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Effects of Laser Process Parameters on Geometrical Characteristics of Aluminized Inconel738 superalloy by laser cladding

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ABSTRACT
Inconel 738 superalloy was aluminized using laser cladding technique. The objective of the research was to investigate the effect of main process parameters of laser cladding; such as laser power, laser scanning speed and powder feeding rate on geometry of single clad track and find processing window. Height, width and depth of penetration were measured using imageJ software. It was found that the height of the clad track was related to combined parameter as $(P/S)^{2/3}(F/S)^{1/5}$. The width of the clad track was independent of the feed rate. Depth of penetration is impressed by all three main process parameters with $PS^{2/3}F^{-2/3}$. Dilution and wetting angle were calculated and the processing window was obtained for having proper limitations for dilution and wetting angle to achieve a qualified coating and can be used as a guideline for aluminizing of In738 via laser cladding technology.

Keywords: Laser cladding; superalloy; combined parameter; processing window; Dilution

1. INTRODUCTION

Nickel based superalloys are attractive family of alloys being used for turbine blades because of their exceptional combination of high temperature strength, toughness and resistance to degradation in corrosive and oxidizing environments [1]. Superalloys are not able to have both proper bulk properties and corrosion resistance with a certain chemical composition [1]. The bulk has to be chosen to have strength and the surface should have corrosion resistance [2]. Aluminide coatings are widely used for the surface protection of superalloys against corrosion damage since stable protective Al_2O_3 scale will protect the substrate material from aggressive environment surrounded a turbine blade in gas turbines [3]. Usual commercial methods for aluminizing are pack cementation [4, 5], hot dip [6], CVD [7], Slurry [8, 9] etc. In these methods, the whole specimen would expose to thermal gradients which might have negative effect on the other properties of superalloys since

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these alloys are highly susceptible to strength loss exposing to high temperature among the process [10].

Laser cladding is an attractive method for turbine blades because of unique situations of the process [11]. The process contains heat transferring among the laser beam, the powder particles and the substrate as well as mass transferring between the melt pool and the powder flow [12]. Laser cladding process transfer heats in a localized area and as a result, heat inputs are lower than current methods of aluminizing. In Aluminizing, the main challenge is to produce NiAl intermetallic compound because of its potential to operate at temperatures above 1150ºC and producing a protective Al_2O_3 layer [13]. Based on equilibrium phase diagram of the Al-Ni binary alloy [11], for the alloys which the used powder for injection has a low melting point compared with the substrate (Al melting point is 660ºC and melting point of Ni is 1455ºC) the Al powder will melt without any problem. Small amount of Ni increases the melting point sharply because of positive slope of the liquidus-solidus line in equilibrium phase diagram. Compositional deposition of Ni by Al rich melt leads to a homogeneous melt pool [11]. This kind of alloys will be desirable candidate for laser cladding. Two persuasive reasons i.e. tiny heat affected zone and cladability of the selected coating/substrate are persuasive reasons to start a research on this new substrate/coating in laser cladding category.

Wide variety of phenomena will affect the laser cladding process and the process involve lots of interactions and physical features which complicate the investigation of the whole process. One of the acceptable procedure to investigate the characteristics of the laser cladding, is to study the effect of process parameters on the geometry of the single clad track; since dimensional features are the outputs of laser cladding process which relate the clad quality to the clad quantity (other outputs which can be studied are porosity, surface roughness, microstructure, cracks, residual stress and dilution) [11]. Several process parameters are effective on laser clad track geometry. The main process parameters are laser power P (w), scanning speed S (mm/s) and powder feed rate F (mg/s) [14]. Although there are other parameters like spot size, energy distribution, sort of carrier and shielding gas, these three parameters play more important role [15]. The geometrical features are height, width and depth of penetration [14]. Recently, some studies focused on investigating the effect of main process parameters on the properties of clad tracks. Most of them based on the research on the effect of one or more parameters on the microstructure [16], mechanical properties or residual stress [14, 17]. Finite element analysis (FEM) is a method to study laser cladding phenomena, which needs the knowledge about heat transfer features. FEM can predict the thermo physical properties [11]. In most of the investigations, just one process parameter can be studied while the others remain constant. Describing laser cladding process based on physical models are really useful but complicated; so finding processing window which relates process parameters and geometry of the laser clad is still necessary for new coatings. Statistical analysis based on experimental study is a useful method to search all three main process parameters in the same time by finding the combined parameter via mathematical concepts. The resulted combined parameters for the dimensional features lead to a processing window which shows a region of the convenient process parameters for a qualified clad track. Researchers are still working on statistical analysis and finding processing window for different substrate/coatings. Oliviera [15] worked on low carbon steel as a substrate being coated by Ni-Cr powder and found that laser power will not have strong effect on the height of the single clad track and also on wetting angle. Costa et al. [18] worked on laser cladding of stellite6 powder on mild steel substrate and found that laser power is an effective factor on laser height. Kumar [19], El Cheikh et al. [20], Ansari et al. [21] and Barekat et al. [22] are the other researchers who worked on different substrate/coating combinations and found processing window. But still there is the lack of knowledge about the relation between the main process parameters and clad geometry.

