Advances in Surf. Treatment vol I

84082

INDUSTRIAL PAPER

LASER APPLICATIONS IN METAL SURFACE HARDENING

John S. Eckersley

ABSTRACT

The acceptance of CO_2 lasers in industry to provide surface hardening is an established fact. Applications number in the hundreds in such diverse fields as automotive, office machines, air compressors, jet engines, military, paper converting, personal products, printing, plastics, forestry, mining, drilling, etc. The wear and fatigue characteristics of laser-hardened surfaces are reviewed. Reference is made to the operating principles of medium to high-power carbon-dioxide lasers. Typical examples are given of other laser processes such as welding, cutting, vaporizing, drilling, scribing, machining, etc.

KEYWORDS

Lasers; Metals; Hardening; Transformation; Melting; Cladding; Alloying: Welding; Cutting; Piercing.

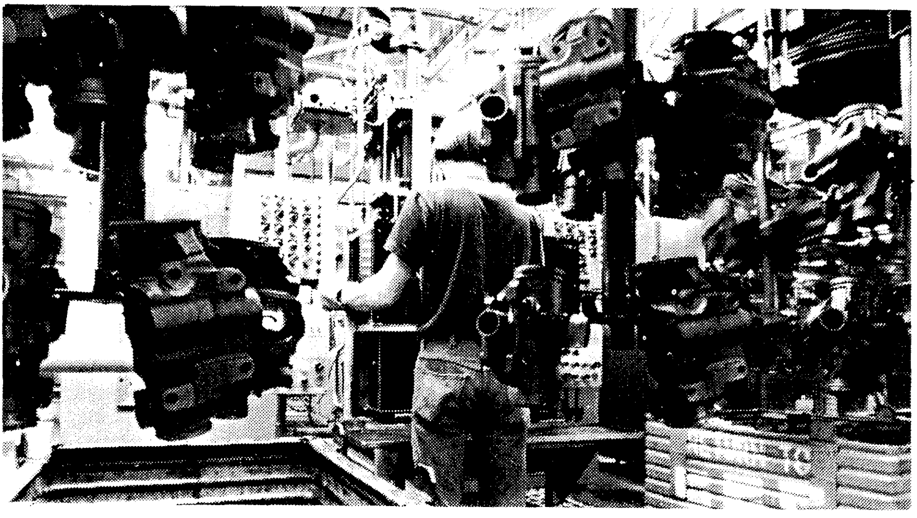


Fig. 1 Transformation hardening of inner bore of cast-iron power-steering gear housings. Seventeen lasers process 33,000 housings daily

INTRODUCTION

"Laser" is an acronym for "Light Amplification by Stimulated Emission of Radiation." Lasers produce light energy over the electromagnetic spectrum from infrared to ultraviolet, including visible light. Unlike conventional light sources, which generate energy at multiple wavelengths within this spectrum, lasers produce light at a single wavelength. In addition, while conventional light sources radiate energy in all directions out from a point, lasers generate light energy with very low beam divergence (almost parallel) which is also coordinated in timing and phase.

These properties of low beam divergence and single wavelength permit laser energy to be focussed to very small areas (typically 0.2 mm diameter) to produce the high energy densities that make lasers particularly useful for industrial applications, such as metal surface hardening, cutting, welding, piercing, scribing and vaporizing. Power densities of the order of 10^6-10^7 W/cm^2 are used in material-processing applications but for most metal surface hardening applications, power densities of the order of 10^3 W/cm^2 are very useful which, even at these levels, are considerably higher than can usually be obtained with conventional heat sources.(1)

Carbon-dioxide lasers, utilizing an active medium of carbon dioxide, nitrogen and helium gases, are generally recognized as the only type of commercially viable laser capable of producing sufficiently high power levels (500 watts to 15,000 watts) for metal surface hardening. Carbon-dioxide lasers also have higher energy-conversion efficiencies than solid-state lasers. CO_2 lasers derive their excellent process efficiency, not so much from the input to output energy ratio, but from the temendously high power concentration of the focussed beam, as will be demonstrated among the examples detailed below.

CO_2 lasers have been used in daily production to harden metals since the early seventies. The initial method employed was transformation hardening, which still remains the most widely applied. Other methods have emerged, and several are now in production. Some are yet confined to the laboratory, but offer enough real potential that they will be briefly discussed. These methods include, in addition to laser transformation or phase hardening, laser surface melting, laser cladding, laser alloying and laser-melt/particle-injection process.

LASER TRANSFORMATION HARDENING

In recent years, the laser has emerged as a fast, energy-efficient surface-hardening tool. The intense energy levels from CO_2 lasers can be optically focussed with great accuracy at selected areas to raise surface temperatures to the austenizing range so rapidly that adjacent unheated metal serves as the quench. The beam can be directed (Fig. 2) at a spot or oscillated to increase the width of a heated zone in a single pass or can even be optically shaped to cover a given area. Case depths of 0.2 to 0.6 mm are typical and usually sufficient: greater depths are difficult if surface combustion is to be avoided. Both beam motion and time can be computer controlled, and precise straight or spiral patterns can be developed with minimum heat-affected zone and little, if any, distortion. To increase the coupling efficiency of the CO_2 laser beam (10.6 microns wavelength) an absorbtive coating, such as manganese phosphate, colloidal graphite or black paint is often pre-applied to the metal.

Medium-carbon steels and cast irons are the most commonly treated materials, although alloy steels, such as 4340, 8620, 52100 and tool steels can also be selectively hardened. Processing rates range from 10 to 60 cm^2 per minute at 500 to 600 watts laser output power for surface hardnesses of Rc 48 to 64 and case depths of 0.2 to 0.6 mm.(2)

A systematic survey of laser surface heat treatment (conducted by IIT Research Institute and Fiat) revealed distinct limits beyond which unacceptable parts would be produced. Within these limits, rapid processes using high beam intensities appear least sensitive to power or speed variances. Power requirements (hence capital investment) can be reduced somewhat by operating at lower surface translation speeds, but maximum hardness levels fall off and the process becomes more sensitive to changes in speed, power or parameters relating to these. However, the surface-hardened area per unit of time is directly proportional to laser power.(3)

