavitation damage. The results obtained have also been compared with AISI 304 stainless steel. Stellite powder containing Cr—28.2, W—4.3, Ni—1.1, Fe—1.4, C—0.92, Co—balance (by % weight) (supplied by H.C. Starck, GmbH Germany) was used as precursor material applied on the surface of stainless steels. High power diode laser (Model ROFIN DL028Q, Germany) integrated with CNC (customised by M/s SIL Pune, India) has been used for the cladding of Stellite on stainless steels at different output energy densities. The laser energy densities (laser power/scan rate × spot diameter) used for cladding were 52, 46, 37, and 32 J/mm^2. Laser beam size obtained was ~4.0 mm using an optics of focal length 166 mm and cladding was performed at a scan rate 10 mm/s. Laser tracks were laid at ~30% overlapping to obtain a uniform clad thickness. Stellite powders were fed through a feeder (GTV-PF-Twin2/2) supplied by GTV, GmbH, Germany. The powder aligned with the laser beam using a co-axial cladding head was focused on the surface of the specimen. Single track, before multiple scanning, at different operating parameters were laid to see the physical appearance of clad and adhesion of the precursor powder to the base substrate.

For hardness and microstructural characterization, cross sections (perpendicular to the length of laser track) of the clad were mounted and polished on emery papers followed by cloth polishing using alumina slurry containing ~0.05 μm particles. The specimens were subsequently etched with aquaregia (a mixture of concentrated nitric acid and hydrochloric acid in the ratio of 1:3). The untreated and laser cladded specimens were viewed under the optical and scanning electron microscope (SEM) (Hitachi S 3400N make). Phase identification was carried out using Seifert 3003 PTS X-ray diffractometer with Cu Kα radiations. The hardness on the cross section at a varied distance from the outermost surface of the cladded stainless steels was determined by the microhardness tester (Leica VMHT auto, GMBH Austria) at a 100 gf load. The average of 8 indents, at each distance from the outer surface, was reported as a mean hardness value.

2.1. Solid particle erosion and cavitation

The solid particle erosion was evaluated using an air jet erosion tester according to ASTM G76-07 standard [24]. Various parameters; the nozzle diameter ~2.8 mm, particle discharge speed (feed rate) ~9.8 g/min, and particle size of the erodent (alumina) ~150 μm were used for the erosion tests. All the specimens were inclined at an angle of 30° with respect to the nozzle axis. The weight loss after erosion test for pre decided time intervals was measured using a digital balance up to the fourth decimal place. All the specimens were subjected to erosion tests for a significantly long duration (up to 40 h) at room temperature. The results have also been compared with the untreated 13Cr–4Ni and AISI 304 stainless steels. The cavitation erosion of the cladded stainless steel was studied by using simple vibratory test method [25] which is most widely used to generate pure cavitation erosion data. In this method, magnetostrictive or piezoelectric ultrasonic transducer is used to produce oscillations of test specimen at a frequency of 20 ± 0.5 kHz in the distilled water. Transducer was connected to a horn (velocity transformer) to produce controlled oscillations. The test was carried out for approximately 30 h in 3.5% NaCl solution at room temperature.

2.2. Potentiodynamic polarisation

Corrosion behaviour of laser cladded and untreated substrates was studied by carrying out potentiodynamic polarisation in 3.5% NaCl solution using Reference 600 Potentiostat (Gamry Instruments, USA). For this, polarisation behaviour of specimen was recorded by sweeping the potential from −100 mV (with respect to OCP) in the noble direction at a constant scan rate of 1 mV/s up to a transpassive region (maximum up to +500 mV vs. SCE). Saturated calomel electrode (SCE) was used as a reference and graphite as a counter electrode. All the experiments were performed at room temperature.

3. Result & discussions

3.1. Clad geometry and dilution

Typical clad geometry obtained during multi scanning at various laser energies is shown in Fig. 1. A few defects/holes are seen in the clad fabricated at laser energy <37 J/mm^2. These defect/holes may be due to relatively higher cooling rates at laser energy <37 J/mm^2 resulting from lower melt volume as compared to that beyond 37 J/mm^2. A lower