

Processing materials with lasers

The laser, a clean source of thermal energy with high power density, can melt metallic and ceramic alloys to produce novel and useful microstructures; it also adapts well to automated processing techniques.

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How can we make an alloy to fit a specific materials requirement? The oldest method of alloy fabrication, casting, has two inherent limitations: Phases with high melting points are difficult to melt; and the cooling of the alloys from the melt is slow, so that alloy segregation and phase separation have time to occur. The other traditional method, powder metallurgy, has helped with the second of these problems: Allowing the homogeneous melt to be cooled in tiny droplets makes it possible at least to limit segregation to the scale of the resulting powder particles.

A number of new techniques based on high-power lasers now have emerged, offering potential solutions to both the high-melting-point and segregation problems in the fabrication of metal and ceramic alloys. These lasers are already gaining acceptance in such materials-processing areas as deep-penetration, autogenous welding; cutting; drilling; transformation hardening, and experimental shock hardening. The very high power densities that lasers can produce, equivalent to thermal sources of temperatures above 20 000 deg C, facilitate the melting of all phases of the alloy. Furthermore, the high power density of lasers also allows melting to be localized at the surface, with negligible subsurface heating, thereby establishing high cooling rates. In this process, called "laser glazing," the extremely rapid chill rates of thin molten zones have produced a variety of novel, extremely homogeneous metallurgical microstructures, including

amorphous alloys—the ultimate in alloy homogeneity. Because of the close structure control it makes possible, the laser glazing process (depicted on the cover of this issue of *PHYSICS TODAY*) is becoming a valuable new tool in materials research.

This article contains a discussion of the emerging materials-processing technology by lasers, against the background of conventional materials processing. We will discuss laser systems, the theory of the new laser applications, some current materials-processing innovations and potential future trends.

Alloy fabrication

The materials we use in our everyday life are becoming increasingly sophisticated and specialized. A material is selected for a specific task because of its properties, its cost and its appearance. In technologically critical areas the achievement of desired properties may outweigh both price and esthetic considerations. For applications in which specific material properties are required, the manner in which such properties are obtained and altered is of principal importance. The properties of the metals and alloys used in the laser-processing research described in this article are determined by their structure.

In primary fabrication, alloys are most frequently produced from the liquid state, so that the final structure is strongly influenced by the way in which thermal energy is added to and removed from the alloy; a thermochemical factor usually also contributes to the alloy's structure.

Probably the single most important problem in the primary fabrication of metallic alloys is the phase separation and segregation in multicomponent alloys that occurs during slow cooling from the melt. These factors lead to undesirably non-

uniform structures with variable properties. Until recently, attempts to solve this problem have been primarily centered around powder-metallurgical processes in which the material is divided into small droplets while it is still a homogeneous liquid. The underlying concept involved is that, if the individual particles have the correct compositions, the maximum segregation distance is restricted to about the size of the solidified droplet.

Recently the value of rapid cooling as a means for preventing or reducing segregation in alloy phases become recognized. However, to carry out processes that include rapid cooling efficiently requires precise energy control. The laser affords such control; this represents perhaps the most important reason for the present use of lasers in materials research and for the present and future use of lasers as materials-processing tools. The laser provides a clean, remote source of thermal energy that can be used effectively in air, vacuum and almost any gas atmosphere. Furthermore, the use and transfer of laser energy is highly adaptable to automation.

New laser techniques

The ability of continuous, high-power lasers to generate power densities of up to 10^8 watts/cm² makes them useful for a variety of materials-processing techniques. Figure 1 displays the spectrum of laser-materials interactions located on a plot of laser power density and interaction time. The materials-processing effects now being utilized include

- ▶ deep-penetration laser welding,
- ▶ laser cutting,
- ▶ drilling of holes,
- ▶ heat treating by transformation hardening and
- ▶ surface alloying.

Although the number of industrial

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manufacturing jobs that are currently being done by each of these laser operations varies from a few (welding, surface alloying) to a large number (cutting), it must be remembered that laser materials processing is still a young and growing technology. In our opinion the feasibility of each of these five operations has been thoroughly demonstrated; their future industrial use appears assured.

Two further techniques for materials processing by laser have been proposed more recently, and these are already well into the research and development stage:

► Laser shock hardening, under investigation at Battelle Memorial Institute,^{1,2} attempts to work-harden materials with the blast wave that accompanies rapid surface vaporization induced by pulsed lasers at very high power densities, over 10^9 W/cm^2 .

