Laser Surface Alloying of Nickel and Chromium (III) Electroplated Carbon Steel with Nd: YAG Laser

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ABSTRACT

Laser surface alloying is one of the post treatment techniques developed to enhance the surface properties of electroplated steels. In this investigation, AISI 1020 carbon steel was selected as the base material. The base material was electrodeposited by nickel followed by trivalent chromium. The thickness of the Ni and Cr layers were approximately 30μm each. The surface of the chromium (III) was melted using 2kW Nd: YAG laser. The laser surface alloying was carried out at different energy densities by keeping laser power at 500W and 650W, at different scanning speeds i.e. 2, 1.5, 1, 0.75, 0.5 m/min and at two different optics arrangements. The energy density was varied from $12x10^6$ J/m^2 to $61x10^6$ J/m^2. The laser surface alloyed samples were examined by Optical Microcopy, Vickers Microhardness tester and Energy Dispersive spectroscopy. It was observed that the laser melted depths varied from 200-800μm based on the energy density.

Keywords: AISI 1020 carbon steel, Nickel, Chromium (III), Electroplating and Laser surface alloying.

1. INTRODUCTION

Electroplating is the most common economic processes for applying metallic coatings of thicknesses between approximately 10 to 500μm on many engineering components. This is primarily because their rates of deposition can provide the required quality in acceptable process times at relatively low capital and operating costs.

Electroplated chromium coatings have been extensively used on engineering parts such as piston rings, work rolls, aircraft landing gear and barrels of gun etc. due to their high hardness, high melting point, tarnish resistance and low coefficient of friction /1-4/.

Under normal conditions, chromium electroplating has a dense, hard oxide layer on a surface, which is responsible for its low coefficient of friction /5/ and good corrosion resistance. The high hardness of the chromium coating gives good support to the oxide "skin', and thus a high resistance to rupture of the surface which would increase the tendency of adhesion. However, under the severe service conditions such as high temperature, gas erosion and severe stressing, damage is easily caused at the substrate/chromium interface /6-9/.

Although chromium plating can result in a hardness of about 800-1000HV at room temperature, they suffer from poor hot- hardness. Also the room temperature

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hardness is drastically reduced after elevated temperature exposure even for short durations /10/.

An important characteristic of chromium electroplating is the high tensile stress, which increases as thickness increases and is relieved by a local micro cracking during electroplating /4, 11,12/. It has been reported that the wear and corrosion resistances of electroplated chromium coatings are associated with their hardness and cracks /9, 13-15/. Coatings with multiple layers have larger resistance to cracks propagation than those with single layer. It has been reported that, coatings with Ni-interlayer exhibited better corrosion and wear resistance combined with toughness /16/. It has been reported that Cr (III) coatings are more promising than Cr (VI) coatings due to environmental and commercial aspects /17/.

In order to improve the damage-resistance of the chromium coating/coating interface/surface, various post surface treatments have been developed and studied by various authors. Thermo-chemical surface treatments /3,6,18-22/ of chromium plated steel by means of carbon or nitrogen or oxygen or boron carrying gases or their combinations are well known processes, called case-hardening processes. The as-plated steel is exposed to carbon or nitrogen or oxygen or boron carrying gases or their combinations at an elevated temperature for a period of time, whereby the gas decomposes and the atoms diffuse through the chromium electroplated steel surface. The conventional thermo-chemical surface treatments have some limitations such as longer treatment time, higher distortion. To overcome the shortcomings plasma assisted processes were developed. Plasma assisted thermo-chemical surface treatments which involves diffusion of atoms into the metal surface in the presence of a plasma environment /23/. Ion implantation /24-27/ is another type of post treatment developed to enhance the surface properties of chromium electroplating. Ion implantation is a material engineering process by which ions of a material can be implanted into another solid, thereby changing the physical and other properties of the solid. Ion implantation is a physical process in which carbon/nitrogen/oxygen/boron ions are physically driven into the metal and made to remain in the lattice as discrete atoms. It is a newer process which shows a great promise. The equipment is expensive, techniques are not fully developed, and there is a need for highly skilled, technically trained operators. With wider usage of this process is expected to become more economical.