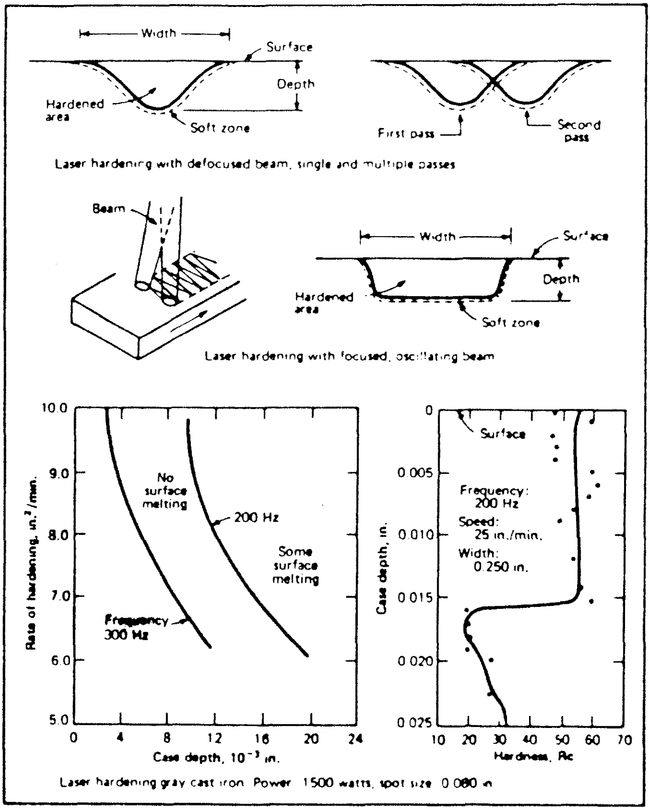


Fig. 2 Laser hardening with focused, oscillating beam extends surface-hardened area while preventing formation of soft zones within hardened area. Graphs by GTE Sylvania show case-depths produced at various hardening rates, as well as hardness profile.

The choice of a laser to perform a surface-hardening operation requires consideration of the total manufacturing process for the part in question. Sometimes, the choice is obvious: it is about the only way to accomplish the task. In other instances, thought must be given to: a) the area that really must be hardened or not hardened; b) distortion and related pre- or post-machining and/or grinding; c) overall process time; d) material substitutions; e) scrap rate, etc.

Power consumption today is a major consideration, as are the other laser consumables, gases and cooling water, but a 1000-watt laser typically operates in the U.S.A. at less than $5.00 an hour. Power consumption must be considered in the same light as the choice of a laser for the process: it is necessary to look at the total manufacturing process. For instance, in the surface hardening of Firing Zone Cutout Cams described below, the laser is reported to consume 0.29 per cent of the electrical energy required for the previously-used hardening process, but many other non-power related savings were also realized. On the other hand, a jet engine manufacturer recognizes that his laser process actually requires more electricity than the previous process, but allows greater process consistency and automation. An engineer at a typewriter manufacturer found he could reduce his energy consumption by laser hardening only the very small area where wear actually occurs, as opposed to the area (about 20 times greater) that he was obliged to harden using induction. However, it should be admitted that the real reason behind the change to a laser was to cut the distortion scrap rate from about 20% down to practically zero!

Steering Gear Housing

Since 1974, Saginaw Steering Gear Division of General Motors has been using CO_2 lasers to internally harden steering gear housings in what is perhaps the oldest and most prolific application of laser transformation hardening: an array of seventeen 1-kW lasers have hardened as many as 33,000 housings per production day (Fig. 1). The housings, which weigh about 5 kg each, are ferritic malleable iron castings and, originally, before lasers became the

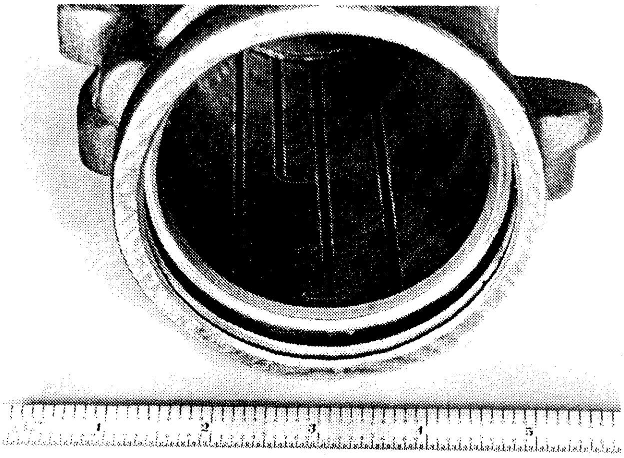


Fig. 3 Four wear stripes produced by laser surface-hardening in the bore of a cast-iron power-steering gear housing

final choice, many alternatives were considered to overcome wear that occurred in the main bore under projected higher operating loads. A change of material reduced wear but decreased machinability; different hardening processes, including clean-hardening, tuftriding, nitriding and controlled annealing, were tried, but all of these processes required an intermediate annealing operation prior to finish-machining to maintain proper concentricity. This, of course, increased cost beyond acceptable levels.

Examination of the resultant wear patterns in the housings indicated that, if these areas in the bore were hardened, the wear would be virtually eliminated. Induction hardening of these areas was tested and wear was reduced by 90%. However, the distortion was so large that the rack piston would not fit into the bore of the housing.

A need for a high-power, extremely controllable surface heating source led to the choice of a laser, and the hardened areas finally evolved into a series of five tracks strategically placed in the high-wear areas (Figs 3 and 4). The tracks are 1.5 to 2.5 mm in width and approximately 0.35 mm in depth. The total distortion created by laser-hardening was not measurable by normal quality control techniques, and the wear rate was 10 times better than the non-hardened areas in worse-case conditions. The application has proven to be very reliable with a maintenance efficiency of about 91% and a process efficiency of 83%, which includes downtime for whatever reason. The mechanical workstations contribute more to the downtime than do the lasers.(4)

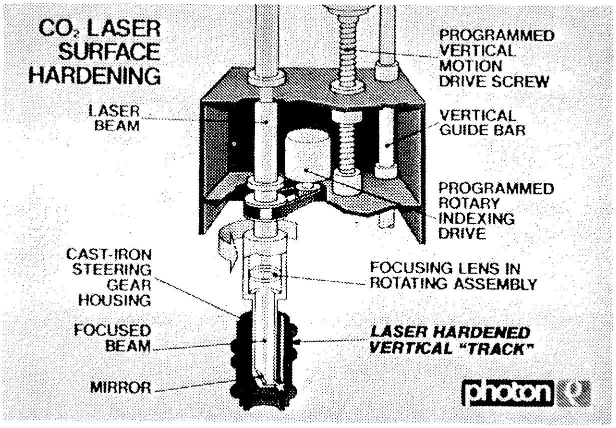


Fig. 4 Drawing shows basic arrangement for laser hardening of internal surfaces

Paper Corrugating Rolls

Perhaps the largest parts to be regularly laser hardened are 1250-kg rolls for corrugating kraft paper. The very abrasiv paper caused excessive wear on the crowns of the flutes and conventional furnace hardening of the entire roll was found to be both energy wasteful and impractical. With the use of a 1.2-kW CO_2 laser the crowns are brought up to Rc 60-63 to a depth of about 1 mm. The corrugating rolls are hardened by Viner Manufacturing Systems, Inc., a laser job-shop in Arvada, Colorado.(5)

