

HIGH POWER LASER PROCESSING OF MATERIALS

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ABSTRACT

The first practical demonstration of a laser device was in 1960 and in the following years, the high power carbon dioxide laser has matured as an industrial machine tool.

Modern carbon dioxide gas lasers can be used for cutting, welding, heat treatment, drilling, scribing and marking. Since their invention over 25 years ago they are now becoming recognised as highly reliable devices capable of achieving huge savings in production costs in many situations.

This paper introduces the basic laser processing techniques of cutting, welding and heat treatment as they apply to the most common engineering materials. Typical processing speeds achieved with a wide range of laser powers are reported. Accuracies achievable and fit-up tolerances required are presented.

Methods of integrating lasers with machine tools are described and their suitability in a wide range of manufacturing industries is described by reference to recent installations. Examples from small batch manufacturing, high volume production using dedicated laser welding equipment, and high volume manufacturing using 'flexible' automated laser welding equipment are described.

Future applications of laser processing are suggested by reference to current process developments.

INTRODUCTION

The Carbon Dioxide Laser emits a beam of infra-red energy that is nearly parallel with a wavelength of around 10.6 microns. The diameter of this beam, and its divergence varies from laser to laser but typically a half kilowatt laser can be expected to have a diameter of 6-8mm and a divergence of a few milli-radians, while a 2 kilowatt laser may have a diameter of 15-20mm and a divergence of one milli-radian.

In over 25 years since its conception, the Carbon Dioxide Laser has been used for a wide variety of techniques, some of which are highlighted in this paper.

Carbon Dioxide lasers fall into 4 basic types, characterising the laser gas flow:-

- Sealed Gas
- Slow Axial Flow
- Fast Axial Flow
- Fast Transverse Flow

Ferranti Industrial Electronics Ltd in Dundee, Scotland, manufacture all 4 types.

In general, the sealed gas systems are used up to about 100 watts. Above that, to about 1.5KW, the slow axial flow is best, it gives the most reliable, most cost effective solution. From about 1.5KW to about 5KW then the gas flow has to be fast axial flow. This is, in general, a less attractive solution than slow flow due to mainly poorer reliability and higher relative cost. The blowers on fast axial flow lasers in particular, can present a problem if not properly designed. They can be unreliable, noisy, transmit high vibration to the system and have limited life. Above about 5KW, fast traverse flow is most efficient, and powers in excess of 25KW can be obtained with such a design.

Ferranti have matched their product line of Carbon Dioxide lasers, to ensure that the best laser is manufactured for the power range in which it is to operate.

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LASER CUTTING

ADVANTAGES

The primary advantages for laser cutting can be summarised easily:-

- Very localised heat input.
- High speed (compared with other methods).
- Narrow kerf (typically less than 0.5mm in most metals).
- No cutting force.
- No tool wear.
- Ease of automation.
- Different materials and thicknesses can be cut without resetting expensive tools.
- Quiet operation.
- Elimination of subsequent machining in most cases.

FOCUSING AND ASSIST GAS

To increase the power density of the beam sufficiently to achieve cutting, it must be focused to a small spot, typically 0.1 to 0.5mm diameter. Despite the high power densities present in such a small spot size, many megawatts per cm², power alone is not enough to achieve good cutting, and an assist gas must be used to aid the cutting process.

The assist gas has many uses:-

- It removes molten and vapourised material from the cutting zone.
- It prevents molten material and vapour from contaminating the focusing lens.
- It can be used to cool the focusing lens.
- If the assist gas contains oxygen, ie; oxygen itself or compressed air, then an exothermic reaction occurs when cutting ferrous metal and cutting speed is increased. When cutting non-metals, where burning is a problem, or to prevent oxide build up on the cut edge of ferrous components, an inert gas must be used.

The assist gas is usually arranged to be co-axial with the beam, this simplifies profile cutting and makes the cut edge more uniform.

Focusing the beam is usually accomplished by lenses, although for very high powers, mirrors are more common due to their higher tolerance to these powers.

Lenses are usually constructed of Gallium Arsenide or Zinc Selenide (although Germanium or Salt lenses are sometimes found).

PULSING

For cutting large shapes which are relatively simple in outline, a Continuous Wave (CW) laser can be used. Here the beam is continuous with on/off control being accomplished by means of a shutter.

