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APPLICATION OF HIGH ENERGY DENSITY HEATING IN HEAT TREATMENT PRACTICE

J. H. P. C. MEGAW

CULHAM LABORATORY
Abingdon Oxfordshire

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J.H.P.C. Megaw

UKAEA Culham Laboratory, Abingdon, Oxon, OX14 3DB, UK

ABSTRACT

The use of high power density heating sources for the localised surface treatment of components offers the potential for energy efficiency, low distortion, and rates of self-quenching which yield useful metallurgical microstructures. In such surface treatment applications, lasers and electron beams (which are uniquely suited to deep penetration welding) are manipulated to power density levels approaching those of modern plasma and induction-based sources. This paper therefore describes relevant features of the respective heat sources, and then discusses in turn some of the specific treatment processes, developments and applications which have been achieved by their use.

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AUGUST 1983

INTRODUCTION

One of the most salient features of thermal surface treatment at high power density is that the effect is localised by the extent of the source, and localised in depth because the heating effect occurs at or close to the component surface, i.e. the process is energy efficient because only the necessary part of the surface is treated. The high intensity flux can result in high surface temperatures and steep gradients into the workpiece, thereby yielding low component heating and high cooling rates, and obviating the need for external quenchant (although possibly increasing the thermal stresses). Rapid treatment rates are achieved, with reduction of distortion and dilution and with the possibility to reduce or eliminate post-treatment machining. Two high energy density sources which readily spring to mind are laser and electron beams. Their distinguishing feature is the ease with which they can deliver intensities of a megawatt per square centimetre or more, and they have opened up new routes for the demonstration of novel metallurgical phenomena. However, it is ironic that, so far, in many practical heat treatment applications they must be defocused to yield much lower intensities. Thus in some cases their capabilities must be compared with specialised versions of some of the longer established high energy density sources such as induction, TIG and plasma arc. Therefore the aim of this paper is to first describe the relevant features of the various heat sources and then discuss in turn the specific treatment processes possible with them.

SOURCES

Lasers

Since the first demonstration of laser action in 1960, vigorous research and development have led to a rapid sustained growth in the number of laser types, in the output powers produced, and in the scope of their applications. In the relatively specialized field of metal working, it has emerged that only a very few laser types dominate and attention is confined here to medium and high power carbon dioxide lasers. There is now a widespread realisation that these merit consideration as production engineering tools for cutting, welding and surface treatment, and their acceptance continues to grow despite their relatively high capital cost and technical sophistication. A recent US survey (1) predicts a tenfold growth in the laser materials processing market by 1990, and around the world significant effort is, and has been, devoted to the development of industrial lasers of $\leqslant$ 10kW power (2-10). Good mode control in particular designs means that 19-25mm weld penetrations can be achieved at ~ 11kW (11)(12). Figure 1 shows the Culham Laboratory 5kW laser CL5 with 3 workstations. For laser surface treatment, extended patterns having intensities down to 10^3 watts/cm^2 are needed, and a variety of techniques can be employed such as defocusing, multimode operation, composite mirror or lens assemblies, vibrating mirrors or rotating multi-facet mirrors. In deep penetration welding, the finely focused beam is coupled with high efficiency (≤ 90%) into the plasma-filled keyhole; in transformation hardening, since a clean metal surface acts as a good reflector to the defocused beam, coatings such a colloidal graphite or manganese phosphate must be applied and can produce absorption up to 80% (13). Surface melting processes utilise intermediate intensities or high scan speeds so that a full keyhole is absent; coupling then depends only partly on geometrical trapping and partly on surface plasma absorption. In considering the laser for production-line heat treatment, the following considerations apply. The laser is versatile and flexible, capable of a range of processes, and has a beam which can be directed through air by metal mirrors and switched or shared between a number of workstations (Figure 1). Using lens or mirror based techniques, the beam pattern at the workpiece can be altered fairly readily. The beam can fuse additives on to surfaces with great precision. Set against these considerations are the comparative youthfulness of the technology (particularly at multikilowatt powers), its high capital cost and the low efficiency of power generation (≤ 7%), although systems based on e.g. carbon monoxide may yield significant improvement in this respect (14).