Laser surface alloying /28-32/ is another type of post treatment developed to enhance the surface properties of chromium electroplating. It is an emerging field, wherein lasers are used for imparting superior surface properties on engineering components. When a laser beam strikes a specimen surface (1) it is absorbed (2) or transmitted (3) or reflected. The absorbed photons are converted to thermal energy resulting in local temperature surge to a depth of few tens of microns depending on the wave length, fluence and average power. Application of lasers in materials processing provide many advantages over conventional methods in terms of increased manufacturing efficiency, decrease in manufacturing costs, ease of automation, superior quality, reliability of the products and enables one to design and develop new products. In laser surface melting, the coating surface to be melted is shrouded by an inert gas. The coating is melted using laser without adding any alloying elements. The elements in the coating diffuse rapidly into the melt pool, and the desired depth of alloying can be obtained in a short period of time. By this means, a desired alloy chemistry and microstructure can be generated on the surface. The degree of microstructural refinement depends on the solidification rate. Using this processes one can obtain fine homogeneous structure due to the rapid solidification rates, little thermal penetration, resulting in little distortion, smooth surfaces, reducing work after processing, process flexibility due to software control and high possibilities for automation.

The objective of the present study is to investigate the effect of energy density produced by an Nd: YAG laser beam on Ni and Cr electroplated AISI 1020 carbon steel in terms of (i) optical microstructure (ii) the microhardness variation along the depth of the coatings and (iii) surface chemical composition.

2. EXPERIMENTAL

The base material was selected as carbon steel (AISI 1020) of dimensions 0.02 m x 0.02 m x 0.005 m (20mm x20mm x 5mm). The chemical composition of the base material (mass %) is C-0.243%, Cr-0.018%, Ni-0.0416%, Mn-1.00%, Al-0.00810%, B-0.0030%, Mo-0.019%, Fe-98.6%.The microhardness of the base material is 175HV at 100g load.

Before electro deposition, the base material was mechanically polished, and then chemically cleaned to remove the contamination. Nickel was electrodeposited on the surface of the base material (30µm) using nickel sulphate bath containing nickel metal (70g/*l*), nickel chloride (60g/*l*), boric acid (40g/*l*), nickel sulphate (200g/*l*). Subsequently chromium (III) was electroplated using bath containing 0.5M/*l* of $CrCl_3.6H_2O$, 0.8M/*l* of HCOOH, 1.0M/*l* NH_4Cl, 1.0M/*l* of KCl, 0/65M/*l* of H_3BO_3, 10g/*l* of NH_4Br and additives at 303 K(30°C) and a current density of $20x10^2$ A/m^2 ($20A/dm^2$) . The microhardness of the chromium (III) plated surface was 875 HV at 100g load. The surface of the chromium (III) layer was melted using 2kW Nd: YAG laser. The laser beam spot diameter was set at $1.5x10^{-3}$ m (1.5mm) for focused beam and $1.62x10^{-3}$m (1.62mm) for defocused beam. The focal length of the beam was 0.3 m (300mm). The laser surface alloying was carried out at different energy densities by keeping laser power at 500W and 650W at different scanning speeds i.e. 2, 1.5, 1, 0.75, 0.5 m/min and at two different optics arrangements.

The experimental apparatus of laser alloying system used in this work is given in **Figure 1** and typical surface modified examples are shown in **Figure 2**.