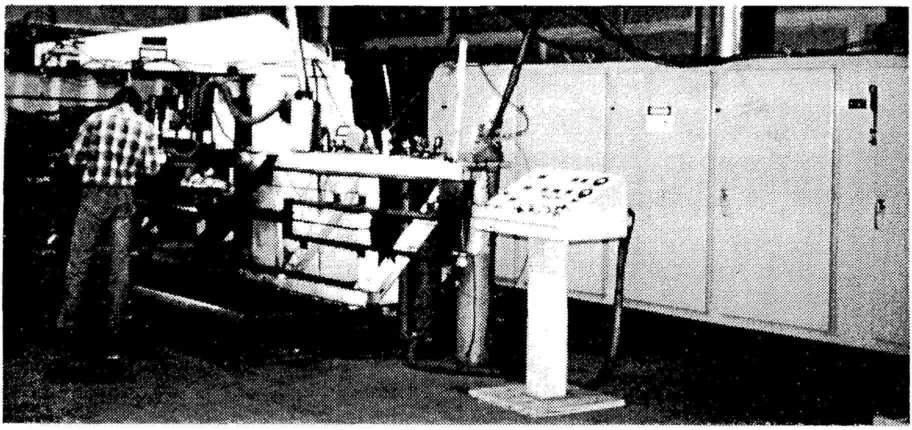


Fig. 5 View of laser hardening machine for processing 10 ft. corrugating rolls

The laser hardening process costs up to $850 per roll but results in a savings to the user of between $12,000 and $20,000 by nearly trippling the life of the roll. The laser-hardening method has been commercially successful for over 5 years. Figure 5 illustrates the laser-hardening machine with a 10-foot-long roll being hardened.

Cutting Blade

In this instance, the problem was to selectively heat treat one side of a cutting blade, yet maintain the toughness of the base material (1050 steel) without the need for tempering (a process requiring high energy consumption which usually can be totally eliminated when using self-quenching laser-hardening). The solution was found by utilizing the precisely controlled laser heat input, so that hardening could take place on one side of the cutting edge, while the other remained relatively soft for fracture prevention. A case depth of 0.6 mm at a hardness level of Rc 60-64 was generated by a 500 watt laser. Coverage rate of 25 cm^2 per minute was achieved.(6) (Fig. 6)

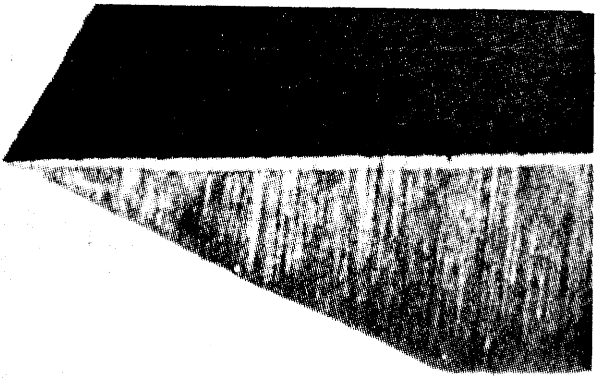


Fig. 6 Cross-section of a laser heat-treated cutting edge

Splines on Motor Shaft

Frequently, resorting to laser processing brings benefits in the down-the-line manufacturing procedures. Typically, a 20-mm diameter splined motor shaft was required to be press-fitted to another part. The shaft was of 1050 steel and when press-fitted, the soft splines became deformed so that a precise fit was not possible. The solution was found by laser hardening the leading edge of the splines to Rc 60+ to a case depth of 0.4 mm. The very fast laser-hardening made the process cost effective using a 500-watt laser.(6)

Diesel Engine Cylinder Bores

The ability to direct a laser beam, by the use of mirrors, into areas that often cannot be reached by other processes makes the laser a natural for hardening the inside surfaces of cylinders and cylinder liners for diesel engines for trucks, locomotives and stationary engines. Material is usually cast iron, and manganese phosphate or black paint is used as an energy-absorbing coating. In one particular instance, the beam from a 1.2-kW laser is directed by a concave mirror that, in addition to bending the beam at 90^{o}, also oscillates to widen the laser track on the surface of the part and focusses the beam as well. The process takes about one minute per part and the energy saving is estimated to be more than 70% when compared to the previous processing methods. Absence of measurable distortion from laser hardening eliminates the requirement for post-grinding.(7) (Fig. 7)

Fig. 7 Seventy percent energy savings are realized during laser hardening of cylinder liners

Firing Zone Cutout Cam

These items are used aboard Navy ships to confine launcher azimuth and elevation angles in order to prevent firing the missile toward ship structures. The contour of the cam corresponds to the nonfiring zone profile that is configured to the layout of the ship superstructure. A cam follower (contact pin), when in contact with the cam, tells the launcher not to fire). (Fig. 8)

The final step in manufacturing of the cam is case hardening, which was being performed by cyanide salt bath nitriding processing of the nitralloy steel cams. Based on 12 cams per year, this method cost $18,000 per year, which includes the high cost of disposing of the toxic cyanide salt waste and the total energy consumption of the 60-kW salt bath for this energy-intensive operation (Costs based upon historical data from the 1970s).

After careful consideration by the Navy, a 1.2-kW laser operated by Laser Application Inc., Baltimore, Maryland, was used to perform the tests required to supplant the time-tested but costly nitriding process. Calculations, after the final laser process was developed, showed that the laser could perform in a few minutes what required 24 hours in the cyanide bath at an electrical energy expenditure of only 0.29% of that required for the nitriding process.

Four steels were tested and AISI 4340 was selected as best because of hardenability, contractor experience and surface smoothness after laser transformation hardening. The nitralloy 135 modified (the original material) was found to be unsuitable because of surface erruptions and roughness upon laser impingements. The final process method chosen involved oscillating the laser beam to a track width of approximately 6 mm and stepping the rotating cam with a Computer Numerical Controlled table to produce parallel tracks around the circumference of the cam. (Fig. 9) A carbon spray coating was applied to the surface of the cam to aid absorbtion of the laser energy.

