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A REVIEW OF LASER BASED MACHINING TECHNIQUES FOR NICKEL ALLOYS

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ABSTRACT

Nickel based superalloys are well known for its superior heat resistance and corrosion resistance as well as minimal thermal expansion property. These materials are effectively used in industries where the part required retaining its stability and strong corrosion resistance properties over a wide range of temperatures. In the present study, an attempt was made to understand the various laser machining processes for the repair and renovation of nickel alloys. The motivation of present work has been received from the industrial scenario where the refurbishments of nickel based materials are still under research.

INTRODUCTION

Nickel-based alloys have a number of unique properties that allow them to be used in a variety of specialized applications. These are used in electric resistance heating elements as a result of their high electrical resistivity and heat resistance. The magnetic properties of nickel-iron alloys are used in electronic devices and for electromagnetic shielding of computers and communication equipment. These alloys have low expansion characteristics and are widely used to make frames in packaging electronic chips and in colour television tubes.

Nickel copper alloys holds excellent corrosion resistance property. The monel series, nickel with ~ 30% copper alloy is widely recommended in valve, turbine blades and marine propeller shafts for their high fracture strength, especially in sea water applications. Nickel chromium alloys are recommended for jet engine applications. The nichrome, nickel with ~ 20% chromium alloys are precipitation hardened by the strengthening phases, γ' phase. However, the γ' phase change tendency at maximum operating temperature limit the usage of such alloys at high temperature applications [1, 2]. Nevertheless, the development of thermal barrier coatings on high temperature turbine components increased the usage of nickel chromium alloys in gas turbine applications.

A laser beam can be positioned and controlled more accurately than any other conventional arc or flame. The laser photon absorption by various materials generate intense heat during laser processing, it is used for high precision machining, drilling and welding operations. The chances of thermal distortion is nil or very minimal in the material because laser machining produces minimum shrinkage. With laser, it even possible to join metallic and non-metallic material. Thin film technology and integration of microelectronic circuits in the electronic field demanded the need of reliable high quality micro-welding without any distortion. In such cases, high precision work without any defects can be achieved by lasers. Successful laser welding of high strength alloy steels, nickel alloys, titanium alloys, etc., has been achieved with 2 to 5 kW continuous wave CO_2 laser.

LASER SURFACE TREATMENT ON NICKEL ALLOYS

Lasers have been used in a number of ways to modify the properties of surfaces in metals. Most often this process is used to harden the surface for providing increased wear resistance or corrosion resistance. Laser applications in surface treatment have been dominated by CO_2 laser using multikilowatt levels, but Nd:YAG, excimer and carbon monoxide lasers are also used in some applications. The electromagnetic radiation of laser beam is used to change metallurgical and mechanical properties. By using a laser beam, the applied energy can be placed precisely on the surface, increasing substrate temperature above the melting temperature. The laser heat treatment usually competes with other processes owing to reduced distortion and high productivity. The laser treatment generally leads to increase in strength, hardness and tribological properties [3].

The laser controlled melting of Inconel 718 in the pressure nitrogen environment after coating with a carbon layer containing 7% TiC particles was examined by researchers [4]. Carbon film resulted in enhanced absorption of laser beam with the presence of TiC particles. It was found that laser scanning resulted in regular melt tracks with overlapping ratio of about 70%. Fine grains with dense layer were present at the surface. As a result of the high cooling rates and difference in thermal expansion, some locally scattered microcracks were occurred in the region near to the surface. Stress relaxation through microcracking suppressed the crack formation in the surface vicinity. Microhardness of the laser treated surface improved as a result of fine grains and formation of nitride compounds.

The precipitation and Cr depletion profiles of Inconel 182 during heat treatment and laser surface melting also experimented [5]. The Cr concentration distributions around the intergranular carbide precipitates for different heat treatments were calculated and compared with experimental values from literature. Good agreement was obtained between the calculated results and the experimental data. The sample after stress relief treatment showed the maximum Cr depletion area and subsequent low temperature sensitization (LTS) treatment with recovery of intergranular cracking (IGC). After laser surface melting (LSM), the sample showed smallest Cr depletion area compared to the sample after LTS and LSM treatments. The results obtained were in good agreement with the IGC values obtained by Streicher test, indicating that this model could be used as an effective tool to predict Cr depletion.

