Residual stresses in Stellite 6 layers cladded on AISI 420 steel plates with a Nd:YAG laser

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Abstract

Clad tracks/layers with good geometry, desirable dilution and hardness can be produced using the optimal process parameters. However, cracking and deformation can occur in the laser cladded products. The tensile residual stress is mainly responsible for the failure of the cladded products. Therefore, different residual stresses control strategies during laser cladding were investigated, such as preheating the substrate, using intermediate layer and using different energy inputs. The residual stresses in clad layers were measured with layer removal and hole drilling techniques. The depth residual stress distributions obtained from both techniques show a good agreement. The residual stresses acting along the cladding direction σ_x and the maximum residual stresses within the clad layer were analysed. The cooling rate and thermal gradient were simulated from our previously developed 2D thermal model. The relations between the cooling rates, thermal gradients, maximum residual stresses and absorbed energy were investigated and the results are discussed. Thermal gradients, cooling rates the maximum residual stresses decrease with energy input. The decay factors between maximum residual stress and absorbed energy and between the cooling rate and absorbed energy are close to each other indicating that a correlation between the maximum residual stress and cooling rate exists. An empirical relation is used to describe such a correlation.

Keywords: laser cladding, layer removal, hole drilling, cooling rate, thermal gradients, residual stress

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1. Introduction

Laser cladding as a surface coating technique, has been used for repair and application of functional coating in different industrial products (Torims (2013)). The economic benefits have driven laser cladding development very quickly in recent decades (Zhong & Liu (2010)). During laser cladding, the surface of the substrate is melted by laser irradiation and a melt pool is created (Steen & Mazumder (2010)). The powder is injected into the melt pool with a nozzle using an inert carrier gas. Both the powder stream and laser beam are focused on the same surface area of the 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 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 such clad tracks (then called clad layer).

Clad layers develop cracks either during production (hot cracking (Zhou et al. (2008))), during storage (delayed cracking (Katayama (2013))), during subsequent machining or in service due to relaxation of residual stresses (Zhuang & Halford (2001)). The high cooling rates, non-linear properties of the materials at elevated temperature and differential shrinkages involved in the laser cladding process are responsible for such tensile residual stresses, which may exceed the yield strength of the clad material resulting in cracking and/or deformations (Brückner et al. (2007)). The relationships between processing conditions and the responses of the material are not well established or understood and there is a need for research.

Cobalt based alloys (Stellites) are well studied in the past decades and are very popular with regard to improvement of the wear resistance of mechanical parts (De Hosson et al. (1993)). They are mixed with other elements such as chromium, nickel, tungsten, molybdenum and carbon. Chromium is added to form carbides and to provide strength in the cobalt matrix and to enhance the corrosion and oxidation resistance. Nickel is added to increase the ductility and reduce the sensitivity to cracking. The large atomic sizes of tungsten and molybdenum can deform the crystal lattice of cobalt matrix and provide additional strength. They also can form hard brittle carbides with carbon. The formed carbides help to stop the movement of dislocations and thereby increase the strength of the matrix. The predominant carbides found in the clad layer made with Stellites are normally the chromium rich (M_7C_3) type with a hardness of approximately 2200 Hv (De Hosson et al. (1993)). This provides the required hardness for the clad layers (550 Hv) and improves the wear resistance. Other carbides such as M_6C and $M_{23}C_6$ were also found in the clad (De Hosson et al. (1993)). If a higher hardness is required for an application, carbides, nitrides and borides with high melting point can be added into the cobalt alloy directly to increase hardness and to improve the wear resistance (Gassmann et al. (2013) and Van Acker et al. (2005)). The strength of the matrix can be improved by

adding hard particles with high melting temperature uniformly. The particle size should be around 0.01 to 0.05 μm , and the distance between these particles should be around 0.1 to 0.5 μm (Benjamin (1970)).

As materials experience different thermal cycles during laser cladding, stresses develop within the clad and substrate materials. Compressive stress is introduced during the heating cycle in the substrate. Tensile stress is introduced during the cooling cycle in the substrate. Depending on the difference in thermal expansion coefficients of coating and substrate material (thermal mismatch), tensile or compressive stresses will be introduced in the clad layers (Masubuchi (2013)). Tensile residual stresses negatively influence the strength and corrosion properties of materials (Mochizuki (2007)). Therefore, it is of primary importance to know how different processing conditions influence the residual stresses (Roth et al. (1990)).

The residual stresses in laser cladding are mainly caused by sharp thermal gradients, thermal mismatch and phase transformations in the microstructures (type I and II residual stresses). Residual stresses can be categorized as macro (type I and II) and micro (type III) stresses. While type I stress acts over a large distance in a material, type II stress acts over a few grains and type III acts within a grain over atomic scale distance. Removal of a part of the material will cause a dimensional change with type I and II stresses, whereas with type III stress there will be no change. Among these stresses, type I is of main interest for a mechanical component. Type II can be important when crack initiation from phase transformation in microstructures is studied. There are many methods for the measurement of residual stress in engineering materials. The principles of these methods are detailed in the reference of Withers & Bhadeshia (2001a) and Withers & Bhadeshia (2001b).

The aim of this research work is to improve our understanding of the response of materials to laser cladding by studying the influence of different process conditions on the residual stresses of the final clad layers. For this purpose, a well studied material, Stellite 6 powder is laser clad on to AISI 420 steel plates. Different residual stress control strategies such as preheating the substrate, adding an intermediate layer and using different energy inputs during laser cladding were investigated and are discussed. The established measurement methods, namely curvature method and hole drilling techniques, are used in this study to evaluate the stress levels in the laser clad layers. In order to investigate correlations among cooling rate, thermal gradient and maximum residual stress in the clad layers, the cooling rate and thermal gradient under different process conditions were simulated with a previously developed thermal model (Ya et al. (2016)).