Electron Beam (eb)

It was first recognised around 1950 that electron microscope technology could provide a means of metal melting and welding, and by some ten years later, production equipment was in existence capable of delivering ~ 5kW and of welding ~ 25mm steel, in vacuum. Thus the succeeding 20 years have seen a period of refinement and expansion of the technology; Figure 2 shows schematically, after (15), a typical eb arrangement. Over the years, emphasis has been placed on a variety of aspects: optical quality, stability and reproducibility; ease and reproducibility of filament replacement; seam tracking for welding; minimisation of X-ray hazards; implementation of computer and microprocessor control; attempts to minimise the adverse effects of vacuum requirement. In surface treatment, the eb (like the laser beam) must be scanned or rastered to increase coverage and reduce power density. The tailoring of specific heating patterns may be facilitated by having the beam describe a dot-matrix array (16). Electromagnetic deflection of the eb is clearly easier than mirror deflection of laser beams. The capital cost of eb equipment depends sensitively on vacuum chamber requirements, and typically at powers of around several kilowatts the technology is similar in price to that of laser, although eb enjoys significantly higher efficiency of beam power generation. The penetration range for 120kV electrons is ~ $20mg/cm^2$ (~ 0.03mm steel) and the coupling of energy is high, except for glancing angles $\lesssim 20^o$. Thus the principal considerations in comparing eb and laser concern operating efficiency, necessity for absorbing coating, and implications of vacuum on handling of parts and materials to be added.

Induction

Induction heating began to attain real commercial significance from around 1930. In comparison to the two foregoing sources, heat is generated very significantly further within the workpiece, and with current penetration scaling inversely as the square root of frequency, it is appropriate here to consider mainly the use of ⩾ 200kHz. The skin depth in steel is ~0.03mm and surface layers ⩽ 1mm can be austenitised and hardened without quenchant. The process is particularly suited to the treatment of circularly symmetric geometries, and the poloidal field distribution around a coil leads to efficient coupling to bars but inefficient coupling to bores. Inductor stand-off must be accurately maintained, so that the process is much less tolerant in this respect than laser or electron beams. If used to generate surface melt layers, there is a risk that these may be disrupted by electrodynamic forces. Inductor design must allow for the sensitivity of the process to component section; at an edge or point, account must be taken of not only the reduced heat sinking there, but also the enhancement of current and therefore heating. (Only the former need be allowed for in laser and eb heating). In the context of localised, high power density heating, it is particularly relevant to note the use of (a) charged capacitor banks to drive the oscillator so that very high power, tightly-controlled pulses can be generated using a low average power supply (17), and (b) induction-resistive heating where a portion of the workpiece becomes part of the coil, Figure 3, after reference (18).

Tungsten Inert Gas (TIG) and Plasma Transferred Arc (PTA) Torches

The TIG torch, first used commercially in welding from about 1940, is shown schematically on the left hand side of Figure 4, with the constricted plasma transferred arc version on the right. The power density applied to a workpiece can lie in the range 10^3 to $10^5 W/cm^2$. Transformation hardening by

TIG torch (19) and by PTA is possible, as are surface melting operations. The torches, like induction heating, lack the ultimate precision capable with laser and eb heating, i.e. whilst the beams can be manipulated or tailored to paint an exact pattern with a sharply defined edge, the physics of magnetic induction and plasmas precludes such total control of the spatial power distribution. The torches are also sensitive to electrode degradation, and they require a 'co-operative' workpiece i.e. maintenance and stability of the arc can be jeopardised by oxides and inclusions. Nevertheless, they have the significant merit of relatively low capital cost.