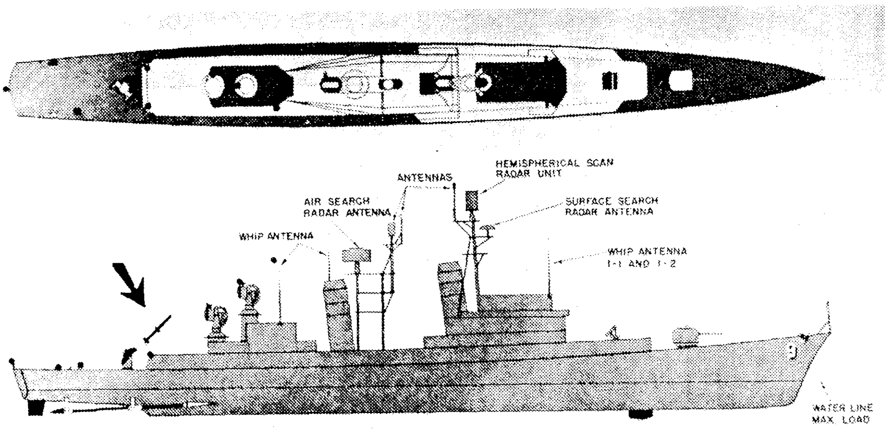


Fig. 8 Illustration of missile being fired, clearing ship superstructure

A summary of the results is provided below:

RESULTS

o Hardness: Profile = Rc 62; Overlap = Rc 51 (very narrow band)

o Depth: Profile = 0.015-0.017 in.; Overlap = 0.009-0.010 in.

o Tolerance: Within 4 min. train - Acceptable
Within 0.001 in. elevation - Acceptable

o Microstructure: Highly refined martensite

o Wear 0.0001 in.

Extensive wear and salt-spray corrosive tests were conducted on laser-hardened cams, which proved to be adequate in all instances. Case depths of 0.25 to 0.5 mm and hardness of Rc 55-67 were easily met, and dimensional tolerances were maintained by proper control of laser power and heat input through dwell time, locally rubbing-off of the anti-reflective carbon spray coating (at edges for instance) and through water-cooling techniques, if needed.

The very well-documented Navy report concludes by recommending the discontinuance of the cyanide salt nitriding process in favor of laser transformation hardening at a cost savings of $16,400.00 per year (for 12 cams).(8)

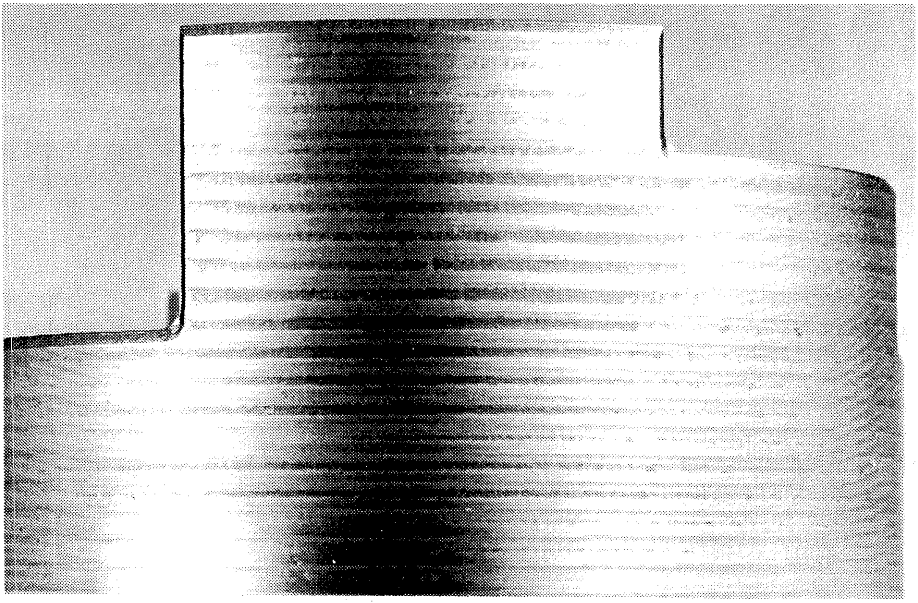


Fig. 9 Parallel laser-hardened tracks around circumference of Firing Zone Cutout Cam

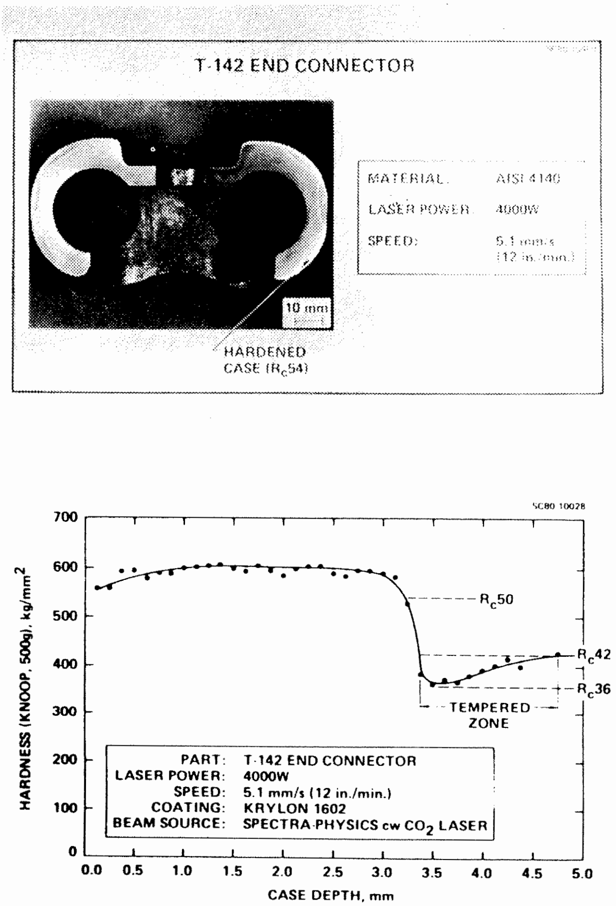
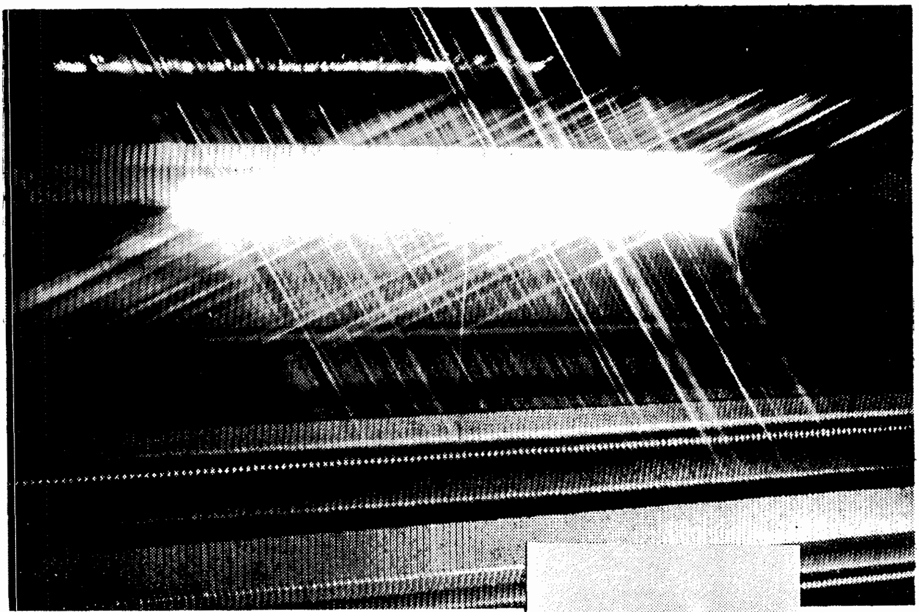