Laser surface texturing with varying dimple densities of 1.8, 7.1 and 11.2% were carried out on the nickel-base composites and the dimples were filled with MoS_2 powder [6]. This process conducted in the temperature range of room temperature to 400°C was able to reduce the friction coefficient to about 0.1. Wear particles were trapped by the microdimples raising the effective lubricating temperature of MoS_2 to about 500°C. The wear life of lubricant at room temperature was extended by laser surface texturing. The texture with the dimple density of 7.1% has shown lowest wear rate and longest wear life.

The Effect of temperature on the sliding wear behavior of laser surface alloyed Ni base on Al–Mg–Si alloy was studied [7]. The hardness of the laser surface alloyed (LSA) specimens exhibited a higher value when compared to the Al matrix reaching upto a maximum value of 1100 HV, 18 times that of Al matrix. The wear rate also considerably reduced for LSA specimens in the range of four to eight times less than that of Al matrix at temperature of 25 to 250°C. The critical temperature of sliding wear resistance of the LSA specimens was also higher than the Al matrix by about 50°C. The hardness of the LSA specimens was reduced as a result of the stress relief in the melted zone at a temperature above 200°C.

The microstructure of the laser-alloyed layer was greatly influenced by re-scanning and resulted in the formation of numerous pores and cracks [8]. This further decreased the specific wear rate. It was found that the wear mechanism was abrasive in nature for the loads and speed used. The coefficient of friction and wear rate were affected by the changes in normal load. Three-body abrasive wear was noticed as a result of rubbing of the alloyed material with the counterface.

Laser surface coating on nickel alloys

The doping effect of WC–Ni on the microstructure and tribological properties of the conventional NiCrBSi coating was investigated [9]. It was found that the WC–Ni added in the laser clad coatings contributed greatly by increasing the microhardness and wear resistance of Ni-based alloy coating. This was attributed to the formation of hard WC phase and partial dissolution of WC particles on the Ni matrix after laser cladding. The friction studies revealed that only mild abrasive and adhesive wear occurred when sliding against the AISI-52100 steel ball and ring counterpart.

Sliding wear test and erosive abrasion wear test revealed the increase in the wear resistance of the laser based Nickel coating upto 27 times than the nickel base alloy [10]. A 50-100 mm wide ring appeared along the particle side of the particle-matrix boundary, showing superior wear and corrosion resistance, higher than even the original central part of the WC-Co particle. Results also proved the high corrosion and wear resistance in the central original part of the WC-Co particle. The SEM and EDS studies revealed the diffusion of alloy elements from the matrix.

The effects of powder feed rate (PFR) and translation speed (TS) of a laser beam on laser cladding with three nickel-based hard facing alloys: Colmonoy 6, Colmonoy 88 and AI-1236 was analyzed [11]. It was found that the ratio of width to height of the single clad pass decreased as PFR was increased and TS was decreased, other things being equal. The extent of dilution decreased with increasing PFR and decreasing TS. In general, the greater the extent of dilution, the lower the hardness of the resultant clad layer. The optimum degree of dilution was found to lie between

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3 and 8% for maximum hardness. It was also seen that the hardness of the clad layer also depended on the hard phases present in it. The hardness of Colmonoy 6 clad layers was found to increase with increasing microstructural fineness brought about by a higher PFR.

The effect of laser beam scanning pattern on dendrite growth morphology was investigated using electron backscatter diffraction [12]. It was noticed that a fiber texture was developed in case of unidirectional laser beam scanning and a rotated cube texture pattern was formed after backward and forward scanning. The studies also revealed that if the laser beam scanning velocity can be selected in a range which can ensure a heat flow direction of about 45°C to the substrate, clad with a highly textured directionally solidified structure can be made on a polycrystalline substrate when the scanning direction is altered by 180° in subsequent layers.

An improvement in hardness was achieved by laser clad Ni–Cr_3C_2 and Ni–WC composite coating on a martensitic stainless steel substrate, and microhardness of Ni–WC coating is higher than that of Ni–Cr_3C_2 having a value of 300 HV [13]. The difference in solidification was responsible for the variation in microhardness. The erosive-corrosive wear rate of laser-clad Ni–Cr_3C_2 and Ni–WC composite coatings decreased by approximately 60% and 30% when compared with that of stainless steel substrate, respectively. The increase of erosive-corrosive wear resistance was closely related to structure state and amount of carbide, microhardness and toughening ability of the clad layer.
The EDS analysis and XRD showed that the laser ablation process was almost congruent, and crystallographic structure was retained in the pulsed laser deposition films of Hastelloy [14]. The microstructure was related with corrosion behaviour using electrochemical tests. It was also concluded that the coated substrate displayed less corrosion rates for thick coatings when compared to uncoated one. This confirmed the ability of Hastelloy thin films to protect corrosion, but bulk alloy showed high corrosion rates.

