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Laser materials processing

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Abstract. The ability of the laser to produce a controlled and intense source of heat is the key characteristic which has led to its recent emergence as an important manufacturing tool. In this paper we have discussed the different techniques of laser materials processing and have given a brief description of their important applications.

Keywords. Laser materials processing; laser welding; heat transfer mechanism; laser cutting; laser drilling; laser glazing; laser cladding; laser alloying.

1. Introduction

Since its inception in the early sixties the laser has progressed from being a laboratory curiosity to a sophisticated industrial tool. Lasers are being used as a controlled intense source of heat for many metallurgical applications, e.g. welding, cutting, drilling and surface hardening. Heat is produced by the absorption of the laser photons. The power density of the laser beam is around a billion times more than that produced by ordinary light. Applications of the laser in processing materials of different thicknesses ranging from 0·1 mm to 100 mm have demonstrated its capability as an important manufacturing tool for engineering industries. The major advantage of laser processing is that it produces a better quality product with minimum distortion at a high rate, a very important production requirement. Also, the same laser can be used for different applications, a very cost-effective factor for any industry.

2. Types of laser and parameters for materials processing

2.1 *Types of laser*

Both solid and gas lasers are being used for materials processing. Solid lasers such as Nd:YAG and ruby are used for thin components while CO_2 lasers are used for the thick ones. The choice of the laser for any particular application depends upon the thickness and physical properties of the material to be processed. The CO_2 and the Nd:YAG lasers have been compared for their performance in table 1. It may be noted that the performance of the Nd:YAG and the ruby lasers will not be very different, especially when compared to the CO_2 laser.

The most important advantage of the Nd:YAG laser is that the reflectivity of most of the engineering materials at its wavelength is much smaller than that at the CO_2 laser wavelength. The advantage becomes more important especially with materials with high thermal conductivity, e.g. Cu and Al. The laser spot size is also smaller in the former case resulting in higher process efficiency. The main advantage of the CO_2 laser over the Nd:YAG laser is its very high laser efficiency due to which high power lasers can be used to achieve high penetration.

Table 1. Comparison of CO_2 and Nd:YAG lasers.

Criterion	CO_2 laser	Nd:YAG laser
Wavelength	10·6 μm	1·06 μm
Maximum average power achieved	100,000 W	800 W
Maximum thickness possible to weld	100 mm	5 mm
Lasing efficiency	10–20%	2–4%
Maximum spot size	Larger	Smaller
Depth of focus	Lower	Higher
Reflectivity of metals	Higher	Lower
Gas consumption	CO_2, N_2, He needed	No gas required
Optics	Special optics	Normal optics
Viewing during welding	Special viewing	Direct viewing
Machine size	Larger	Smaller
Price	Costlier	Cheaper

2.2 *Laser parameters*

Laser beam power, interaction and laser beam diameter are the main parameters for materials processing. The interaction time is equal to the pulse duration in the case of pulsed lasers and is inversely proportional to the processing speed in the case of continuous wave (CW) lasers. The type of process, e.g. welding, cutting and drilling, where lasers find application depends mainly upon these laser parameters, as illustrated in figure 1. It may be noted that a combination of high power density and low interaction time is used for cutting while that of low power density and high interaction time is used for heat treatment. Intermediate power density and interaction time are required for welding where melting is needed.

2.3 *Material parameters*

Laser performance also depends upon material properties such as absorptivity, thermal conductivity and specific heat. Absorptivity is one of the most significant parameters for laser interaction as the efficiency of laser processing depends on the absorption of the energy by the workpiece. Absorptivity of most of the metals and alloys is very small, i.e. less than 10% of the incident beam energy, but can be increased either by the use of a reactive gas or by material surface conditioning. The surface can be conditioned by applying absorbent powder or by forming anodized film, both of which have been found to be very effective (Arata and Miyamoto 1978). Also, it has been reported (Jorgenson 1980) that the addition of oxygen to argon shielding during welding increased the absorption and achieved a higher weld penetration.