In general, however, cutting involves producing intricate shapes and so a laser capable of pulsing is the best solution. The average power of the laser can be controlled by turning the laser on and off electronically thousands of times per second. In this way a precise amount of power can be incident upon the surface of material resulting in perfect cutting everytime. Without pulsing, too much power may be used resulting in wide kerf widths, large heat affected zones and even burn out of the material.

As an added benefit of pulsed lasers, most of them exhibit a peak of power 2 to 3 times their CW level for a short time each pulse. This enhanced pulsing has many names, and benefits the cutting process by enabling more efficient coupling between the beam

and the workpiece.

Figure 1 shows a typical power output from a pulsed laser.

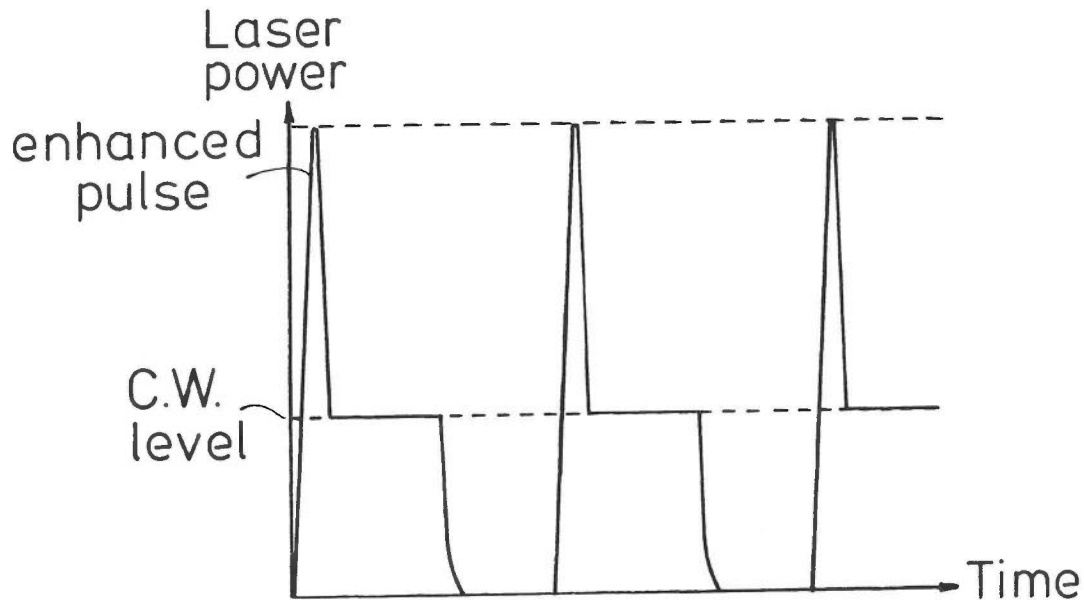


Figure 1: Enhanced Pulsed Laser Output (Ferranti MF Series Laser)

MODE

Laser beam quality is also to be considered when cutting. Two lasers of the same power may cut very differently depending upon the profile of the laser beam. The best profile for cutting has been determined to be of Gaussian form, in laser terminology this is called TEM₀₀. This is the lowest order mode of operation of the laser and results in the best cutting performance. The Ferranti MF series of lasers give TEM₀₀ at all times. Higher order modes non Gaussian in shape, result in non-optimum cutting either by virtue of lower speed, poorer quality or less penetration. Figure 2 shows the beam profile shapes for Gaussian mode (A) and a higher order mode (B).