► Laser glazing, a process being developed at United Technologies Corporation, has far-reaching implications for materials research. This process is a new and elegant method for reproducibly and controllably attaining rapid solidification and solid-state cooling of materials.

The technique of laser glazing involves rapidly traversing the surface of a material with a laser beam focussed to a power density in the range of 10^4 – 10^7 W/cm^2 . The apparatus used is schematically depicted in figure 2. This procedure yields a thin melt layer at close to 100% melting efficiency; that is, the substrate remains cold. Due to the steep temperature gradient established by the process, rapid solidification and subsequent solid-state cooling take place following the passage of the laser beam. Average quench rates in excess of 10^8 deg C/sec have been achieved in melt thicknesses in the 1–10 micron range, with correspondingly lower quench rates in thicker sections. The

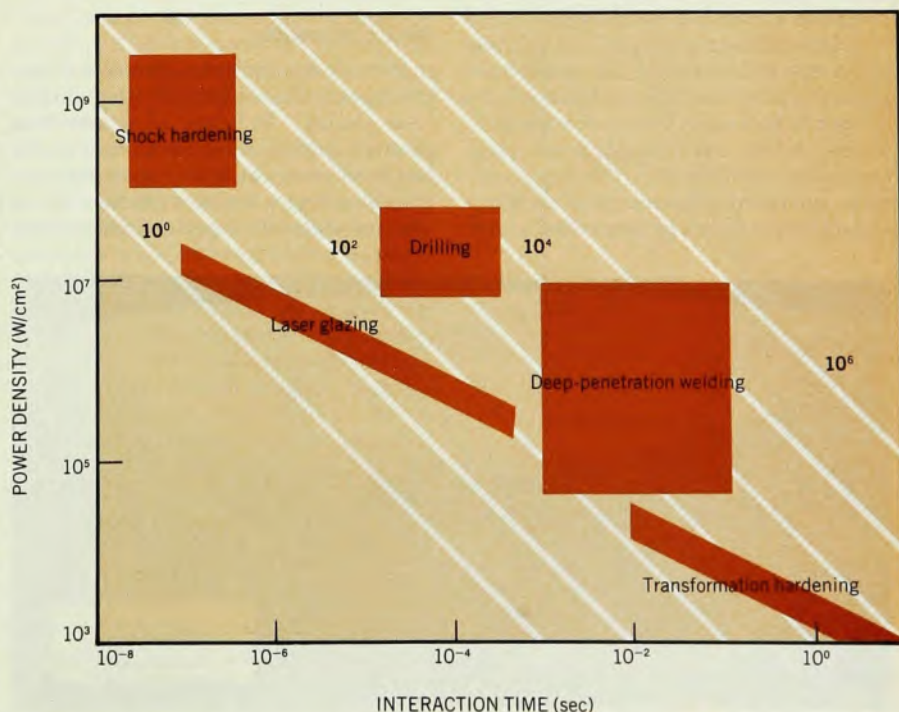
inset in figure 2 shows the appearance of a typical laser-glazed sample. The light micrograph in figure 3 shows a transverse cross section of the same laser-glazed palladium-copper-silicon alloy.

The relationship between laser power density, interaction time and melt depth may be calculated by finite-element analysis procedures for any material with accurately known thermal properties. Figures 4 and 5 are graphs of these relationships for pure nickel. Figure 3 shows that the melt depth achieved in a given

material can be determined by specifying either

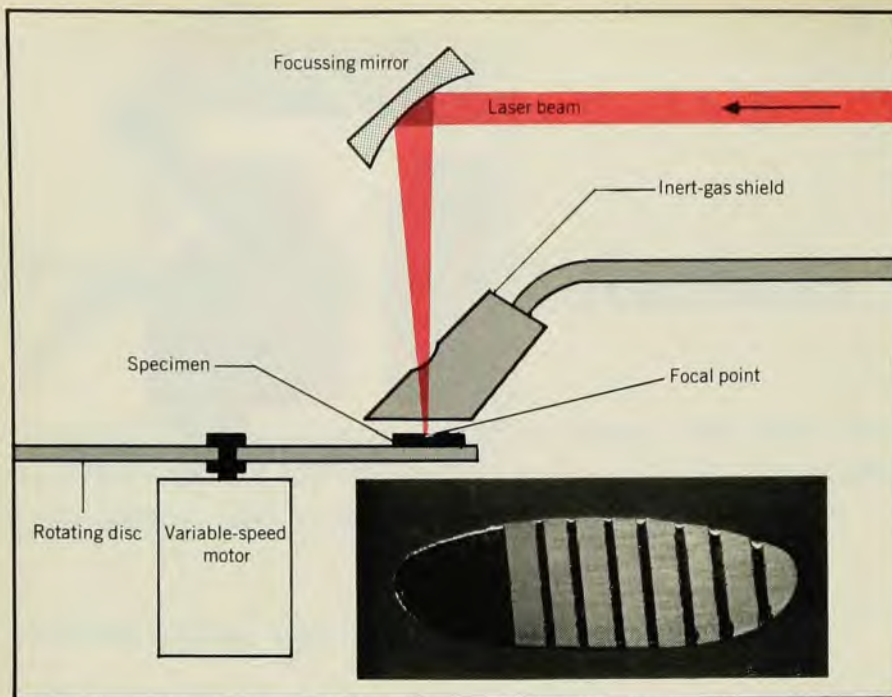
- the total absorbed energy and the time during which it is absorbed, or
- the absorbed power density and the time for which it is absorbed.

