Industrial Imaging Controls Laser Surface Treatment

High-speed image capture and analysis create a more reliable laser process.

by Gert-Willem Römer, Marten Hoeksma and Johan Meijer

Laser surface treatment comprises a family of techniques that can improve wear, fatigue and erosion resistance of machine parts. These techniques are slowly moving from the research laboratory to the factory floor, but variations in part size and processing parameters produce wide fluctuations in surface characteristics.

To carry out this kind of treatment with reproducible high quality, users must carefully control the laser process. At the University of Twente in The Netherlands, we have developed a real-time process control system based on industrial imaging.

Treating the surface

Laser surface treatments such as transformation hardening, melting, alloying and cladding can improve wear and fatigue resistance of metal machine parts. At the surface of the metal part, the laser beam's electromagnetic energy converts to heat.

The improvement of the surface layer is based on rapid thermal cycling; after being heated by the laser beam, the material self-quenches as the heat conducts into the cold bulk material. The cooling rates are higher than those of conventional heat treatments. This thermal cycle results in microstructural refinement, phase transformation or formation of supersaturated solid solutions. This allows a user to create parts with surface properties totally different from the bulk material.[1]

Laser surface treatments generally fall into two classes: thermal processes and thermochemical processes.

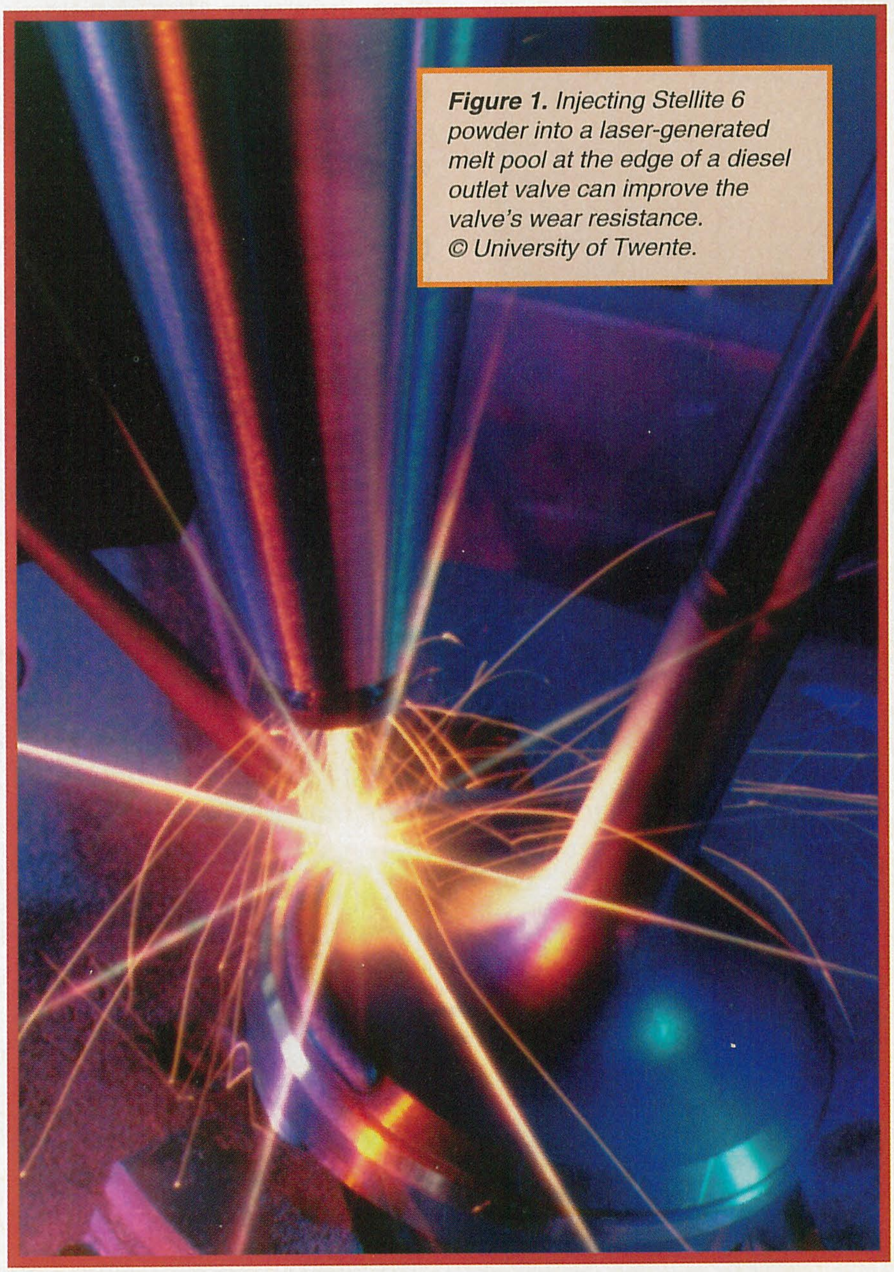


Figure 1. *Injecting Stellite 6 powder into a laser-generated melt pool at the edge of a diesel outlet valve can improve the valve's wear resistance. © University of Twente.*