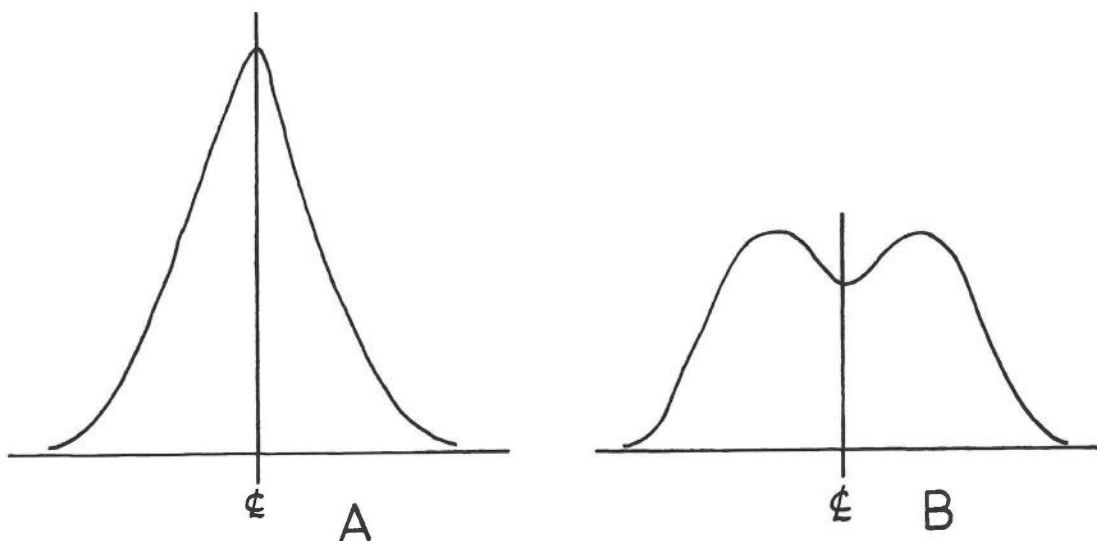


Figure 2: Laser Beam Intensity Profiles

POLARISATION

The laser beam output is usually randomly polarised, that is to say it is linear but varies in direction with time. The speed and quality of cut in metallic materials will vary depending upon the relative orientation between the direction of cutting and the polarisation vector. To overcome this variability, optics must be introduced to circularly polarise the laser beam, in this way uniform metal cutting is achieved, regardless of direction of cut.

MATERIALS

Not all materials lend themselves to laser cutting. Copper, brass, bronze, aluminium are difficult to cut due to their high reflectance at 10.6 microns and their thermal conductivity properties. However, they can be cut if the conditions are exactly correct and they are not too thick. Some non-metals, like polycarbonate, PVC and kevlar can be cut with a laser but produce hazardous fumes during cutting and the edge finish is not as good as most other non-metals. Excluding these exceptions then, the vast majority of common industrial materials can be cut by a Carbon Dioxide laser.

For example, using 400 watts of power, 1mm type 304 stainless steel can be cut at speed in excess of 4 metres/minute with a typical kerf width of 0.2mm. With a change to machine speed and assist gas pressure, the same laser can cut steel 5mm thick. The edges will be square and dross free. Using a 1KW laser stainless steel up to 10mm thick may be cut at production speed and excellent quality.

Cutting non-metals has some very interesting side effects. Acrylic can be given a "flame finished" edge with no further finishing necessary due to a combination of gas pressure and laser power. Certain types of glass can be cut very cleanly, as can cardboard, ABS plastic, plastic film, cloth. Wood especially has an attractively "stained" edge.

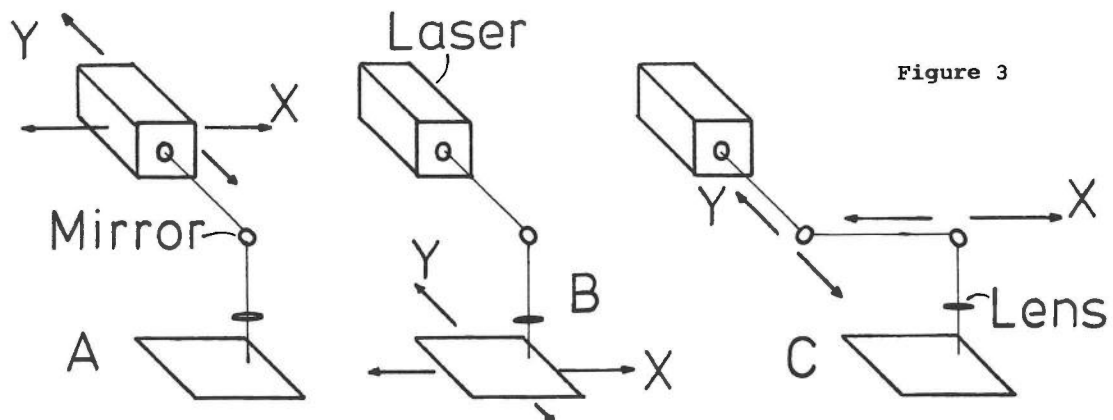
More recently the development of multi-kilowatt lasers with TEM₀₀ beam profiles such as the Ferranti AF Series Lasers will enable greater thicknesses to be cut, however it is thought that their main use will be for high speed (30 metres/min) cutting of thinner steels to replace the blanking process and associated tool changes.