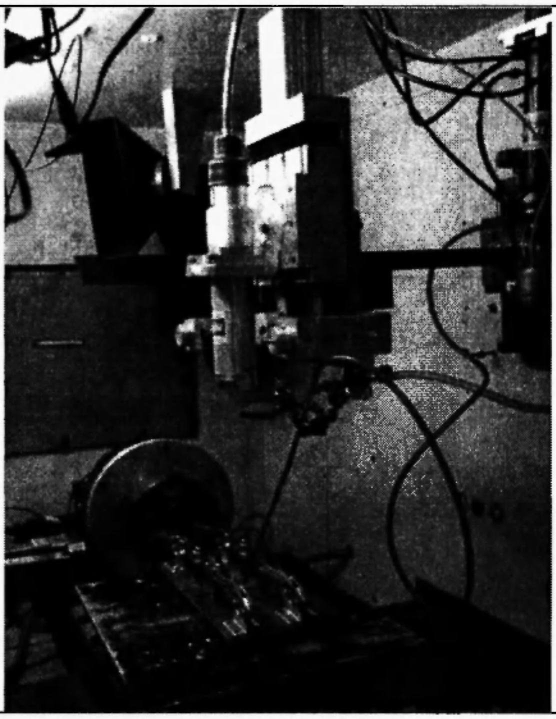

Fig. 1: Schematic representation of laser surface alloying system

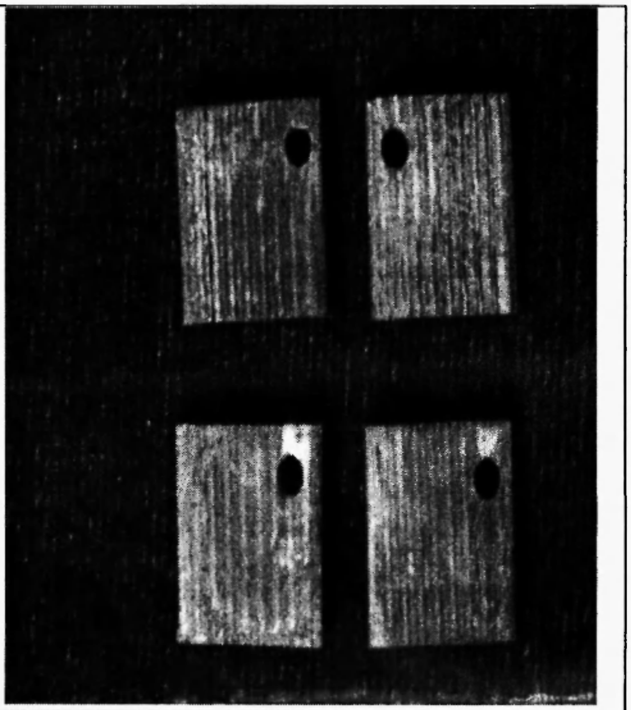

Fig. 2: Laser surface alloyed samples

An inert gas shield was used to minimize oxidation of the sample. Argon gas at 25 *l* min^{-1} was supplied into the shield. Vickers microhardness measurements were made as a function of alloyed layer depth. Energy dispersive spectroscopy was used to find out mass %. Optical microscopy was used to examine the alloyed zone structure.

Laser surface alloying parameters for various samples are given in the following **Table 1**

Table 1

Laser surface alloying parameters:

Sample No	Trial No	Coating thickness (µm)	Laser processing conditions				Melted depth (µm)
			Power (W)	Speed (m/min)	Nature of beam	Energy Densityx 10^6 (J/m^2)	
A2	1	63	500	2	Defocused	12	202
A3	2	67	500	1.5	Defocused	16	225
A10	3	60	500	1	Focused	25	295
A20 (H)	4	65	500	0.75	Defocused	31	364
A20	5	65	500	0.75	Focused	34	412
A14	6	62	500	0.5	Defocused	47	572
A7	7	65	500	0.5	Focused	51	618
A15	8	64	650	0.5	Defocused	61	864

The energy density developed by the laser beam is given by the following equation: /28/

Energy density (J/m^2) = power density x Interaction time

3. RESULTS AND DISCUSSIONS

3.1 Optical Microstructural observations:

Fig. 3: Optical microstructure at energy density = 12x10^6 J/m^2

Fig. 4: Optical microstructure at energy density = 16 x 10^{6} J/m^2

Laser surface alloying was not observed below 16x10^6 J/m^2 (**Figures 3 and 4**). In this case, coatings were partially disturbed and the surface modification was observed in the base material. The coatings were partialy disturbed, this may be due to energy density generated by the laser beam was not sufficient to melt the Ni & Cr coatings. The microstructure of the base material was modified due to heat conduction. The ferrite and pearlite microstructure of carbon steel may be transformed in to amorphous microstructure in the modified zone. The laser melted depth was around 200 µm. At 25 x10^6 J/m^2 to 34 x10^6 J/m^2 energy

