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Cladding of Tribaloy T400 on Steel Substrates using a High Power Nd:YAG Laser

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Abstract

Tribaloy T-400 is a cobalt based alloy with molybdenum additions, which has been developed for improved resistance to high temperature wear, galling and corrosion. Its hardness is provided by a hard intermetallic Laves phase, dispersed in a tough matrix of cobalt rich eutectic or solid solution. However, cracking limits its applications such as hard facing using laser surface cladding/coating. The primary aim of this work is accomplished by cladding crack free Tribaloy T-400 layer using a high power Nd:YAG laser. The optimal process conditions of cladding crack free Tribaloy T-400 coating on different steel substrates were obtained. The effects of iron dilution on the hardness of clad Tribaloy T-400 coating are investigated. Dilution determined from clad geometry is verified from dilution calculated from an analysis

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of the composition of the clad. Microstructures of clad layers produced using optimal process parameters with and without preheating the substrate were analysed by Scanning Electron Microscopy (SEM). The chemical compositions of different phases present in the clad were analysed by Energy Dispersive X-ray Spectroscopy (EDS). Presence of phases with FCC and BCC structures and Laves phase ($Co_{3.6}Mo_2Si_{0.4}$) in the clad were identified and analysed by X-ray Diffraction (XRD). The residual stresses in the clads were evaluated using hole drilling technique. The correlation between the process conditions and the resulting microstructures are discussed. Based on the results of this research, further scaling up to industrial application of laser cladding of Tribaloy T-400 is promising.

Keywords: Laser cladding, Tribaloy T-400, Co-Cr-Fe system, optimal conditions, Laves phase, XRD, residual stress

1. Introduction

Surface degradation of industrial components servicing in the harsh working environments, often caused by wear and corrosion, requires surface modification to restore surface properties. It is economically beneficial to repair the surface of a damaged component or to improve the surface wear and corrosion resistance to extend the service life time. This may be realized by coating a super alloy layer which resists wear and corrosion. Laser cladding offers many attractive advantages over conventional coating techniques for both repair and functional coating. During laser cladding, the surface of the substrate is melted by laser irradiation and a melt pool is created. The metal powder is injected into the melt pool either with a co-axial or an off-axial noz-

zle using an inert carrier gas (Ya et al. (2013)). A powder stream is formed once the powder particles exit the nozzle tip. Both the powder stream and laser beam are focused on the same surface area of a substrate. The powder becomes molten and is captured by the melt pool on the substrate material. Metallurgical bonding takes place between the coating material and substrate by the solidification of the melt pool. A shielding gas (such as argon, nitrogen or helium) is used to protect the melt pool against oxidation. A clad track is produced on the substrate surface when the laser beam and powder stream are travelling together with respect to the substrate. In practice, a surface is clad by overlapping several clad tracks (then called as clad layer).

It is known that the pot hardware of galvanizer is subjected to a corrosive medium, the molten Zn-Al alloy (Zn bath). In the process of galvanizing, the rolled steel strip is submerged into the Zn bath at 734 ± 2 K. The thickness of the Zn layer on the steel strip is controlled by the driving motors and rollers which control the speed and tension of the strip. Normally, there are three rolls used to guide the steel strip through the Zn bath (Zhang & Tang (2003)). The surface of the rolls is continuously being attacked by the Zn bath causing corrosion and wear damages as the rolls are usually submerged in the Zn bath. Dross formation on the rolls during galvanizing is due to the reactions between molten Zn bath and other elements in the rolls. The pot hardware made of metallic materials is known to react with galvanizing baths to form intermetallic phases which has been reported by Richards et al. (1994), Lynch (1987) and Tadeusz (1940). Other researchers also reported that the protective cermet coatings applied by various techniques were also found to react with Zn bath during long-term immersion (Zhang & Tang

(2003), Sikka (2005) and Nsoesie et al. (2013)). The complicated chemical and metallurgical reactions between the rolls and Zn bath are mainly responsible for such damages.

Production line is often interrupted by the wear and the dross build-up on the surface of pot rolls. The galvanizing operations experience typically a down time every two weeks to change the metallic hardware submerged in the Zn bath. In addition, there are costs of materials replacement of the rolls and their accompanying accessories such as bearing components. If dross formation can be avoided or suppressed by the coated layer/layers on the roll, the service time of the rolls will be improved.