Selective Laser Melting
Selective laser melting induced microstructural changes composing of columnar structures having primarily {200}textured γ" phase precipitate columns in Inconel 718 [15]. These fine γ"precipitates averaged 35 nm along their major axis and approximately 7 nm along the minor axis in contrast to the larger precipitate sizes in the as-fabricated and hot isostatic pressed (HIP) components. The microindentation hardness was about 24% lower than the HIP samples but still 18% higher than the as-fabricated samples. There was no apparent or consistent variance in mechanical behavior of Inconel 718 alloy components fabricated in argon or in nitrogen.

The microstructural of a nickel-base superalloy, Nimonic 263 after selective laser melting process (SLM) was homogeneous but remains out-of-equilibrium as a result of very high cooling rate of the melting pool (10^5 °C/s) [16]. Because of the high cooling rate of the melting pool, the as-processed microstructure of the Nimonic 263 alloy showed some dendrites with a fine interdendritic zone in the range of 50 nm. A fine distribution of $M_{23}C_6$ carbides was also present along the grain boundaries. At room temperature, the as-fabricated samples exhibit high yield strength and high ultimate strength even though they are only strengthened by solid solution and strain hardening. The direct aging treatment presents tensile properties close to the SLM properties.

LASER GAS NITRIDING
The laser gas assisted nitriding of Hastelloy G in terms of thermal stress variations and stress fields generated during and after the laser processing using finite element method was studied [17]. Microstructural and metallurgical changes were studied after laser nitriding. The sharp temperature drop around the laser spot was due to high cooling rates. The stress levels remained high in the region where temperature gradient was high. The cross sectional examination of the laser treated region showed nitrided layer of uniform thickness, free from cracks and pores. It was noted that the size of the heat affected zone was very narrow and attributed to melting to a low depth.

Aging was carried out on Hastelloy C-276 at temperatures of 650°C and 850°C for a duration up to 240 h. Hardness remained constant for the samples aged at 650°C [18]. Microanalysis of the precipitates indicated that they were rich in Mo and W. The concentration of W in the precipitates was much higher as a result of higher value of W in the alloy. SEM examination of the fractured samples showed that they failed mainly through brittle mode. It was concluded that aging at 850°C raised the hardness and decreased the ductility of the material with the production of Mo rich μ phase.

The microstructure of laser surface melted Ni-base Alloy 600 shows Chromium depletion occurred along the grain boundaries of the sensitized Alloy 600 with the formation of two different shapes of precipitated Cr carbides such as

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Cr-rich $M_{23}C_6$ and Cr_7C_3 [19]. Dislocation density was very low in the laser melted zone (LMZ), and the carbides were completely dissolved at the grain boundaries close to LMZ and partially dissolved at the boundaries far from the LMZ. The microstructure of the LMZ consisted of fine cells with precipitates of a TiN type along the cell and grain boundaries. However, no Cr-rich carbide was formed in the LMZ during rapid solidification.

A 5kW CO_2 laser was used for the surface modification of Ni and Ni–Cr–B–Si on Al–Mg–Si Alloy [20]. It was concluded that porosity-free zone could be generated by LSA and Al_3Ni particles were present only in LSA Ni sample. Three specific regions were there in the LSA Ni–Cr–B–Si sample namely surface region in the melted zone, bottom region in the melt zone and amorphous phase in the bottom region from top to bottom. In the first region, Al_3Ni particles were present and Al_3Ni_2 particles were seen in the second region. Al–Ni–Cr amorphous structures were dispersed in the third region. Another important observation was that the hardness of the LSA Ni– Cr–B–Si sample increased sharply when compared to Al-matrix and Ni specimen and also the amorphous structure was 18 times harder than Al marix.