Fig. 10

Track Parts for Tanks

Under contract from the U.S. Army Tank - Automotive Command, Rockwell International has been conducting laser-hardening of the end connectors (Fig. 10) and center guides for the tracks on the M-1 and M-60 Combat Vehicles.

Laser phase transformation is being brought about by the use of a 5000-watt laser at a process time of 60 seconds per part to produce a case depth of 3 to 5 mm at a hardness of Rc 55. An absorbtive coating of black acrylic paint is used. Laser-hardening has been chosen because of precision location of the hardened zones and the great depth of hardened casing required by the very severe service conditions.



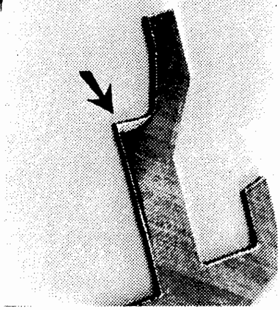


Fig. 11 Interposer bars, loaded several hundred to a rack, pass under laser-beam for self-quench hardening

Fig. 12 Close-up of hardened zone on interposer bar used in electric typewriters

Interposer Bars

Used in an electric typewriter each time a key is depressed, the impact area of the interposer bar requires it to be hardened (Rc 58 min) to prevent premature wear. Induction hardening was used for several years to harden the entire end of the interposer but more stringent dimensional tolerances made necessary a search for a more controllable method. Because of the relatively slow heat input of induction and lack of very precise control inherent in the process, an area about 20 times that of the local area where the actual impact occurs had to be hardened. A search of alternative methods soon revealed that the laser was the only tool able to respond to the need for hardening only an area 1 mm wide by 3 mm long to a depth of 1 mm. (Figs 11 and 12).

After spray with colloidal graphite, the racks travel at a controlled speed under the lens of a 1.2-kW laser, presenting the exact area to be hardened to the defocussed (about 3 mm spot) laser beam. Because the flat bars are all clamped in close contact with each other, there is sufficient mass to permit a self-quench.(9)

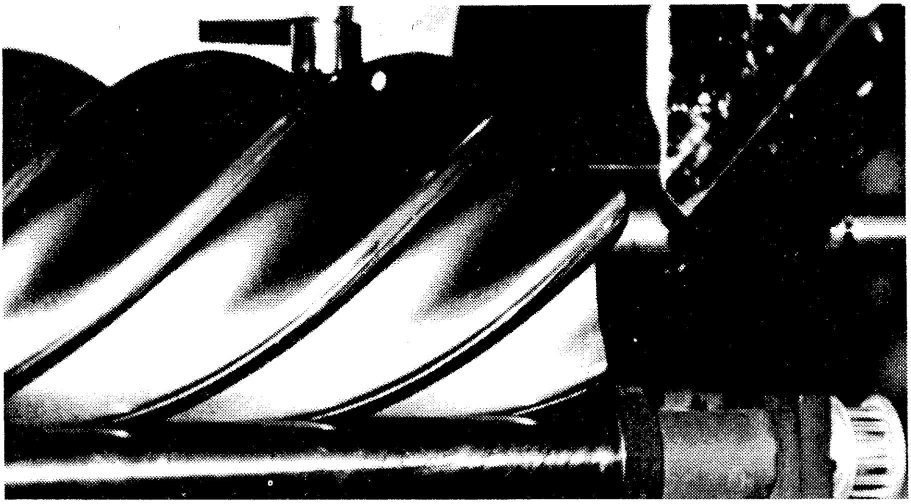


Fig. 13 Compressor-screw rotates under laser beam to harden wear surfaces

Compressor Screws

Screw-type compressors employ a pair of mating, counter-rotating screws to compress gases. The closer the gap tolerance between the mating screws, the higher the pressures that can be attained. Unfortunately, it also means increased wear on the rotating screws. Correction of distortion by grinding of flutes after hardening is extremely difficult and time consuming, so that most forms of hardening cannot be used, and the laser becomes an obvious choice of its minimal overall heat input.

A cam device rotates the compressor screw as it moves from left to right under the laser beam, so that the helical form of the surface to be hardened is always correctly presented to the beam. (Fig. 13) A narrow laser hardened track coincident with the contact path is sufficient to ensure against excessive wear of the two expensive screws, and no further finishing is required.(9)

Electric Razor Cutter Combs

Conventional hardening caused unacceptable embrittlement and distortion on the very fine teeth of cutter combs for electric shavers. A special technique had to be developed, masking half the beam from a 500-watt laser, to prevent overheating of the tips of the very fine teeth and to prevent distortion. Material is a 0.7% carbon steel, coated with MoS_2 spray, hardened to over Rc 60 in 3 seconds.(7) (Fig. 14)

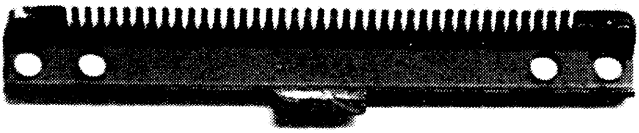


Fig. 14 Cutter-combs for electric-shavers are hardened using masked laser beam

LASER SURFACE MELTING

When a molten metal cools and solidifies rapidly, it often assumes different metallurgical phases than would occur during the slower cooling that usually accompanies conventional castings or other solidification techniques. Since laser energy can be used to heat very thin layers of metal surfaces, very high solidification rates are possible, and super-saturated phases typically occur. The effects of laser surface melting on Stellite #12 are shown in Fig. 15, which illustrates at high magnification the difference between the surface-melted layer and the Stellite #12 base metal. When some cast irons are surface-melted, the resulting lediburitic phase is significantly harder than any simple transformation hardened phase. On the other hand, a laser surface-melted tool steel is likely to form a softer, super-saturated austenitic phase. Upon subsequent tempering of this phase, extremely fine carbides precipitate, and the melt-zone hardness may exceed that of the original material. Laser surface melting offers the possibility of greater hardness than transformation hardening and it seems especially promising in the improvement of abrasive and sliding wear resistance.(10)