SYSTEMS

The laser cutting system can be divided into 3 types:-

- Moving Laser Systems Fig 3 A
- Moving Workpiece Systems Fig 3 B
- Moving Optic Systems Fig 3 C

Figure 3 shows a stylised view of the three types.



Combinations of two of the three types can also be found. The choice of which type mainly depends upon the laser and the material to be cut. Obviously the laser in a moving laser system must be compact and rugged enough to survive and operate whilst on the move. Speeds in excess of 10 metres a minute can be generated and accelerations up to 1g have been recorded. The gantry system carrying the laser can be made big enough

to cope with even large flat sheets. Figure 4 shows such a moving laser system using a Ferranti MFK 1100 Watt laser. This system is installed in GEC Turbines in Manchester, England.

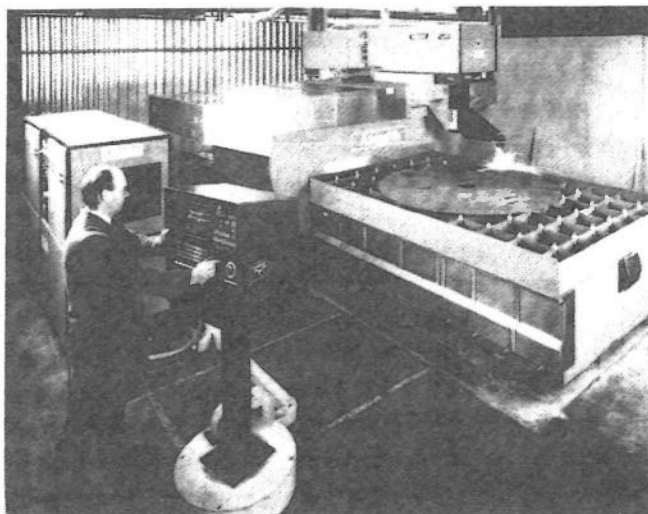


Figure 4: Moving Laser System

Moving workpiece systems are chosen where the component is relatively small and light. Machines of this type can be made compact for use in very confined areas. Figure 5 and 6 show moving work systems, the former utilising an MF400 and the latter an MFK, this system is installed at NEI Parsons, Newcastle, England.



**Figure 5
Moving Work System (Ferranti MF400 Laser)**

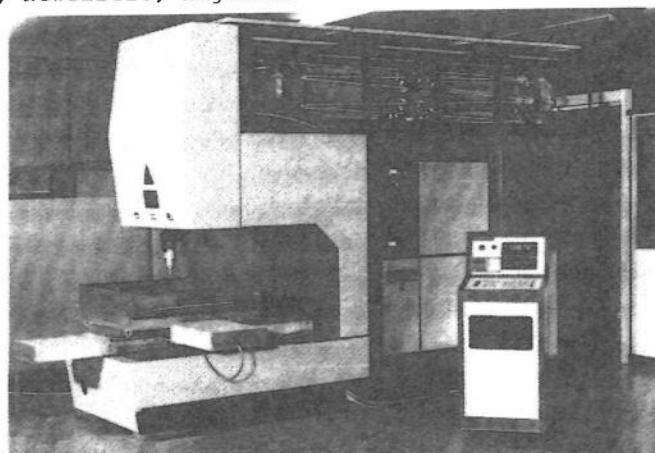


**Figure 6
Moving Work System (Ferranti MFK Laser)**

Moving optic systems use the extremely directional nature of the laser beam, and by a series of mirrors move this beam over the workpiece. Only lasers with very good pointing stability can be used on large moving optics systems, for, if the beam moves an appreciable amount, then the moving optics system will not be able to cope.