Research has been conducted to identify "high performance" pot hardware materials (Nsoesie et al. (2013), Zhang & Tang (2003). For this purpose, a cobalt based coating materials (Tribaloy family) were developed over the past decades (Kennametal (2015) data sheet). TribaloyTM alloys are developed for resistance to high temperature wear and corrosion. They are either nickel or cobalt based alloys with larger amount of molybdenum which contributes to the formation of Laves phases (MMoSi, M is Co or Ni), which are intermetallic phases (Zhu et al. (1999); Przybylowicz & Kusinski (2000)). However, it will be expensive to replace the rolls (usually made of steel) with "high performance" materials completely as most of them are made of super alloys. Improving the surface performance of the rolls in Zn bath by coating a superalloy is a cost-effective approach.

Zhang & Tang (2003) investigated the Zn bath reactions with different materials during galvanizing process for a better understanding of the reaction kinetics. Laser clad layers of Stellite 6, Tribaloy T-400C, T500M

(Fe-based super alloy) and AISI 316L with WC were produced in their experiments. The samples from these materials were immersed in the Zn bath for different durations. They concluded that iron-based alloy appears to experience preferential attack by the Zn bath. The Fe_2Al_5 provides ideal sites for the nucleation and build-up of dross on the surface. Their study indicated that Mo-rich intermetallic phase resists the attack from the Zn bath.

Przybylowicz & Kusinski (2000) reported that Tribaloy T-400 powder (45 μm grade) was laser cladded on both iron (0.45 % C) and nickel based (IN 718) substrates using a CO_2 laser with 2.6 mm laser spot. In their experiments, Tribaloy T-400 clad layer was deposited using 1000 W laser power and 8 mm s^{-1} cladding speed. The substrate used in their experiment had the dimensions of 25 x 25 x 6 mm^3 . The clad layer was produced by overlapping clad tracks (30 % of overlapping). Substrates were preheated to 723 K to prevent cracking. They reported that the strength of this material is mainly due to the Laves phases (mainly Mo-rich intermetallic phases). Co_3Mo_2Si Laves phase was found when the cladding is performed on 0.45% C steel substrate and CoMoSi Laves phase was found when the cladding is performed on IN 718 substrate. They also reported that the hardness in the clad layer was uniform and reached 63 HRC (equivalent to 780 Hv) with the dilution around 4% and 12% for steel and IN 718 substrates, respectively.

It is reported that about 50 Vol. % of CoMoSi Laves phase of hardness upto 1300 Hv present in Tribaloy T-400 provides the adhesive wear resistance (Kusinski et al. (2000)). The Mo addition provides high temperature strength to the Co based matrix. The Cr content in both matrix and Laves phase contributes to their corrosion resistance (Schmidt & Ferriss (1975)).

Fe and Ni addition stabilize the FCC matrix crystal structure (Sims (1969)). On the other hand, the Mo and Cr addition, by reducing the stacking fault energy, enhance the plastic deformation induced FCC to HCP crystal structure transformation in the Co base matrix (Sims (1969); Antony (1983)). This enhances the plastic deformation increasing the work hardening rate. The increased work hardening rate was reported to be beneficial for abrasive wear resistance (Atamert & Bhadeshia (1989)).

Tribaloy T-400 is therefore selected as a candidate for laser cladding the surface of the rolls as Mo rich intermetallic phases are expected to be the primary phases in the clad layer. However, due to its high hardness, crack free clad layer is difficult to produce. Although defect free samples were produced with CO_2 laser as mentioned earlier, a 723 K preheating temperature may affect the mechanical properties of the substrate material and cause significant iron dilution in clad layer. Also preheating a bulk substrate material to such a high temperature will present some practical difficulties. There is a need for further research and improvement. The primary aim of this research is to laser clad defects free Tribaloy T-400 clad layer with a Nd:YAG laser.