The goal of this study is to use laser cladding method for aluminizing of Ni based superalloy substrate. The objective of this research is to relate the quality of the coating to quantified features of a single clad track obtained in different main process parameters. Processing window will be obtained to have limited area based on appropriate dilution and wetting angle.

2. MATERIALS AND METHODS

Inconel738 superalloy was used as substrate material. Chemical composition of the material was listed in Table 1 and was compared by the standard values of Inconel738. The substrate was wire cut into 20×20×2 mm specimens. The surface of the specimen was polished using SiC papers, cleaned ultrasonically in acetone and washed in distilled water.

Powder of pure Al (50-100 µm, 99%, Fluka) was used as the injection powder. Coaxial laser cladding system equipped with a 0.7kW pulsed Nd: YAG laser PIM3475 with the wavelength of 1064nm and a powder feed unit which split a powder into four identical streams was used. A CNC machine which can move in xyz directions, provides the movement of the specimens. Spot size was 1mm and kept constant during the process. Pulse duration was fixed at 3ms and the used frequency was 30 Hz. Argon was used as the shrouding gas for carrying the powder stream and shielding laser beam. The velocity of the gas for shielding the laser beam kept on 20 l/min. The detailed laser main parameters are presented in table 2.

The cross section of the single clad tracks was mounted with SiC paper up to grade 5000, polished and rinsed in distilled water. SEM micrographs were used for measuring geometrical parameters such as clad height – h (mm), clad width - w (mm) and clad depth of penetration – b (mm) using imageJ software. A typical cross section of a clad track is shown in Figure 1. The clad angle θ is the angle between the surface and the cladded area which represent wettability of the surface by the coating. X-ray diffraction (XRD) analysis was performed for phase detection using Philips model PW3710 with anode Cuk_{α} and λ=1.54Å.

Table 1. Chemical composition of Inconel 738 super alloy

element	C	Co	Cr	Mo	W	Nb	Al	Ti	Ni
substrate	0.15	8.4	15.3	1.7	2.8	0.9	3.4	3.4	Bal.
In-738 [13]	0.15-0.2	8-9	15.7-16.3	1.5-2	2.4-2.8	0.6-1.1	3.2-3.7	3.2-3.7	Bal.

Table 2. laser parameters used in this research

Main process parameters	The values were tested
Power (W)	60,85,115,150
Scan rate (mm/s)	1,2,3,4
Feed rate (mg/s)	5,10,15

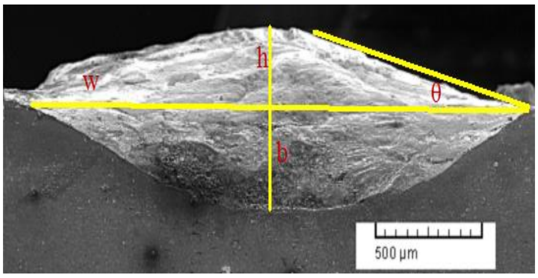

Fig. 1. Geometrical features of a laser clad track.