2. Experiments and their setup

2.1. Laser cladding experiments

Laser cladding setup

A Trumpf HL4006D Nd:YAG laser with a maximum output of 4 kW laser power was used to perform the experiments. The laser beam was guided through

90 a fibre system and focused onto the surface of the substrate material perpendicularly. The laser zoom optics used in this work was designed to study the effect of different laser profile on the laser cladding process (de Lange et al. (2005)). A PixelINK PL-A741 CMOS camera was used to control (online feedback control) the melt pool width by adjusting the input laser power. This controller, together with the zoom optics, is detailed in the thesis of Hofman (2009). The powder was delivered by a Sulzer Metco Twin-10 C powder feeder and injected into the processing area through either a co-axial nozzle or an off-axial nozzle. All the optics and nozzles are integrated with an ABB IRC5 IRB 2600 robot arm with 6-DOF controlled with a computer allowing for flexible and fast positioning. Such a system is shown in Figure 1.

Figure 1: An overview of laser cladding setup.

100 A laser spot size of 3.0 mm was used in this research. For a 3.0 mm laser spot size, the working distance from the laser optics is 147 mm . The PowerMonitor and PowerMonitorSoftware Version 2.48 from Primes were used to measure the laser beam profiles. An industrial ILT co-axial nozzle was used during laser cladding experiments. The characteristics of powder stream/cloud from this feeding nozzle was investigated in a previous study (Ya et al. (2013)).

Materials used

110 Stellite 6 (cobalt based powder) was cladded on AISI 420 steel substrate. The chemical composition of these materials is summarized in Table 1. The size of the powder particle and the dimensions of the steel substrate are summarized in Table 2. The composition and particle size of Inconel 625 and Stellite 21 powder used to produce an intermediate layer to reduce thermal stresses are also indicated in the same tables.

Table 1: Chemical composition of coating and substrate materials in wt. %.

Materials	Nb	C	Si	Mn	Cr	Mo	W	Fe	Ni	Co
AISI 420	-	0.2	<1.0	<1.5	13.0	-	-	Bal.	-	-
Stellite 6	-	1.22	1.22	0.26	29.5	0.08	4.6	1.72	2.29	Bal.
Inconel 625	3.65	0.05	0.25	0.30	22.3	8.80	-	3.4	Bal.	-
Stellite 21	-	0.27	0.75	-	27	5.5	-	1.5	2.75	Bal.

Table 2: The dimensions of materials used in the experiments.

Materials	Length (mm)	Width (mm)	Thickness (mm)	Particle size (μm)
AISI 420 plate	200	25	12	-
Stellite 6	-	-	-	50-160
Inconel 625	-	-	-	50-160
Stellite 21	-	-	-	50-160

Cladding layers and different process conditions

For most industrial applications, a certain clad height ($> 1 \text{ mm}$) is required. This requirement is realized by either cladding single layer at low speed or cladding multiple layers on top of each other. Both cases were investigated in this research. In the later case, the first Stellite 6 layer was cladded on the surface of AISI 420 substrate ($200 \text{ mm} \times 25 \text{ mm} \times 12 \text{ mm}$) with a 50 % overlap ratio. Then, the second Stellite 6 layer was cladded on top of the first clad layer. When an intermediate layer (Inconel 625 or Stellite 21) was used, it was cladded as the first layer.

The process conditions used to produce these samples are shown in table 3. To investigate the effect of preheating on the resulting residual stress in the clad layer, samples (S7-1 and S7-2, S7-6 and S7-7, S7-8 and S7-9) were produced with same process conditions (energy input, powder feeding rate and number of clad layers) at different initial temperature of substrate. To investigate the effect of cladding with interlayer on resulting residual stress in the clad layer, samples (S7-3 and S7-4, S7-10 and S7-11) were produced with same process conditions as sample S7-1. To investigate the effects of effective energy input on the resulting residual stress, samples (S1-2, S4-1 and S3-1) were produced. Effective energy input (E_e) was defined as ($E_e = P_l / (DV_c)$) in our previous study (Ya et al. (2016)), where P_l is the laser power, D is the diameter of laser spot and V_c is the cladding speed. Sample S3-1 has a single clad layer produced at lower cladding speed and samples S1-2 and S4-1 are with two clad layers produced at higher cladding speed. The effective powder feeding rate of sample S3-1 is higher than samples S1-2 and S4-1. The effective powder feeding rate is defined as $\dot{m}_e = \dot{m} / (DV_c)$, where $\dot{m}$ is the powder feeding rate. For each condition, duplicate samples (S7-1 to S7-11) were produced for comparison of the residual stresses obtained from layer removal and hole drilling experiments.

In all cases, the overlap between clad tracks is 1.5 mm (50% overlap ratio). The final clad layer length and width were 180 mm and 21 mm , respectively. The final clad thickness along with the dilution are listed in Table 4. Dilution is defined as the mixing ratio between the coating and substrate materials. In

Table 3: Process conditions.

Sample code	Laser power (W)	Clad speed ($mm\ s^{-1}$)	Powder feed-ing rate ($g\ s^{-1}$)	Effective ener-gy input ($J\ mm^{-2}$)	Specific feed-ing rate ($10^{-3} \times g\ mm^{-2}$)	Clad layer number	Initial tem-perature (K)	Inter layer
S7-1 and S7-2	1400	15	0.165	33.33	3.92	2	298	no
S7-6 and S7-7	1400	15	0.165	33.33	3.92	2	473	no
S7-8 and S7-9	1400	15	0.165	33.33	3.92	2	573	no
S7-3 and S7-4	1400	15	0.165	33.33	3.92	2	298	Stellite 21
S7-10 and s7-11	1400	15	0.165	33.33	3.92	2	298	Inconel 625
S1-2	1400	20	0.220	25	3.92	2	298	no
S4-1	1800	20	0.220	32.14	3.92	2	298	no
S3-1	1400	10	0.220	50	7.84	1	298	no

145 principle, dilution refers to elemental ratio of the mixing. Schneider (1998) has shown that such elemental ratio can be correlated to the clad geometry. Hence, the geometrical definition of dilution as defined by Abbas & West (1991), viz. ratio of melt depth in substrate to total clad height expressed in percentage, is used in this work. The calculation of dilution can be found in the reference of Ya et al. (2016).