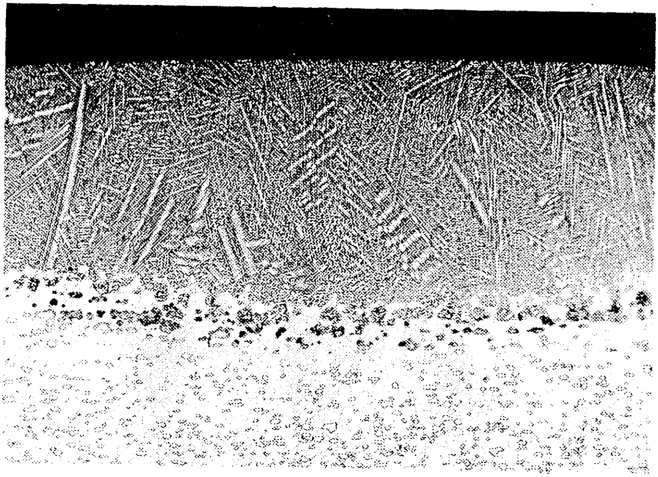


Fig. 15 Difference between surface-melted layer and Stellite #12 base metal can be seen in this high magnification photo

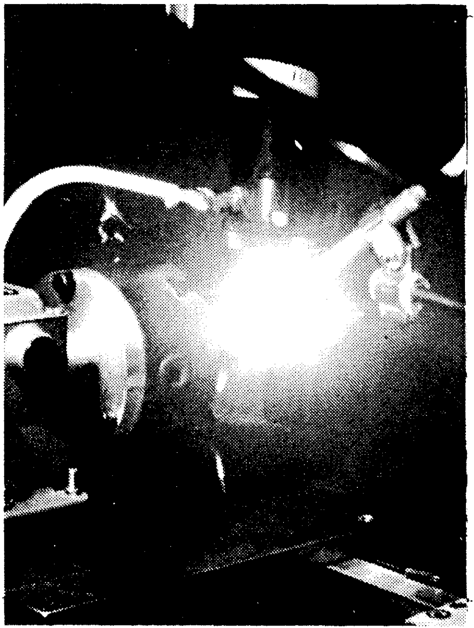


Fig. 16 Automotive Camshafts. Cast iron camshafts are being hardened in the lobe areas by laser surface melting and rapid resolidification under shielding gas. The process, using a 1.2-kW laser, has the advantages of being distortion-free, requiring very little surface finishing and using only about 20% of the energy required for the competitive inert-gas-welding process.(7)

LASER CLADDING

Laser cladding involves applications of wear and/or corrosion-resistant alloys to selected areas of a base metal, producing improved surface characteristics. Cladding or hard-facing alloys are usually cobalt, nickel or iron base, the selection of alloy (or even mixture of alloys) is based on factors such as service conditions, base materials, cladding process and cost.

Cladding or hard-facing procedures are well-established using conventional heat sources, but lasers offer some distinct advantages, particularly for very critical parts, such as jet-engine blades and diesel-engine exhaust valves (Fig. 17), valve seats (Fig. 18) and rocker arms (Fig. 19). The advantage of the laser is that the heat input is very fast, so that the cladding material melts with the minimum amount of heat being absorbed by the substrate material. The dilution of the clad deposit by mixing with the softer substrates is avoided while obtaining an excellent metallurgical bond. Much of this type of work has been accomplished by the use of very high power lasers which can provide an integrated beam with sufficient power density to cover an area as large as 10 x 10 mm.(10,11,12,13)

Rock-Drilling Bits

Figure 20 shows a portion of a rock-drilling bit during laser cladding. The bits are subject to concentrated erosion at the mud-jet ports. The erosion was the life-limiting factor of the drill bit. The erosion problem was solved by laser cladding an area around the mud-jet ports with nickel boron and tungsten carbide to a depth of 0.2 mm and the life-limit was transferred to the cutters, where it should be. The resultant 20% increase in performance produces a savings per drill bit of over $5,000 for an expenditure of only $100 for the laser cladding. A 1.2-kW laser is used.(14)

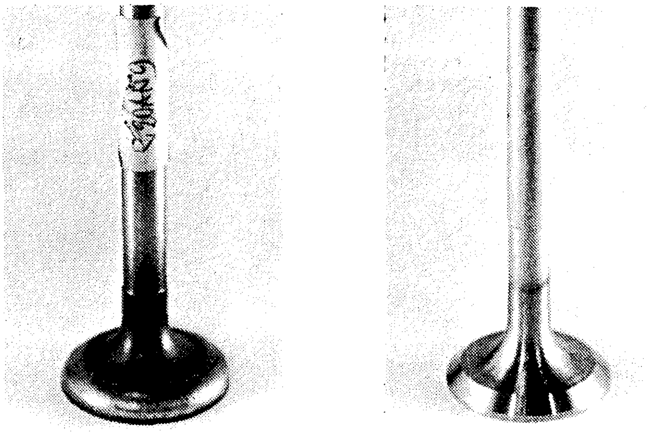


Fig. 17 Diesel-engine exhaust-valves, laser clad on sealing surface. Before and after grinding

LASER ALLOYING

Laser alloying differs from laser cladding in that the material added to the substrate is mixed into the surface rather than deposited on top of it, and so does not radically change part-surface geometry. Laser alloying involves many of the same requirements as cladding and offers the same benefits to industry, including the relative freedom in choosing processing parameters, such as depth of alloy and localization of treatment.