Two main outputs of laser cladding which explain the quality of the laser clad track are dilution and wetting angle that relate quantified geometrical features to the quality of the clad track [1, 11]. Dilution defined by equation (1), where b is the depth of penetration (mm) and h is the height of the clad track (mm) [14]

$$D\%=\frac{b}{h+b} \quad (1)$$

Another impressive factor, i.e. wetting angle can be calculated assuming the clad track cross section as a segment of a circle according to equation (2) where θ is wetting angle, h and w are height and width of a single track, respectively [23].

$$\theta=180-2\tan^{-1}(2h/w) \quad (2)$$

The main laser parameters; P, V and F have maximum effect on the quality of laser coating process [17–20]. The relationship between the variables is expressed by mathematical pattern which can be linear or non-linear. If the interdependency pattern is put in a linear equation, it is called a linear regression equation. The linear regression to examine the relation between an independent variable X and the dependent variable Y which is the geometrical dimension of the coating. The regression linear equation can be expressed by following equation [19]:

$$Y=aX+b \quad (3)$$

Here the combination of main process parameters; $P^{\propto}F^{\beta}S^{\gamma}$ can be can be assumed to be the independent variable (X). Therefore, the equation 3 can be written by follows [15].

$$X=a(P^{\alpha}F^{\beta}S^{\gamma})+b \quad (4)$$

where a and b are line parameters and can be defined by excel software and MATLAB software was used for defining α, β and γ.

3. RESULTS AND DISCUSSION

In order to obtain a dense and uniform coating with suitable adhesion to the substrate, laser parameters should be selected appropriately. Main laser process parameters are power (w), scan rate (mm/s) and feed rate (mg/s) [24]. Figure 2 shows the single clad tracks micrographs in different main processing parameters. The laser parameters and also geometric dimensions are represented in table 3. The geometric dimensions of the claddings were measured by Image J software. The cross section map can reveal some aspects of the effect of process parameters on laser clad geometry. Increasing in laser power led to more depth of penetration and increasing in F/S value resulted less penetration depth which is visible in micrographs, also the height of the single clad tracks increased with increasing of laser power or F/S value. Showing these results on a graph can be helpful to understand and analyze the relations between geometrical features and process parameters.

According to figure 2, the height, width and depth of the clad track are impressed by three main process parameters (P, F, and S). Higher laser power means higher temperature, so more amount of powder particles will be melted during the process [28, 29], which means the increase in laser clad height. Increasing powder feed rate and decreasing scan rate causes more amount of powder reaching to the surface of the substrate resulting more height of single laser track. Most of the researches were in agreement with the fact that all three main process parameters had important role on the height of a single clad track [14, 18, 20, 30, 31]. For some substrate/coatings laser power did not affect the height of clad track [15, 12, 22]. As it is shown in figure 2, increasing laser power led to higher width due to input level of energy in the central part of the melt pool promotes by higher laser power. It creates a gradient in surface tension (Marangoni effect) that is the result of the higher temperature gradient between the edge and central part of the melt pool [22] and causes extended width of the clad track. Increased speed of the process means less time for interactions between laser beam and the surface of the substrate. As a result the outward shear stress on the surface of the melt pool decreases and thinner width build up during the process [32]. More feed rate causes more amount of powder in the melt pool and more portion of the energy will be absorbed by the injected powder and causes decrease of the width. From another point of view, increase in feed rate means more interaction between powder and the substrate. These two features of feed rate led to negligible effect of feed rate on width of a single clad track. The same result was obtained for different substrate/coatings by Steen et al. [33], De Oliviera et al. [15], Oceliek et al. [12], Ansari et al. [21], and Elcheik et al. [20]. Moreover, the penetration depth decreases by increasing laser power causes more temperature gradient in the melt pool and therefore the amount of the substrate that engages to the interactions increase. By increasing the feed rate, the absorbed energy by the powder increase and the input energy melts the powder instead of the substrate and as a result, the penetration depth decreases. Most researches are in agreement with the obtained results [15, 14, 20, 31, 34].