The most common form of laser cutting is 2 dimensional X and Y, with a small Z axis movement to allow for focusing. However it is becoming more popular to have 5 or 6 axis cutting systems. These fall broadly into two types. The robot system, whereby the robot moves an articulated beam guide carrying the laser beam over the worksurface. Figure 7 shows a picture of such a system using a Ferranti MFK 1100 Watt laser.

As no fibre optics exist for high power CO₂ lasers, this articulated arm is constructed of mirrors, guiding the beam down the robot arm to the focusing nozzle. The other type is the gantry type, an extension of the moving optic system, where X, Y and Z axes move the beam to a point in space and the Alpha and Beta axes tilt and rotate the beam. This latter type is more suited to trimming large pre-formed steel or plastic panels in, for example, the automobile industry.

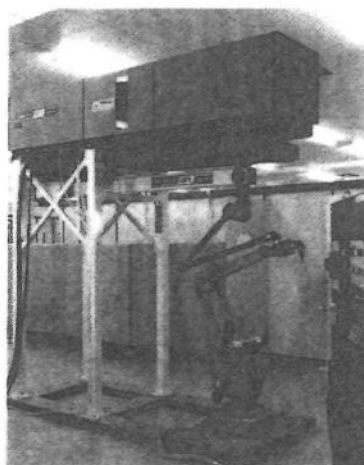


Figure 7: "Cobra" Laser-Robot System
(Ferranti MFK 1100 Watt Laser)

LASER WELDING

Laser welding is basically a simple process, requiring no filler wires, fluxes, electrodes or ancillary equipment. The power density used for welding is similar to that used for cutting, and so the same laser system may be used for both cutting and welding, and in some systems the conversion is software controlled.

A keyhole welding process, similar to electron beam welding, occurs with laser welding, however no vacuum chamber is required. If the parts to be welded are a close fit then no filler material is required. To prevent oxidation, argon or helium are used to shield the weld while it is being formed.

ADVANTAGES

The advantages of the laser technique can be summarised, compared with arc or resistance welding.

- Low heat input to the material, minimising distortion.
- Very rapid welds.
- Easily automated process.
- No weaving required.
- The only consumable is shielding gas, apart from normal laser requirements.
- It forms a narrow deep weld.
- It can be applied in confined areas.
- Access to only one side of the material is required.

MATERIALS

The range of materials which may be welded by laser is vast and includes the bonding of dissimilar alloys, carbon steels, plain steels, stainless steel, nickel alloys, copper and aluminium alloys/ (These last two again require precise control over the laser and machine parameters to achieve good quality results).

For a given material thickness, as a rough rule of thumb, laser welding requires 5 times the power compared with laser cutting. Some important parameters required for cutting play no part in the welding process. Polarisation for example is not important for laser welding as the interaction is with the vapours in the keyhole rather than the side of the cut.

THE PROCESS

To form a laser weld, the beam must be focused to just under the surface on the centreline of the joint. Initially much energy is reflected, but as the surface is heated, the reflectivity decreases until the material melts and vapourises. The removal of the material results in a hole being formed. This is called the "keyhole". The vapour pressure inside the keyhole prevents the molten walls from collapsing. As the beam moves over the material, the hole moves with it, the material solidifying behind forming a deep weld. Figure 8 shows this keyhole process.

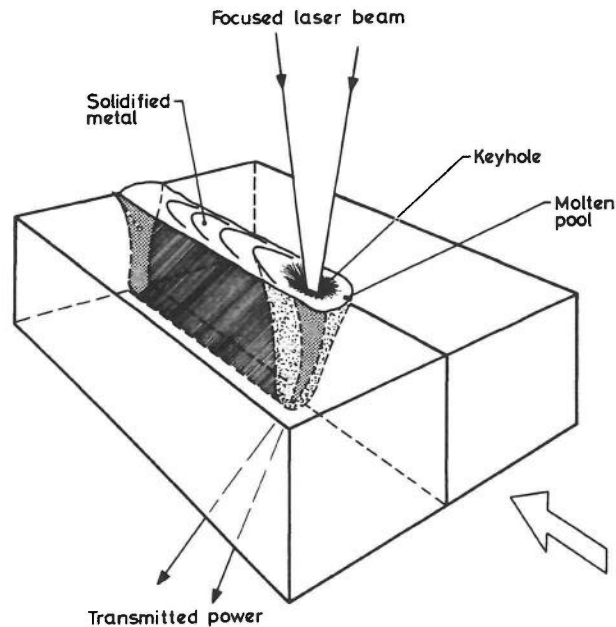


Figure 8: Keyhole Formation

Stainless steel that has been cut by a laser using oxygen as an assist gas does not weld satisfactorily due to the oxide layer on the cut surfaces. However if say, argon is used to cut the stainless, then it can be welded together very easily by the laser, as no oxide is formed.