Having established melt depth as a function of the power density, we may determine the cooling rate from figure 4. For a given melt depth the cooling rate increases with absorbed power density, because the interaction time decreases so that less heating of the solid substrate



Operational regimes for the laser techniques used in materials processing. The dependence on the combination of applied power density and interaction time is here shown for a variety of commercial and experimental processes; the boundaries are approximate. The diagonals are lines of constant specific energy, with values indicated in J/cm^2 .

Figure 1



Laser glazing apparatus, schematically diagrammed. The workpieces, arranged around the circumference of a rotating disc, are irradiated by the focussed beam of a high-power laser. The beam passes through a hole in an inert-gas shield. The inset shows the result: a laser-glazed sample of a palladium-copper-silicon alloy. (Also see the cover photo.) **Figure 2**

material occurs; figure 5 shows this.

Some valuable features for materials research by the laser-glazing technique are that it is relatively inexpensive, highly controllable and reproducible. The process is already being used to screen large numbers of candidate alloys for programs aimed at developing new alloys with beneficial structures. If any of these alloys are to be used in the amorphous (glassy) state, their applications will be limited to those at relatively low temperatures, below the instantaneous glass transition temperature. Other structures, such as ultramicrocrystalline alloys and alloys produced by controlled-phase

decomposition will be usable at much higher temperatures. Laser glazing has proved both efficient and economical, as a result of the relatively low cost per run and the large number of specimens that can be processed simultaneously under identical conditions.

Research results

Let us consider some examples of microstructural modifications produced by laser glazing. In figure 3 it can be seen that the slightly off-eutectic base metal has been recast as a homogeneous, single-phase region by laser glazing. In an electron diffraction pattern taken from



Light micrograph of a laser-glazed sample in transverse cross section. The alloy, of palladium with 4.2% copper and 5.1% silicon, is normally crystalline. Because of the rapid chilling characteristic of the laser glazing process, however, the part in the laser pass is amorphous; this was verified by electron diffraction and observation of the fracture surface. **Figure 3**

this region only diffuse rings are observed, clear evidence that the glazed region of the Pd-Cu-Si alloy is amorphous, that is, a glassy metal without a regular crystal lattice. Further evidence for the amorphous nature of this material is given by the veiny nature of fracture surfaces revealed by scanning electron microscopy and the massive localized flow of material (intensive shear bands) surrounding microhardness indentations. We see therefore that intimate contact with a crystalline base alloy of identical composition does not preclude the establishment of the amorphous state with sufficiently rapid cooling rates.

In the sample slab of Pd-Cu-Si alloy shown in the inset of figure 2, the laser glaze passes were made at speeds from 12.7 (right) to 88.9 cm/sec (left) with a CO₂ laser focussed on the surface. The portion at the left was glazed with overlapping passes at a linear speed of 76.2 cm/sec, which provided a surface coverage rate of approximately 300 cm²/min, a rate that appears economically attractive for some types of surface treatment.

In a laser-glazed sample of a TLP-21 alloy of nickel with (by weight) 15% cobalt, 15% chromium, 5% molybdenum and 2.75% boron, the laser-glazed area was again homogeneous and appeared to be featureless as compared with the multiphase, inhomogeneous base alloy. Microhardness indentations gave very high readings, up to 1400 diamond pyramid hardness (DPH), in the glazed region, as compared to a base-alloy hardness in the range of 650 DPH. Even at these high hardness values, the presence of intensive shear bands around indents attests that these materials possess some ductility. Estimates based on the measured microhardness suggest extremely high yield strengths, $(3-5) \times 10^5$ psi.