SURFACE MELT QUENCHING

The application of heating intensities $\sim 10^5 W/cm^2$ for times of order milliseconds to metal workpieces can result in the creation of layers several tens of microns thick which melt and then quench at rates $\lesssim 10^6$ °C/s. The resulting structures will be microcrystalline or, in appropriate compositions, amorphous (metallic glass) and may have interesting and useful metallurgical and mechanical properties. For example, these microcrystalline structures may exhibit, in addition to a highly refined as-cast grain size, enhanced solid state solubilities, modification of segregation behaviour, and formation of metastable phases. Although chill casting from a melt can produce rapidly quenched foils and ribbons, the attraction in applying high intensity heating to a surface lies in the potential to coat a component with a durable skin; for example, heating may be achieved by rapidly scanning a laser beam (20) or an electron beam over the surface. Whilst a considerable body of such work concerns the creation of amorphous layers in PdCuSi, NiNb, FeB, or aims to study in detail non-equilibrium thermodynamic processes of diffusion, segregation, precipitation etc, it is more appropriate here to summarize briefly work aimed at creating microcrystalline layers having possible practical application. Of the non-ferrous materials, the nickel-base superalloys have attracted attention because of the potential to improve gas-turbine design, and multikilowatt CO_2 lasers have been used to investigate quenched structures in alloys such as Mar M200, B-1900, U-700 and IN-100 (20). Similar treatments have been applied to Zircaloy (21) and titanium alloys (22) to create a martensitic skin with the objective of improving resistance to stress corrosion cracking. Laser treatment of Al (23) and Al-1.2Mn (24), by pulsed ruby and CO_2 lasers respectively, considerably modified the surface finish and yielded some indications of improved corrosion resistance. Turning now to ferrous materials, considerable attention has been directed to surface treatment of steels and, in particular, tool steels since it is hoped that improved tool lifetime and cutting performance may result from small grain size and homogeneous dispersion of fine carbides. Splat quenching of steel commonly results in the formation of δ-ferrite and austenite due to stabilization of these phases at high cooling rates and because fine grain size lowers the M_s temperature (25). The effect is enhanced by increasing carbon level, and work on laser surface melting of 1C-1.4Cr steel (26) showed considerable stabilisation particularly where an absorbing colloidal graphite coating may have been alloyed into the surface. Laser or electron beam treatments of A2 (27), M2 (28) and M42 (29) tool steels also tend to show retained δ ferrite and austenite, so that subsequent heat treatment is necessary to destabilise the austenite to martensite and to promote secondary hardening effects. Figure 5 shows (29) microhardness results for M42 steel treated with a scanned electron beam; the peak hardness is claimed to be higher than conventional treated materials, and for increasing scan speeds, further stages of tempering are required to bring about optimum secondary hardening. It is necessary to remember that in much of the published work on rapid surface melt quenching, there is either little mention of residual stresses in the layers, or indications of cracking are noted. This aspect requires due attention, as does assessment of the relative merits of electron and laser beams. Intuitively, at least, it would appear that an eb would couple to the workpiece with greater efficiency and stability, particularly in the absence of a full keyhole. This is borne out in at least one published account (30). For an example of production application of surface melt quenching we must turn to much slower cooling rates and use of a TIG torch in recasting a wear-resistant white iron (ledeburitic) layer on cast iron camshafts (31). Rotation of the lobes under the torch, which is scanned side-to-side, results in creation of an approximately 1mm deep layer with the characteristics shown in Figure 6. Although probably not yet in production, electron and laser beams have been used to investigate creation of similar ledeburitic layers (32)(33)(34); Figures 7 and 8 show (35) the improvement in wear resistance resulting from laser surface treatment of grey cast iron, and the control which can be exercised in the creation of transformed layers (having ledeburitic surfaces) by suitable choice of power density and interaction time.