Fig. 5: Optical microstructure at energy density = 25x 10^6 J/m^2

Fig. 6: Optical microstructure at energy density = $34x10^6$ J/m^2

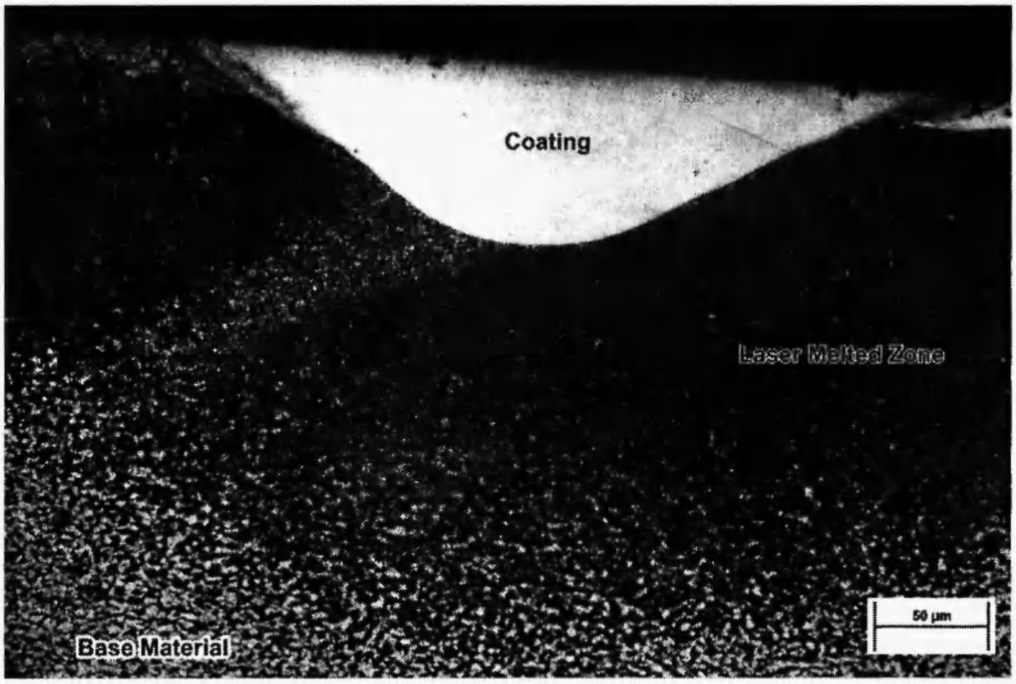

Fig. 7: Optical microstructure at energy density = $47x10^6$ J/m^2

Fig. 8: Optical microstructure of coating interface at energy density = 47×10^6 W/ m^2

