

Process control of laser surface alloying

G. R. B. E. Römer, J. Meijer, and J. Olde Benneker*

In spite of the many advantages of laser surface treatment, such as high production rates and low induced thermal distortion, and its great potential for modifying the surface properties of a wide range of new and existing materials, industrial applications are still limited. This is not only because of the relatively high cost of laser systems; another significant problem is the high sensitivity of laser surface treatments to process disturbances and to small changes in processing parameters. A change of only 10% in absorbed laser power, for example, can cause a change of up to 50% in case depth. Real time process control is therefore required to increase the stability, reproducibility, efficiency, and productivity of laser surface treatment.

Laser surface treatments, such as transformation hardening, (re)-melting, alloying, and cladding, are used to improve the mechanical, tribological, chemical, or thermal surface properties of engineering components,¹ and they are gradually entering mainstream industrial use.² Integration of the laser source, CAD-CAM methods, and automated workpiece handling equipment has created a highly flexible surface treatment system,^{3,4} but one which lacks the reproducibility of standard industrial machining operations. It is well known that processing quality can vary significantly during laser surface treatment, and variations in quality may be observed between processing sequences performed with (apparently) constant operating and material parameters. Furthermore, it has been found that even within a single processing sequence and without any adjustment being made to the process parameters, the quality of the resulting treatment may be unstable.⁵ These quality variations are a result of the high sensitivity of laser surface treatments to small disturbances that may lead to unacceptably large errors in the processing result.⁶⁻⁹

Process disturbances

Process disturbances, which result in perturbation of the desired temperature field in the workpiece, can be categorised as being either extrinsic or intrinsic: intrinsic dis-

turbances arise from fluctuations in properties of the workpiece itself, while extrinsic disturbances arise from fluctuations in properties of the subsystems composing the laser surface treatment system.

Extrinsic disturbances

The major extrinsic perturbations are varying laser beam properties and varying beam velocity; other possible disturbances include changes in properties of the shielding gas supply and in the dimensions and intensity profile of the laser spot. For CO₂ laser sources both low and high frequency fluctuations in laser power have been reported, the former when the laser is first switched on and drift occurs before stabilisation at the nominal power, and the latter as a result of non-linear amplification of laser radiation as well as reflection of radiation back into the resonator.

Variations in beam velocity may be caused by mechanical instability (vibration) but more importantly by the acceleration of the workpiece handling system¹⁰ in, for example, complex beam tracking manoeuvres. At constant laser power, reduced beam velocity will increase and increased velocity will decrease the workpiece temperature. This disturbance could be compensated for by introducing feedforward control, although this would require extensive modelling or experimental data analysis to establish a relationship between power, velocity, and processing result.

Intrinsic disturbances

Important intrinsic disturbances are variations in absorptivity and material properties, and complex workpiece geometry. The absorptivity (coupling coefficient) of laser

radiation in metals may vary by as much as 100% during processing,¹¹ depending as it does on surface temperature and morphology, both of which can also be subject to significant variations. As the absorptivity of CO₂ radiation by metals is low, high laser power is required for processing, and so small increases in absorptivity can result in very large increases in absorbed flux. Such variations are usually reduced by increasing the workpiece absorptivity. In the case of transformation hardening this can be achieved by careful application of a thin (50 µm) graphite or MoS₂ layer,^{2,12} which increases the absorptivity to around 70% and is removed after processing. With surface melting the solution is often to roughen the workpiece surface by sandblasting. Neither one of these techniques (nor any of the other possibilities) is an ideal practical solution; absorptivity is therefore usually assumed to be constant in laser surface treatment and variations are interpreted as process disturbances.

Further disturbance to the desired temperature field can be caused by local variations in thermal properties of the workpiece, i.e. thermal conductivity, heat capacity, and thermal diffusivity. Fluctuations in these properties are hard to predict and can be caused by local anisotropy, inhomogeneity, and contaminants such as non-metal inclusions.

The temperature field can also be perturbed by edge features and small geometrical irregularities in the workpiece, at which heat accumulates because the heat is reflected at the workpiece edges. Disturbances of this type are significant only if the dimensions of the workpiece are smaller than or of the same order as the heat penetration depth. In extreme cases the increased bulk temperature can destroy the workpiece by encouraging excessive melting at the boundaries (Fig. 1). It is comparatively straightforward to predict the effects of geometry on temperature by finite element modelling,¹³ however this approach requires a unique calculation for each distinct

* Laboratory of Mechanical Automation, Department of Mechanical Engineering, University of Twente, PO Box 217, 7500 AE Enschede, The Netherlands.