3. Laser welding

Laser beam welding (LBW) is defined as a welding process wherein coalescence is produced by the heat obtained from the application of a concentrated coherent light beam impinging upon the surface to be joined. Laser beam welding has many advantages: (1) it produces deep penetrating weld, (2) melting efficiency is very high and therefore heat-affected zone (HAZ) is very small, (3) depth to width ratio is very high, (4) it can be used in inaccessible areas, (5) it is capable of welding thin to

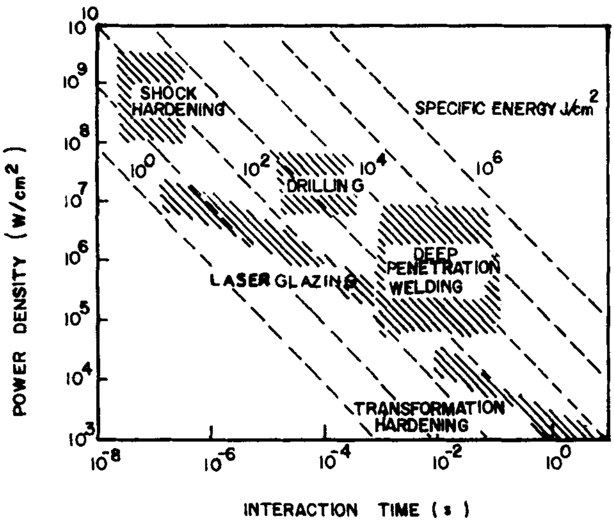

Figure 1. Process parameters for laser materials processing.

thick components, (6) it is capable of welding dissimilar metals, (7) welding speeds are very high and therefore high production rate can be achieved, and (8) direct contact of weld joint is not needed and therefore a clean weld is produced.

In other words, it has all the advantages offered by electron beam welding (EBW), a more popular welding technique. However, LBW has many advantages over EBW and therefore is a more versatile welding technique. Some of the advantages of LBW over EBW are: (1) it does not require the vacuum attachment which is an essential pre-requisite in most EBW, (2) it is insensitive to electric and magnetic fields, (3) X-rays are not generated, (4) it can be more easily focused, aligned and redirected by optical elements and therefore can be easily transmitted and manipulated over long distances in difficult environments, (5) spiking, underbead, spatter and root porosities common in EBW are not present, and (6) most laser machines are multi-purpose and consequently can be used for different applications like welding, cutting and drilling.

3.1 *Heat transfer mechanism*

In conventional low heat density welding processes heat is transferred from the surface by conduction while in laser beam welding process energy is transferred through keyhole formation, similar to that in the electron beam welding process. Keyhole formation in high power laser beam welding results from vaporization of the substrate. The pressure produced by the vapour in the crater causes displacement of the molten material upwards along the walls of the keyhole. This hole acts as a black body and aids in the absorption of the laser beam as well as the transfer of the heat deep into the material, as illustrated in figure 2. According to Klemens (1976) the keyhole or cavity is formed only if the laser beam has sufficient power density.

The formation of the keyhole in deep penetration welding increases the absorption of the beam by the material to more than 90% of the incident power. This keyhole mechanism with higher absorption leads to better melting efficiency of

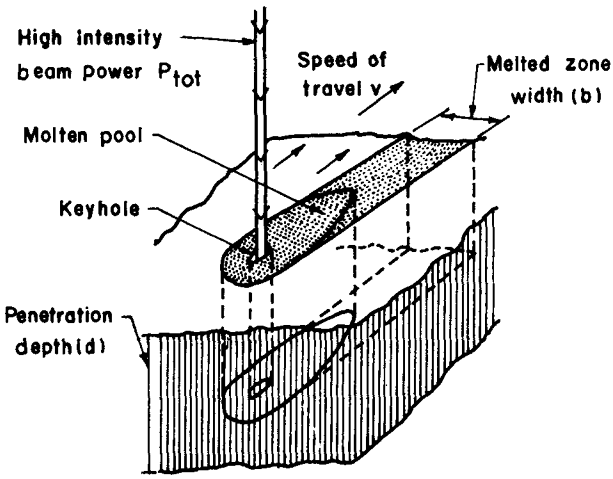

Figure 2. Keyhole mechanism.

the order of 70–80% compared to 3–5% in gas tungsten arc welding process and thus compensates for the low efficiency of the laser.