The results of laser glazing a carbide-reinforced eutectic alloy are exhibited in figures 6 and 7. It can be seen in figure 6a that the original base alloy is neither uniform nor homogeneous. For initial homogenization of the alloy, a deep penetration, weld-like pass is first made, which, because it is *not* a thin skin, cools at a rate slow compared to a glaze—but rapid compared to the cooling rate experienced by the specimen during its initial manufacture. This structure, as shown in part b of this figure, is considerably more uniform than the initial alloy. The structure is uniformly dendritic and, as is shown in the extraction replica, part c, contains interdendritic regions of a fine, filamentary eutectic with the dendrites themselves appearing to be homogeneous solid solutions. In the extraction process used to produce figure 6c, the matrix region in the dendrites and between the fibers in the interdendritic regions have been removed with acid solutions to reveal only the fibers of carbide. A second, high-speed pass following the initial pass resulted in much more rapid cooling. In

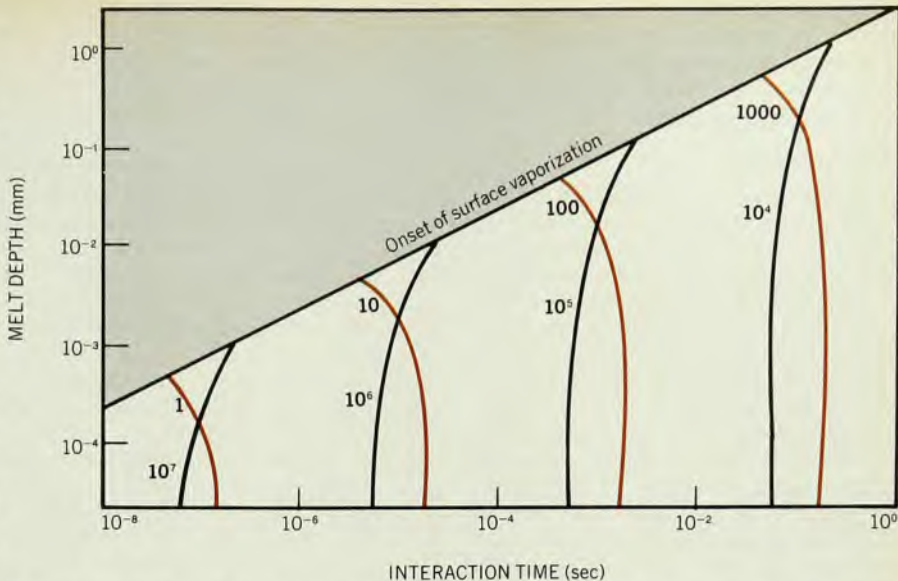
this case the carbides were redistributed into a fine equiaxed network, as illustrated in part d.

Figure 7 contains a transmission micrograph of the region shown in figure 6c. It reveals that the original carbide-reinforced alloy has been separated into two potentially important morphologies by the rapid cooling resulting from laser melting. The interdendritic regions contain homogeneous, single-phase, solid solutions supersaturated with carbide relative to the "normal" solid-solution phase.

These regions are thus candidates for controlled solid-state decomposition (precipitation) with the potential of being developed into a new class of alloys dispersion-strengthened with carbides. The techniques required for optimal aging of such metastable solid solutions are not readily available now. The precise energy-delivery and control capability of the laser suggests its use as a potential method for accomplishing such a process. Experiments to define the extent of the enhanced solubilities of potentially useful carbide phases in eutectic superalloys are in progress.

The second potentially useful phase mixture in figure 7 consists of carbide whiskers dispersed in the solid-solution matrix of the interdendritic regions. Interestingly, the rapid cooling has displaced the eutectic point considerably towards increased volume fraction of the carbide reinforcing phase. Whereas the alloy normally exhibits a eutectic at 13.8% (by volume) of carbide, the eutectics in the interdendritic regions contain nearly 50%. Other instances of displacement to higher fractions of second phases with fully eutectic structure have been observed. Eutectic structures of very high carbide content such as that in figure 7, have not been produced previously from the melt. The use of rapid cooling to produce such structures may eventually lead to materials with improved hardness and wear-resistance characteristics. This would have obvious implications in areas such as cutting tools and abrasion- or erosion-resistant coatings.