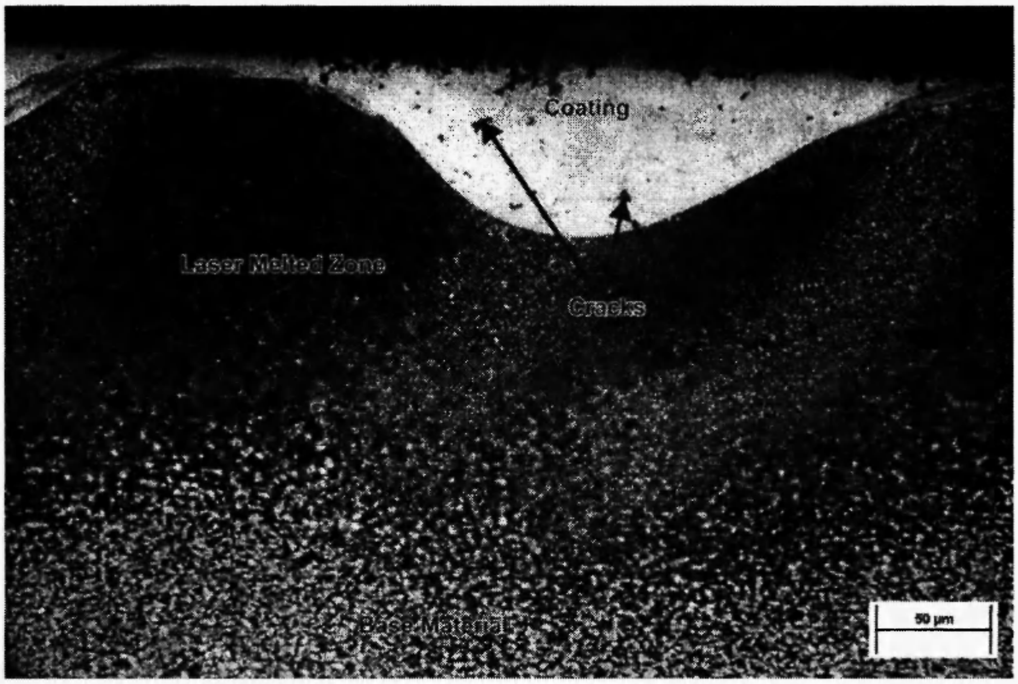

Fig. 9: Optical microstructure at energy density = 51×10^6 W/ m^2

Fig. 10: Optical microstructure at energy density = $61\text{x}10^6$ W/ m^2

density, the laser surface alloying was not observed (**Figures 5 and 6**). But the surface layer was disturbed by the laser beam and part of the coating material evaporated. The laser melted depth was around 290-350 µm alloying was observed. The optical microstructure was observed with almost zero cracks. Coating was not uniformly distributed along the width of the sample (**Figure 7**). The optical microstructure confirms this. Metallurgical bonding between coating and the base material was observed (**Figure 8**). The laser melted depth was approximately 572µm. Above 50 $\text{x}10^6$ J/m^2 energy density, the laser surface alloying was observed but cracks were found .This may be due to heating followed by faster cooling rate(i.e., solidification cracks) (**Figures 9 and 10**). The cracks are not desirable. The laser melted depth was around 600-850µm. The melting temperatures involved during laser materials processing are extremely high. Attainment of such high temperatures coupled with the very cooling rates of the order of 10^7 K s^{-1} result in a metastable microstructure. Such a heat treatment conditions result in the resolidification of the melted zone in the epitaxial fashion /33/.

At 12 $\text{x}10^6$ J/m^2, surface hardness was observed as 870HV at 100g load. In the laser alloyed zone, approximately two-fold increase in hardness was observed **(Figure 11).** At 16 $\text{x}10^6$ J/m^2, surface hardness was observed as 875HV at 100g. In the laser alloyed zone 2.5 times increase in hardness was observed compared with base material hardness (**Figure 12**). In both the cases, increase in hardness in the alloyed zone may be due to microstructural refinement.

25 $\text{x}10^6$ J/m^2 to 34 $\text{x}10^6$ J/m^2, microhardness was observed as approximately 760HV to 825HV. The decrease in surface microhardness may be due to evaporation effect of chromium (III). Also, decrease in surface hardness may be due to formation of Ni-Cr solid solution. In the laser alloyed zone 2 to 2.5 times increase in microhardness was observed (**Figures 13 and 14**).

At 47 $\text{x}10^6$ J/m^2, surface microhardness was observed as 680HV **(Figure 16).**The decrease in microhardness may be due to less chromium % in the surface (15%Cr). In the laser alloyed zone 2 to 5 times increase in microhardness was observed. This may be due to inward diffusion of chromium joins with carbon in the base material and forms chromium carbide

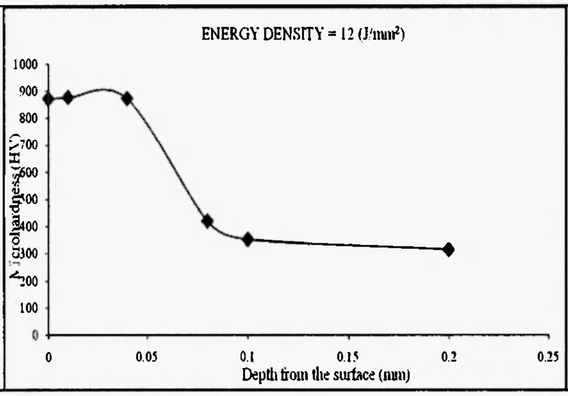

Fig. 11: Microhardness profile along the depth at energy density = 12 x10^6 J/m^2

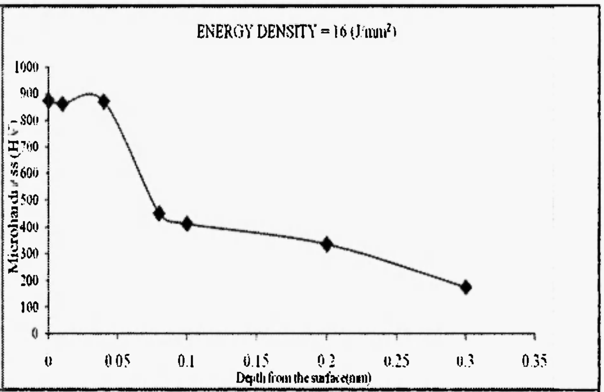

Fig. 12: Microhardness profile along the depth at energy density = 16 x10^6 J/m^2