3.2 *Applications of laser welding*

Laser welding has been used for many industrial applications. In fact it has started replacing conventional welding techniques for economic reasons. Bolin and Maloney (1975a) have used the laser technique to weld wires to terminals on a shunt plate used in telephone switching facilities. This laser system has resulted in a great improvement in throughput over the previous hand soldering technique and has eliminated the necessity to strip the insulation from wires prior to joining as the insulation was removed by the laser pulse itself. Bolin and Maloney (1975b) have also reported laser repairing of expensive vacuum tubes in which a missed weld was discovered after sealing the glass tube—the Nd:YAG laser beam passes freely through the glass. They have also reported welding of high reliability thermocouple junctions.

Laser can easily be applied to weld thin materials to thick structures. Welding of these joints by conventional techniques is rather difficult as it produces uneven heat distribution depending upon the weld geometry and materials. It has been reported (Morgen Warren 1979) that this asymmetry in heat distribution decreases significantly at high welding speed and therefore laser welding can be easily applied in such cases.

Laser welding is also a useful technique for welding dissimilar materials. A number of combinations like tantalum to nickel, beryllium/copper to palladium, monel to cupronickel, cupronickel to Kover or low C-steel have been successfully welded. In fact various guidelines (Gagliano *et al* 1972) have been published for selecting suitable binary combinations of pure metals for laser welding. Laser has proved to be extremely useful for producing welds near heat-sensitive glass–metal seals. Laser welding has been utilized in the sealing of a variety of lithium batteries.

Lasers are being used in the nuclear industry in a number of applications like fabrication of instrumented fuel elements and welding of waste containers (Lewis 1984). Welding of standard fuel elements and spacers to fuel pins has been done at

BARC and the quality of welds is better than that produced by the conventional techniques presently employed (Dilip Kumar *et al* 1985).

4. Laser cutting

The general characteristics of laser cutting process are sufficiently attractive and unique to explain the great breadth of applications which have been or are being developed. The laser cutting of metal provides certain decided advantages over conventional cutting methods. These are: (1) sharp corners can be cut since laser cutting is almost a point-source cutting, (2) there is minimum distortion and a narrow heat-affected zone, (3) it produces a very narrow kerf giving a saving in material, (4) it is possible to weld cut edge directly, (5) there is no tool wear as the process is contact-free, and (6) high cutting speed is achieved.

4.1 *Mechanism of laser cutting*

There are a number of ways in which laser can be used to cut different materials: (i) vaporization, (ii) gas-assisted melting and blowing, (iii) oxygen-assisted burning and blowing, (iv) thermal stress cracking or controlled fracturing, and (v) scribing. Both the oxygen gas assisted and inert gas assisted processes are more commonly used in metal cutting. In the oxygen gas process, the heat of the exothermic reaction is also utilized for cutting and therefore higher cutting rate can be obtained. The gas jet also serves to expel the molten material produced from the cut. The important parameters for laser cutting are laser power, cutting speed, nozzle diameter, nozzle gap, and type of gas and its pressure. The optimum value of each parameter depends on the type of material and its thickness and must be experimentally determined for a particular application.

4.2 *Applications of laser cutting*

Laser cutting has been performed on steels, titanium and its alloys for aircraft industries, superalloys for high-temperature applications and zirconium alloys for the nuclear industry. Diel (1976) has reported laser cutting of titanium alloy components. Titanium splice plate for the F14A horizontal stabilizer was cut by Grummar Aircraft Corporation using laser. It has been reported that laser cutting resulted in a saving of 17·6 man-hours/aircraft and $1350 in material/aircraft in 1976.

High power laser is required to cut Al alloys because of their high reflectivity values. Wessling (1977) has reported savings in set-up time and material and achieved an overall saving of 60–70% by laser cutting of aluminium alloys compared to the conventional methods of blanking and router cutting. Forbes (1976) has reported laser cutting of stainless steel sheet for Westland Lynz helicopter blade manufacture and that laser installation has paid for itself in 10 months. In car production, small batches of parts are required of various sheet materials and are ideal for laser cutting. The Ford company in Cologne installed a 400 W laser in 1974 and found that laser cutting was 12 times faster than previous methods of shear, nibble and grinding. Insulation removal on copper for electrical connection or salvaging has been performed by laser. No cutting of Cu is observed because of high reflectivity and thermal conductivity. Laser cutting has been used in the nuclear industry to cut the radioactive wrapper off the fuel rods in the reprocessing of fuel (Lewis 1984). The laser itself is outside and unaffected by radioactivity while only the beam is passed into the hot area. Zircaloy-2 has also been laser-cut successfully at BARC (Dilip Kumar *et al* 1984) by argon-assisted laser cutting process and an accuracy of $\pm 0{\cdot}025$ mm with 80 μ surface finish has been achieved.