Some very recent observations on alloy steels provide a final example of the utility of laser glazing as a research technique to produce rapidly cooled materials. In D6-AC steel, combinations of laser-glazing passes were applied to the samples. In one such case an initial glazing treatment at 25.4 cm/sec was used to homogenize the surface-layer composition; then a single, shallow pass at 50.8 cm/sec was applied over the first. This dual-pass technique provided high hardnesses within the second (faster) pass and somewhat lower hardnesses in the lower regions of the first pass. There were two tempered zones, both low in hardness, with the greatest softening just below the deep, more slowly cooled first pass. Hardness achieved in the glazed (melted)



The surface melting characteristics of nickel, obtained from an analog computation. The black curves are for constant absorbed specific power, with values indicated in W/cm^2 ; for the colored lines absorbed energy, shown in J/cm^2 , is held constant. The melt depth is thus determined from the interaction time and either absorbed energy or power.

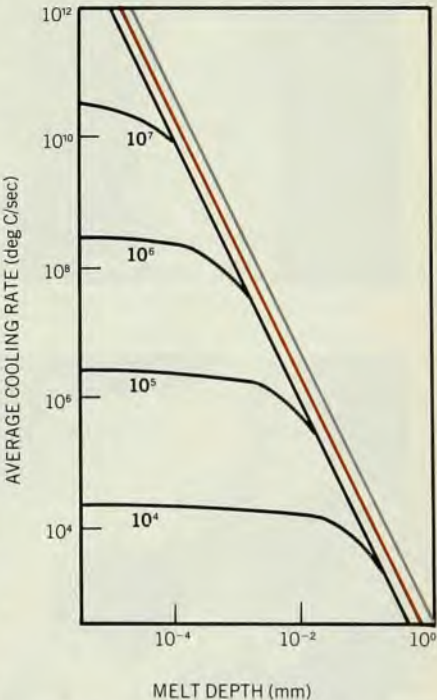
Figure 4

region averaged over 100 DPH above the unaffected base metal, and hardnesses in the single-pass zone increased by an average of 30 DPH above those in the dual-pass melt. The highest values were achieved adjacent to the solid-liquid interface, at which the fastest cooling occurs, and they decreased with distance into the liquid. Within the heat-affected (recrystallized) zone, the reverse was observed, the softest region being adjacent to the interface and the hardest region at the outermost edge of the recrystallization zone, where the finest grains were observed. This supports the theory that grain-size strengthening can contribute significantly to the total strength of martensites.

A single-pass, low-rate laser-glazing experiment on M-50 alloy steel is shown in figure 8. Cracks are noted in the substrate, which is brittle and contains large numbers of visible carbides; however, these cracks do not run into the laser-glazed region. Within this region the carbides are dissolved and remain mostly in solution, with only some very fine carbides being resolved at higher magnifications within the melt region. In the solidified region hardness increases as much as 200 DPH above the starting material were found. There was a correspondingly significant average increase in hardness of the glazed region over that of the base metal. The peak hardness measured close to 1000 DPH, without the large carbides that are clearly visible (at a magnification of 100) in the original alloy. This indicates that the more uniform distribution of carbon provides an alternative means of hardening. From the observed behavior of substrate cracks, the glazed area appears to be more crack resistant than the base alloy. Further,

because the laser-glazed region is more homogeneous, it would be expected to be more corrosion resistant than the base material. The mechanisms by which the high hardnesses are achieved in this and other rapidly cooled alloy steels are therefore being investigated actively.

After the initial success of laser glazing, thinking was quite naturally directed to



Effect of power density and melt depth (from figure 4) on the cooling rate. The absorbed power, in W/cm^2 , is indicated on the curves. The black diagonal shows the onset of surface vaporization and the gray line shows the theoretical maximum cooling rate for nickel. The colored line between them is for "splat" cooling of iron on copper.

Figure 5

other means of using lasers in the processing of materials for sophisticated control of structures and properties. Let us turn to some of these advanced concepts of laser processing.

Structure control

As we have indicated, laser glazing represents an improved, more reproducible technique for the production of rapidly cooled metals and alloys. The field of rapid quenching of materials has been the topic of considerable research, as indicated by two comprehensive reviews.^{3,4} In these Howard Jones reports that, although numerous techniques for rapid quenching exist, they are not generally easy to control or reproduce. The products of rapid quenching include amorphous alloys and a variety of supersaturated and metastable phases, such as supersaturated solid solutions, homogeneous microcrystalline structures and off-composition, fully eutectic microstructures with small interphase spacings.