Laser alloying is accomplished by a controlled melting of a workpiece surface to a desired depth using a laser beam, with the simultaneous addition of alloying elements as powder, strip, wire or pre-form. The process becomes a rapid method of localized alloy synthesis. Thus, a desired composition can be generated on site, so that a less expensive base material, AISI 1018 steel, for instance, can be locally modified by the addition of 16% chromium to a stainless-steel-type surface possessing a martinsitic structure to resist wear, erosion, corrosion and high-temperature oxidation. The process is applicable to such items as process valves, pumps and turbine components. Similarly, very hard surfaces can be generated locally.(10,11)

LASER MELT/PARTICLE INJECTION

A variation of the laser surface cladding/alloying technique has evolved at the Naval Research Laboratory. The process has convenient application to non-ferrous metals such as aluminium and titanium-based alloys, where fewer options are available, and, therefore, is reviewed here, even though the process is very new and no production applications currently exist. Great improvements in wear characteristics were observed in both 5052 Al and Ti-6Al-4V alloys by the injection of TiC (titanium carbide), improvements that should arouse the interest of light-weight equipment manufacturers, in particular. On the other hand, preliminary results suggest that laser melt/particle injection may also be suited to the manufacture of carbide-hardened cutting tools using a base of AISI 4340 tool steel, for instance.

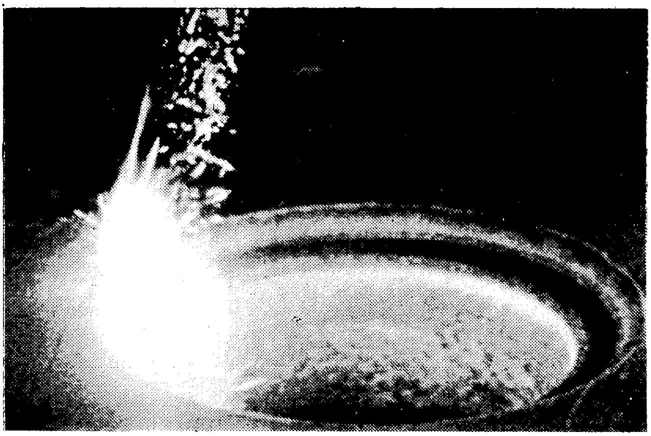


Fig. 18 Cladding being applied to valve-seat area in engine block

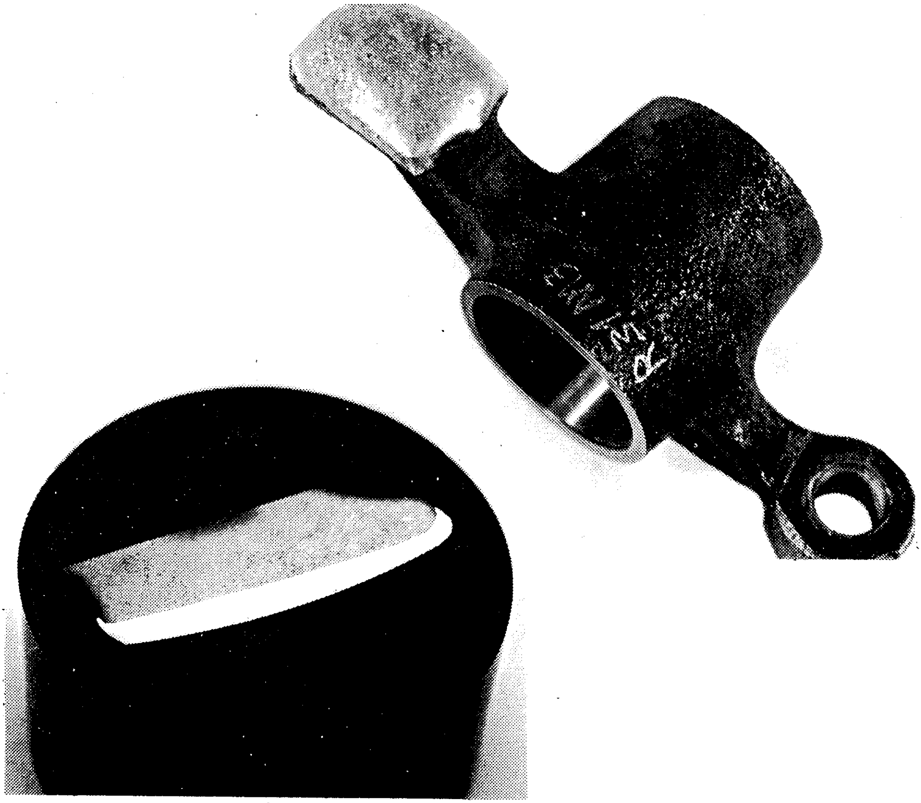


Fig. 19 Rocker-arm after laser cladding and before grinding. Insert metallurgical section of laser clad deposit (white area)

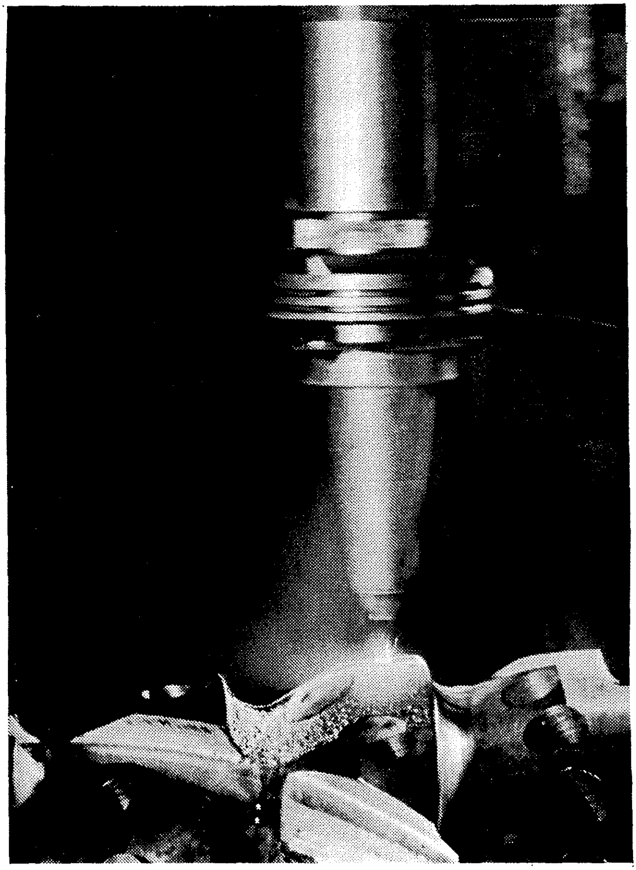


Fig. 20 Portion of rock-drill bit during process of laser cladding of mud-jet ports

The method for injecting particles into surfaces is shown schematically in Fig. 21, where a converging laser beam is seen to melt a liquid pool on the surface of a metal substrate moved relative to the beam. Powder particles are blown from a fixed nozzle into the melt pool and incorporated into the surface as the trailing edge of the pool solidifies. Processing is done in a vacuum chamber in a soft vacuum. A high-power laser was used to produce good laser melt/particle injection structures at power levels between 4 and 7 kW.(15) (Fig. 22).