5. Laser drilling

Drilling is one of the rapidly growing areas which make use of lasers. It is an attractive way of making small holes particularly at high production rates. The distinct advantages of the laser are: (1) hard or soft material can be drilled, (2) it is a non-contact process, so there is no tool wear, (3) there is no chip problem, (4) high precision with higher speed can be achieved, (5) aspect ratio (ratio of the depth to the diameter of the hole) is high, and (6) drilling angular holes is easy.

In hole drilling with laser not all of the ejected material is vaporized. Molten material at the surface of the hole may be ejected as hot, glowing globules. When a hole begins to be produced in the target the vapour builds up a pressure which causes a flow of the matter towards the exit aperture. This flow can bring some of the molten material formed along the boundaries of the crater. Chun and Rose (1970) have shown that the per cent amount of material removed in liquid phase is significant and is a function of laser pulse duration, as shown in figure 3. The depth to which material can be vaporized in a single pulse is very limited. However, deeper holes can be drilled owing to the flushing process which removes materials as unvaporized droplets. If repeated laser pulses are delivered to the same area of target deep holes may be drilled (Charscan *et al* 1978), as shown in figure 4. This suggests that it is more efficient to drill deep holes with multiple laser pulses of low energy than with a single high energy pulse. The holes resulting from multiple pulse drilling are less tapered and better defined than the single-pulse holes.

The hole depth increases with input energy density up to a limiting value. Aspect

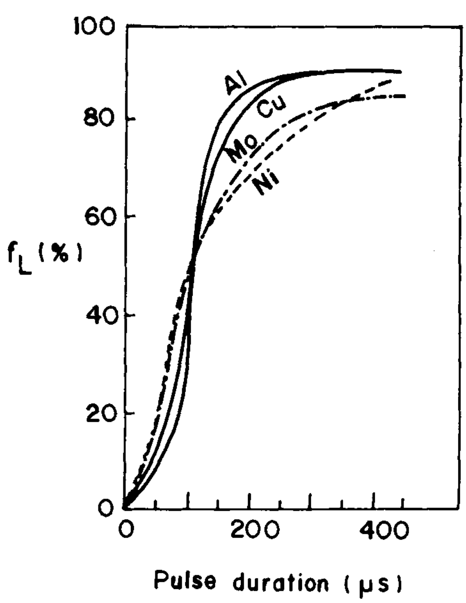

Figure 3. Material removed (%) in liquid phase as a function of laser pulse duration.

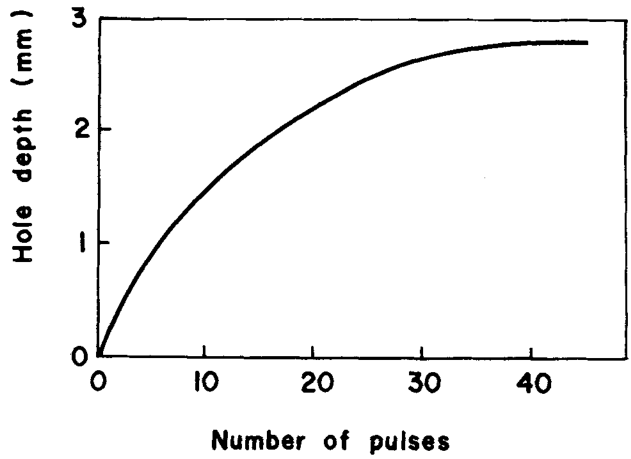

Figure 4. Effect of repeated pulsing on hole depth.

ratio of the order of 8–12 : 1 has been achieved in metals and alloys. The depth of drilling can be increased marginally by ultrasonic vibration of the workpiece during drilling as reported by Mori and Kumehera (1976). The characteristics of the hole also depend on laser pulse shape, wavelength of radiation and focal position. Diameter of hole as a function of lens focal length and laser power has been studied by Kato and Tamaguchi (1968), as shown in figure 5.

Limitations of laser drilling are (1) limited depth of penetration due to the limited amount of deposited laser energy, (2) recondensation of material around the entrance to the hole which results in a crater-like lip and needs refinishing operation, (3) taper in holes which requires careful control in temporal and spatial properties of laser, and (4) wall roughness due to resolidified material.

