Iraqi J. Laser, Part A, Vol. 4, pp. 13- 19 (2005)

IRAQI JOURNAL OF LASER

Microstructural Characterization of Rapidly Solidified Laser Clad Layers Manufactured by Laser Processing of Inconel 617

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(Received 13 March 2005; accepted 12 October 2005)

Abstract: The microstructures of rapidly solidified laser clad layers of laser cladding of Inconel 617 with different nickel-aluminum premixed clad powders are discussed. The effect of different cladding speeds on the microstructures of rapidly solidified laser clad layers is discussed too. The detailed microstructural results showed that different growth mechanisms are produced during rapid solidification. These are planar, cellular, cellular/dendritic and dendritic.

Introduction

Rapid Solidification has attracted much researchers interest in the field of science and technology [1-3]. These interests are related to many benefits as refined segregation, extend the limits of solubility, formation of metastable phase including amorphous phase [4,5]. Laser surface processing that required surface melting and specially laser cladding is the most important rapid solidification process that can be applied by overlay one metal or alloy on another with minimum controlled dilution [6]. The phase selection, growth velocity, chemical composition, long range order and microstructure of a solidifying phase or phases are functions of the local conditions at the solid/liquid interface [7], i.e., the dependent and independent variables of laser cladding process influence these.

Lei et al. [8] found that the microstructure of clad layers of a laser clad TiN composite coating on AISI 1045 steel contains a γ nickel solid solution, TiN particles, and a fine eutectic of γ nickel and $(Fe,Cr)_{23}C_6$ in the interdendritic regions. The bonding zone, which is about 6 μm thick is a γ nickel growing from the bottom of the molten pool with planar crystal morphology. They also found that partial dissolution occurred at the edges of original TiN particulates and their growth was independent of the fine dendrites which were found during resolidification. While Niu and Chang [9] found that the microstructural evolution during laser cladding of gas-atomized M2 tool steel on the mild steel substrate vary from a cellular or dendritic structure of δ ferrite and austenite to a matrix of martensite and retained austenite.

The microstructural features of steel containing 22%Cr, coated with Cr_2O_3 by laser processing were studied by Van den Burg and De Hosson [10]. They pointed out that after laser coating the Cr_2O_3 powder has completely transformed to $Fe_{0.3}Cr_{2.7}O_4$. Dispersed in the coating are metallic particles with composition FeCr and a bcc structure. Addition of Si to the ceramic material, either from the steel matrix or from the ceramic powder, results in a dendritic solidification structure of Cr_3O_4 dendrites and a Si-containing glassy phase. The dendrites are oriented vertically in the coating.

This work aimed to study the chacterization of microstructures of laser cladding of Inconel 617 with different premixed clad powders at different conditions.

Experimental Work

A 2 kW continuous wave CO_2 laser was used in this work. Inconel 617 in the form of plate of thickness 6 mm with chemical composition illustrated in Table 1 was used as a substrate material. Inconel 617 plate that laser would clad has the dimensions of 75 x 40 x 5.5 mm. Before laser cladding took place, the substrate material was shot blasted to increase the roughness and then cleaned with alcohol to remove any foreign materials. The substrate material was mounted horizontally on a hydraulically moved x-y table.

Table 1: Chemical composition of Inconel 617.

Chemical Composition %							
Fe	Cr	Mo	Co	Ti	Si	Al	Ni
1.25	21.7	8.9	12.4	0.45	0.06	0.73	54.1

The table was moved at different cladding speeds of 1, 3.9, 5.3, 10, 13.3, 22 and 35 mm/s and 1.65, 3.2, 4.5, 7.3, 8.1 and 11.2 mm/s for premixed clad powder mixtures of Ni-10%Al and Ni-30%Al respectively. The substrate material that mounted horizontally was located at a certain distance beneath the nozzle determined from the calculated distance of the focal length to obtain spot size of the laser beam of 5 mm. The powder was thrown using copper tube located 15 mm distance from the substrate material with angle of 30° with the substrate. The feeding rate of powder was fixed at 10 g/min for premixed clad powder mixture of Ni-10%Al with constant power of 1.7 kW and 8.9 g/min for premixed clad powder mixture of Ni-30%Al with constant power of 2 kW. The mode structure that used in this work is TEM_{00}.

