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Effect of feed rate on laser surface cladding of cold rolled carbon steel

Abstract-*Oil and gas industries require much equipment and tools having extra ordinary hardness, strength, wear and chemical properties. They have been established well that the important manufacturing processes to achieve these properties are laser cladding of special alloys on cheap substrates such as carbon steels. In order to achieve the optimum properties for these industries, controllable dilution between substrate and clad coating should obtained. In this study, the performance of laser cladding is found to be controlled by two important outputs geometry dimensions and microstructure. The geometry dimensions include many features of clad width, clad height, cont act angle, depth of penetration and dilution area. In order to determine the quality of clad coatings, these features were correlated with laser processing parameters such as specific energy. An experimental study has been concentrated on determine the all dimensions and dilution area on cladding Ni- 5 wt% Al mixed powder on a cold rolled low carbon steel. Wide ranges of traverse speeds in the range of 1.5 to 12.5 mm/s were used to produce clad coatings with different dilutions from the substrate. The laser power, laser beam diameter and powder feed rate employed were 1.8 kW, 2.5 mm and 10 g/min respectively; the specific energies used were 58 to 480 J/mm^2. Many single or combined features were developed and their values were determined for cladding tracks having different dilutions. It was postulated that the successful cladding process could be described by new developing terms such as effective clad thickness, effective clad dimensions, dilution aspect ratio and effective specific energy. The data obtained could be used effectively to distinguish between cladding and highly alloyed tracks as a function of specific energy and geometry dimensions of the deposit coatings.*

Keywords: *Laser cladding; Laser alloying; Dilution; Effective clad dimensions; Effective specific energy*

How to cite this article: M.A.Ali Bash ,F.F.Sayyid ,A. I. Mohammed ,A.M. Mustafa and A. M. Resen , "Effect of feed rate on laser surface cladding of cold rolled carbon steel ", *Engineering and Technology Journal*, Vol. 35, Part A, No. 9, pp.922 -929, 2017.

1. Introduction

Laser technology has been enjoyed advanced progress since discovering the first solid state ruby laser by Maiman [1]. Laser processing of material such as welding, drilling, cutting and surface engineering increased rapidly due to the important characteristics of laser beams. These are monochromticity, coherency, flexibility and intensity. These surface engineering includes many surfacing and coating processing such as heating, melting, alloying and cladding [2-4]. The laser surface engineering gained much attention and research except laser cladding. There is a relatively less detail investigations regardless the greet offers of many academic institutions [5,6]. Steen, Weerasinghe and others worked hardly at Imperial college and Liverpool university for design laser cladding apparatus and systems and also to outline the cladding principles [7-10]. Also many researchers around the world developed models and mechanisms to understand the cladding process [11-13].

During the last twenty years or so, laser cladding advanced smoothly as an important laser material processing field to achieve coatings in surface engineering [14,15]. Laser cladding using continuous wave CO_2 laser has gained considerably importance in many cost effectiveness industrial applications such as automotive, navy, aerospace and many others [16]. Careful design and precise selection of processing and laser variables should be considered and gained high attentions [17]. These will be reflected on producing control coating with a minimum dilution, repair many advanced system and producing many prototypes [18]. However, laser cladding requires moderate power density (10^2-10^4

https://doi.org/10.30684/etj.35.9A.9
2412-0758/University of Technology-Iraq, Baghdad, Iraq

W/mm^2) and interaction time (0.1-1 s), but it considers as a difficult task to obtain reliable claddings [19]. This is mainly due to produce a minimum dilution with substrate as possible and smooth overlapped [20].

Annually, there are huge numbers of transportation and aerospace components require repair due to wear, corrosion and fatigue. Cladding techniques were employed to solve these failures using many traditional processes such as plasma spraying and welding [21,22]. Many advantages have been reported from these traditional repair techniques such as large deformation, wide heat affected zone and low integrity surface layer arises from high energy sources. On the other hand, laser cladding showed many advantages in this regard to obtain high quality surfacing layer with effective cost [23].

Many studies have been taken place for laser cladding many substrates o repair metal components using laser cladding with metal powders. Laser cladding of medium carbon steel with stainless steel power has been made by Song et al. [24]. They produced clad regions having good metallurgical bonding with the substrate. They consist of Very fine epitaxial dendrite microstructure without defects. High quality metallurgical bindings between substrate and stainless steel have been also observed by Lin et al. [25]. No noticeable increases in hardness were obtained in clad regions compared with the substrate. This work is designed to develop new cladding terms as a function of specific energy to be used effectively to describe the cladding process and distinguish it from laser alloying.