5.1 *Applications of laser drilling*

It is found that laser is cost-effective for hole diameters between 0·01 mm and 1·5 mm (Murphy 1987). It is generally difficult to drill holes smaller than 0·01 mm in diameter using laser because of an inability to maintain adequate depth of focus at this spot size. Holes larger than 1·5 mm in diameter may be made by trepanning, but this method is inherently slower and more tedious. The technical literature of different suppliers is full of examples using pulsed lasers. Some of the applications in laser drilling are enumerated below.

Holes of 0·76–2·5 mm diameter in turbine power generator combusters and transition ducts made of a tough alloy (a Ni-Cu-Mo-F alloy) have been made. Mechanical drilling (60 s/hole) and electrochemical machining (180 s/hole) were slow while such fine holes could not be made by mechanical punching. Using an Nd : YAG laser, the Buleva watch company has improved precision by 10 times and reduced the adjustment time to 1/20. Holes with 0·2 μ diameter have been obtained with a frequency-quadrupled YAG laser.

6. Laser surfacing

The possibility of modification in the structure and the chemistry of metal surfaces

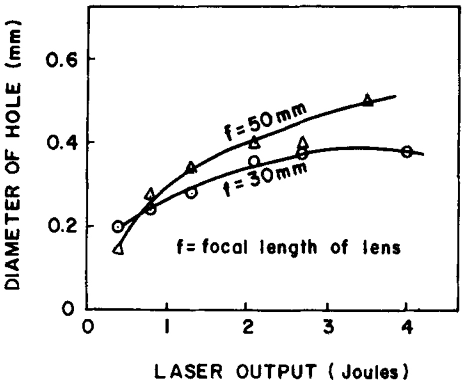

Figure 5. Diameter of hole as a function of lens focal length and laser power.

by laser has led to a new, rapidly growing science called laser surface treatment. The surface treatment is required for improving metal surface characteristics for better corrosion- and wear-resistance and other mechanical properties or combinations of these. Various laser surface treatment processes like annealing, hardening, surface alloying/cladding and laser glazing, which use different laser parameters and other factors, are available. Some of these processes have been formally carried out using heat sources other than laser but have become the subject of additional interest with the availability of laser as heating source.

6.1 *Laser heat treatment*

Laser heat treatment offers many distinct advantages over conventional heat treatment, such as: (1) it offers a very small HAZ surrounding the heat-treated area and thus areas near heat-sensitive components can be readily treated, (2) a small area of a part can be heat-treated without affecting bulk properties, (3) less distortion is involved since less heat is used for a shorter duration, and (4) in transformation hardening it does not require a separate quenching operation and little or no post-heat-treatment operation, which is the real cost-saving factor. Initially laser was used only for selective surface hardening for wear reduction, but later it began to be used to change metallurgical properties by changing surface composition.

As explained earlier the surface reflects most of the incident laser radiation. Creation of the key-hole at high laser power and the resulting increase in absorption are utilized in welding and cutting but are to be avoided in heat treatment. It is therefore generally recommended that lower power density and a coating on the material surface to be laser-irradiated to reduce reflectivity be used, thus increasing heating efficiency.

Cast iron and carbon steels have been surface-treated by laser. The final structure of the carbon steel depends upon the final temperature reached during the laser irradiation and the cooling rate following irradiation. In laser heat treatment each local area has had a different thermal cycle which can result in different mixtures of the common steel phases. Depth of hardening and hardness values mainly depend upon power density of the laser beam, interaction time, and composition and microstructure of the steel.

Laser heat treatment is being applied industrially to increase the surface hardness and wear resistance in many alloy systems. These applications include heat treatment of internal base surface, gear shaft, gear housing, etc.

Laser surface heat treatment to stainless steel after welding to desensitize the HAZ and restore complete resistance to inter-granular corrosion has been reported by Nakao *et al* (1986).