ALLOYING

The process consists of melting a workpiece surface to a controlled depth and incorporating into it elements (which are preplaced or fed to the interaction point) to create a layer offering enhanced properties, although with a concentration gradient normal to the surface. Most published work concerns use of lasers, a considerable amount of it dealing with application of pulsed lasers to thin films deposited on substrates, and with the emphasis on phenomena such a diffusion, metastability etc. Work with scanning high-power laser (or electron) beams is possibly more relevant to engineering applications, and for example investigations have been carried out on the alloying of one or more of Cr, C, Mn and Al on AISI 1018 steel (36). Where the additive melting point is significantly higher than that of the substrate, appropriate treatment conditions can result in the latter flowing and encasing the additive powder particles; increasing energy density results in controlled dissolution of the particles. Two good examples of this are silicon on alumimium alloy and carbides on metal substrates. Figure 9 shows an example of the former (37); parts a, b and c correspond to the 5kW laser beam being scanned at speeds of 67, 56 and 42mm s^{-1} respectively. Whilst at the highest scan speed there has been insufficient energy input for the eutectic matrix to adequately form and totally encase the silicon particles, the voids disappear at the two lower scan speeds although hardness also decreases. The hardness of the primary silicon is 980HV and that of the structure at b is ~ 350HV; this structure showed a wear rate approaching one quarter the level seen with the untreated substrate. In the work involving carbides (38), TiC and W have been delivered in a gas stream and 'injected' into a laser-melted surface layer on Fe, Ni, Ti, Al and Cu base alloys, and it is reported that several of the metal/carbide combinations exhibit good resistance to abrasive wear. Similar effects have been demonstrated using eb (39).

CLADDING

In contrast to the foregoing, the aim here is to create on a workpiece a fused layer of additive which is metallurgically bonded by the melting of the thinnest possible skin of substrate, thereby minimising dilution. The use of automated high power density sources such as TIG, PTA and laser are attracting increasing interest and acceptance in the nuclear and aerospace industries where coating integrity and microstructure are crucial. TIG normally operates with wire-feed, and two investigations (40)(41) (the latter related to nuclear power plant where there is a strong incentive to find a replacement to cobalt-base alloys) have demonstrated that defect-free deposits can be achieved in both the reference cobalt alloys and in alternatives having a nickel base. In the PTA process metal powder is fed into the plasma; it is claimed (42) that the process is less parameter sensitive than that of TIG, and that the buffering action of the molten pool between the workpiece and the arc, combined with the heat distribution in the constricted plasma, result in low and reproducible levels of dilution. Figure 10 from reference (42) shows a transverse section of a PTA track of Stellite 6 on constructional steel; torch power was ~ 2kW and it was weaved side to side to achieve the width shown. Laser cladding is also well suited by having the additive in powder form, and the process appears to have much in common with PTA. The laser lends itself particularly to precision components, and one of its most notable production applications is the use of a 2kW unit for cladding of gas turbine blade interlocks (43). The cobalt-base clad layer is very sensitive to potential dilution by the nickel-base substrate, which is in turn prone to HAZ cracking if subjected to excessive heat input. The laser has successfully replaced manual TIG, with increase in productivity and decrease in material usage, heat input and number of production stages. Finally, Figure 11 from reference (37) shows another precision application, here of Stellite on a cast iron test piece and after post-deposition machining.