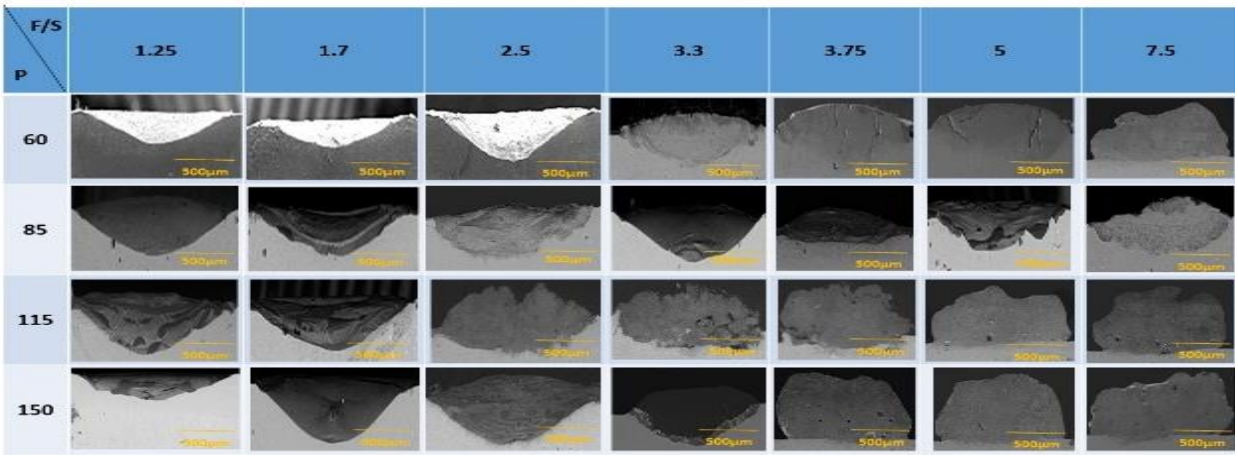

Fig. 2. Cross-sections of single clad in the different samples.

The correlations between the clad height, clad width and clad depth and P, S and F are shown in Figure 3 (a, b and c) and the result is summarized in table 3. Comparing the obtained results with those published in the literature for different coating/substrates systems, the results are in agreement in a way that most of them agreed the dependence of the height to all three main process parameters. In fact, the intensity of these effects are different which refers to difference in thermal phenomena such as heat transfer coefficient, different melting points, thermal conductivity, thermal diffusivity, and etc. [12, 15, 20, 22]. Two main outputs of laser cladding which explain the quality of the laser clad track are dilution and wetting angle that relate quantified geometrical features to the quality of the clad track [11, 21]. Combined parameters of dilution and wetting angle are shown in figure 4. In one hand, the objective is to minimize dilution to have less affected zone and on the other hand, strong metallurgical bond is needed among the coating and the substrate [35]. Acceptable dilution which covers these necessities is between 5 to 10% [19, 21]. This range would be appropriate for single clad tracks. A complete coating derived from overlapping these single tracks that leads to the consumption of a portion of energy by the previous track being established on the surface. So, the range of 15% and 25% would be adequate [36]. Another impressive factor, i.e. wetting angle between 30º and 70º is an accepted range to have an appropriate bead shape and porosity free clad layer [20, 37]. These two factors relate to geometrical features of the single clad track that are calculated before. High regression coefficient confirms the equations. These results are in agreement with the results obtained for NiCrAly coating on Inconel 738 superalloy [21].

Processing window is a graph which shows the limited amount of main process parameters in order to have a high quality (porosity free, low dilution crack free, strong metallurgical bonding). To have three related variables (P, F, S) in a two dimensional graph, approximation should be considered. The axes can be selected based on the results of a selected substrate/coating. In some researches [21] P and F/S were selected as the axes of the graph. In Some processing maps P and S/F have been chosen as the axes [12, 15]. For some substrate/coatings a good quality region has been shown in a graph which relates effective energy density (j/mm^2) with effective powder deposition density [38, 33]. In this research, the processing map was drown in a graph which the power of the laser beam is the vertical axes and F/S (g/m), the amount of powder delivered per length of a single clad track [15] is the horizontal axes. Processing window for laser cladding of Al powder on In738 superalloy substrate is represented in Figure 5 which shows the limitations of processing parameters for having an appropriate coating. The curves are drown in constant values of width (0.8, 1.6, and 2) which are shown with horizontal-dashed lines and for constant values of height (0.05, 0.3, 0.5, 0.7, 1) are shown by dotted curves. Circle dotes show different main process parameters which were tested. Limiting values of dilution and wetting angle made a certain part of the plot for appropriate processing parameters that are shown by the shaded area. This processing window is an aid in the optimization of clad conditions for laser cladding of Al powder on In738 superalloy substrate.