6.2 *Laser glazing*

Laser glazing is a relatively high power density, low interaction time process in which the laser is allowed to fall on the material to melt the surface layer producing a sharp temperature gradient (10^5 °C/cm) between the liquid surface and the solid base. Since there is intimate solid/liquid contact very rapid quenching of the melt results in fine grains, supersaturated solid solution and amorphous structure which would confer excellent properties such as wear- and corrosion-resistance and strength to the material. The final structure depends upon the ratio of the temperature gradient and the solidification rate which in turn depend on laser parameters and physical properties of the material. Increasing the gradient rate ratio causes progressive change in the solidification characteristics starting from dendrite-cellular, dendritic-plane front growth, while increasing the cooling rate reduces the diffusion path and results in finer structure. In laser glazing the crystalline base is in good contact with melted surface and produces favourable sites for nucleation for recrystallization. However, in some cases it has been found that under the appropriate conditions of fast cooling the alloy can be made amorphous by laser glazing.

A smooth machined surface is exposed to the focused laser beam. No coating is used in this case as it is ineffective at the high power densities required for laser glazing operation; additionally, there is a good possibility of the melt zone being contaminated by the coating material. Inert gas shield is used to prevent atmospheric contamination and supress plasma formation, as shown in figure 6. However, the cooling due to the inert gas flow is negligible in comparison to the heat-sinking effect of the base material.

Laser glazing has been tried in many systems for achieving microstructural changes. The resulting improvement in the fatigue (30% or more) of AISI 1045 steel has been reported by Gnanamuthu (1979) and Singh *et al* (1981). Improved wear properties of laser-glazed grey cast iron have also been reported (Blarasin *et al*

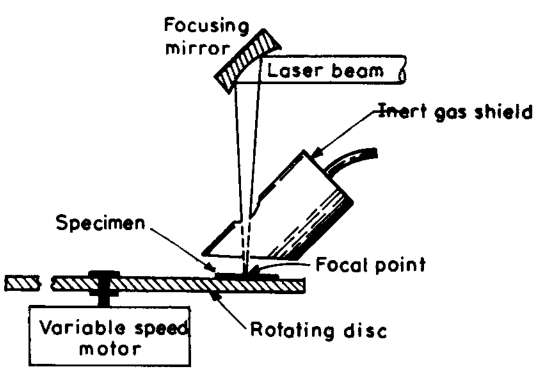

Figure 6. Schematic drawing of laser glazing process.

1983). Laser glazing of S.S. 430, S.S. 304, Incoloy (800) and Hastealloy has resulted in enhanced oxidation resistance, as shown in figures 7 and 8. Laser glazing of aluminium alloy (Al–12% Mn) improved its resistance to uniform corrosion in hydrochloric acid and in sodium citrate solution (McCafferty *et al* 1982). Beneficial effects have also been observed in the case of Zr- and Ti-based alloys.

6.3 *Laser surface alloying/cladding*

Laser surface alloying is a process which utilizes the high power density available from focused laser sources to melt coatings and a portion of underlying substrate. The irradiation of the coated surface by laser causes both the coating and the base metal to melt, followed by interdiffusion in the liquid state and resolidification at a very fast rate due to self quenching A wide variety of chemical and microstructural states can be obtained depending upon the material, laser parameters and coating thickness. Thus the chemical profile of the surface alloy layer can be controlled in this process. In laser surface alloying all forms of surface coating techniques like vacuum evaporating, plating, flame spraying, plasma spraying, powder coating, thin foil application and ion-implantation, and all the three types of laser systems, viz. Q-switched, pulsed and CW laser, including both Nd:YAG and CO_2, have been attempted. In general laser surface alloying processes can be classified into two categories, those which apply additional material before the laser operation and

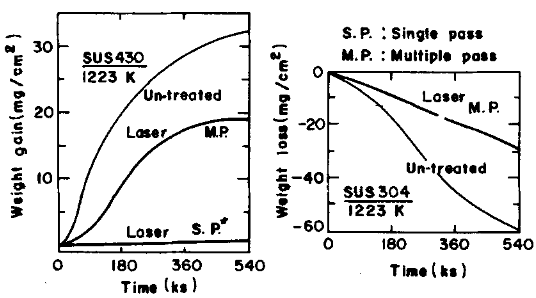

Figure 7. Changes in weight gain (loss) of the laser treated and untreated steels oxidized at 1223 K (calculated from thickness of oxide films).