TRANSFORMATION HARDENING

Here, typical applied power densities are around $3kW/cm^2$ averaged over the pattern. With dwell times of order 0.75s, depths $\leqslant$ 1mm can be readily hardened without quenchant in irons and steels. Tracks of this depth are normally more suited to imparting wear resistance than component strengthening. The localisation of the heating results in minimal distortion and provides the main motivation for use of these sources. Prediction of the thermal response of the workpiece, particularly in the case of laser and electron beam heating, is relatively straightforward if the workpiece thermo-mechanical properties are known, and many accounts exist of calculations for moving heat sources of arbitrary distribution. However, one-dimensional heat-flow models frequently predict transformed depths adequately (13)(35). Prediction of the metallurgical response of the workpiece is more difficult (39)(44) since the characteristic brevity of the process cycle means that whilst alloy and tool steels are easily treated, structures with widely dispersed graphite or carbide require greater care. For example (45), in a normalised 0.4% carbon steel, the brief excursion above austenitising temperature at the bottom of the case results in insignificant diffusion of the carbon and although the pearlite transforms to martensite, the ferrite remains largely unchanged. In contrast, at the top of the case the carbon diffusion results in a homogeneous martensitic structure, whilst in the intermediate region the structure grades between the two extremes. Figure 12 shows (45) results from the treatment of such a steel. The lower part of the figure shows the scaling of transformed depth with dwell time, for three intensities. The upper shows that for each intensity, the hardness of the working surface goes through a maximum; times below the optimum yield inadequate heating, and those above yield inadequate (slack) quenching. Turning to the question of residual stresses in self-quenched layers, it appears that a full quantitative understanding and control of their distribution is not easily achieved and remains to be demonstrated. The main contributions to the final distribution are of course a compressive component arising from transformation to the lower density martensite, and a possible tensile component arising from the cooling of material which has undergone a local plastic expansion. Distributions produced with quenchant are expected to be different from those produced without. The evidence is however that surface compressive stresses can be achieved, and such results are reported, for example for hardening by laser (46)(47) and electron beam (48). Fatigue testing of laser treated and untreated rotating bend steel specimens (49) showed increase in fatigue life by a factor of 15 and improvement by as much as 30% to the fatigue limit, Figure 13. Probably the best known production line applications for lasers are those of bore hardening in the US motor industry at powers up to 5kW (50)(51). In one of these, a ferritic malleable is successfully hardened because of the high surface temperature. A recent account (52) of several other US industrial applications underlines the use of localised wear patterns (spirals and straight tracks, as distinct from all-over hardening) and the attendant minimum distortion. Other accounts describe production applications of laser hardening of microscope slideways (53). It may be that the automation of laser hardening will be facilitated in due course by devices such as that shown in Figure 14, where laser and robot technology have been integrated (54). Electron beams are receiving growing acceptance for production line use, and Figure 15, after reference (16), illustrates a good example where US automatic transmission cams in SAE5060 steel are selectively hardened. The electron beam describes a pattern on the prealigned grooves in a stack of 3 cams. The stack is then indexed for sequential groove treatment. Total venting and evacuation time per cycle is 14s and the treatment time, including indexing, is $\sim$ 24s. Finally, Figure 16 shows a production line application of RF induction-resistance heating (55). It is the hardening of teeth on steering racks at a production rate of 500 per hour.

CONCLUSIONS

This paper has attempted to compare and contrast features, applications and developments of a number of surface heating sources which may be classified as having 'high' power density. In many applications, laser and electron beams, although capable of offering high power densities uniquely suited to deep penetration welding, are effectively down-rated to levels comparable to modern plasma and induction-based sources. Technical and economic evaluations and comparisons therefore require increasing care and, broadly speaking, the flexibility, controllability and precision of the newer sources must be weighed against the lower capital cost and continuing refinement of the longer established sources. Each source has found a market, and although only time will tell, it seems likely that each will continue to find its niche for some considerable time to come.

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Fig.1 5 kW Laser and Workstations at UKAEA Culham Laboratory.

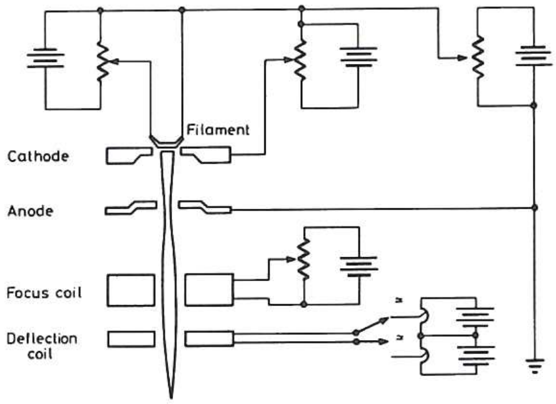

Fig.2 Electron Beam Schematic (15).

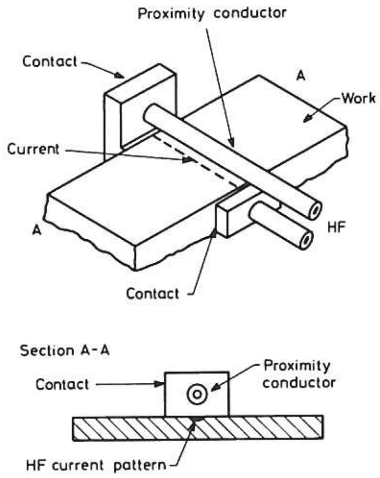

Fig.3 HF Resistance Heating (18).