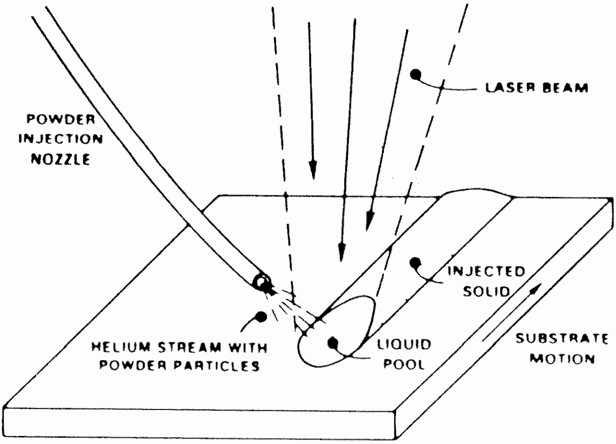


Fig. 21 Schematic showing injection of particles into a melt-zone established by a high-power laser. The particles are carried by a stream of helium

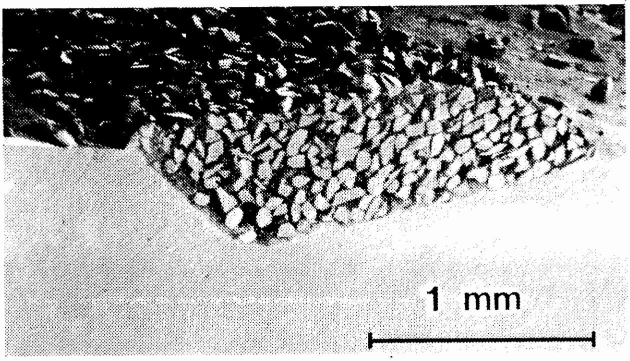


Fig. 22 SEM photo of laser melt pass in a sample of Ti-6Al-4V injected with -170+200 mesh TiC. This experiment used a laser power of 6 kW and a sample translation speed of 5 cm/s

LASER BI-METAL WELDING

Yet another approach in using lasers to provide a long-wearing surface is employed by Omark Canada Ltd. to produce chain-saw guide bars. The "nose" of the bar sustains the high wear-causing friction. The body of the bar is made of high-quality tool steel, and to this are fitted two strips of stellite, preformed in a U-shape to the contour of the "nose". These are laser welded to leave a groove through which run extensions of the links of the saw chain. (Fig. 23).

The entire process is fully automated and each weld takes 8.5 seconds, using the energy of a 1.2-kW laser, three of which are in continuous production operation.(16)

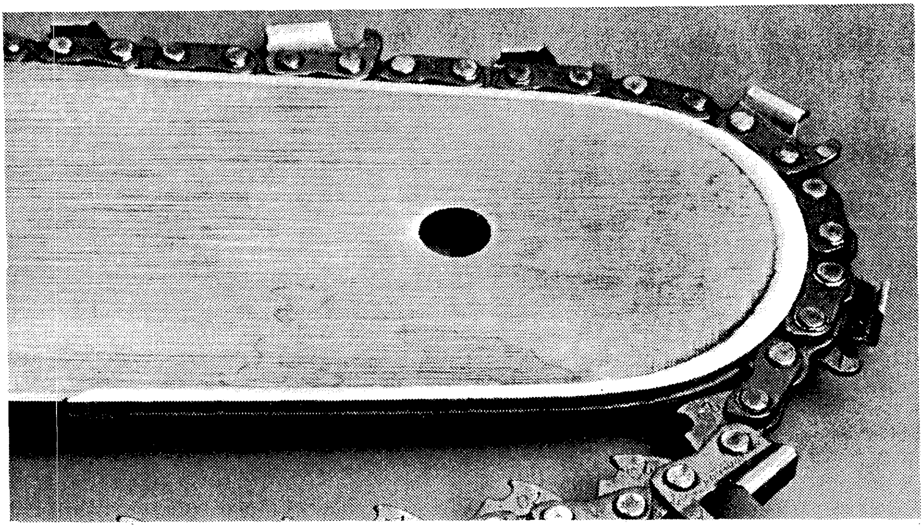


Fig. 23 Close up of chain-saw guide-bars showing Stellite wear-strips that are laser-welded to tool-steel bar in high-friction area

RESIDUAL STRESSES FROM LASER HARDENING

While the above examples amply illustrate the effects of laser processing on such mechanical properties as increased surface hardness with the resultant resistance to wear of various kinds and to erosion and some forms of corrosion, because of the relatively light case generated, an improvement in overall tensile strength or elasticity of a part should not be expected. On the other hand, the volumetric change associated with martensitic transformation is a principle cause of inducing residual stress distributions in case-hardened steels. It is therefore reasonable to expect high residual surface stresses of a compressive nature to be present after laser transformation hardening with the resultant improvements in resistance to tensile stress-related failure modes, such as bending fatigue and stress corrosion cracking in the laser-hardened areas. Relatively little testing has been done in these areas, but results are well indicative of the presence of residual compressive surface stresses. For instance, specimens of AISI 1045 steel, after laser-hardening to Rc 52 on one face and Rc 61 on the other, showed compressive stresses in the order of 462 Mpa (67KSI) and a fatigue-life improvement of 15%, as compared to the non-treated specimens.(17)

Another interesting example is that of laser cutting or profiling. Stainless-steel plate-valves for air compressors are cut out using CO_2 lasers. When tested for bending fatigue, the valves exhibited an improvement of 15% in fatigue-life when compared to photo-etched valves.(18) This is not surprising since the laser-cut edge is also transformation hardened as it is being laser cut, but the fatigue improvement becomes more interesting when it is noted that the laser-cut edge, although essentially burr-free, exhibited very sharp corners in comparison to the relatively rounded corners of photo etching.

Using lasers solely as a means of introducing compression stresses is probably not very practical or justifiable unless, perhaps, very localized areas are involved, since a process such as controlled shot peening can introduce higher compressive stresses over larger areas much more economically.(19) What is significant in the above tests and others, is that the laser transformation-hardened surfaces and laser-cut surfaces showed no effects that were detrimental to bending fatigue-life.(20)

SUMMARY

The application of Carbon-Dioxide Lasers to produce hardened surfaces on metals has been well illustrated here, but CO_2 lasers are by no means limited to hardening processes: more and more applications are being found each day. Significantly, the number of material-processing CO_2 lasers in industry reaches into the thousands, worldwide. A recent publication lists many of the specific applications that are current in such widely diverse fields as electronics and communications, graphics and packaging, aerospace, automotive, consumer products, home appliances, office products, construction products and transportation.

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