2.Experimental Procedures

A fast axial 2 kW continuous wave CO_2 laser has been operated at 1.8 kW power and 2.5 mm laser beam diameter. Single clad tracks were deposited on cold worked mild steel substrates (0.16% carbon) traversed at different speeds from 1.5 to 12.5 mm/s relative to the laser beam (Table 1). The steel substrates were shot blasted with approximately 200 µm average size particle of silica to enhance the absorptivity and remove the oxide films. In order to increase the absorption of 10.6 µm wave length of laser beam and improve the coupling efficiency between substrate and laser beam, the substrate was swiped with thin film of carbon dag. It is very important in a successful laser cladding employing continuous feeding of powder into the melt pool, design the laser and processing variables very carefully. Preliminary experiments were performed to select the powder feed rate, uniformity of injection and the aligned angle with the substrate (Fig. 1). The best conditions were found and selected to be approximately 14 g/min feed rate and the angle approximately 30^o. The thoroughly premixed 95 wt% Ni and 5 wt% Al powders was fed to the laser melt pool using a 3 mm diameter copper tube with approximately 10 mm distance from the steel substrate. The average particle sizes of Ni and Al are 105 µm and 220 µm respectively. Very low argon gas rate was delivered inside the screw powder feeder to maintain uniform injection of the mixed powder to the laser melt pool.

The single clad tracks processed were cut to produce transverse sections. These sections were hot mounted, ground and then polished with 1 µm diamond paste. All the dimensions including clad width, clad height, contact angle, maximum depth of dilution and dilution area were determined employing calibrated optical microscope, scanning electron microscopy and Image J programme. This paper is concentrated on measuring the clad dimensions in order to correlate them with specific energy. New useful terms based on geometry dimensions and specific energy was developed and found to be effective in describing the laser cladding process.

Table 1: Laser and processing parameters studied.

TEM laser mode	**00**
Raw laser beam diameter, D	20 mm
Focal length, f	125 mm
Shrouding gas, Argon	2.2 SLPM
Laser power, P	1.8 kW
Laser beam diameter, d	2.5 mm
Traverse speed, V	1.5-12.5 mm/s
Interaction time, t	0.2-1.67 s
Power density, P_A ($4P/\pi d^2$)	367 W/mm^2
Specific energy, S (P/dV)	58-480 J/mm^2

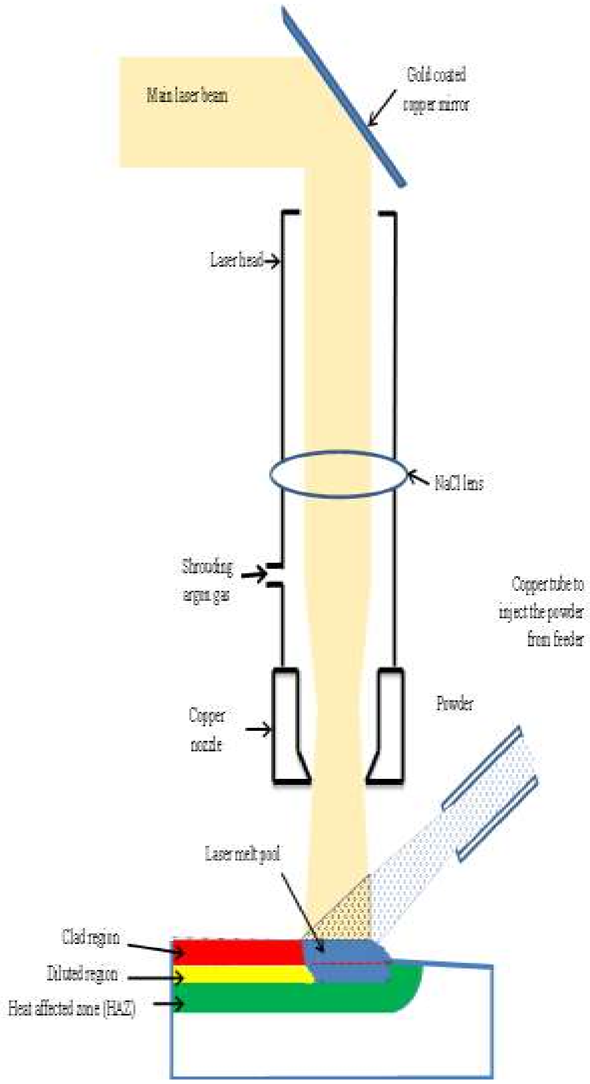

Figure 1: Schematic diagram of laser head and principle of laser cladding showing the different features of clad coating.