Laser welding can be carried out at high speeds, for example stainless steel washing machine drums at 6 metres/minute with a 1KW laser, room thermostat assemblies at 9 metres/minute with a 400 watt laser. However for a maximum penetration, the speed must be reduced to less than 1 metre/minute. The plasma in the keyhole must not be allowed to escape the keyhole easily, and carefully designed gas jets enable it to be confined. Using such plasma control techniques, a Ferranti 10KW laser has welded 25mm thick steel in a single pass. Figure 9 shows a 5KW laser, the Ferranti CL5, used for such types of welding. Originally designed by Culham Laboratories and now built under licence by Ferranti, the CL5 and CL10 are ideal for deep penetration welds.

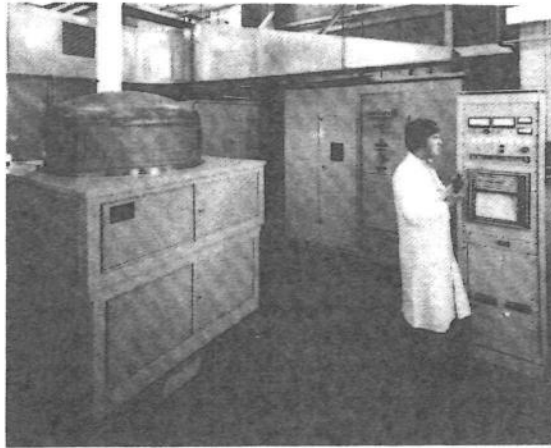


Figure 9: Ferranti CL5 Laser (5KW Transverse Flow Laser)

Welding can be accomplished with plain butt joints, overlap, tee-butt or tee-flared joints.

Welding non-metals can also be a very successful operation. Polyethylene, PVC, glass and man-made fabrics can be welded together. Very low powers are often required, however this can imply that using a high power laser means increased productivity. For example one plastic bag manufacturer is using a Ferranti 400 watt laser to weld polythene bags at several metres a second.

A good fit up and jiggling of the parts to be welded is essential. The gap in a clinch weld for example must be no more than 10% of the thickness of the material otherwise an unsatisfactory weld will result. Often the advantage for laser welding is the fact that the penetration can be controlled. For example welding tube to plate parts for heat exchangers, the tube must not be perforated, so the weld penetration is only half way through the tube wall. On a car door clinch, the weld penetrates through two layers of metal and only half way through the outer skin, leaving no blemish on the outer skin.

Recently the welding of galvanised coated steel has been successful in the Ferranti facility in Dundee.

LASER HEAT TREATMENT

Surface transformation using lasers covers many areas, glazing, hardening, alloying and annealing. The three main areas are Hardening, Alloying and Cladding.

THE HARDENING PROCESS

Transformation hardening, the most commonly applied laser heat treatment, is induced by heating a metal above a critical temperature and then rapidly quenching rather than allowing equilibrium phases to form by slow cooling. The most common transformations of interest are the formation of very hard martensitic structures in steel and the modification of cast iron.

It is essential that surface melting does not occur and that rapid quenching does occur, this is usually achieved by conduction into the body of the material, ie, it is self-quenching.

Transformation hardening is achieved by moving an unfocused laser beam across the surface of the material, ensuring by controlling power density and speed of traverse, that melting does not occur. In this way a thin surface layer is heated and then rapidly cooled by conduction once the beam has passed.

Other scanning methods can be used to heat small areas, and fairly complex optical systems can be designed to move a partially focused beam over a wider surface area. Higher order mode beam profiles can be used effectively here.