After laser cladding process took place, transverse sections were taken. Etching was made by swapping the polished specimen surface with etching solution of 50Vol.%HNO_3 and 50Vol.%HCl.

Results and Discussion

The typical transverse clad layers of laser cladded Inconel 617 with Ni-10%Al and Ni-30%Al premixed clad powders are illustrated in Figs.1 and 2 respectively. The microstructure of these clad layers indicates that there are three distinct regions.

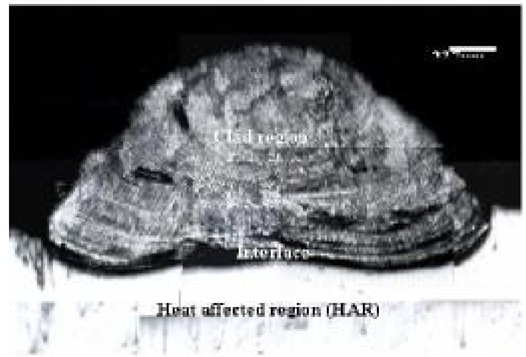

Fig. 1: Macrostructure of clad layer of laser cladded Inconel 617 with Ni-10%Al premixed clad powder at cladding speed of 5.3 mm/s.

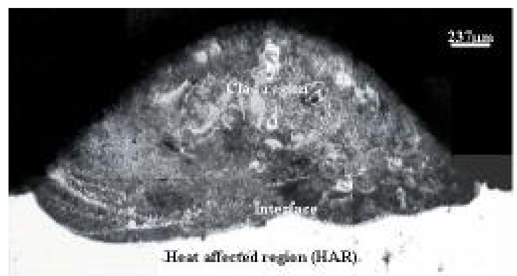

Fig. 2: Macrostructure of clad layer of laser cladded Inconel 617 with Ni-30%Al premixed clad powder at cladding speed of 4.5 mm/s.

These regions are clad region, heat affected region (HAR) and finally heat unaffected region (substrate) which is not appeared in these figures. In clad region, mixing between the clad material and substrate takes place. The evaluation of this region is very important from industrial application point of view. Laser cladding is the process in which low substrate distortion occurred compared to other laser surface melting processes [11]. Therefore, it is very important to study this region. The heat unaffected region do not enter as a substrate alone to clad layer evaluation process but enter into evaluation from the degree of mixing with the clad layer, i.e. dilution percentage. Other regions which are discussed elsewhere [12] and not distinguished by the present work are unmixed region and partially melted region. Unmixed region is defined as the region of substrate that melted but did not mix with the clad layer material. This is because there is no enough time for mixing to take place between clad layer and substrate. While in partially melted region, lower melting point phases melt while the remaining material remains solid.

Fig. 3 shows different microstructures obtained in the clad layer of laser cladded Inconel 617 with Ni-10%Al premixed clad powder at cladding speed of 3.9 mm/s. These changes in microstructure are determined from the change in cooling rate G.R where G is temperature gradient in ºC/m and R is solidification rate (in m/s) along the clad layer. The substrate acts as a heat sink, therefore, the cooling rate will be as high as possible in the clad layer/substrate interface region and decreases as depart from the clad layer/substrate interface to the outer clad surface. From these figures, different types of growth can be observed. The volume fraction of each growth region is different in each clad layer. These growth types are planar, cellular, cellular/dendritic and dendritic.