3. Results and discussion

Fig. 2 shows the typical transverse sections of laser cladding/alloying of Ni-based on cold worked low carbon steel. This figure shows clearly the general features produced at any cladding laser coatings. It should be noted that these coatings having wide areas of heat affected zones (Fig. 3). Careful examinations of the transverse sections showed the presence of interesting many sub-zones. Optical and SEM micrographs at different magnifications show clearly the sound interfaces between the cladded and heat affected zones (Fig.4). No any cracking was observed at the coatings under all specific energies used. Investigation of upper surface of the coatings revealed the roughness was less than 25 µm.

In order to correlate the clad dimensions with laser dependent or independent parameters, these different dimensions which obtained from upper surface and transverse section should be firstly defined and determined clearly (Table 2). The SEM data obtained from this work may be used to postulate the % dilution. Fig. 5 represents these dimensions and terms critically. These are (i) maximum clad height (h), (ii) clad width (W), (iii) maximum depth of dilution (h_d), (iv) total deposited area, (v) diluted area, (vi) clad area, (vii) depth of heat affected zone, (viii) area of heat affected zone, (ix) contact angle (θ) and (x) penetration angle (β). The relationship between these dimensions and specific energy are shown in Fig. 6. This figure and Table 2 shows clearly, the successful laser clad regions can be obtained with increasing the specific energy to more than 400 J/mm^2. It was capable to produce thick clad height of approximately 500 µm with lower dilution.

It was demonstrated that with dilution area higher than 25% [26], a considerable alloying from the substrate will produced (Fig. 7). At a specific energy higher than 150 J/mm^2, the clad heights are increased considerably. On the other hand, the clad width changed relatively slower than the clad height (2450-2500 µm). All the clad widths were relatively similar to the laser beam diameter (2.5 mm). This may be explained due to the effective laser beam having high power density is sufficient for covering area higher than area of the total laser beam diameter defined by Duley (1/e^2) [27] or Ready (1/e) [28]. It should be mentioned that the relatively small width of clad coating at the highest specific energy used (480 J/mm^2) is considered due to the corresponding higher clad height. This leads to higher total volume of clad region compared with lower specific energy (Fig. 7). The relationship between the depth of dilution (not dilution area) with specific energy shows the minimum values obtained at the lowest specific energies (Fig. 6).

Table 2: Different geometry dimensions of clad region at different specific energies.

No.	V, mm/s	S, s	W, µm	h, µm	d_h, µm	h + d_h, µm	HAZ, µm	h/d_h (H_d)	W/h (A_r)	W/d_h (W_d)	h/W (H_w)	d_h/h (D_h)	h/d_h x W/d_h (W_h)
1	1.5	480	2423	579	111	690	579	5.21	4.18	21.82	0.239	0.192	91.2
2	3.2	225	2655	387	131	518	1006	2.95	6.86	20.26	0.146	0.339	140
3	4.8	150	2525	256	134	390	878	1.91	9.86	18.84	0.101	0.523	185.8
4	6.6	109	2010	146	134	280	642	1.09	13.76	15.00	0.073	0.918	206.4
5	9.1	79	1175	78	70	148	437	1.11	15.06	16.78	0.066	0.897	251.8
6	12.5	58	1110	36	24	60	313	1.5	30.83	46.25	0.033	0.666	1425.9

V: Traverse speed, mm/s; S: Specific energy, J/mm^2; W: Laser cladding width, µm; h: Laser cladding height, µm; d_h: Depth of dilution, µm; h + d_h: Total clad thickness, µm; HAZ: Heat affected zone, µm; (A_r): Aspect ratio; h/d_h: Effective clad thickness; W_h: Effective clad dimensions; W_d: Dilution aspect ratio; S_h: Effective specific energy.