4. CONCLUSION

The main purpose of current research is statistical analysis in laser cladding of Al powder on In738 substrate and find the proper process parameters limit to achieve an acceptable coating. Following results are obtained:

- The height of the clad track is related to all three main process parameters. Increase in power and feed rate, increase the height and more scan rate causes less height of the clad track.
- The feed rate does not effect on the width of the clad track.
- Depth of penetration is impressed by all three main process parameters.
- Dilution and wetting angle are calculated and the processing window was obtained in order to have proper limitations for dilution and wetting angle to achieve a qualified coating and can be used as a guideline for laser cladding of Al powders on In738.

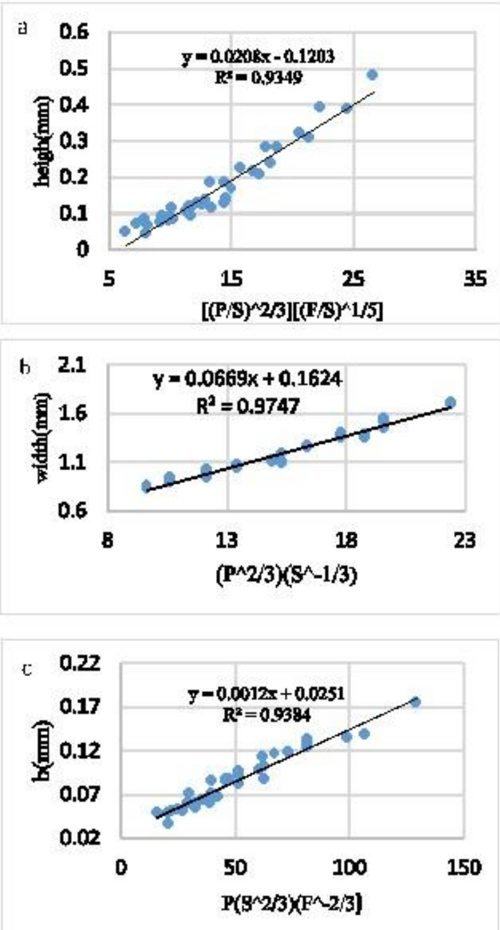

Fig. 3. Combined process parameters for three geometrical features of a) height, b) width and c) penetration depth.

Table 3. Combined parameters for three clad geometries

Clad geometry	Combined parameter	Regression coefficient
Height	$(P/S)^{2/3}(F/S)^{1/5}$	0.93
Width	$P^{2/3}S^{-1/3}$	0.97
Depth of penetration	$PS^{2/3}F^{-2/3}$	0.94