Table 4: The height and dilution of the clad layers.

Sample Code	S7-1	S7-6	S7-8	S7-3	S7-10	S1-2	S4-1	S3-1
	S7-2	S7-7	S7-9	S7-4	S7-11			
Clad height (mm)	1.26	1.54	1.53	1.50	1.49	1.02	1.26	1.05
Dilution (%)	18.70	19.90	20.15	17.5	15.51	10.73	17.3	21.8

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Figure 2 schematically shows the laser clad layer/layers on a substrate. The dimension of the caldded layer and the used steel plate in this study are also indicated in figure 2.

2.2. Residual stress measurements

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Successive layer removal and incremental hole drilling techniques were used in this research to determine the stresses within clad layers. The stress equilibrium is disturbed when a part of the material is removed either by layer

Figure 2: A schematic representation of the laser cladded layer on a steel plate and typical dimensions.

removal or by hole drilling. The material will assume a new equilibrium by a change in shape or dimension. Such a change is measured and the corresponding stress relaxed is computed. The residual stresses in samples (S7-1 to S7-11) were measured using both layer removal techniques and the hole drilling and the result are compared. The residual stresses in samples (S1-2, S4-1 and S3-1) were measured using only the layer removal technique.

Layer removal experiments

The layer removal technique is based on curvature measurements (Withers & Bhadeshia (2001a)). The clad layers can induce stresses which will cause the substrate to bend. By measuring the resulting changes in curvature after removing the coating or clad layers successively, it is possible to calculate the corresponding variations in stress as a function of thickness. The principle of the layer removal technique is schematically shown in Figure 3.

A simple beam supported device was built and used in experiments to measure the deflection of samples (Figure 4a). The distance between two supported points is 168 mm. A digital (Linear Variable Differential Transformer) LVDT was placed at the centre to measure the deflection. The accuracy of the LVDT is $\pm 0.1 \mu m$. Figure 4b shows a grinding machine which is used to remove a certain amount of material of the clad layer. The deflection of the steel plate was measured before and after a layer (200 μm) of material was removed. The stress distribution along the thickness of the clad layers was calculated from the deflection differences before and after each layer was removed. The cladded plate was rigidly clamped in the grinding machine during the layer removal. The curvature was measured after unclamping.

In the clad layer, a three dimensional stress field will be present. Stresses in the cladding (x) direction will be high while the stresses transverse to the cladding direction (y) are expected to be smaller. The stresses in the x -direction

Figure 3: Principle of layer removal technique.

(a)

(b)

Figure 4: Setup for layer removal experiments; a) deflection measurement setup; b) layer removal by surface grinding.

185 are calculated from the spring back of the bar in the z -direction after removal of the clad layer. The stress levels will generally vary with the depth from the top of the clad layer.

A constant moment M over the length of the steel plate is supposed to cause the deflection in the z -direction. The backspring in the z -direction at $L/2$ due to a bending moment M is (Hofman et al. (2007)),

$$D_{ef} = \frac{M(L/2)^2}{2EI}, \quad (1)$$

where I is the moment of inertia of the cross section (bar + clad layer) and E is the Young's modulus. Based on the first order linear mechanics, the inertia of beam and clad layer can be summed up as ($EI = E_c I_c + E_s I_s$, where subscript c refers to clad and s refers to substrate). The moment M can also be expressed

in terms of the stresses in the removed part of the clad layer as,

$$M = d_c A \sigma_{av}, \quad (2)$$

where d_c is the distance from the neutral axis to the centre of the removed layer, A and σ_{av} are the cross-sectional area and the average longitudinal stress of the removed layer respectively.

Hole drilling experiments

The hole drilling technique involves drilling a blind hole around which change in strain is measured using a rosette of strain gauges. Although it is possible to deduce the variation in stress with depth by incrementally deepening the hole, it is difficult to obtain reliable results at depths greater than 0.4 times of the rosette diameter (Schajer (1988)).

Figure 5: Hole drilling, a) schematic drawing of hole drilling setup; b) experimental setup (Van Puymbroeck et al. (2016)).

Hole drilling experiments were performed according to the ASTM standard test method E837 (ASTM International Designation E837-13a (2013)). The schematic drawing and actual setup of hole drilling are shown in Figures 5a and 5b, 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 layer (50-150 μm) on the surface of the clad layer was ground off, to remove unmelted 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 during the hole drilling experiments. Each time the drilling depth was maintained at 40 μm . The strain data was recorded after each drilling step.

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

$$\begin{cases} \sigma_{max} = \frac{\varepsilon_1 + \varepsilon_3}{4A} - \frac{1}{4B} \sqrt{(\varepsilon_3 - \varepsilon_1)^2 + (\varepsilon_3 + \varepsilon_1 - 2\varepsilon_2)^2} \\ \sigma_{min} = \frac{\varepsilon_1 + \varepsilon_3}{4A} + \frac{1}{4B} \sqrt{(\varepsilon_3 - \varepsilon_1)^2 + (\varepsilon_3 + \varepsilon_1 - 2\varepsilon_2)^2} \\ \tan(2\beta) = (\varepsilon_1 - 2\varepsilon_2 + \varepsilon_3)/(\varepsilon_3 - \varepsilon_1), \end{cases} \quad (3)$$

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 direction and σ_{max} direction.