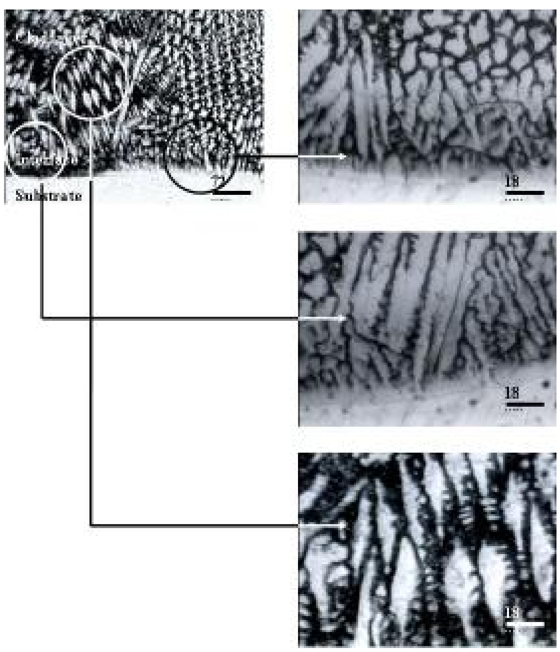

Fig. 3: Microstructure of clad layer/substrate interface region of laser cladded Inconel 617 substrate with Ni-10%Al premixed clad powder at cladding speed of 3.9 mm/s.

Planar growth occurs for alloys only under low growth rate or high temperature gradient [13]. The condition for a stable planar growth may be given by the equation [14]:

$$G/R \geq - m_L C_L^* (1 - \kappa) / \kappa D_{th} \qquad (1)$$

where m_L is slop of the liquidus, C_L^* is liquid concentration in equilibrium with solid concentration (C_s^*) at solid/liquid interface, κ is partition coefficient (C_s^*/C_L^*), and D_{th} is thermal diffusivity in the liquid (m^2/s). Therefore, G/R is a very important parameter that determines the morphology of solidification and hence the occurrence of planar growth. As a result of this, G/R gives the limit of absolute stability (around 1 m/s solidification rate R) after which the structure solidified in a diffusionless manner, i.e., planar growth [15].

Cellular/dendritic growth can be distinguished from cellular growth as a result of the length of the cell which is much larger than the cell spacing. Furthermore, the cell tip is sharp as in the dendrite tip. In the region below cellular/dendritic growth, dendritic growth is built up. As shown in Fig.3, the dendrites that present are primary with initial growth of secondary dendrites but the main growth type is primary dendrites. Secondary dendrites form because the approximately paraboloidal interface of the dendrite tip becomes unstable. The driving force for the instability is constitutional supercooling in the liquid just back from the dendrite tips [16].

The dendrites formation is related to rapid cooling rate that occurred due to the substrate that acts as a heat sink but this rapid cooling rate is lower than that for cellular growth. While the highest cooling rate is needed for planar growth. The breakdown of planar interface into cellular or dendritic structure depends on the region of constitutional supercooling ahead of planar interface. If the region of constitutional supercooling is large as a result of low solidification rate, a dendritic growth is dominant. On the other hand, if the supercooled layer is thin, the growth of fully developed dendrites is not possible because of the limited depth of the supercooled layer into which they can grow. In this case, the instability of interface may result in the formation of cellular structure in which the cell walls are defined as a region of high solute concentration. The mechanism of dendritic growth is related to the formed nucleus at the planar interface which has a number of equivalent crystallographic directions along which crystal growth may occur. A considerable amount of latent heat is evolved in the direction of crystal growth, causing the temperature of the adjacent liquid to rise. This temperature may exceed the freezing temperature of the alloy, so that further growth of the crystal in this direction will be stopped.

In a perpendicular direction, the liquid region will have a lower temperature, since there has been no crystallization and consequently no heat evolution. Therefore the crystal will grow in the new direction until heat is dissipated from the initial region of crystal growth. When the temperature of this region drops to a sufficient value below freezing point, the crystal will assume its original direction of growth until reaches other point, where again the temperature will rise and further growth of the crystal will stop. Then again growth of the crystals occurs in a direction perpendicular to the original direction of growth. This sequence of processes leads finally to the structure characteristic of dendrites [17].

In Fig. 4, cellular growth with elongated cells before it converted to regular cells can be seen clearly after planar growth region.