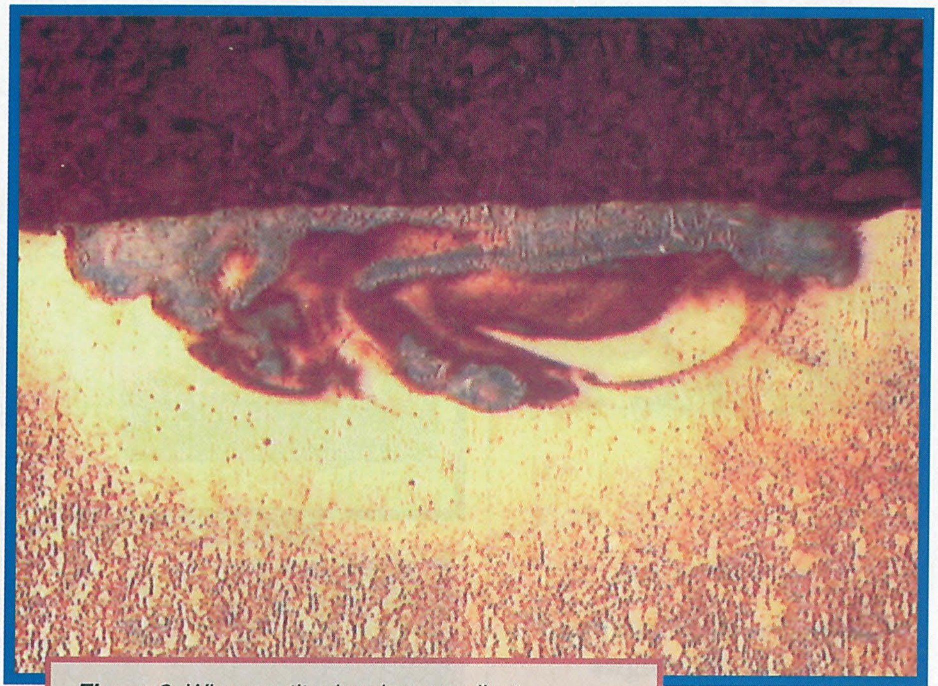


Figure 2. Whereas titanium has excellent mechanical and chemical properties, its wear resistance is poor. Laser surface alloying with nitrogen produces gold-colored titanium-nitride, which offers extreme microhardness and other advantages.

Thermal processes (e.g., transformation hardening and remelting) modify surface properties by changing the microstructure of the surface layer. Thermochemical processes (e.g., alloying, dispersing and cladding) modify the surface composition by adding new materials to the laser-generated melt pool. These materials then may react chemically with the melted bulk material.

A typical application of a laser surface treatment is laser cladding of the edge of a diesel outlet valve (Figure 1). The edge of a valve is subject to abrasive wear because of the high temperature of the exhaust gases and collisions of the valve with the valve seat in the engine. By injecting a cobalt-based powder into the melt pool, we can fuse a wear-resistant cladding at the edge, resulting in a wear-resistant layer only where it is really needed. This technique extends the valve's lifetime and is considerably less expensive than making the whole valve out of a wear-resistant material.

As another example of an application for laser surface treatment, titanium is an important material in the aeronautics, medical and chemical industries because of its excellent mechanical and chemical properties, such as high specific strength, good biocompatibility and high corrosion resistance. However, it shows low resistance to sliding and abrasive wear.

When titanium melts and the melt pool is exposed to nitrogen, titanium-nitride forms. This compound shows extreme microhardness (Vickers hardness HV = 2000 to 3000 kg mm^{-2}), high melting temperature, high temperature stability and low electrical sensitivity, and also displays the aesthetic qualities of the golden color (Figure 2).

Controlling the process

Compared with conventional surface-treatment techniques such as flame spraying and plasma spraying, laser surface processing is more flexible, fast and easily automated. It also produces parts with better surface quality and less thermal distortion of untreated areas.[2]

Despite its advantages and the great potential to modify the properties of a wide range of parts, industrial applications of laser surface treatment are still limited because the practice is relatively new and investment costs for capital equipment are high.