2. Experimental details

2.1. Experimental setup and materials

A Trumpf HL4006D Nd:YAG laser with a maximum output of 4 kW power was used to perform the experiments. The laser beam was guided through a fibre system and focused on the surface of the substrate material perpendicularly. Laser cladding is achieved by either pre-placed powder or blown powder techniques (William & Jyotirmoy (2010)). The blown powder

technique is applied in this research. The powder was delivered by a Sulzer Metco Twin-10 C powder feeder and injected into the processing area through an off-axial nozzle. Standard optics ($f=300$ mm) was used to defocus the laser beam to a spot of 4.8 mm in diameter. The working distance from the optics was 613 mm. All the optics and nozzles are integrated with an ABB IRC5 IRB 2600 robot arm with 6-DOF controlled by a computer allowing for flexible and fast positioning.

The dimensions of materials used in the experiments are listed in table 1. The chemical compositions of the different steels used in experiments are listed in table 2. Thinner DIN 2393 steel plates of 3 mm thickness were used in experiments to determine powder efficiency and single clad bead geometry Ya et al. (2016), which are important parameters for a proper design of the overlapped clad layers. Tribaloy T-400 powder was laser cladded on DIN 2393 steel plates for powder efficiency evaluation. Three clad tracks were laid on the steel plates with an interval of 15 mm. The plate weight difference before and after cladding and the powder feed rate were used to estimate the powder efficiency. It is easier and more accurate to measure thin steel plates instead of bulky and heavy steel plates. Tribaloy T-400 clad layer was laid on St355 J2 plates for cracking sensitivity and metallurgical investigations. Thicker (24 mm) St355 J2 steel plates were used in such experiments to prevent bending during cladding of overlapped tracks by providing sufficient constraints to withstand the developed residual stresses. Further, a thicker plate sample will be representative of a real product when considering the involved heating/cooling thermal cycles.

Table 1: The dimensions of materials used in the experiments.

Materials	Length (mm)	Width (mm)	Thickness (mm)	Particle size (μm)
DIN 2393 steel plate	110	50	3	-
St355 J2 steel plate	210	100	24	-
Tribaloy T-400	-	-	-	50-165 μm

Table 2: Chemical compositions of the different materials used in experiments (in *wt.%*).

Materials	C	Si	Mo	Co	Cr	Fe	other
DIN 2393 steel plate	0.17	-	1.4	-	-	Bal.	0.1
St355 J2 steel plate	0.22	0.55	-	-	-	Bal.	1.0
Tribaloy T-400	0.08	2.5	28.0	Bal.	8.5	1.5	2.5

2.2. Optimized process parameters

To obtain optimal clad shape, laser cladding with ramped power was performed to determine the optimal laser power, cladding speed and powder feeding rate. In order to evaluate the powder efficiency, a METTLER AE200 digital micro-balance was used to measure the weight of the clad samples. Based on the clad shape, the appearance of clads and powder efficiency, a laser power of 3000 W, a cladding speed of 10 mm s⁻¹ and a powder feeding rate of 0.22 g s⁻¹ are obtained as optimal processing parameters. The measured powder efficiency is around 75% and the aspect ratio of clad track is around 5 ($W_c/h_c = 4.6 \text{ mm} / 0.85 \text{ mm} = 5.41$). The optimization procedures based on the powder efficiency and ramped laser power are detailed in the thesis of Ya (2015).

2.3. Optimized process conditions

A 50% overlap ratio is used to produce the clad layer with a length of 200 mm, a width of 28.8 mm and a thickness of around 1.15 mm ($\pm 60 \mu\text{m}$ surface waviness). Multiple cracks appeared in the clad layer produced with optimal process parameters (figure 1, the upper clad in the figure). The dye penetrant test was used to detect the surface cracks in our experiments. This indicates that preheating the substrate is required to reduce the thermal mismatch between coating and substrate materials, which is one of the strategies used to reduce the residual stress (Ya (2015)).

Figure 1: Eliminating cracking by preheating substrate to a temperature of 523 K;
Upper clad: clad layer with cracks; Lower clad: clad layer without cracks.

2.4. Cracking sensitivity

Cracking sensitivity was defined (as number of cracks/clad length) to indicate the cracking tendency. Laser experiments were performed on the steel plates preheated at different temperatures (323 K, 373 K, 423 K, 473 K, 523 K). The steel plates were preheated uniformly with a hot plate. Figure 2a shows that increasing the preheating temperature reduces the number of cracks as the thermal stresses between the coating material and substrate is expected to be reduced.