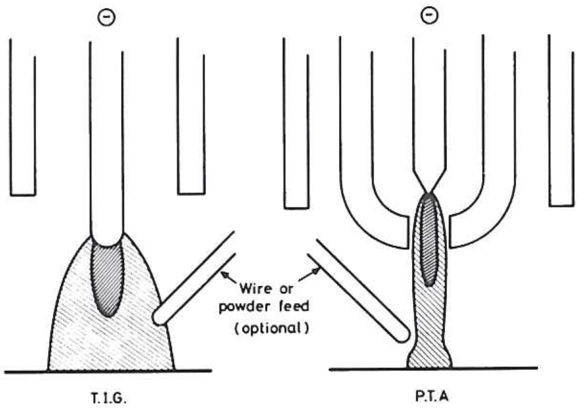

Fig.4 TIG and PTA Schematic.

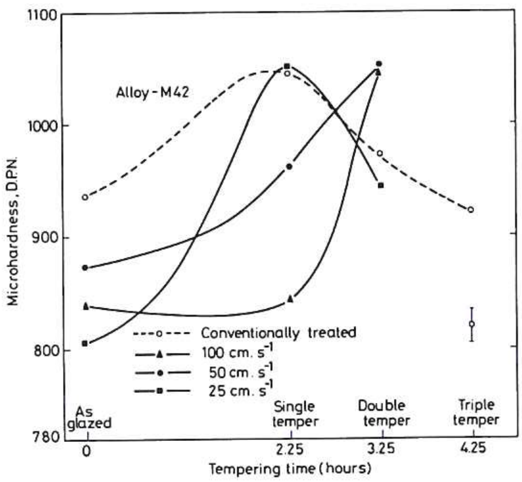

Fig.5 eb Treatment of Tool Steel (29).

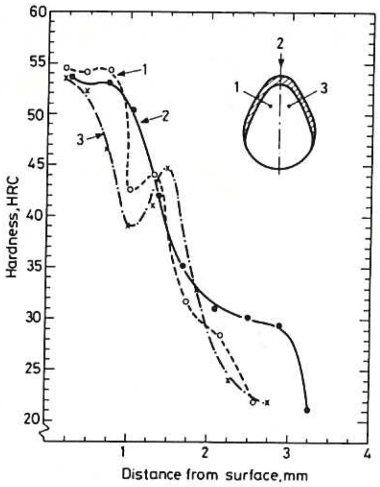

Fig.6 TIG melted layer on cast iron camshaft (31).

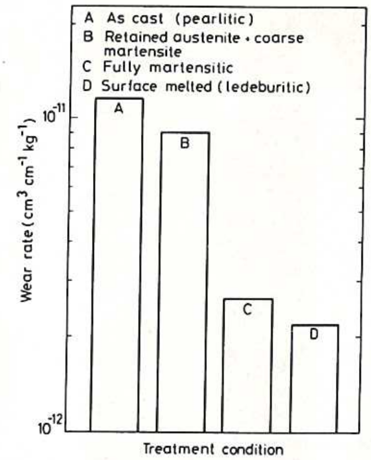

Fig.7 Wear rates of microstructures produced by laser (35).

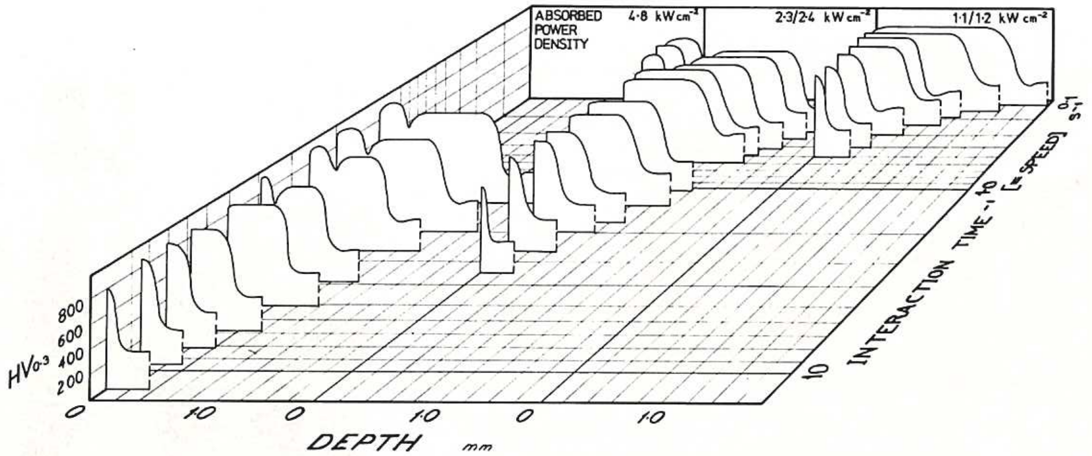

Fig.8 Hardening response of grey iron to laser surface treatment (35).