From the standpoint of microstructures, rapid cooling promotes greater microstructural homogeneity in multi-component systems that can be achieved by slower cooling (casting) or by normal powder-metallurgical processes. The

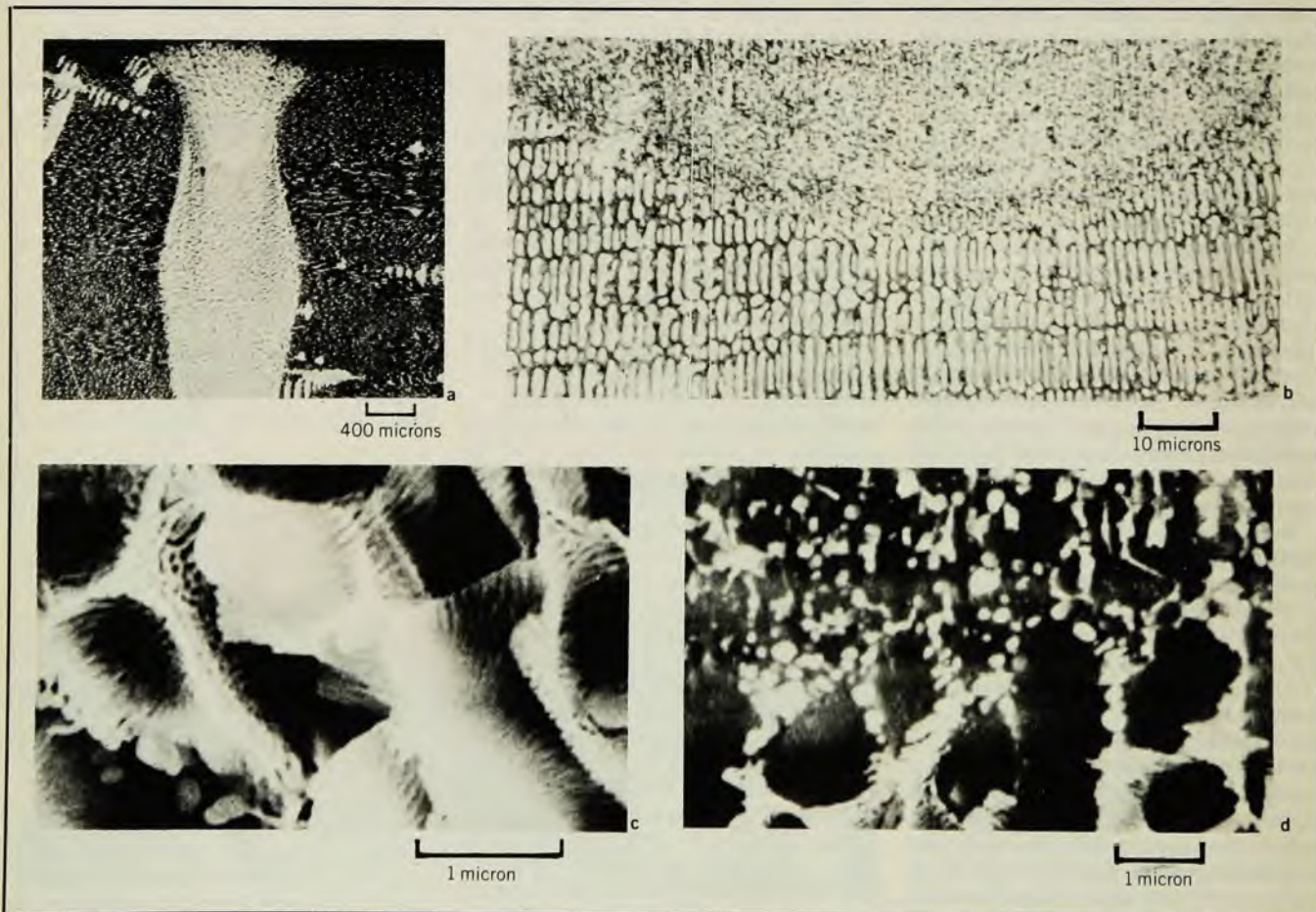
improved homogeneity offers the potential for improving mechanical properties, such as fatigue and fracture resistance, and chemical properties, such as corrosion resistance and catalytic activity.

In addition, amorphous alloys have exhibited extremely high yield strengths and hardnesses while maintaining a high degree of ductility. This long-sought-after combination—strength and ductility—could eventually help to produce improvements in the erosion and wear resistance, and in the fracture resistance of high-strength materials. Rapidly quenched amorphous and crystalline structures have also exhibited unique magnetic and electronic properties, making structures produced by rapid cooling candidates for application in the magnetic and electronic properties area.