3. Experimental results and discussions

Residual stress acting along and transverse to cladding direction

An example is shown in Figure 6a, where the principal residual stresses and angle β in sample S7-1 (for cladding conditions see Figure 7) are calculated using the strains measured with the hole drilling technique and Equation 3. The principal stress σ_{max} makes an angle of β with respect to cladding direction x . The residual stresses along the cladding direction (σ_x) and transverse to the cladding direction (σ_y) are calculated using the following expression,

$$\sigma_x, \sigma_y = \frac{\sigma_{max} + \sigma_{min}}{2} \left(1 \pm \frac{1}{\sqrt{(1 + (\frac{\tan(2\beta)}{2})^2)}} \right). \quad (4)$$

The σ_x and σ_y measured with layer removal technique by Frenk et al. (1991) showing that the values of σ_y is slightly smaller than σ_x . Only σ_x is considered in all forthcoming figures and discussions as the cracking during laser cladding is often observed transverse to the cladding direction (Zhao et al. (2009)). The transverse cracking indicates that the maximum tensile stress (σ_x) is above the ultimate tensile strength of the clad material on the uniaxial tensile stress state. As the σ_x is higher than the σ_y shown in Figure 6b, the stress level of σ_x will determine cracking. The clad/substrate is a sandwich and cracking most frequently occurs in the clad where the residual stresses are the highest and stresses in the substrate are of less importance.

Comparison of residual stress results from the two measurement techniques

Figure 7 compares the residual stresses σ_x measured with the layer removal and hole drilling techniques. The process parameters and sample code are also listed in Figure 7 below the graph. The residual stresses calculated from the layer removal and hole drilling techniques agree well with each other. The residual stresses are compressive in thin layer of about $300 \mu m$ from the clad surface, which become tensile and increase in magnitude with increasing depth. The

(a)

(b)

Figure 6: a) Principal stresses and angle (sample S7-1) measured with hold drilling technique; b) calculated σ_x and σ_y of sample S7-1.

maximum stress level is reached near the clad/substrate interface. The successive layer removal involves mechanical grinding which can introduce stresses and alter the stress due to cladding process alone. Generally such grinding stresses act over a small depth. The results indicated in figure 7 show a good agreement between the stress measurement results of the two techniques. Similar residual stress distributions of the residual stress after laser cladding were also observed by others (De Oliveira et al. (2006), Hofman (2009) and Bendeich et al. (2006)).

Figure 7: Comparison of residual stresses (σ_x) measured with layer removal and hole drilling techniques.

Effect of preheating on residual stresses

Figure 8a shows the measured residual stresses of the clad samples produced under different preheating conditions. Sample S7-1 (no preheating) showed a maximum residual stress value of 764 MPa. Sample S7-6 (substrate preheated to 473 K) showed a maximum residual stress value of 630 MPa. Sample S7-9 (substrate preheated to 573 K) showed a maximum residual stress value of 518 MPa. In all cases, the maximum residual stresses were lower than the ultimate tensile strength (1265 MPa) provided by the powder manufacturer. No cracks were found in these samples.

Figure 8a also shows that the residual stresses are effectively reduced by an increasing preheating temperature. During laser cladding, thermal stress appears due to localized heating and cooling. Strain variations are caused by the large thermal gradients and differences in cooling rates between the laser processed area and the rest of the materials. Plastic strain occurs when the thermal stress is larger than the yield stresses of both materials, which leads to the development of residual stresses after the materials cool down to room temperature. The amount of plastic strain accumulated will determine the residual stress level. Preheating reduces the thermal gradients and cooling rates (Brückner et al. (2007)), hence the residual stresses are reduced.

Figure 8b shows the hardness profile of the clad layer produced with and without preheating the substrate. About 50 Hv_{0.2} of hardness reduction was observed in the top (second) clad layer. A larger hardness reduction (about 100

(a)

(b)

Figure 8: a) effect of preheating on residual stresses; b) hardness profiles of clad layers produced with preheating.

$Hv_{0.2}$) was observed in the first cladded layer. This may be due to the increase of dilution under preheating conditions. When the substrate is preheated, less laser energy is required to melt the substrate. Increased dilution is expected as the excessive laser power contributes to the increase of the melt depth.

265 *Effect of intermediate layer on residual stresses*

Frenk et al. (1991) reported that there is no beneficial effect of using an

intermediate layer to reduce the residual stress when laser cladding Stellite 6 on martensitic stainless steel. In their work, a continuous wave CO_2 laser with 2 mm spot size was used to clad Stellite 6 on X20Cr13 steel substrate. A cladding speed of 13.3 mm s^{-1} was used and the powder feeding rate was 0.1 g s^{-1} . A lateral displacement of 0.6 mm between the clad track was used, which indicating a 70 % of overlap ratio. Austenitic stainless steel 304 was used as the intermediate layer and was considered that it can act as a thermal barrier for preventing high dilution due to its low conductivity. The residual stress of the clad layers was measured using the layer removal technique. Their experimental results show a high residual stress (around 1000 MPa) close to the interface between the Stellite 6 layer and the substrate. A similar residual stress level (around 1000 MPa) was also found at the interface between the Stellite 6 clad layer and the intermediate layer.

In this research, two different powder materials (Stellite 21 and Inconel 625) were used as an intermediate layer. The residual stresses in clad layers were measured using the layer removal technique which are shown in Figure 9. A clear reduction of residual stresses was observed when laser cladding with an intermediate layer. This contradicts the conclusion of Frenk et al. (1991) that laser cladding with an intermediate layer is not a promising technique to reduce the residual tensile stress in the laser clad layer.