Figure 2: Cracking sensitivity, a) cracking sensitivity and preheating temperature; b) cracking sensitivity and cladding speed.

Clad layers were produced using the obtained optimal laser power and powder feeding rate at different processing speeds (5, 10, 15, 20 mm s⁻¹). Figure 2b shows that the number of cracks increased with increased cladding

speed. When increasing the cladding speed, a high thermal gradient is expected (Ya (2015)), leading to larger residual stress and cracks. Preheating can help to reduce the thermal gradient and cracking as evidenced by the less number of cracks measured in the clads produced with preheating at 523 K (Figure 2b).

It can be concluded that the Tribaloy T-400 is sensitive to cracking and preheating is needed during laser cladding. A preheating temperature of 523 K was found to be optimal. Crack free sample under this condition were obtained as shown in figure 1 (the lower clad in the figure). Study of the cracking mechanisms is not the focus of this paper and hence not discussed.

2.5. Phase identification with X-Ray Diffraction (XRD)

The clads were analysed using X-Ray Diffraction (XRD) with $\text{CoK}\alpha$ radiation (30 kV/40 mA). The XRD patterns were recorded using a fully-automated Bruker D8 diffractometer equipped with a primary monochromator and an area sensitive detector (GADDS). The experimental setup using a GADDS detector is schematically illustrated in Figure 3. Each recorded frame covers approximately $30^\circ 2\theta$. Thus, four frames have been recorded for a long XRD pattern between 20 and $120^\circ 2\theta$. Measurement time for each frame was 450 s to obtain approximately 3000 counts for the strongest reflection. Beam size was $500 \mu\text{m}$ using a mono-capillary collimator. A quantitative determination of phase proportions was performed by Rietveld analysis. Unit cell parameters, background coefficients, preferred orientations, profile parameters and phase proportions were refined using the Topas software package for Rietveld refinement. The refinement strategy was adapted to the complex microstructure of the material. The strong texture (preferred

Figure 3: Schematic overview about data acquisition and processing using a X-ray diffractometer equipped with an area sensitive detection system (GADDS).

orientation) of phases within the steel and the clad layer strongly influences the intensities of certain reflections. In order to derive consistent results, texture correction was restricted to the main reflections of FCC and BCC phases using the March-Dollase approach (Zolotoyabko (2009)). All diffraction lines of sufficient intensity were analysed using full pattern approach.

2.6. Residual stress measurements (hole-drilling strain-gage method)

Hole drilling experiments were performed according to the ASTM standard E837. The schematic drawing and actual setup of hole drilling are shown in Figures 4a and 4b, respectively. EA-XX-062RE-120 strain gauge rosettes were used to measure the strains during the hole drilling experiment. In order to attach the rosettes on the surface of the clad layers, a flat and smooth surface is required. A thin layer (50-100 μm) on the surface of the clad layer was ground off, to remove unmelt powder particles and the surface waviness. A data acquisition conditioner (D4 from Micro-Measurements) was connected to the strain gauge rosette to record the micro-strain changes

Figure 4: Hole drilling, a) schematic drawing of hole drilling setup; b) experimental setup (Van Puymbroeck et al. (2016)).

during the hole drilling experiments. The drilling depth was maintained at $40 \mu m$. The strain data was recorded after each drilling step.

The residual stresses were calculated with measured microstrains using the following equations,

$$\left\{ \begin{array}{l} \sigma_{max} = \frac{\varepsilon_1 + \varepsilon_3}{4A} - \frac{1}{4B} \sqrt{(\varepsilon_3 - \varepsilon_1)^2 + (\varepsilon_3 + \varepsilon_1 - 2\varepsilon_2)^2} \\ \sigma_{min} = \frac{\varepsilon_1 + \varepsilon_3}{4A} + \frac{1}{4B} \sqrt{(\varepsilon_3 - \varepsilon_1)^2 + (\varepsilon_3 + \varepsilon_1 - 2\varepsilon_2)^2} \\ \tan(2\beta) = (\varepsilon_1 - 2\varepsilon_2 + \varepsilon_3) / (\varepsilon_3 - \varepsilon_1), \end{array} \right. \quad (1)$$

where σ_{max} and σ_{min} are the principal stresses; ε_1 , ε_2 and ε_3 are the strains measured with gauges 1, 2, 3 positioned at 0° , 90° and 135° to the cladding

direction; A and B are the gauge constants and β is the angle between the X (cladding) direction and σ_{max} direction.