The M-N coating prepared by reactive magnetron sputtering (RMS) at 400°C consisted of two phases: MN and γ (Ni, Fe). A small quantity of the γ N1 phase indicated the decomposition of the γ N1 phase into the MN phase whereas γ (Ni, Fe) phase occurs at this temperature in the case of RMS deposition [21]. The bulk sample produced a nitrided layer without any change in the crystal structure after nitriding at 400°C. The lattice parameter of the nitrided layer gradually decreased from 0.393 to 0.355 nm from the outermost surface to the substrate. The nitrided layer mainly composed of the γ N1 phase, with minor amounts of MN phase and γ (Ni, Fe), indicating the decomposition of the γ N1.

The comparative study on microstructure and properties of nano-CeO_2 and Sm_2O_3 particulate reinforced nickel-based composites by laser deposition [22]. It was found that the addition of n-CeO_2 and Sm_2O_3 decreased the lattice constant of γ- Ni. The microhardness, wear resistance and corrosion resistance of the coatings were greatly improved by n-CeO2 and Sm_2O_3 addition, and 1.5% n-CeO_2 showed best performance. The intercrystalline corrosion occurred in nickel alloy coating, whereas uniform corrosion played a major role in n-CeO_2 and Sm_2O_3 coatings.

The failure of Hastelloy C-276 pump impeller that suffered general corrosion in 32% hydrochloric acid at ambient temperature in a chemical plant was also investigated by few researchers [23]. The corrosion attack was crystallographic in nature and was severe at the interdendritic arm spacing as well as the boundaries of columnar grains, resulting in deep grooves. Hastelloy was not suitable in this condition involving 32 % HCl where the temperature could reach upto 50°C in summer.

The effect of LSM on the intergranular corrosion of the sensitized nickel alloy 600 by double loop electrochemical potentiokinetic reactivation method in de-aerated 0.01 M H_2SO_4+ 20 ppm KSCN at a scan rate of 0.5 mV/s at room temperature was studied [24]. Severe intergranular fracture was induced by the sensitization treatment at 600°C for 24 hours as a result of the precipitation of Cr-rich carbides and Cr depletion at the grain boundaries. The optimized condition showed high degree of sensitization for the sensitized alloy 600 by suppressing general and pitting corrosion. Another important observation was that laser surface melting significantly improved the resistance to intergranular corrosion by decreasing the degree of sensitization.

The effect of ceria (CeO_2) on the wear and corrosion of laser-clad nickel-based alloy coatings was investigated [25]. The results showed that CeO_2 refined the microstructure of clad coatings and became very compact. The microhardness improved as a result of the addition of CeO_2. There was improvement in friction and wear properties of the clad coatings due to ceria addition. The friction coefficients reduced and wear resistance improved after the process. The addition also resulted in the decrease of corrosion rate.

SUMMARY

A detailed study was also conducted to understand the microstructural and mechanical changes during the laser treatment on nickel alloy. The tribological properties, in specific, oxidation and hot corrosion behavior were found to be a dominant property to improve the surface characteristics of nickel alloy and many researchers tried different methods to improve it. The coating of aluminum alone or with any of cobalt, hafnium and titanium exhibited better protection against thermal oxidation for nickel alloys. The formation of Al_2O_3 scale during the early stage of oxidation enhanced the oxidation resistance property of the base alloy.

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In order to achieve a better coating, there are numerous surface treatment techniques have been performed. The techniques, such as nitriding, carburizing, oxidation, physical vapor deposition (PVD) and chemical vapor deposition (CVD) executed to improve the surface properties of nickel alloy. In addition to this, laser was also used in surface modification. The coatings made by laser techniques exhibited strong metallurgical bonding with the substrate materials, owing to their high energy density. The laser techniques such as laser surface remelting, laser texturing, laser alloying and laser cladding were successfully carried to improve the surface properties of nickel alloys. The coatings prepared by laser cladding exhibited dense microstructure due to very high cooling rate and thermal gradient. The rapid solidification during laser cladding process attributed to obtain excellent coatings with improved tribological properties.

In recent times, there is more interest created towards laser based metal deposition on nickel and titanium alloys. Despite that, the residual thermal stress induced as a result of rapid heating and cooling showed more attention required on selection of laser process parameters. The selection of optimal parameters helped to exhibit very good metallurgical bonding and improved mechanical properties in the deposited region. It was also found that the technique satisfied the necessary requirements for industrial applications.

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