Figure 9: Effect of using an intermediate clad layer on the residual stresses.

The major difference between their work and the present research is in the intermediate layer materials used. The difference in thermal expansion for different materials will introduce different levels of thermal stress during laser cladding. Therefore, the thermal expansion coefficients of Stellite 6, Stellite 21, Inconel 625, AISI 304 and AISI 420 at elevated temperature are compared in Figure 10. The high thermal expansion coefficient of AISI 304 will introduce

high thermal stresses during laser cladding. Thermal stress is considered as the main cause of the residual stress according to Masubuchi (2013) and Song et al. (1999), AISI 304 should not be considered as an intermediate layer to reduce the residual stress in this case. The thermal stress can be minimized by choosing interlayer materials with thermal expansion coefficients similar, or close to the clad and substrate material.

Figure 10: Thermal expansion coefficient of different materials at elevated temperatures (Desai & Ho (1978); Avedesian et al. (1999)).

A hardness reduction in the Stellite 6 layer is observed (Figure 11) when Stellite 21 (290-430 Hv as-cast) is used as an intermediate layer. This may be due to the 2-4 % of nickel present in Stellite 21 which promotes the cobalt to form an FCC structure (Bleil & Derow (1970)). A larger hardness reduction is observed (Figure 11) when nickel based Inconel 625 (200 Hv as-cast) is used as an intermediate layer. This may be due to extensive mixing between Stellite 6 and Inconel 625. Stellite 21 is therefore preferable for use as an intermediate layer to reduce residual stresses. It can be concluded that austenitic stainless steel 304 is not suitable for use as an intermediate layer due to its high thermal expansion coefficient, when cladding Stellite 6 on martensitic stainless steel. A ductile material with a thermal expansion coefficient similar to the clad or substrate is preferable for use as an intermediate layer. Reduced residual stresses during laser cladding can be realized by using an intermediate layer.

Effect of effective energy input on residual stresses

Figure 12 shows the residual stresses of clad layers produced with different effective energy inputs. Sample S3-1 shows the lowest residual stress level. The maximum residual stress measured in sample S3-1 is 289 MPa , which is far smaller than the residual stresses measured in sample S7-1 (764 MPa), sample

Figure 11: Hardness profiles of clad layers produced with different intermediate layers.

S4-1 (982 MPa) and sample S1-2 (1183 MPa). Among all of these samples, sample S3-1 was produced with the highest effective energy input, as shown in Table 3. At a low cladding speed, thermal gradients and cooling rates are expected to be low. Thermal stresses developed are also expected to be low. A low residual stress is therefore observed in sample S3-1. It should be mentioned that sample S3-1 was produced with a single clad layer.

Figure 12: Influence of effective energy input on residual stresses.

Figure 13 shows the hardness profiles of clad layers produced with different

effective energy inputs. Relation between effective energy input (Φ_l) and energy absorbed (E_{ab}) is indicated in equation 5. The absorbed energy (E_{ab}) is formulated by taking into account the process parameters and preheating of the substrate. It follows that,

$$E_{ab} = \left(\frac{P_l}{Dv_c} \gamma_s + \frac{P_l}{Dv_c} \gamma_p \eta_{at} \right) A_{clad} + C_{ps} V_s \rho_s (T_p - T_r), \quad (5)$$

where $\frac{P_l}{Dv_c}$ is the effective energy, which is determined by the laser power (P_l), cladding speed (v_c) and the laser spot size (D), γ_s is the absorption coefficient of the steel substrate, γ_p is the absorption coefficient of the powder material, η_{at} is the percentage of laser power attenuated by the powder, A_{clad} is the area covered by the clad layer, C_{ps} is the specific heat of the substrate, ρ_s is the density of the substrate and V_s is the volume of the substrate, and T_p is the preheating temperature.

From Figures 12 and 13 it may be concluded that when the hardness is not affected by the dilution significantly, a high effective energy input is preferred in laser cladding. Therefore a low cladding speed and higher laser power are advantageous in laser cladding. To obtain high production rates in industrial applications, use of larger laser spot size, high laser power and low cladding speed are suggested.

Figure 13: Hardness profiles of clad layers produced with different energy inputs.

Cooling rate, thermal gradient and absorbed energy during laser cladding

The cooling rates and thermal gradients are schematically shown in Figure 14. The cooling rate ($\Delta T / \Delta t$) at any location refers to temperature (T_{max}) at time (T_{in}) when the laser has just traversed minus room temperature (equal to ΔT) divided by time taken (Δt) to cool down to room temperature. The

thermal gradient is given by the difference between the temperature at the clad surface and the temperature at any location divided by the distance in between (Δz).

Figure 14: Schematic drawing of the cooling rates and thermal gradients during laser cladding.

Temperature distributions in clad layers produced under the conditions listed in Table 3 were simulated using the thermal model reported in our previous publication (Ya et al. (2016)). The clad layers produced with intermediate layers were excluded from the simulation due to the difficulties in simulating the mixed material properties at elevated temperatures. The relationships between cooling rates and thermal gradients were investigated as they are expected to contribute to the development of residual stresses in the clad layer.

Figure 15 shows the simulated cooling rates extracted at the centre of the clad layer at different locations along the depth (z, mm), for different samples. The cooling rates decrease from the top of clad layer to the substrate. The cooling rates in the substrate are much smaller than in the clad layer.

Figure 15a shows the cooling rates in the clad layers produced with and without preheating. The cooling rates in sample S7-1 (no preheating) were higher than the cooling rates in the preheated samples (S7-6 and S7-9). The smooth transition of the cooling rates from the clad layer to substrate in preheated samples indicates that the thermal mismatch between coating material and substrate is reduced. The slower cooling rates in the preheated samples will reduce residual stresses.