2.7. Metallurgical analyses

The microstructure, hardness and composition of the clads were investigated using standard microscopy techniques. Cross sections of the clad track/layers were prepared through standard metallographic procedure. The microhardness of the specimens was measured with a LECO microhardness tester (LM100^{AT}) before etching the specimens. An optical microscope (LECO M2500) and a SEM (JEOL JSM-7001F) with EDS analyser (Thermo Scientific, UltraDry) were used for analysing the microstructure and elemental composition. Another SEM (FEI Quanta 400) with EDS analyser from Oxford Instruments was used to determine the composition profile of the clads. The measured composition of the clad layer was used to calculate the dilution which was used to validate the dilution measured from the dimensions of the clad.

2.8. Geometrical and metallurgical dilution in laser cladding

Dilution (d) has two definitions: metallurgical and geometrical (Toyserkani et al. (2004)). In principle, dilution refers to elements ratio of the mixing between substrate and the coating materials in the solidified melt. The metallurgical dilution is defined as the percentage of the total volume of the surface layer contributed by melting of the substrate (Bruck (1988)). Based on the composition, dilution is defined as

$$d = \frac{\rho_c(X_{c+s} - X_c)}{\rho_s(X_s - X_{c+s}) + \rho_c(X_{c+s} - X_c)} \quad (2)$$

where ρ_c is the density of melted powder alloy [kg m^{-3}], ρ_s is density of substrate material [kg m^{-3}], X_{c+s} is weight percent of element X in the total surface of the clad region [$\text{wt.}\%$], X_c is the weight percent of element X in the powder alloy [$\text{wt.}\%$], and X_s is the weight percent of element X in the substrate [$\text{wt.}\%$].

Schneider & Meijer (1998) has reported that such elements ratio can be correlated to the clad geometry. The geometrical definition of dilution as defined by Abbas and West (1991) is calculated from

$$d = \frac{A_{mix}}{A_{mix} + A_c} \times 100\% \approx \frac{h_{mix}}{h_{mix} + h_c} \times 100\%. \quad (3)$$

where h_c is clad height and A_c is clad area above substrate surface, h_{mix} is the melt depth and A_{mix} is mixing area below substrate surface (see figure 5).

Figure 5: A schematic view of the cross section of a single clad track.

Experimental evidences on agreement of dilution results from these two methods based on detailed compositional analyses are not available in the literature. In the following section, results from this research are presented and discussed.

3. Results and discussion

3.1. Dilution and hardness

Figure 6 shows the cross sections of clad samples produced under optimal process parameters without and with preheating. Without preheating, cracks appear in clad layer. About 21 % of dilution is observed in the first two clad

Figure 6: Cross section of overlapped clad layer, a) produced without preheating; b) produced with preheating.

tracks and the dilution in remaining clad tracks is in the range of 2 % to 14 %. The dilution was measured from clad geometry. A detailed account of dilution measurements is provided in later part of section 3.1. At the beginning of the process, large amount of laser power is transmitted through powder stream and heat up the substrate (Ya et al. (2013)). Consequently, deeper laser penetration and larger mixing (dilution) with substrate are observed in the first two clad tracks. As the used laser has a Gaussian beam profile,

the deepest laser penetration into substrate appears at the centre of a clad track. The laser power is partially used to remelt previously deposited clad track. Hence lesser energy is available for subsequent tracks due to the 50 % overlapping of tracks. Thus, less laser penetration and mixing with substrate are observed in subsequent laid clad tracks and the process becomes stabilized. This explains why we get a larger substrate melting and dilution at the beginning of the cladding process which reduces to a stable level further on.

Similar effects are observed also from the cross section of the preheated sample. With preheating, about 45 % of dilution is observed in the beginning and the dilution reduces to about 20 % in the subsequently laid clad tracks. Preheating the substrate can be considered as an extra energy input supplemental to the laser energy. Hence laser penetration, melting and mixing with substrate are expected to be more when comparing to the sample without preheating (figures 6a and 6b).