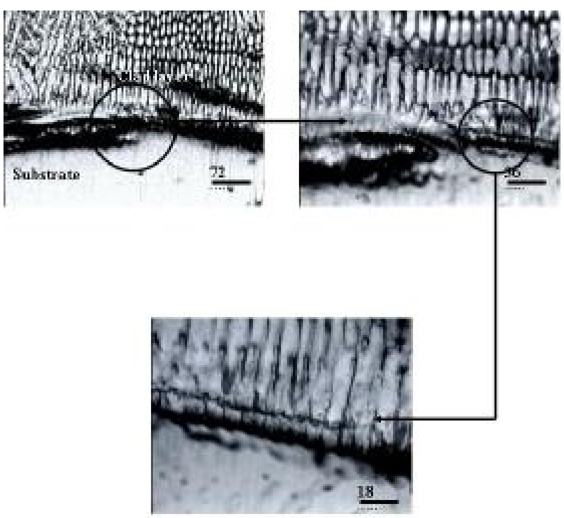

Fig. 4: Microstructure of clad layer/substrate interface region of laser cladded Inconel 617 substrate with Ni-10%Al premixed clad powder at cladding speed of 5.3 mm/s.

The size of cells varies from region to other region as a result of changes in cooling rate along the clad layer. The elongated cells gradually segment as G/R is increased, also becoming finally regular cells. Since regular cells are obtained at high G/R regardless of orientation, they are primarily a result of solute diffusion [16]. In the central region of clad layer (Fig. 5) mixed growth of cellular and dendritic can be observed. The dendrites that recognized in the central region of clad layer accompany with initial stage of secondary dendrites formation.

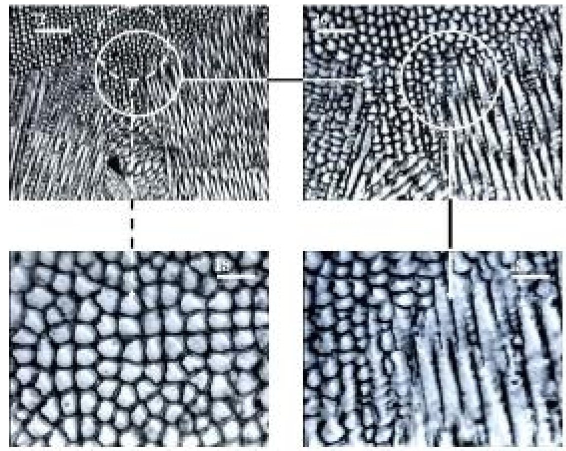

Fig. 5: Microstructure of clad layer central region of laser cladded Inconel 617 substrate with Ni-10%Al premixed clad powder at cladding speed of 5.3 mm/s.

While cellular growth can be shown only in the region near the outer clad surface but with different morphology and size (Fig. 6).

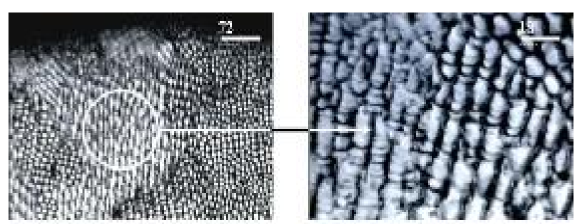

Fig. 6: Microstructure of near external surface of clad layer of laser cladded Inconel 617 substrate with Ni-10%Al premixed clad powder at cladding speed of 5.3 mm/s.

The same observations that related to growth morphology can be shown clearly in Fig. 7 in which planar growth is the dominant mechanism of growth in the clad layer/substrate] interface followed by cellular and dendritic growth.

In the central region of clad layer, the two mechanisms of solidification, cellular and dendritic, remain the same. While cellular growth mainly takes place in the region near the outer clad surface.

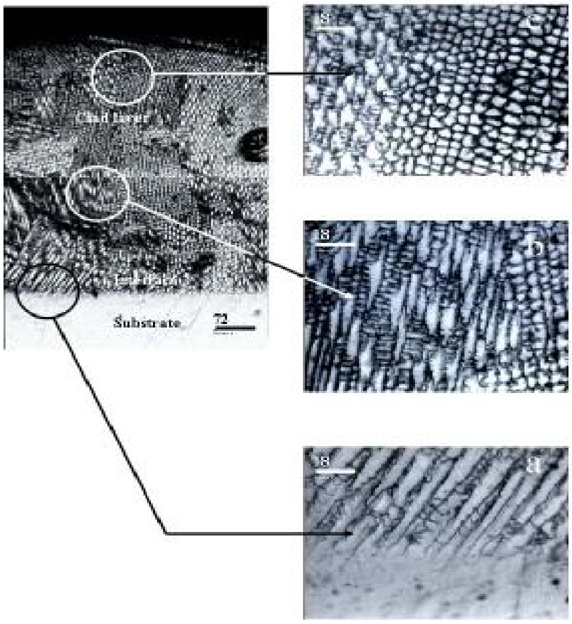

Fig. 7: Microstructure of laser cladded Inconel 617 substrate with Ni-10%Al premixed clad powder at cladding speed of 13.3 mm/s, (a) clad layer/substrate interface region, (b) central region of clad layer, (c) near external surface of clad layer.