Figure 15b shows the cooling rates in the clad layers produced with different total absorbed energy inputs. At corresponding depths, the cooling rates decreased with increasing absorbed energy. Sample S3-1 clad at a slow cladding speed shows the lowest cooling rates. Sample S4-1 clad at a slightly lower absorbed energy than sample S7-1 shows slightly higher cooling rates. Sample S1-2 clad at a high cladding speed (lowest absorbed energy) shows the highest cooling rates.

The cooling rates in sample S3-1 are compared with the cooling rates in preheated samples (S7-6 and S7-9) in Figure 15c. The cooling rates in sample S3-1 are marginally higher than those in the preheated samples which indicates that larger residual stresses may be expected in sample S3-1. In reality, this is not true if we compare the stress distributions shown in figure 12 (for sample

(a)

(b)

(c)

Figure 15: Cooling rates of clad layers from the clad top to the substrate under different process conditions, a) with and without preheating the substrate; b) different processing parameters; c) cooling rates in the clad layers of sample S3-1 and preheated samples (S7-6 and S7-9).

375 S3-1) and in figure 8a (for samples S7-6 and S7-9). This may be attributed to the fact that sample S3-1 had a simple clad layer while samples S7-6 and S7-9 had two layer. The cooling process and its contribution to stress development

are not be compared.

When comparing the cooling rates in the substrate as seen in Figures 15b and 15c, samples (S1-2, S4-1, S7-1 and S3-1) without preheating show higher cooling rates than samples (S7-6 and S7-9) with preheating. Heat from the clad is extracted by the substrate through conduction driven by the temperature difference, which is indicated as cooling rates. With preheating, the temperature difference between clad and bulk of the substrate is less and consequently the cooling rates will also be lower. With preheating, the entire substrate bulk will be at a higher temperature which also aids slower cooling.

Maximum residual stress and absorbed energy

The residual stresses in Stellite 6 clad layers produced under different process conditions (Table 3) were measured and discussed in previous sections. The difference between these process conditions is the energy absorbed (E_{ab} , J) by the materials during laser cladding. Depending on the amount of energy absorbed by the materials, the temperature distributions during the cooling process are different. The cooling rates vary as the energy absorbed by the materials changes. Signes (1972) has pointed out the importance of evaluating the cooling rates with the correct absorbed energy. The plastic strains developed during laser cladding are affected by both the cooling rates and thermal gradients (Steen & Mazumder (2010); Dowden (2009)).

Depending on the maximum residual stress, cracks can appear when the maximum residual stresses developed during laser cladding exceed the ultimate tensile strength of the materials. Figure 16 shows the maximum residual stresses in the clad layers with corresponding absorbed energy. Maximum residual stress levels are observed to decrease when the absorbed energy increases. Increased absorbed energy will increase the cooling time and lower cooling rates are expected (Brückner (2012)).

Sample S3-1 should be excluded (Figure 16) when the changes of maximum residual stress with the increased absorbed energy are analysed. The main difference between sample S3-1 and other samples is in the number of clad layers produced. Sample S3-1 was produced with only one clad layer. The rest of the samples were produced with two clad layers. However, sample S3-1 was presented in Figure 16 to show the residual stress difference in clads with two layers and with one layer. The absorbed energy in the clad layer of sample S3-1 is lower than the absorbed energy in the preheated samples (S7-6 to S7-9). The maximum residual stress in sample S3-1 was expected to be higher than the residual stress in the preheated samples. However, the measured maximum residual stress in the clad layer of sample S3-1 was lower than those in the preheated samples. This has been pointed out earlier.

The cooling rates at the locations where the maximum residual stresses appeared in the clad layers were extracted from FE simulations and are shown in Figure 17 together with stress data of Figure 16. An exponential decay of the cooling rates with increased absorbed energy was found based on data from all the samples. However, sample S4-1 did not follow this trend. This may be due to the fact that the location of the maximum residual stress in sample S4-1 (500

Figure 16: The maximum residual stress levels in the clad layer at different absorbed energy levels.

Figure 17: Cooling rates and the maximum residual stresses as a function of total absorbed energy.

425 μm from the original surface of the substrate) differs from the corresponding locations (between 0 to 300 μm from the original surface of the substrate) in other samples. Both maximum residual stress and the cooling rate show an exponential decay trend with increasing total energy absorbed by the materials.

Figure 18a compares the thermal gradients of the samples produced at different process conditions. The thermal gradients in the preheated samples (S7-6 and S7-9) and non preheated sample S3-1 are lower than in samples (sample S1-2, S4-1 and S7-1) without preheating. Although the cooling rate in sam-

ple S3-1 was slightly higher than in the preheated sample (S7-6 and S7-9, in Figure 15c), the residual stresses are lower due to the lower thermal gradient in sample S3-1 than the thermal gradients in the preheated samples (S7-6 and S7-9, Figure 18a). With the same laser power (1400 W), the clad layers in the preheated samples were produced at a higher cladding speed (15 mms^{-1}) than the clad layer in the sample S3-1 which was produced at lower cladding speed (10 mms^{-1}). Although the thermal gradients in the preheated samples were reduced, they are still higher than the thermal gradients produced in sample S3-1. A high cladding speed increases the thermal gradients in the clad layers, leading to higher residual stresses. This is supported by the experimental results obtained by Hofman (2009) that with increasing cladding speeds, the resulting residual stresses increased.

The thermal gradients at the locations where the maximum residual stresses appeared in the clad layers were also extracted from the simulations and are shown in Figure 18b together with stress data of Figure 16. Also, an exponential decay of the thermal gradients with the increased absorbed energy was found.