The new dimension of structural control that the above examples have shown to be possible with laser glazing and related laser processing techniques could have far-reaching effects on the materials field. The development of laser glazing as a technique for investigating the effects of rapid cooling on the microstructure and properties of metals and alloys has served to highlight other key capabilities of lasers for the processing of materials. These unique capabilities are:

- ▶ the very high energy densities that can be achieved;
- ▶ the precise control of energy delivery possible with lasers;
- ▶ the precise control and definition of interaction time attainable;
- ▶ the accurate control of the location of energy deposition that results from the fine focus, as well as the inherent ease of beam transmission and control, possible with lasers;
- ▶ the lasers' ability to operate outside of a vacuum, for example in the atmosphere or in gas mixtures at a wide range of pressures;
- ▶ the unparalleled adaptability to automation demonstrated to be characteristic of lasers, and
- ▶ the fact that lasers constitute a clean and remote source of energy for materials processing.

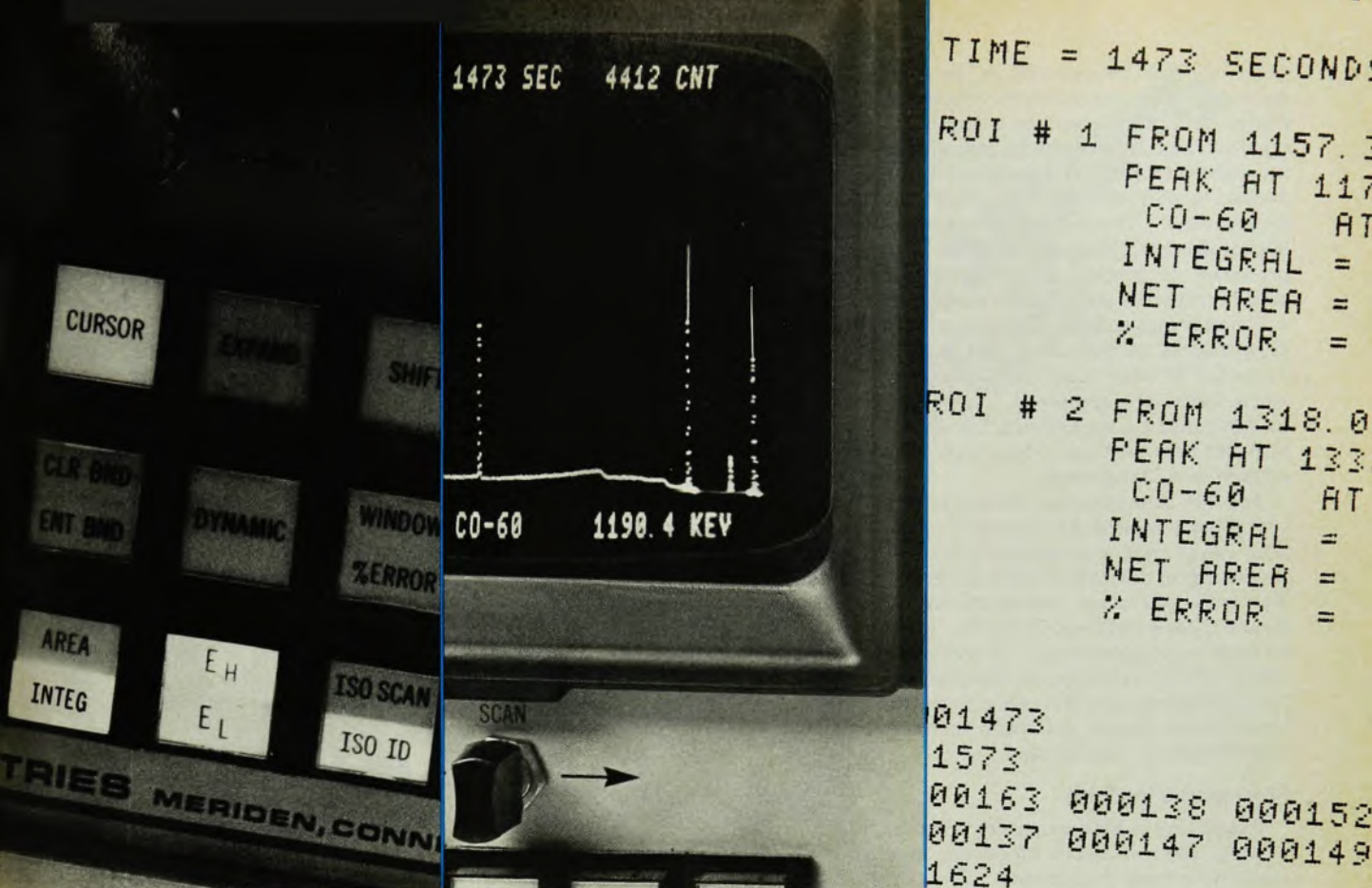
These advantages of lasers have opened the door to a variety of new processing techniques. Although these are now only in the conceptual stage, they are relatively simple procedures based on the demonstrated capabilities of lasers. A prime example is use of the laser for precisely controlled heat treatment. Let us consider the requirement for precise, short-term aging at high temperatures of supersaturated solid solutions that are ca-