Figure 7 shows the microhardness profiles obtained across the depth of different clad tracks. The hardness decreases with increased dilution. The reasons for difference in dilution at different clad tracks have been discussed in previous paragraphs. Dilution by iron is expected as it is the main element in the steel substrates (table 2) which will contribute to a hardness reduction (Halstead & Rawlings (1985)). Some microstructure changes are expected due to the dilution, which will lead to reduced volume fraction of Laves phase.

Based on the hardness profile shown in figure 7, a dilution range of 15% to 20% is the region of interest for laser cladding of Tribaloy T-400

Figure 7: Microhardness profiles of different clad tracks.

as it still provides sufficient hardness required for the application. Further Scanning electron microscopy (SEM)/Energy-dispersive X-ray Spectroscopy (EDS) analyses and X-ray Diffraction (XRD) were performed to investigate the microstructures of the clad layer produced with and without preheating the substrate.

In order to assess the uniformity of dilution (elemental distribution) in the clad layer, different clad tracks with different melt depth (dilution) were selected. They are tracks 2 and 9 of clads produced with cladding speeds of 5 mm s^{-1} and 10 mm s^{-1} without any preheating. In both cases, track 2 had a maximum dilution and track 9 had a low but uniform dilution for reasons discussed earlier while explaining the observations depicted in figure 6. It is to be pointed out that though the samples for this analysis and for the hardness measurements were cut from the same clad plate, they are cut at different lengths from the start position. EDS analyses were performed at several locations across the clad tracks from the clad top region to the substrate at

Figure 8: (a) EDS measurement locations on the clad, (b) composition of elements at corresponding locations, (c) measured typical spectra from clad and (d) substrate, Sample: track 2 of clad produced with 10 mm s^{-1} cladding speed (no preheating).

small intervals (of about $80 \mu\text{m}$). Figure 8a indicates the measured locations on track 2 of sample produced at 10 mm s^{-1} cladding speed. The distribution of the detected elements are indicated in figure 8b. The typical spectrum from the clad and the substrate can be seen in figures 8c and 8d, respectively. The composition (in wt. %) within the clad layer ranged for different elements,

viz. (in wt.%); cobalt 35.7 to 47.7, molybdenum 13.7 to 27.8, iron 22.1 to 36.2, chromium 6.4 to 8.0, silicon 1.4 to 2.7 and Manganese 0 to 0.5. There was no evidence of any of the elements from the Tribaloy T-400 having diffused into the substrate during the cladding process.

Figure 9: Comparison of dilution values calculated from metallurgical and geometrical dilution definitions.

The metallurgical dilution was calculated using the data obtained from EDS measurements (elemental distributions along the clad depth) as an average of all measurements within the clad. The geometrical dilution was calculated using clad geometry (clad height and melt depth) measured with an optical microscope. Data from the chosen four clad tracks were analysed and a fit was made. The dilution values calculated from the two definitions agree well with each other and the results are shown in figure 9. A 5 % of error is introduced to visualise the deviation of the dilution values obtained from the two methods of measurements. These results clearly demonstrate

that the elemental dilution in a laser clad can be accurately represented by dilution values calculated from the clad geometry measured using an optical microscope.

3.2. Microstructure changes with and without preheating

Figures 10 and 11 show SEM images of the clad tracks with about 20 % dilution obtained without and with preheating, respectively. These two clads have different microstructures, characterized by the different morphology. Both samples contain the primary white and eutectic phases, but a dark phase appear in the clad produced with preheating. To investigate these phases, EDS analyses were performed on each phase and the obtained average chemical compositions of the clads are listed in the table 3. The white primary phase is expected to be $Co_kMo_lSi_m$ (k, l, m are atomic fractions) type of intermetallic Laves phase, the dark and the eutectic phases are expected to be the mixture of Co-rich solid solutions. Each result is an average of measurements at 9 similar locations and in each measurement the counting time was 30 seconds which was adequate to get sufficient intensity of the EDS.

Table 3: The table includes the compositions of all the phases (in wt.%).

Phases	Si-K	Cr-K	Mn-K	Fe-K	Co-K	Mo-L
White phases (no preheating)	3.81	7.35	0.30	2.67	48.71	37.17
Eutectic phases (no preheating)	0.75	11.73	0.20	5.89	69.00	12.43
White phases (preheated)	4.18	5.93	0.22	3.29	46.28	40.11
Dark phases (preheated)	0.98	9.93	-	9.28	65.94	13.87
Eutectic phases (preheated)	0.72	11.55	-	5.51	69.03	13.19

Figure 10: Microstructure of the clad layer with 21% dilution produced without preheating (cladding speed 10 mm s^{-1} , Track 2).