Also, laser surface treatment processes are extremely sensitive to small changes in processing parameters such as laser power and beam velocity. For example, a change of only 10 percent in absorbed laser power, at constant processing speed, may cause a change of 50 percent in case depth. Therefore, real-time process control is required to increase the stability, reproducibility, efficiency and productivity of laser surface treatment.

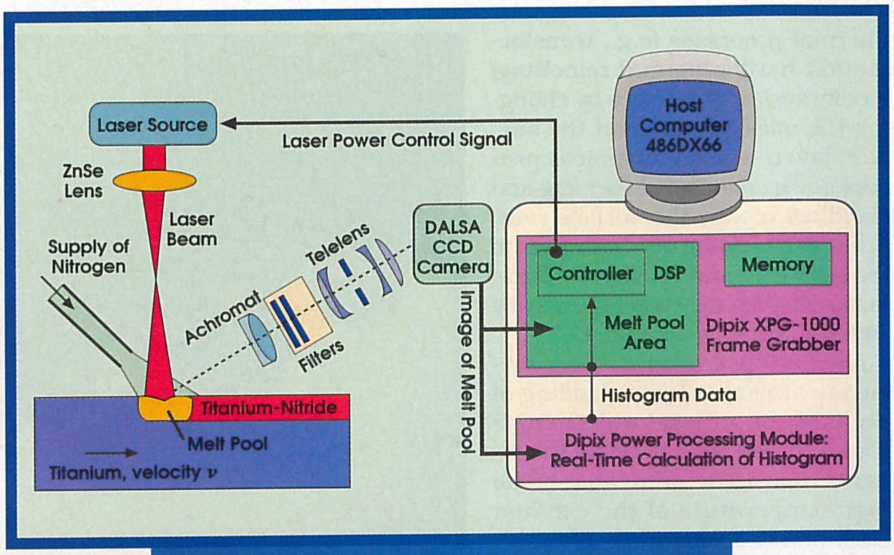
Most laser surface alloying uses a fixed set of machine parameters. Two types of disturbances can produce deviations in processing quality:

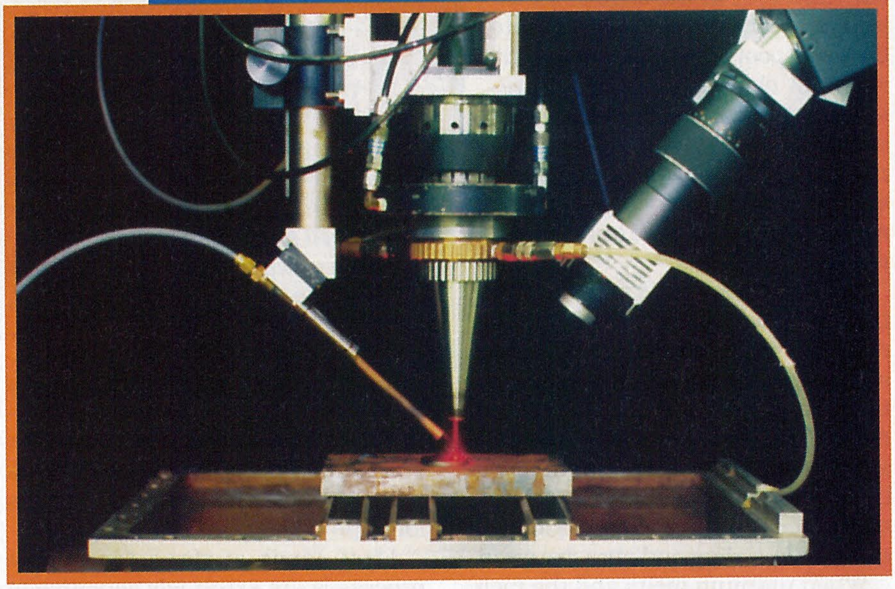
- Varying absorptivity at the surface. Just a fraction — indicated by the absorptivity or coupling-coefficient $A \in [0,1]$ — of the laser radiation is absorbed and transformed into heat. The dynamics of this coupling-coefficient are complex and nonlinear, and therefore difficult to predict. Moreover, it varies during processing and depends on the temperature of the product and its surface conditions, such as roughness.
- Complex products. When the laser beam approaches an edge or passes over a small part, the absorbed heat tends to accumulate. Excess heat can produce too deep a melt pool or can destroy the part.