Such an exponential decay can be expressed as,

$$y = y_0 + A \exp((-x - x_0)/t), \quad (6)$$

where y is a response to a x variable, x_0 and y_0 are fitting constants, A is an amplitude value and t is a decay factor. The fitting parameters obtained are listed in Table 5. The decay factor (t) of cooling rate and the maximum resid-

Table 5: Exponential fitting parameters of cooling rates, thermal gradients and residual stresses.

Terms	y_0	x_0	A	t
Residual stress (MPa)	522.98	41.28	639.59	19.35 ± 7.97
Cooling rate (Ks^{-1})	30.05	41.28	495.80	24.46 ± 3.04
Thermal gradient (Kmm^{-1})	239.76	41.28	2.137×10^3	14.54 ± 1.20

ual stress are closer to each other. This implies that another empirical relation between cooling rates and the maximum residual stresses can be established within the tested range and materials. For any absorbed energy which depends on the process parameters (equation 6), the cooling rate can be simulated using the numerical thermal model. Empirical correlations between process parameters and the maximum residual stress may be established for the investigated process conditions and materials. Hence it may be possible to calculate the maximum residual stress empirically from cooling rates. In further analyses of the empirical relation between cooling rate and absorbed energy, samples S3-1 and S4-1 are excluded for reasons discussed earlier.

Empirical relations between cooling rates, thermal gradients and maximum residual stresses

Figure 19a shows the relations between cooling rate, thermal gradient and absorbed energy in logarithmic scale. The cooling rate and thermal gradient

(a)

(b)

Figure 18: a) Thermal gradients along the depth of laser clad samples; b) thermal gradients and the maximum residual stresses versus total energy absorbed.

decrease linearly with increasing absorbed energy. The slope of cooling rate fit is very close to the slope of the thermal gradient. This indicates that either cooling rate or thermal gradient can be used to relate with the maximum residual stress. Cooling rate is used in this investigation.

Figure 19b shows the relation between cooling rate, maximum residual stress and absorbed energy in logarithmic scale. Using the linear fit data shown in the

(a)

(b)

Figure 19: a) The cooling rate, thermal gradient and absorbed energy in logarithmic scale; b) the cooling rate, maximum residual stress and the energy absorbed in logarithmic scale.

table of figure 19b, the following expression was obtained,

$$\sigma_{max} = \frac{\Delta T}{\Delta t} \frac{10^{2.46}}{E_{ab}^{1.69}}, \quad (7)$$

which can be used to estimate the maximum residual stress in the clad layer. A value of 2.46 used in the equation is the difference in the intersects of the

linear fits of maximum residual stress and cooling rate. A value of 1.69 used
470 in the equation is the difference between the slopes of the two fits. These values
are expected to be different for different cladding materials. When different
combination of materials are used for laser cladding, experimental or numerical
investigations are required to estimate these values.

Based on the observations discussed in this and previous sections, residual
475 stresses developed during laser cladding can be estimated from either cooling
rate or thermal gradient for different processing conditions. With optimized
thermal gradients, clad layers with low residual stresses can be produced. It is
possible to optimize the thermal gradients by controlling the absorbed energy
through adjusting the laser power and cladding speed.

480 4. Conclusion

Residual stresses were evaluated with layer removal and hole drilling tech-
niques. The residual stresses along cladding direction σ_x are higher than the
residual stresses transverse to cladding direction σ_y . The measured residual
stresses from both techniques agree well with each other.

485 Different residual stress control strategies during laser cladding were investi-
gated. Residual stresses can be reduced during laser cladding by preheating the
substrate or by using an intermediate layer or by adjusting the energy input.
A ductile material with a thermal expansion coefficient similar to the coating
or substrate is preferred for use as an intermediate layer. Among the three
490 strategies, the energy input had the highest influence followed by using an in-
termediate layer and preheating in that order. In all cases, the effect on dilution
and resulting hardness changes should be taken into account before application.

An exponential decay relationship between the maximum residual stress and
absorbed energy was found. Similarly, an exponential decay relationship be-
495 tween the cooling rate and absorbed energy was found. The decay factors be-
tween maximum residual stress and absorbed energy and between the cooling
rate and absorbed energy are close to each other. From these, a correlation
between the maximum residual stress and cooling rate was derived. Such rela-
tionships are valid for the chosen material combinations and process parameters
500 ranges.

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505 References

Abbas, G., & West, D. (1991). Laser surface cladding of stellite and stellite-SiC
composite deposits for enhanced hardness and wear. *Wear*, 143, 353–363.