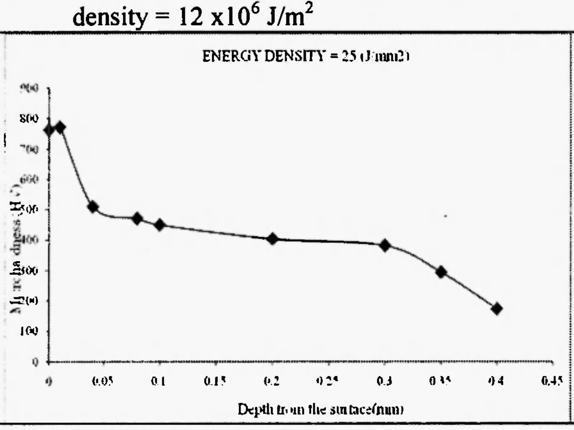

Fig. 13: Microhardness profile along the depth at Energy Density = 25 x10^6 J/m^2

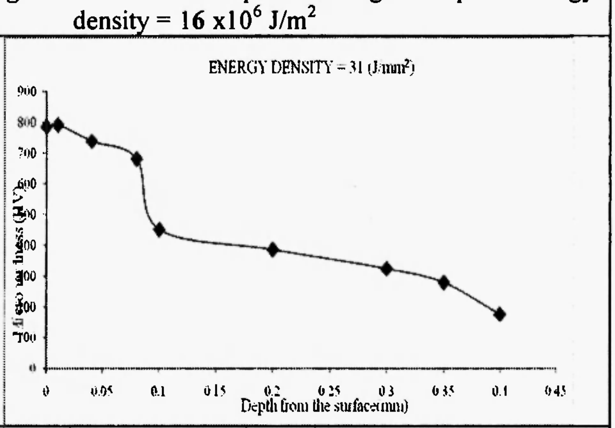

Fig. 14: Microhardness profile along the depth at Energy Density = 31 x10^6 J/m^2

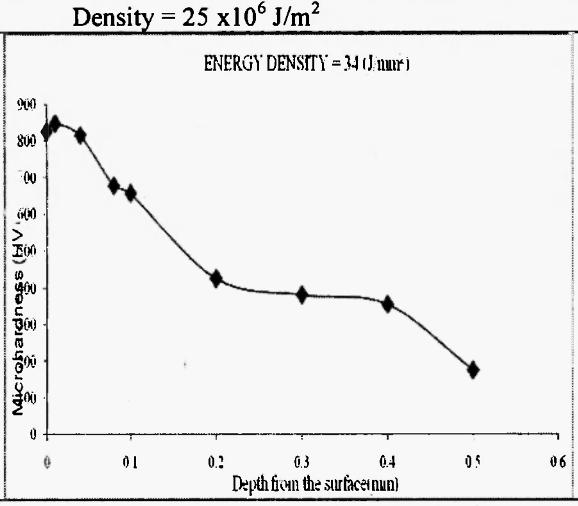

Fig. 15: Microhardness profile along the depth at energy density = 34 x10^6 J/m^2

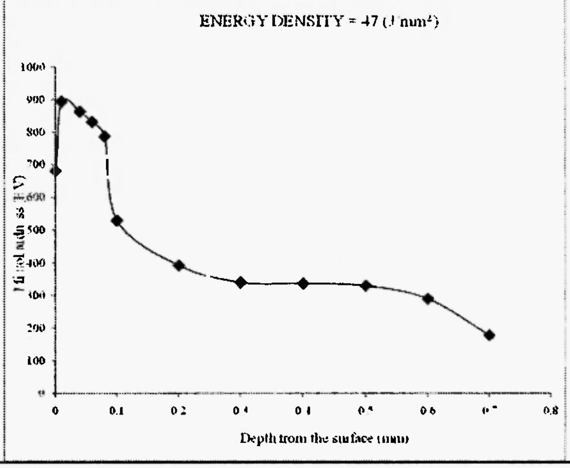

Fig. 16: Microhardness profile along the depth at energy density = 47 x10^6 J/m^2