The microstructure of clad layers of laser cladded Inconel 617 with Ni-30%Al premixed clad powder (Figs. 8-10) do not differ highly compared with the microstructure of clad layers of Ni-10%Al premixed clad powder. A distinct features that do not exist in previous Ni-10%Al clad layers figures are the different stages of growth that exist in the clad layers especially in Figs. 8 and 9. In Fig. 8, elongated cellular structure with different growth direction is developed but with supersaturated solid solution.

The rejected solute from the solid solution concentrates along the elongated cellular structure boundaries. The second region is the formation of precipitated solid solution with distinct particles of Ni_3Al in the matrix of solid solution [18]. After this, large particles of Ni_3Al exist in the clad layers which act as a transition region between precipitated solid solution and dendritic growth region.

It is obvious that planar growth could not occur in the clad layer/substrate interface region as the first stage of solidification instead of elongated cellular structure or any other type of growth as recognized in the clad layers of premixed clad powder of Ni-10%Al.

This can be explained on the basis that the planar region is developed but because the constituents of solid solution greater than its ability to accommodate them, therefore, the excess of solute rejects and precipitates in similar manner to second phase particles along cell boundaries. It is clear from the comparison of this region or any other region near the clad layer/substrate interface that mixing between molten of the clad layer and the substrate, i.e., dilution percentage, plays a dominant role in producing these distinct morphology of microstructures in the regions of interface and near interface. It can be observed that cells of supersaturated solid solution have been taken place in the clad layer of 3.2 mm/s cladding speed as the first stage of solidification (Fig. 9).

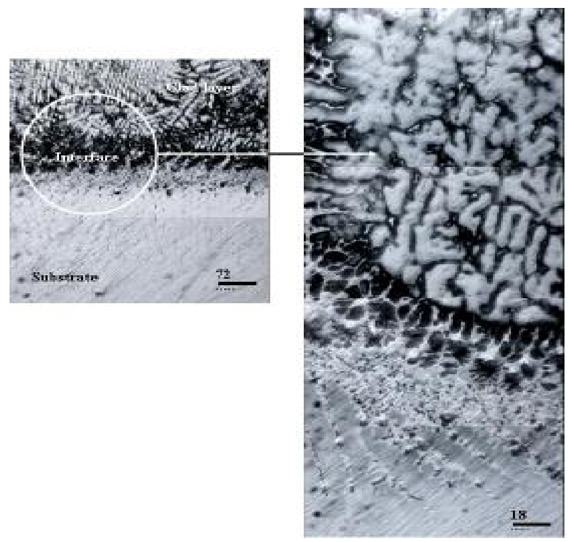

Fig. 8: Microstructure of clad layer/substrate interface region of laser cladded Inconel 617 substrate with Ni-30%Al premixed clad powder at cladding speed of 1.65 mm/s.

The rejected solute can be recognized around the cell boundaries which form Ni_3Al intermetallic compound [18]. Dendritic growth is the dominant mechanism of growth in the region that followed supersaturated cells but the size of dendrites is differ from region to other region.

In Fig. 10 large region of elongated cellular structure can be recognized with excess of solute that rejected along its boundaries as compared with other clad layers. In this clad layer, primary and primary with secondary dendrites can be seen clearly.