- ASTM International Designation E837-13a (2013). Standard test method for determining residual stresses by the hole-drilling strain-gauge method, .
- 510 Avedesian, M. M., Baker, H. et al. (1999). *ASM specialty handbook: magnesium and magnesium alloys*. ASM international.
- Bendeich, P., Alam, N., Brandt, M., Carr, D., Short, K., Blevins, R., Curfs, C., Kirstein, O., Atkinson, G., & Holden, T. (2006). Residual stress measurements in laser clad repaired low pressure turbine blades for the power industry. *Materials Science and Engineering: A*, 437, 70–74.
- 515 Benjamin, J. S. (1970). Dispersion strengthened superalloys by mechanical alloying. *Metallurgical transactions*, 1, 2943–2951.
- Bleil, H., & Derow, H. (1970). Elevated temperature instability of stellite 6 B., . USA.
- 520 Brückner, F. (2012). *Modellrechnungen zum Einfluss der Prozessführung beim induktiv unterstützten Laser-Pulver-Auftragschweißen auf die Entstehung von thermischen Spannungen*. Ph.D. thesis Fraunhofer Institute Dresden, Germany.
- Brückner, F., Lepski, D., & Beyer, E. (2007). Modeling the influence of process parameters and additional heat sources on residual stresses in laser cladding. *Journal of Thermal Spray Technology*, 16, 355–373.
- De Hosson, J. T. M., Zhou, X., & Burg, M. v. d. (1993). Structure-property relationship of metal-ceramic interfaces produced by laser processing. *MRS Proceedings*, 319, 21.
- 530 De Oliveira, U., Ocelik, V., & De Hosson, J. T. M. (2006). Residual stress analysis in Co-based laser clad layers by laboratory X-rays and synchrotron diffraction techniques. *Surface and Coatings Technology*, 201, 533–542.
- Desai, P., & Ho, C. (1978). *Thermal linear expansion of nine selected AISI stainless steels*. Technical Report Defense Technical Information Center Document. USA.
- 535 Dowden, J. (2009). *The Theory of Laser Materials Processing: Heat and Mass Transfer in Modern Technology* volume 119. Springer Science & Business Media.
- Frenk, A., Marsden, C., Wagnière, J.-D., Vannes, A., Laracine, M., & Lormand, M. (1991). Influence of an intermediate layer on the residual stress field in a laser clad. *Surface and Coatings Technology*, 45, 435–441.
- 540 Gassmann, R., Nowotny, S., Luft, A., Reitzenstein, W., & Shen, J. (2013). Laser cladding of hard particles rich alloys. *Proceedings of ICALEO '92*, 92, 288–300.

- 545 Hofman, J., Pathiraj, B., & Meijer, J. (2007). Experimental investigation of residual stresses generated during laser cladding. *Proceedings of ICALEO '07*, (pp. 953–960).
- Hofman, J. T. (2009). *Development of an observation and control system for industrial laser cladding*. Ph.D. thesis Enschede. The Netherlands.
- 550 Katayama, S. (2013). *Handbook of laser welding technologies*. Elsevier.
- de Lange, D., Hofman, J., & Meijer, J. (2005). Influence of intensity distribution on the melt pool and clad shape for laser cladding. *Proceedings of the Third International WLT-Conference on Lasers in Manufacturing 2005*, (pp. 323–327).
- 555 Masubuchi, K. (2013). *Analysis of welded structures: Residual stresses, distortion, and their consequences*. Elsevier.
- Mochizuki, M. (2007). Control of welding residual stress for ensuring integrity against fatigue and stress–corrosion cracking. *Nuclear Engineering and Design*, 237, 107–123.
- 560 Roth, M., Hauert, R., Frenk, A., Pierantoni, M., & Blank, E. (1990). Residual stress formation in laser treated surfaces. *Laser/Optoelektronik in der Technik/Laser/Optoelectronics in Engineering*, (pp. 532–537).
- Schajer, G. (1988). Measurement of non uniform residual stresses using the hole drilling method. Part I stress calculation procedures. *Journal of Engineering Materials and Technology*, 110, 338–343.
- 565 Schneider, M. (1998). *Laser cladding with powder, effect of some machining parameters on clad properties*. Ph.D. thesis University of Twente Enschede. The Netherlands.
- Signes, E. (1972). Simplified method for calculating cooling rates in mild and low alloy steel weld metals. *Weld. J.* 51(10), 473–484), .
- 570 Song, W., Zhu, B., Zhang, J., Cui, K., & Zhang, Q. (1999). The effects of expansion coefficient of laser cladding layer on cracking sensitivity. *Journal of Huazhong University of Science and Technology*, 27, 42–44.
- Steen, W., & Mazumder, J. (2010). *Laser Material Processing*. (4th ed.). Springer London.
- 575 Torims, T. (2013). The application of laser cladding to mechanical component repair, renovation and regeneration. *DAAAM International Scientific Book*, .
- 580 Van Acker, K., Vanhoyweghen, D., Persoons, R., & Vangrunderbeek, J. (2005). Influence of tungsten carbide particle size and distribution on the wear resistance of laser clad WC/Ni coatings. *Wear*, 258, 194–202.

- Van Puymbroeck, E., Nagy, W., & De Backer, H. (2016). Use of the hole drilling method to determine residual weld stresses in bridge constructions. In *The first European-Mediterranean Conference in Structural Engineering and Construction (EURO-MED-SEC-1)* (pp. 1–1). 585
- Withers, P., & Bhadeshia, H. (2001a). Residual stress. Part 1—measurement techniques. *Materials science and Technology*, 17, 355–365.
- Withers, P., & Bhadeshia, H. (2001b). Residual stress. Part 2—nature and origins. *Materials Science and Technology*, 17, 366–375.
- 590 Ya, W., Hernandez Sanchez, J., Pathiraj, B., & Huis in 't Veld, A. (2013). A study on attenuation of a Nd:YAG laser power by co-axial and off-axial nozzle powder stream during cladding. *Proceedings of ICALEO '13*, (pp. 453–462).
- Ya, W., Pathiraj, B., & Liu, S. (2016). 2D modelling of clad geometry and resulting thermal cycles during laser cladding. *Journal of Materials Processing Technology*, 230, 217–232. 595
- Zhao, H., Zhang, H., Xu, C., & Yang, X. (2009). Temperature and stress fields of multi-track laser cladding. *Transactions of Nonferrous Metals Society of China*, 19, s495–s501.
- Zhong, M., & Liu, W. (2010). Laser surface cladding: the state of the art and challenges. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, 224, 1041–1060. 600
- Zhou, S., Zeng, X., Hu, Q., & Huang, Y. (2008). Analysis of crack behavior for ni-based wc composite coatings by laser cladding and crack-free realization. *Applied Surface Science*, 255, 1646–1653.
- 605 Zhuang, W. Z., & Halford, G. R. (2001). Investigation of residual stress relaxation under cyclic load. *International Journal of Fatigue*, 23, 31–37.

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