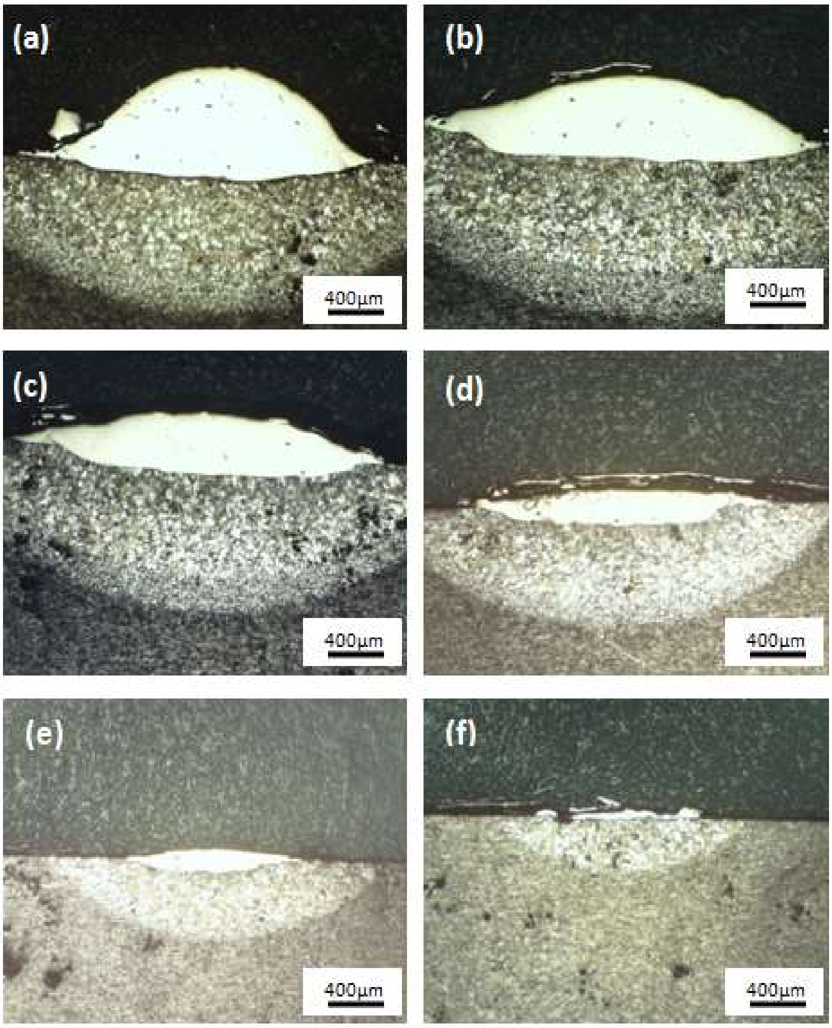

Figure 2: Transverse cross sections of clad coatings showing the variation of the geometry dimensions at different specific energies (J/mm^2) (a) 480, (b) 220, (c) 150, (d) 109, (e) 79 and (f) 58.

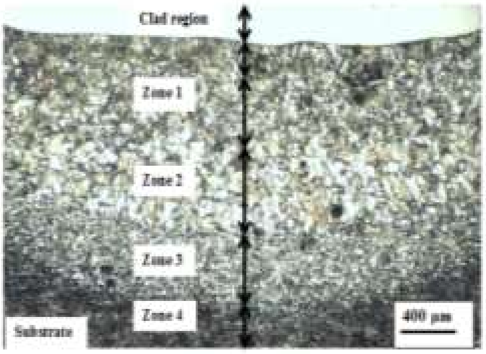

Figure 3: General appearance of clad coating showing the different zones of heat affected zone.

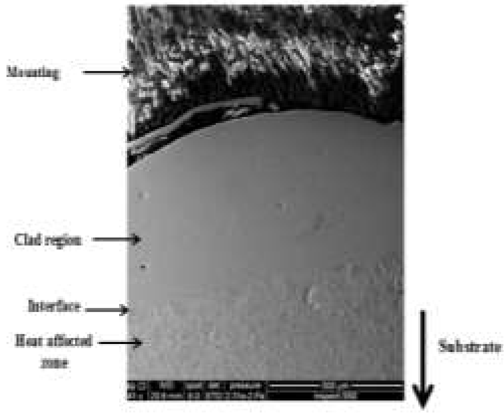

Figure 4: SEM micrograph of transverse section of clad coating showing the sound clad region and sharp interface between clad and HAZ.