All steel that can be hardened in the conventional methods can be hardened by the laser. The carbon content of the steel plays a great part in the final level of hardness

achieved but hardness of $H_v = 700$ have been exceeded on 0.75% carbon steels.

Cast Iron can also be hardened, but much depends upon the distribution of the carbon in this material. If the carbon distribution is not uniform then the hardening process may have to be lengthened to try to allow for the carbon to diffuse throughout the material. Obviously cast iron of this type will require more stringent processing parameters.

Typical depths of hardening for steel and cast irons are 0.75 to 1.00mm, and the rate of hardening depends upon laser power, material composition, absorbing layer on the surface, hardness depth required, etc.

Advantages

The advantage of using a laser to perform transformation hardening are:-

- Very localised heat input.
- Negligible distortion of the component.
- Treatment of specific areas as required.
- Access to confined spaces is possible, eg, hardening the inside of small bores.
- Short cycle time required.

The obvious uses for such laser hardening systems are in the automobile or aerospace industry, eg engine components, gears, transmission joints, etc, in the production of gun barrels, to harden the interior rifling for example, and general industrial tools and dies. One advantage of using a laser system could first cut the shape required for, say, a trim die, and then go back over the top edge using a defocused beam to harden that edge. This has definite advantages in the production of tools and dies.

The Surface Alloying and Cladding Processes

Alloying is a process by which the surface of a material is first melted and then additional elements are added to this melted area so changing the composition of the surface. Cladding involves bonding a new material to the existing surface and minimal mixing of the materials occurs.

Both alloying and cladding require higher power densities than hardening, usually by a factor 2 to 3, however similar optical systems can be used to perform all three processes. Additional equipment is required to introduce the alloying elements to the surface, these elements maybe powder, wire or sheet and can be previously positioned on the surface or be applied during the process.

Alloying

In surface alloying, the depth of the alloyed layer is equivalent to the depth of melting and is controlled by the power density and interaction time. Fine homogeneous structures are generally found due to the high cooling rates achievable with the laser process. Most studies have concentrated on alloying of Chromium, Carbon, Niobium, Vanadium or Manganese to low carbon and low alloy steels, although work has been performed on treating aluminium alloys with silicon.

Advantages

The advantages of laser alloying are:-

- Low component distortion due to low heat input.
- Treatment of complex shapes possible.
- Fine control of melt zone depth possible.
- Accurate surface profile possible to save expensive alloying material and to minimise machining operations.

Cladding

While alloying relies on the complete mixing of the coating and substrate, cladding on the other hand required minimum mixture of coating and substrate. Obviously there must be some mixing at the interface between the two materials for good adhesion, but with laser processing this can be reduced to about 2% (substrate into coating). Other methods of cladding, for example the submerged arc process, may result in 50% mixing.

Common substrates include low alloy steel and stainless steels, while coating materials have included Stellite, Cobalt and Nickel. Cladding thicknesses, using multi-kilowatt lasers, can be between 0.1mm and 5.0mm, achieved in a single pass, although thicker depositions may be achieved with multiple passes.

Advantages

The advantages of using a laser for cladding are:-

- Minimum dilution of the coating material.
- Minimum distortion due to low heat input.
- Accurate profiling of clad surface possible, minimising waste of expensive cladding material.
- Reduced machining due to accurate deposition.

CONCLUSION

More and more industries are installing laser systems for a wide range of applications. The majority of the applications involve cutting, however as welding and surface transformation by laser are becoming established, they will grow in popularity.

Laser processing offers speed, versatility, accuracy, low running costs, no tool wear and ease of use.

Cutting requires good beam mode (TEM₀₀), circular polarisation, stable mode, good pointing accuracy and stable divergence. Many types of system are available each offering advantages for the end user.

Welding and heat treatment usually require higher powers, no polarisation (although some heat treatment developments are using polarised beams), stable mode and divergence. Higher order modes are more suited to these applications than TEM₀₀, although the Gaussian mode can be used.

Pulsing is essential for fine profile cutting in metals and has advantages in some welding applications.

The wide range of machines, matched with the appropriate laser, provide a very broad spectrum of industrial machine tools for many applications.

No doubt that the future will see the laser trend continuing and many more systems installed in all kinds of industrial areas.