Figure 11: Microstructure of the clad layer with 20% dilution produced with preheating (cladding speed 10 mm s^{-1} , Track 6).

3.3. Quantitative phase analyses using XRD

The XRD measurement locations across the metallographically polished clad samples are schematically illustrated in figure 12. An area of 30 mm (in width) x 3.5 mm (in depth) encompassing the clad layer, interface and substrate was analysed using a step size of $500 \mu\text{m}$. The sample was stationary and mounted on a XY stage. The collimated X-ray beam of $500 \mu\text{m}$ is

projected on to the sample surface. The irradiated area on the sample surface will be elliptical in shape in X-direction, as the sample is inclined with respect to the incident X-ray beam during XRD measurements. However, X-ray spot size in Y direction is always kept at $500\ \mu\text{m}$. An offset of $250\ \mu\text{m}$ offset from the top surface of the clad layer was maintained to avoid interference from the clad surface edge. At each measurement location, phase identification and quantitative phase analyses were done. Only representative results are presented here.

Figure 12: Schematic drawing of the XRD measurement locations across the clad samples.

As a reference, the Tribaloy T-400 powder was also analysed and the obtained XRD patterns is shown in figure 13. The strongest diffraction peaks appear in the 2Θ range 40° to 60° . The presented phases were identified to be the Co-rich FCC phase (about 53 wt. %) and Laves phase ($\text{Co}_{3.6}\text{Mo}_2\text{Si}_{0.4}$, about 47 wt. %) were identified to be present. There is no BCC phase presents in the powder material.

Figure 14 and Figure 15 show the variations of the identified phases with

Figure 13: XRD pattern of Tribaloy T-400 powder.

depth from the top of the clads towards the substrate. The measurement

Figure 14: XRD quantitative analysis of Tribaloy T-400 clad at different depth from surface (no preheating, cladding speed 10 mm s^{-1} , track 6).

locations and direction are indicated in the top figure. The XRD patterns obtained at all locations are indicated in the left figure. The calculated weight percentage of the different phases are indicated in the right figure. The main phases in the clads are expected to be Co-rich FCC and Laves phases. BCC

Figure 15: XRD quantitative analysis of Tribaloy T-400 clad at different depth from surface (preheated, cladding speed 10 mm s^{-1} , track 6).

phase (α -Fe) is expected to be present in the substrate.

Figure 14 shows that the proportion of the Laves phase is marginally higher (3-7%) than the Co-rich FCC phase in the clads produced without preheating. At the first measurement location which is centred at $250 \mu\text{m}$ from clad top surface, the FCC phase and Laves phase are in equal proportions and BCC phase is absent. With increasing depth, both Laves and FCC phase contents decrease reaching zero at locations beyond 1.5 mm from the interface/fusion line. On the other hand, the BCC phase increases with depth and reaches 100 wt.% at around 1.5 mm from the interface. However, in case of clad produced with preheating, at all measurement locations, the Co-rich FCC phase content was larger (by 6 to 25 wt.%) than the Laves phase content. In the first two measurement locations lying, 250 and $750 \mu\text{m}$ from the clad top surface, the BCC phase is absent. For the rest, all phases displayed similar trends with increasing depth, as seen with the non-preheated sample.

Some anomalies are noticed in the results shown in figures 14 and 15.