An alloy of cobalt, tantalum and carbon is homogenized by successive laser glazing passes at increasing cooling rates. Photo a shows the entire cross section of the two-pass melt, and a part of the region of intersection

of the melt zones is enlarged in b. The dendritic lower part is shown in c, and the more rapidly cooled upper part, in d; both further magnified and after extraction with acid.

Figure 6



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pable of being decomposed in the solid state to form dispersion-strengthened alloys. After such a solution is formed by rapid cooling, the laser can be used to heat the material rapidly and maintain it at a desired temperature for a precisely controlled time. This capability promises improved control of aged structures. The processes of surface (skin) aging for graded properties and selective step aging, which take into account the temperature dependences of nucleation and growth behavior, become much more practical when lasers are employed. A mathematical analysis quantifying the conditions for various types of laser aging has already been completed.

Another area in which the essentially unlimited temperature capability of the laser can be used to advantage is the melt processing of difficult-to-melt materials. The high equivalent temperatures afforded by the laser superheat the liquid enough to homogenize it. If the availability of high-temperature containment (crucible) materials becomes a problem, the self-containment approach, known as "skull melting," can be used.

Processes of the future

In addition to these examples, a variety of other laser materials-processing concepts have been formulated. They include various types of machining and atomization, new methods for alloying and shape fabrication, directional solidification and gradient annealing, epitaxial solidification, coating and weld bonding. These and other novel concepts for using lasers to process materials have been evolving rapidly. As a group, they are taking shape as an integrated concept for the future processing of materials.

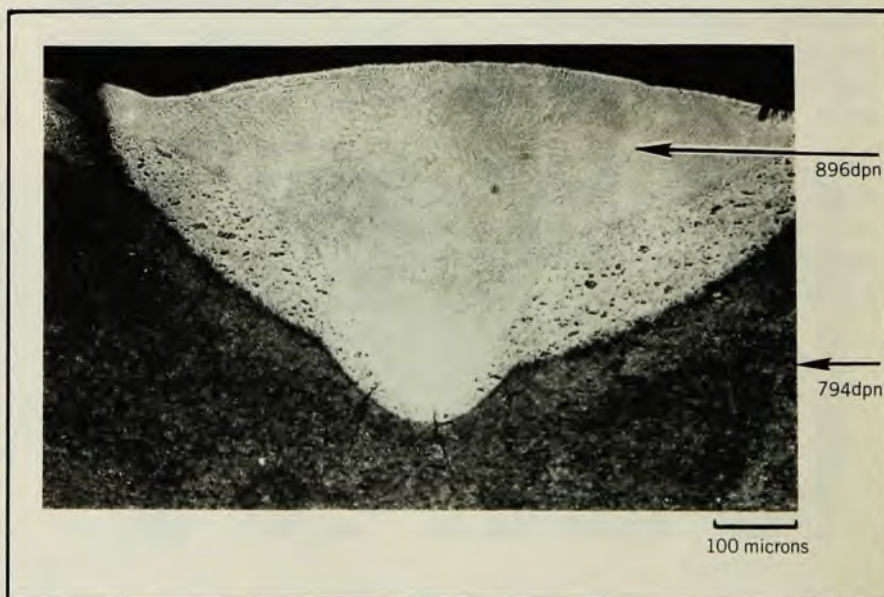
Because it provides a clean, remote source of energy, and because it can be used to deliver energy with great precision and reproducibility, laser processing will enable us to improve the precision with which we can specify and control microstructure in metallic and ceramic alloys. Because the microstructure ultimately determines the specific properties of a given alloy, this is a significant step towards optimization. The laser promises to be an ever more useful tool for materials processing. Through laser glazing and other evolving developments, the laser is serving to facilitate important materials development and processing research.

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An extraction replica of the region of the CoTaC-3 alloy shown in part c of figure 6. This transmission micrograph shows a dendritic solid solution and a fine eutectic. Figure 7



The strength of M-50 steel was considerably increased by laser glazing in the cross section shown. The mean microhardness in the treated region was 896 dpn, as compared to 794 dpn for the base metal. The processing speed was 25.4 cm/sec. The cracks visible in the photo do not extend into the glazed region, in which the carbides are dissolved. Figure 8