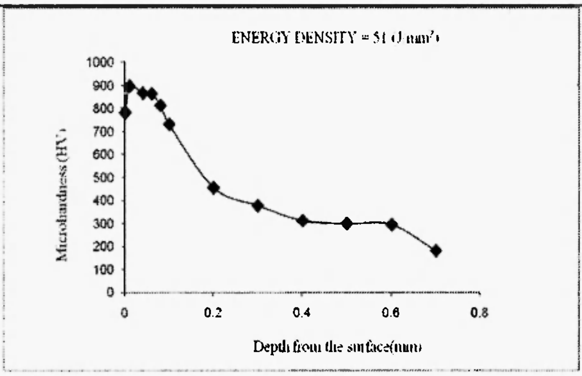

Fig. 17: Microhardness profile along the depth at energy density = 51 x10^6 J/m^2

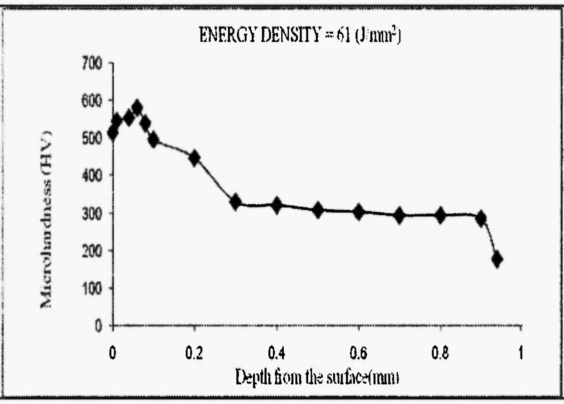

Fig. 18: Microhardness profile along the depth at energy density = 61 x10^6 J/m^2

At 51 x10^6 J/m^2, the surface microhardness was observed as 782 HV. In the laser alloyed zone 2 to 5 times increase in microhardness was observed (**Figure 17**).

At 61 x10^6 J/m^2, the surface microhardness was observed as 520HV (**Figure 18**).The decrease in surface microhardness is due to less chromium % in the surface (2%).

3.3 EDS analysis:

The chemical composition of samples laser surface alloyed at 16J x10^6 J/m^2, 47 x10^6 J/m^2, and 51 x10^6 J/m^{2}were analyzed by using Energy Dispersive Spectroscopy. The Results are given in **Table 2.**

Table 2
EDS Results Summary

Energy Density	**EDS Results**
Below 16 x10^6 J/m^2	Surface alloying was not observed. The surface has the following chemical composition Cr -99.96%, Ni-0.04, Fe-0% (**Figs. 19 and 20**).
25 to 34 x10^6 J/m^2	Surface alloying was not observed. It has been observed some % of Cr was evaporated. The surface chemical composition: Cr-33, Fe-28, Ni-40 (**Figs. 21 and 22**).
At 47 x10^6 J/m^2	Laser surface alloying was observed. Coating was not uniformly distributed along the width. Mixing of Cr & Ni with the base material was observed. The surface has the following chemical composition Cr-17%, Ni-50%, and Fe-33% (**Fig.23 and 24**).
Above 51 x10^6 J/m^2	Laser surface alloying was observed for a very deeper depth i.e., 200µm. This is not desirable because surface and nearby surface region should have sufficient % of chromium then only the wear resistance of the coatings can be enhanced. The surface chemical composition: Cr-1%, Ni-12% and Fe-87% (**Fig. 25 and 26.**).

4. CONCLUSIONS

1. Based on the energy density, the laser melted depth varies. The laser modified depth was varied from 200 µm to 800 µm based on the energy density. For 12 x10^6 J/m^2, the depth was around 200 µm. For 61 x10^6 J/m^2, the depth was around 800 µm.
2. Below 16 x10^6 J/m^2, the Ni and Cr layers were partially disturbed but the surface modification was observed in base material. This may be due to insufficient energy generated by the laser beam.
3. From 25 x10^6 J/m^2 to 34 x10^6 J/m^{2}energy density, the some % of Ni and Cr in the surface was removed away from the surface due to evaporation. To avoid

this problem, graphite or boron paste may be applied above the chromium (III) coating before doing laser surface alloying.

4. The laser surface modification was observed at 47 x10^6 J/m^2 energy density. Metallurgical bonding between coating and base material was observed. Approximately five-fold increase in micro-hardness was observed in modified zone compared with base material. Surface has 10% Cr and 30 % Ni.
5. Above 51x10^6 J/m^2, laser surface modification was observed but the optical microstructure shows some cracks. The cracks are not desirable because coating wear and corrosion resistance decreases.

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