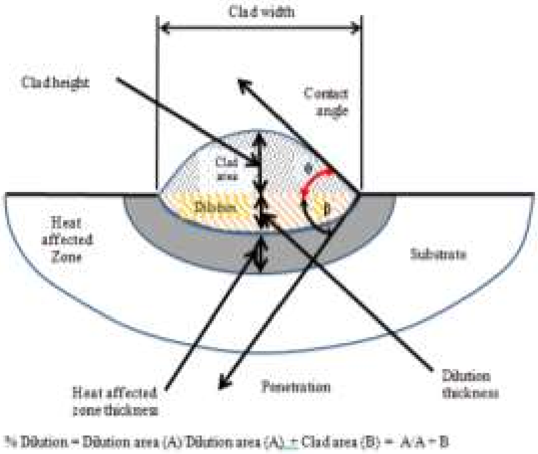

Figure 5: Cross section view of the clad region showing the geometry dimensions and contact angle.

The relatively low depth of dilution at higher specific energies compared with intermediate specific energy is due to the higher clad height at high specific energies. This can be seen clearly for the relationship between clad height + depth of dilution (Fig. 6). At specific energies higher than approximately 60 J/mm^2 and lower than 150 J/mm^2, the dilution depths are high relative to the clad height. These are related directly to the total thickness of the clad coating (clad height + depth of dilution). At specific energies approximately lower than 80 J/mm^2, the clad heights are thins and as well as the depths of dilution are thins. Consequently the depths of dilution/clad height are high (Table 2). At the same time, increasing the specific energies lead to increase both clad height and depth of dilution with different trends. In this cases, the dilution are still high but the depth of dilution/clad height is low (Table 2).

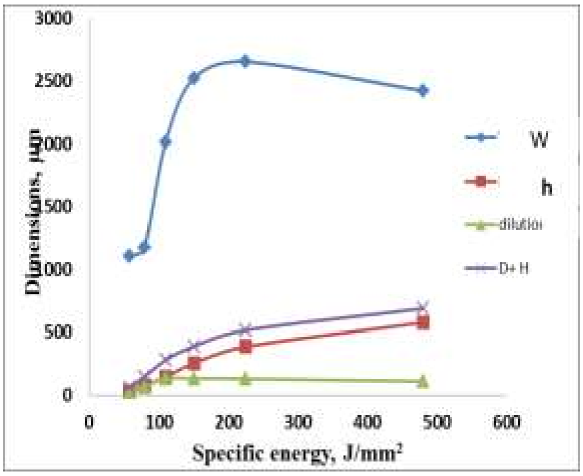

Figure 6: Geometry dimensions of clad width (W), clad height (h), depth of dilution (d_h) and total clad thickness (h + d_h) as a function of specific energy for Ni- 5 wt% powder clad on steel substrate.

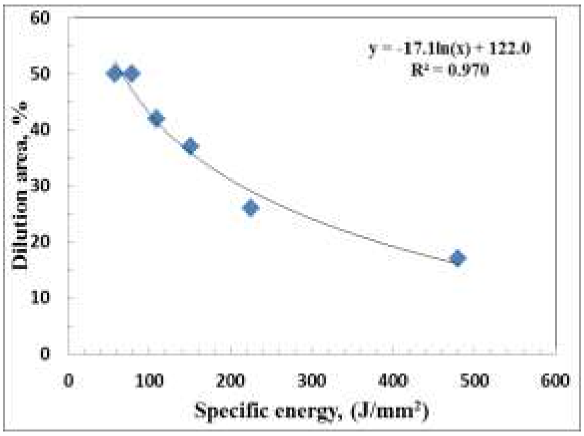

Figure 7: Area dilution% as a function of specific energy showing the high correlation.

The interesting high light point observed is that the suitable conditions for laser cladding when the clad thickness/depth of dilution "effective clad thickness" (h/h_d, H_d), H_d is high in the range of 3-6. They are achieved with good metallurgical bonding with the substrate (HAZ) without any defects (Table 2). These requirements were obtained at specific energy higher than 200 J/mm^2. It was also observed that the corresponding width/depth of dilution "dilution aspect ratio" (W/d_h) (W_d) which represents the suitable conditions for laser cladding can be achieved at relatively critical small window of approximately 20-22. Careful analysis of the clad height/depth of dilution (h/d_h) and clad width/depth of dilution (W/d_h) data revealed that two possible cladding features were obtained dependent on the values of multiply h/d_h x W/d_h "effective clad dimensions" (W_h) (Table 2). At values of approximately 80-150 "effective clad dimensions" successful clad were produced with lower dilution. Increasing the value of W_h to more than 140 produced clads with higher alloying elements from the substrates. It is very interest to observe that this new feature, W_h can be used effectively to describe the border between laser cladding and laser alloying.