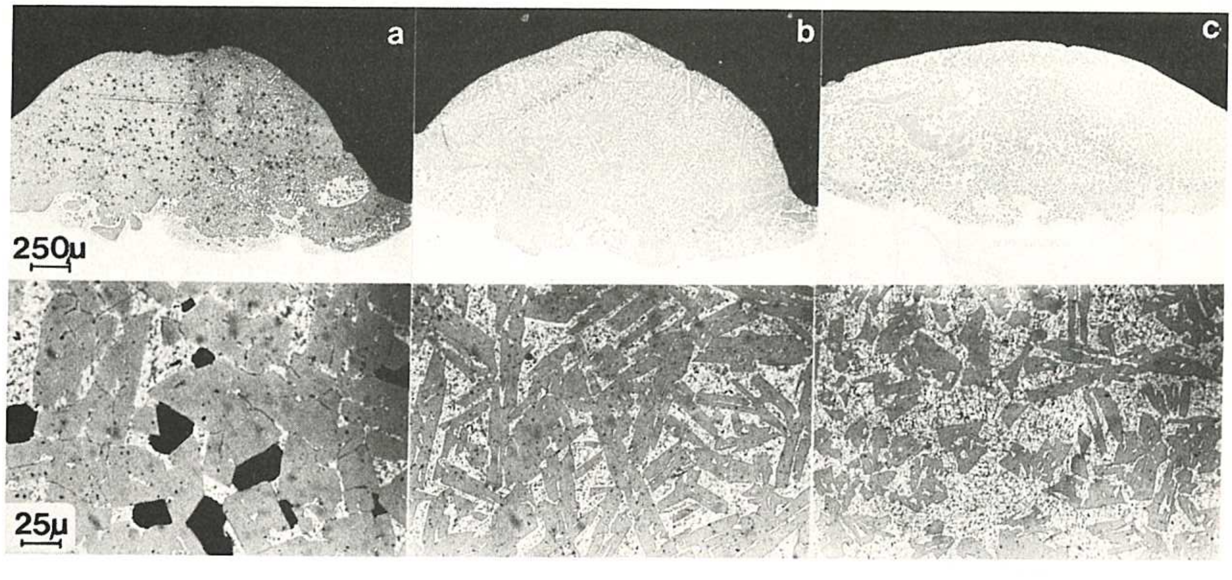

Fig.9 Laser alloying of Si on A1 alloy (37).

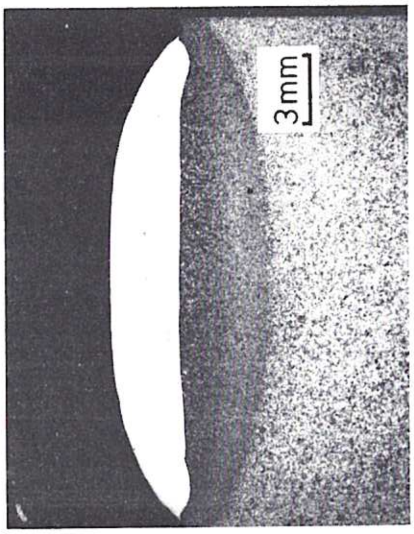

Fig.10 PTA-clad track on steel (42).

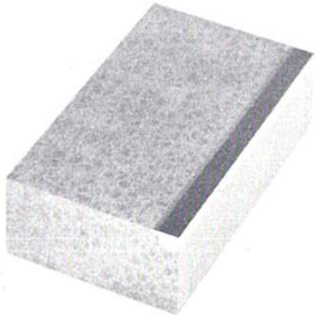

Fig.11 Laser-clad edge on cast iron (37).