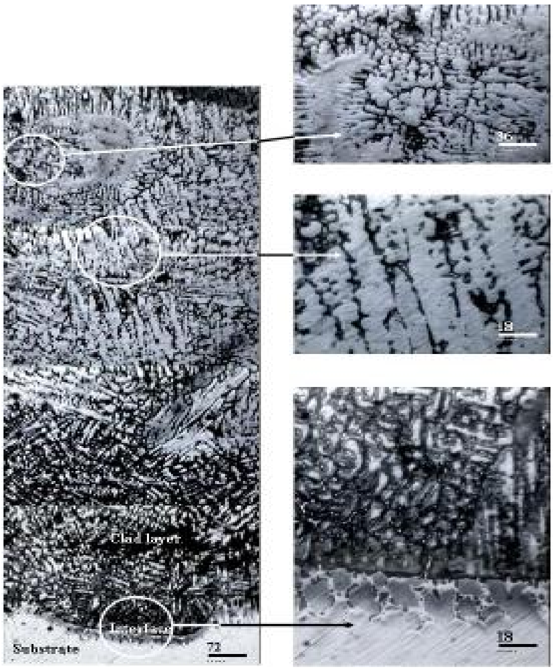

Fig. 9: Microstructure of clad layer/substrate interface region and clad layer central region of laser cladded Inconel 617 substrate with Ni-30%Al premixed clad powder at cladding speed of 3.2 mm/s.

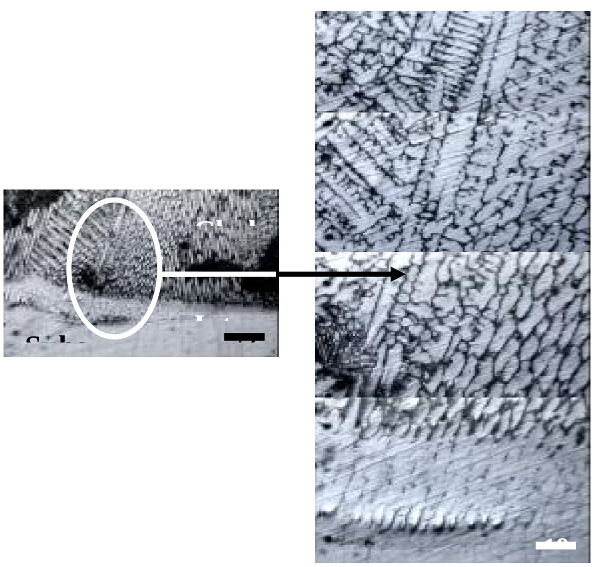

Fig. 10: Microstructure of clad layer/substrate interface region of laser cladded Inconel 617 with Ni-30%Al premixed clad powder at cladding speed of 11.2 mm/s.

The increase of solute that rejected along dendrite boundaries as compared with elongated cellular structure is clearly observed. This can be related to the decrease in cooling rate which permits excess of solute to be rejected and then precipitate.

Fig. 11 Microstructure of some microstructural segregation that developed in some positions of clad layer central region of laser cladded Inconel 617 substrate with Ni-30%Al premixed clad powder at cladding speed of 7.3 mm/s.

Some segregation in the chemical composition can lead to produce featureless microstructures as recognized in Fig. 11. This may be related to segregation in the premixed clad powder between aluminum and nickel. This segregation reflects the segregation in chemical composition compared with the chemical composition of other regions and therefore reflect its effect on cooling rate.

Conclusion

Laser cladding of Inconel 617 under the effect of rapid solidification can produce different regions. These are clad, heat affected and heat unaffected regions. Different microstructures are obtained depending on the selected premixed clad powder mixture and laser cladding independent variables. These microstructures are characterized with growth mechanism. These growth mechanisms are planar, cellular, cellular/dendritic and dendritic in which the mechanism of each growth is different compared with other.

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دراسة التركيب المجهري لطبقات الاكساء بالليزر تحت تاثير التجمد السريع المصنعة باستخدام المعاملة بالليزر لسبيكة Inconel 617

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الخلاصة

تمت في هذا البحث دراسة التركيب المجهري لطبقات الاكساء بالليزر الناتجة بفعل عملية التجمد السريع وذلك باستخدام مساحيق مسبقة الخلط بتراكيز مختلفة من النيكل-المنيوم وتحت تاثير سرع اكساء مختلفة. اوضحت نتائج دراسة التركيب المجهري حصول العديد من اليات النمو اثناء عملية التجمد السريع والتي تتمثل بالنمو المستوي، الخلوي، الخلوي/الشجيري والشجيري.