As indicated in figure 8b; the distribution of Cr, Si, Mn elements in the clad layer are fairly uniform, the Fe content slightly increased (from 25 to 35 wt.%) approaching towards the interface/fusion line and Co and Mo contents fluctuate about certain mean values whenever the EDS scan encountered Laves phases. The BCC phases which are possible in the clad layer are; ferrite/ α -iron, α -Cr, Mo, Fe-Cr, Fe-Cr-Mo (hypothetical cl54 ferrite structure (Qiu (1992)), CoCrFe (17, 53, 30 wt. %). It is unlikely that any of the elements of this Tribaloy T-400 or iron from substrate are in free form as they all can form solid solutions freely with each other. Further, at the first measurement location, the measured BCC content is zero, in both samples. Also, the BCC content in the substrate does not reach 100 wt.% level immediately after the interface/fusion line. It may be possible to detect FCC phase in the HAZ of the substrate, if any retained austenite is present. It is highly unlikely that Laves phase is present in the substrate, as the composition analyses have not indicated any diffusion of elements from the clad into the substrate. With these considerations, it may be pertinent to assume that the results of XRD phase measurements very close to the interface may not be accurate due to possible errors in X-ray beam positioning with respect to the region of interest in the clad and beam divergence. A more detailed metallurgical investigation will be required to clarify these anomalies.

An interesting outcome of this analysis is that with preheating the proportion of the Co-rich FCC phase is higher than the Laves phase in the clads (figure 15). Consequently, the reduction of Laves phases in the clads will lead to reduced hardness (figure 7) as intermetallic Laves phases is the main contributor to the hardness. This increase in FCC phase content will

improve the clad resistance to cracking. The Fe dilution promotes and stabilises the Co-rich FCC structure (Halstead & Rawlings (1985)) as indicated from the Co-Cr-Fe phase diagram (Davis et al. (2000)). Therefore, the dilution of the Fe helps to prevent cracking during laser cladding of Tribaloy T-400. However, there should be an upper limit of the dilution value, beyond which the hardness of the material will drop significantly adversely affecting the properties of the clads. Such a limiting dilution value is observed for another cobalt alloy (Satellite 6) also, which is reported by Ya (2015).

3.4. Residual stresses measurements

The results of the hole drilling experiments performed on samples with and without preheating are shown in Figure 16. It is evidently clear that preheating the substrate during laser cladding Tribaloy T-400 on St355 J2 steel substrate significantly reduces residual stresses (σ_x acting along the cladding direction.). The maximum residual stress in the clad layer without preheating the substrate was found to be at and near the clad surface which reaches about 3500 MPa by calculation, which is larger than the estimated ultimate tensile strength (around 2200 MPa) of this material. As this is unrealistic, measured stress values above the ultimate tensile strength are excluded from the figure16. With preheating the maximum residual stress is about 1250 MPa. The stresses at all locations within the clad are tensile in nature.

It can be concluded that the preheating reduces the residual stresses during laser cladding of Tribaloy T-400 on the steel substrate. The iron dilution will stabilise the Co-rich FCC structure which reduce the cracking tendency.

Figure 16: Residual stresses measured with hole drilling technique.

4. Conclusion

The following conclusions can be draw based on results of this research,

- Optimal process conditions for laser cladding of Tribaloy T-400 on steel substrates without cracking were experimentally determined (3000 W of laser power, 0.22 g s^{-1} of powder feeding rate, 10 mm s^{-1} of cladding speed at 523 K preheating temperature).
- The Fe dilution in the clad layer from the substrate will lead to a hardness reduction due to an increase in the Co-rich FCC phase with attendant decrease in the hard Laves phase.
- The Fe dilution increases with the preheating temperature.
- Based on the SEM/EDS analyses performed, it is clearly established that dilution determined from elements mixing ratio and clad geometry correlate and agree very well.
- The Laves phase is identified as $(\text{Co}_{3.6}\text{Mo}_2\text{Si}_{0.4})$. The proportion, morphology and distribution of the Laves phase in the clad are influenced by the preheating during laser cladding. Preheating during laser cladding of Tribaloy T-400 effectively reduces the tensile residual stresses and the risk of cracking.

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Highlights

- Crack free Tribaloy T-400 clad layers were produced with a Nd:YAG laser.
- Laves phase presented in the clad layer is identified as $\text{Co}_{3.6}\text{Mo}_2\text{Si}_{0.4}$.
- Crack sensitivity of Tribaloy T-400 during laser cladding is evaluated.

Figure 1

(a)

(b)

Figure 2

Area sensitive detector (GADDS)

X-ray
source

Post
processing

Phase identification

Figure 3

Figure 4

Figure 5

(a)

(b)

Figure 6

Figure 7

(a)

(b)

(c)

(d)

Figure 8

Figure 9

Figure 10

Figure 11

Figure 12

Figure 13

Figure 14

Figure 15

Figure 16