Stabilizing the melt pool

Both disturbances change the shape and dimensions of the melt pool.[3] For example, increasing absorptivity also increases the dimensions of the melt pool and the size (expressed in meters squared) of the melt pool area at the surface. The same relation holds for disturbances of the melt pool dimensions attributed to the complex geometry of a part.

At the University of Twente, we have developed a control system based on an industrial imaging system that measures the melt pool in real time and uses this information to compensate deviations from the





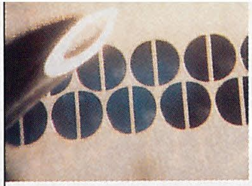
Figures 3 and 4. A CO_2 laser melts the titanium surface, while a nozzle sprays nitrogen. An industrial imaging system analyzes and controls the melt pool by adjusting the laser power. © University of Twente.

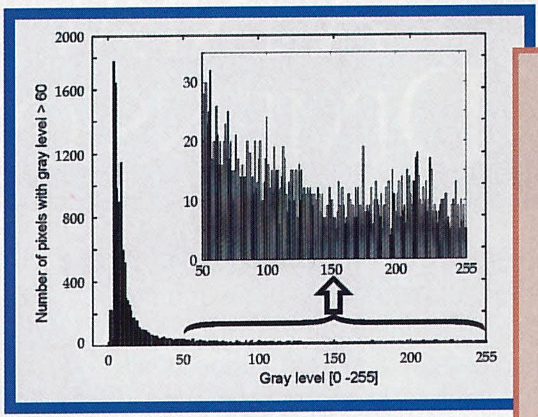
desired melt pool size by adjusting the laser's power level. This control system produces a constant melt pool depth across a part.

In our setup, we used a CO_2 laser to create a melt pool on a sample of $TiAl_6V_4$ (Figures 2, 3 and 4). A copper tube supplied nitrogen to the melt pool from the left for alloying to titanium-nitride. An X-Y stage (a = 3 m/s^2) moved the titanium sample under the laser beam. We used 1500 W of laser power and a processing speed of 90 mm/s.

To increase the laser's power density, we focused the beam with a planoconvex lens of zinc-selenium, a material that is highly transparent to the 10.6-µm wavelength of CO_2 laser radiation. We also used a lens with a relatively large focal length (f = 154.5 mm) to ensure that our process analysis and control system could observe the melt pool.

The requirements for the detector in our process analysis and control system were a good spatial, temporal and thermal resolution; the latter was to detect the melt pool edge accurately. During laser surface processing with a beam diameter of 1





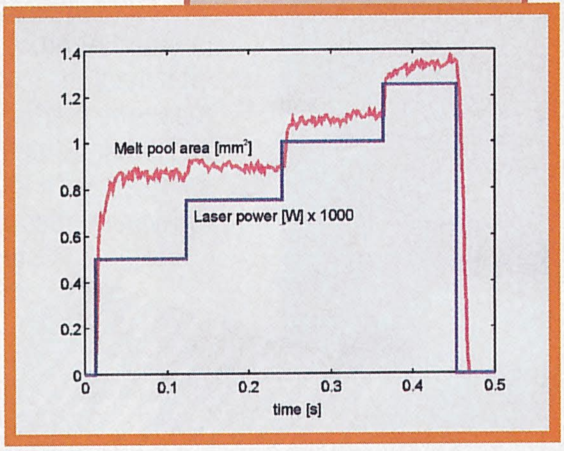


Figure 5. *The control system uses a histogram (a) to calculate the melt pool area about 800 times per second. The melt pool area shows a strong correlation with laser power; in (b) it increases steadily as power increases in four steps from 500 to 1250 W.*

mm, the time constants governing the controllable dynamic phenomena are 3 to 5 ms. We chose the components of the imaging system to meet these dynamics.

For detection, we chose a CA-D1-128A camera from Dalsa Inc. of Waterloo, Ontario, Canada. The camera has a silicon charge-coupled device (CCD) detector with an active area of 2.048 × 2.048 mm, and 128 × 128 photogate photoelements (16 × 16 µm, 16-µm pitch and 100 percent fill factor). During exposure, signal collects on the active area of the CCD chip. At the end of the exposure time the frame transfers at high speed into the storage area of the chip. After transfer, the exposure of the next frame is started. Meanwhile, the data from the storage area is transferred, line by line, to the output. The camera is equipped with an optional board, which converts the camera signals from analog to a digital RS-422, 8-bit output. Hence, each pixel can represent 256 gray levels. The camera can be configured to generate up to 830 frames per second, or 1.2 ms per frame.