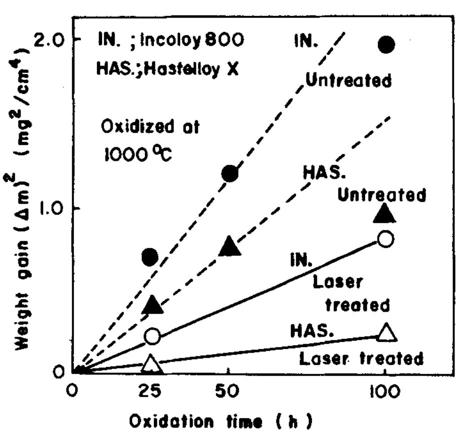

Figure 8. Oxidation behaviour of laser treated and untreated incoloy 800 and hastealloy X.

those which apply it during the laser processing. The latter process of concurrent deposition has the advantage of eliminating the predeposition process but needs higher power and is used to build larger thickness for commercial applications.

In the case of laser cladding both wire feed and powder feed techniques during laser processing have been reported. Figure 9 shows a typical laser cladding process, using the powder feeding technique. Laser surface alloying/cladding has been applied to a large number of systems for different applications. Both metals/alloys and ceramics have been deposited on different substrates. The laser surface alloying/cladding process has been applied to improve properties like hardness, chemical passivity, strength characteristics, wear resistance and high-temperature oxidation behaviour of the substrate material.

Surface alloying of iron-based alloys has been studied in greater detail because of the technological importance of these alloys. Efforts have been made to produce hard, wear- and corrosion-resistant stainless surfaces on ferrous alloy substrates by adding Cr, Mo and Ni. Gnanamuthu (1980) has obtained a composition of 3·5% Cr, 1·9% C and 1·3% Mn having a martensitic phase on the surface of an AISI steel. Chiba *et al* (1986) have studied the corrosion behaviour of ferrite and austenite surface alloys prepared by laser surface melting of Cr-plated and Cr–Ni-plated mild steels. They have observed that laser irradiation brings about homogeneity in the melted zone which in turn enhances the passivity of the alloy in 1 N H_2SO_4 and 1 N H_2SO_4 + 0·5 N NaCl solution. Locke (1978) has obtained a uniform, hard alloyed region of 0·05″ thickness by adding carbon and chromium, as

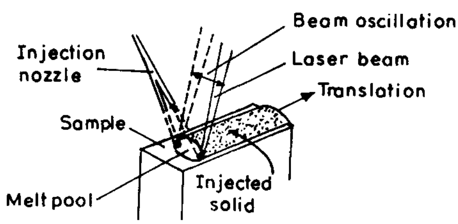

Figure 9. Schematic representation of laser melt particle injection process.

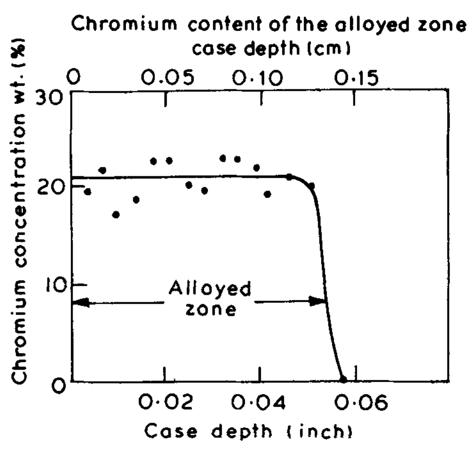

Figure 10. Chromium concentration in laser alloyed AISI 4815 steel.

shown in figure 10. Surface alloying of iron by Mo (28–36%) up to 300–500 μ depth has also been used to increase hardness.

Another area of laser surface modification is the deposition of TiC/WC particles on different substrates, e.g. iron, nickel, titanium, aluminium and copper base alloys, for producing wear-resistant surfaces. Many other metal/particle combinations appear to be feasible, as excess vapour under laser melting is the only limitation to this process. Ayers (1981) has deposited TiC on aluminium (5052) using TiC powder in the size range of -70 $+100$ mesh to -325 mesh. It has been found that laser surface-processed samples performed substantially better than the same alloy in the original condition. The processed surfaces exhibit wear rates that are only a few per cent of those of untreated alloys and compare favourably with commercial wear-resistant alloys.

Hard surfacing by cladding alloy steel with stellite, or depositing Ni-8 Mo-3 Al-12 alloy on alloy for turbine disk, or depositing pure Ti on Ti alloy for optimum corrosion/mechanical properties can be easily done by laser surfacing. The process is therefore capable of producing a variety of material combinations for different engineering applications.

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