It was also found that it is possible to produce an effective clad thickness of approximately 579 µm at 480 J/mm^2 specific energy. Analysis of the different quality of cladded regions showed that there is a critical factor may use for cladding rather than alloying. This is the amount of specific energy per depth of dilution namely S/d_h (S_h), "effective specific energy" (J/mm); it is equal to 0.6 to 0.8. Increasing the value of S_h to higher than 0.9 produces highly diluted regions. It is produced alloying regions rather than cladding regions. This is out the designed goal for laser cladding which requires metallic coating with a minimum dilution from the substrate with high metallurgical bonding. Table 3 demonstrates clearly that in order to obtain successful clad with metallurgical bonding and lower dilution, the values of H_d, W_d, W_h and S_h should be around 3-6, 20-22, 80-150 and 0.6-0.8 respectively. Table 3 lists these new different dependent parameters which developed to be used to describe the successful cladding regions rather than alloying without chemical analysis.

The bonding between clad coatings and substrate as observed from SEM are perfectly good metallurgical bonding under all specific energies used which produced cladded or alloyed regions. No discontinues clad tracks were produced due to absence of high energy enters the melt pool (Fig. 2). A direct relationship between the contact angle and specific energy was maintained. The bonding of the clad coatings was found to be highly correlated with the contact angle (Fig. 8). This is directly related to the flow of cladding alloy as a function of specific energy. The contact angle was increased considerably with increasing the specific energy (corresponding to higher interaction time (d/V with decreasing the traverse speed). This increasing of contact angle is due to highly increasing the solid/liquid component of the clad region. Decreasing the contact angle with reducing specific energy is related directly to the higher ratio between depth of dilution and clad height (Table 2). It should be mentioned that the contact angle has an effect on the penetration angle (angle between the substrate and penetration area). Increasing the contact angle has a consequence effect on reducing the penetration angle. This is due to increasing the adhesion energy. Regardless, the good metallurgical bonding for all specific energies used, different contact angles were formed for laser cladding and to some extent alloying (high dilution). Laser claddings were obtained at contact angles higher than 38^o, at contact angles lower than 22^o, alloying coatings were formed rather than cladding.

Table 3. Values of developed new variables terms derived from this study to describe the successful cladding process.

Parameter	Term	Symbol	unit	Value
Clad height/depth of dilution	Effective clad thickness	H_d	-	3-6
Clad height/dilution x clad width/dilution	Effective clad dimensions	W_h	-	80-140
Clad width/depth of dilution	Dilution aspect ratio	W_d	-	20-22
Specific energy/clad thickness	Effective specific energy	S_h	J/mm	0.6-0.8

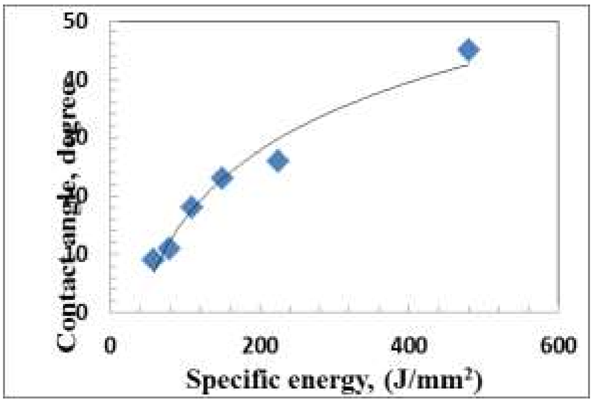

Figure 8: Contact angle of laser clad Ni-5 wt% Al alloy at different specific energies.

Conclusions

1- The dilution of cladding process assessments can be successfully obtained from dimensions of clad region.

2- The efficiency of cladding process with lower dilution from the substrate can be increased with increasing specific energy and using the suitable power feed rate.

3- It is Possible to describe the validity of cladding coatings at different specific energies as function of strong ratios between clad height/depth of dilution, clad height/depth of dilution x clad width/depth of dilution and clad width/depth of dilution. The best values of clad height/depth of dilution, clad height/depth of dilution x clad width/depth of dilution and clad width/depth of dilution to produce minimum dilutions are 6-8, 80-140 and 20-22 respectively.

4- There are critical values for specific energy/clad thickness for successful cladding regions with a minimum dilution within the range of 0.6-0.8 J/mm^2.

5- Many new developed cladding terms namely effective clad thickness, effective clad dimensions, dilution aspect ratio and effective specific energy.

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