We adapted the camera's dynamic range to the thermal dynamic range of the melt pool by using an RG1000 optical filter from Schott Glaswerke of Mainz, Germany. This filter transmits the near-IR. To protect the camera and its optics against the high temperatures of the melt pool (up to 3500 °C for liquid titanium-nitride), we placed the camera 200 mm from the melt pool and used an additional KG1 optical filter from Schott. Unlike laser welding and cutting, laser surface treatment of titanium with nitrogen ejects very little material from the melt pool, so there is no need for additional equipment to protect the camera optics.

To obtain a 1:1 projection of the melt pool on the CCD chip at this distance, we used a combination of an achromatic lens and a commercially available photocamera telelens. We placed the camera optics at an angle of 30° to the laser beam's optical axis. To compensate for the deformation of the scene, the camera is configured with a correction angle of 30°.

The process control system sends the camera's data in real time to an XPG-1000 frame grabber PC board from Dipix Technologies Inc. of Ottawa. The board plugs into a 486/66-MHz IBM-compatible PC. The frame grabber has 4 MB of on-board memory and a 50-MHz TMS320C40 digital signal processor from Texas Instruments Inc. of Dallas.

To increase image processing speed

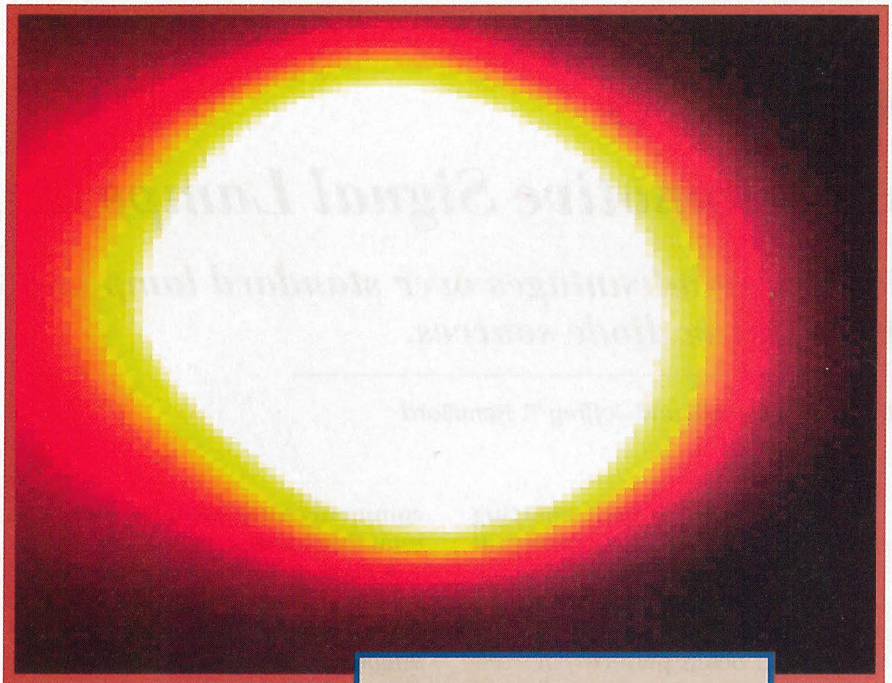


Figure 6. A camera watches the melt pool during the alloying of titanium. Colors indicate temperature levels.

and enable calculation of the melt pool surface area in real time, we extended the frame grabber with a Dipix histogram power processing module. This optional PC board operates parallel to the frame grabber and calculates a histogram of a 128 × 128-pixel image (Figure 5a) in only 0.5 ms. The digital signal processor then uses the histogram data to calculate the melt pool area.

When calibrating the system for our setup, we found that pixels with a gray level over 60 represent temperatures over 1600 °C (the melt temperature of pure titanium). Summing up all pixels with a gray level over 60 and multiplying this number by $(2.048)^2/(128)^2$ yields the melt pool area in millimeters squared.

In our first experiments, the results have been promising. We have already seen (Figure 5b) that there is a strong relation between power level and melt pool area. However, the melt pool area shows some delay in following the laser power, and the measurements exhibit some "noise" because of the high dynamics of the melt pool.

We plan to test short-wave pass filters from Andover Corp. of Salem, N.H., in place of the long-wave filter to increase the system's sensitivity for temperatures very close to the melt temperature of titanium. We also will improve the performance of the control system by simultaneously controlling the laser power and relative velocity of the laser beam to the part. These changes certainly will improve the control system's performance. □

References

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