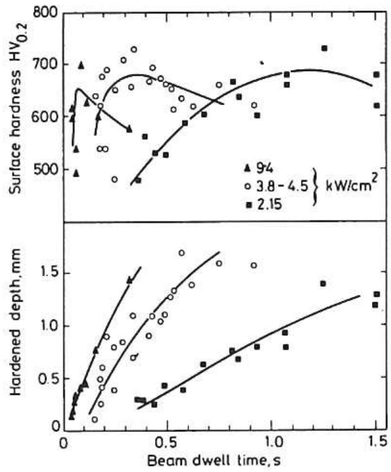

Fig.12 Laser hardening of o.4C steel (45).

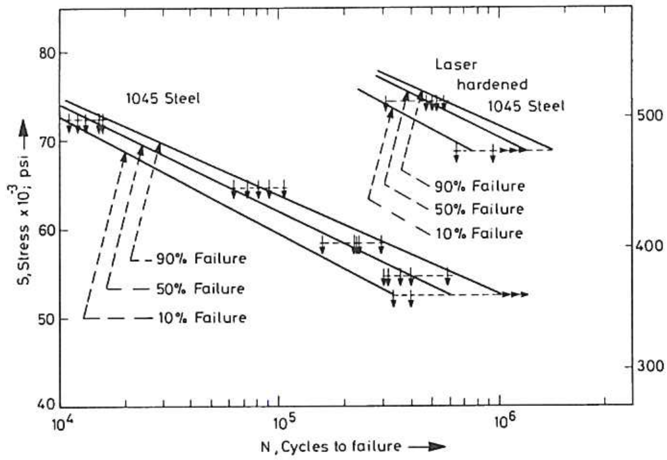

Fig.13 Improvement to fatigue performance by laser treatment (49).

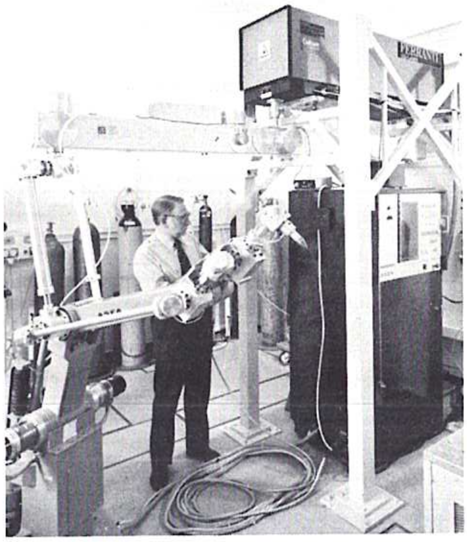

Fig.14 Combined laser, beam-guide and robot (54).

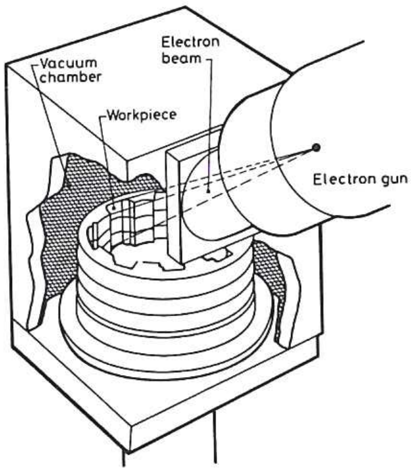

Fig.15 Production-line cam hardening be eb (16).

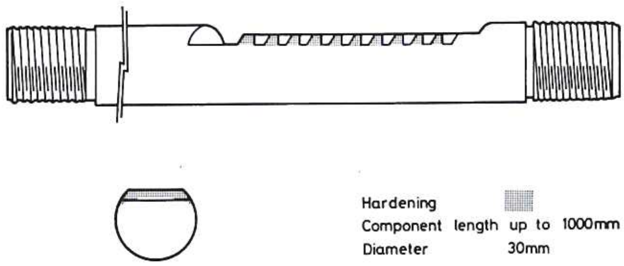

Fig.16 Production-line steering-rack hardening by HF resistance heating (55).