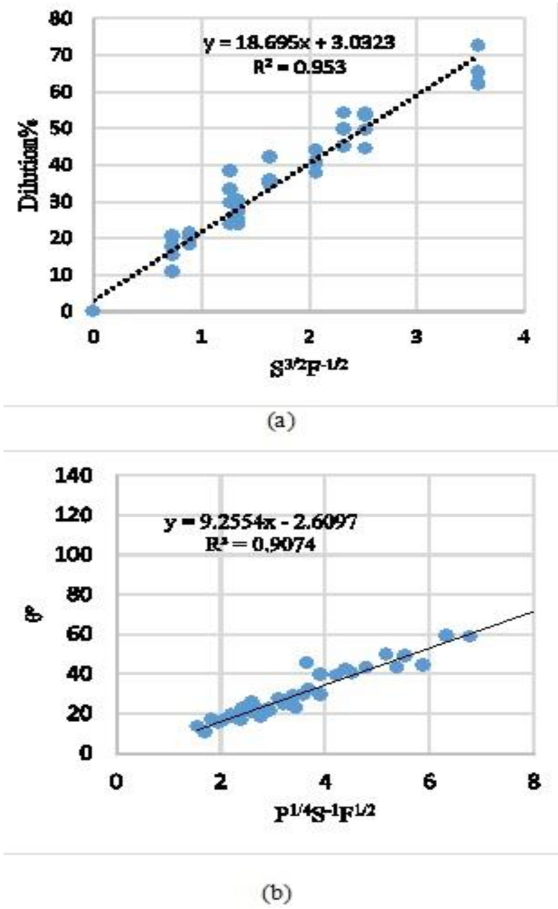

Fig. 4. Combined parameter for a) dilution and b) wetting angle.

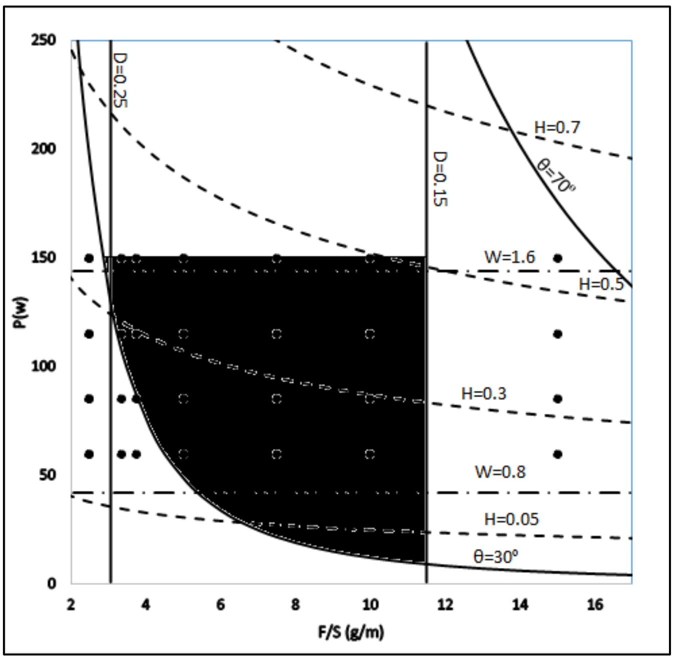

Fig. 5. Processing window for laser cladding of Al powder on In 738.

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مجله شیمی فیزیک و شیمی نظری
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اثر پارامترهای فرآیند لیزر برروی خصوصیات هندسی سوپرآلیاژ پایه نیکل آلومینایز شده به کمک روش روکش‌دهی لیزری

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چکیده

آلومینایزینگ سوپرآلیاژ پایه نیکل اینکونل ۷۳۸ به روش روکش‌دهی لیزری انجام شد. هدف از این تحقیق، بررسی اثر پارامترهای اصلی فرایند نظیر توان لیزر، سرعت روبش و سرعت پاشش پودر بر روی تک‌خط لیزر و تعیین نقشه فرایند می‌باشد. پارامترهای هندسی تک‌خط لیزر یعنی ارتفاع، عرض و عمق نفوذ به کمک نرم‌افزار Image J تعیین شدند. مشخص گردید که ارتفاع خط لیزر با پارامتر ترکیبی $(P/S)^{2/3}(F/S)^{1/5}$ ارتباط خطی دارد. عرض روکش مستقل از سرعت پاشش پودر است. عمق نفوذ پرتو لیزر تحت تاثیر هر سه پارامتر اصلی فرایند به شکل $PS^{2/3}F^{-2/3}$ می‌باشد. نقشه فرایند محاسبه گردید و محدوده مناسب از پارامترهای اصلی فرایند طوری تعیین شد که میزان رقیق‌شدگی و زاویه ترشوندگی میزان قابل قبولی داشته باشند تا پوششی با کیفیت ایجاد گردد. این نقشه فرایند به عنوان راهنمایی برای آلومینایزینگ سوپرآلیاژ پایه نیکل به روش روکش‌دهی لیزری قابل استناد می‌باشد.

کلید واژه‌ها: روکش‌دهی لیزری؛ سوپرآلیاژ پایه نیکل؛ پارامتر ترکیبی؛ نقشه فرایند، رقیق‌شدگی

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