1 Serious workpiece distortion resulting from excessive melting at boundary during laser surface treatment

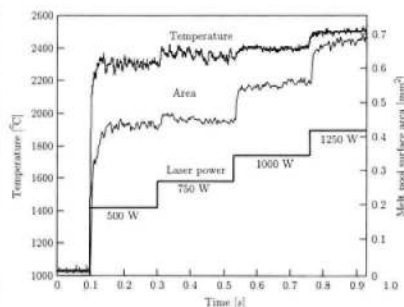
workpiece geometry and is computationally demanding.

Process control

To reduce the influence of time varying operating parameters and process disturbances on the processing result, and without approaching the individual variations in process conditions as unrelated problems, it is necessary to use real time feedback control during laser surface treatment. This is achieved by taking real time measurements of quantities that are known to have a direct relationship to processing quality and by subsequent intervention in the process when its quality is about to be jeopardised, as determined by a comparison of the desired and actual process conditions.

The purpose of laser surface treatment is to have all locations in a predetermined surface layer of the workpiece undergo a thermal cycle defined to meet certain requirements in terms of the resulting microstructure of the workpiece. As detection and correction of the processing quality take place in the laser-material interaction zone, the desired thermal cycle must be translated into requirements defined within the laser reference frame. This translation indicates that constant process quality is obtained if the temperature field within the surface layer does not change.

For processes involving a liquid phase (remelting, alloying, dispersing), the requirement for an invariant workpiece temperature field has been found to be well met by a specification stating that the



2 Changes in melt pool temperature and surface area induced by step changes in laser power during surface alloying of Ti-6Al-4V with nitrogen

dimensions (surface area and depth) of the laser melt pool must be kept constant during processing. Figure 2 shows the changes induced in melt pool temperature and surface area by step changes in laser power during the surface alloying of Ti-6Al-4V with nitrogen. Temperature was measured with an Impac ISQ-LO ratio pyrometer (diameter of measurement spot 0.45 mm, accuracy $\pm 3^\circ\text{C}$) and surface area using a thermographic camera system developed at the University of Twente. As can be seen from Fig. 2, increases in laser power have a more pronounced influence on melt pool area than on temperature, i.e. the major effect of raising the laser power is that more material is melted.

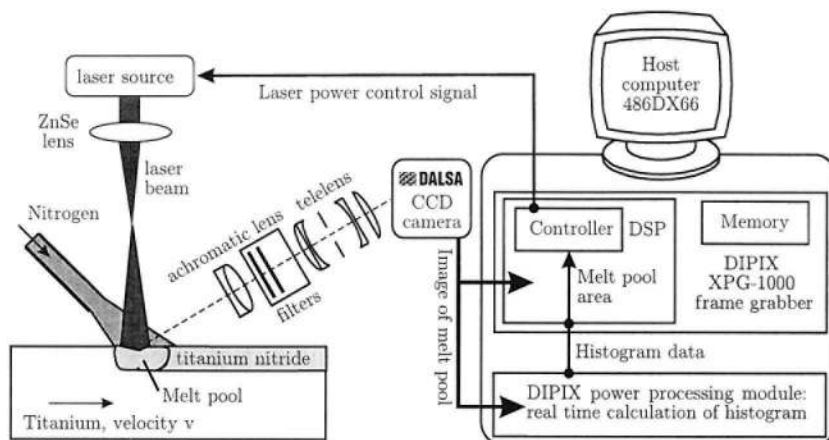
Thermographic camera based control system

The vision system developed in the Laboratory of Mechanical Automation at the University of Twente consists of a Dalsa area scan digital camera and a Dipix frame grabber under PC control (Fig. 3).¹⁴ The camera is equipped

with a high sensitivity Si detector with an active area of 2×2 mm, made up of 128×128 photoelements, each of which can represent 256 scales of grey; it can be configured to generate up to 830 frames per second. The dynamic range of the camera was adapted to the thermal dynamic range of the melt pool by the use of a near ir optical filter. To protect the camera and optics from the high temperatures in the melt pool (up to 2500°C for liquid TiN), the apparatus was placed at a distance of 200 mm from the substrate. The overall detection system combines high spatial resolution with satisfactory temporal and thermal resolution.

Images generated by the camera are uploaded in real time to the image grabber PC board, configured so as to maximise image processing speed (image histogram calculation time 0.5 ms). The image histogram data are used to calculate the melt pool area: from calibration experiments it was found that pixels with a grey scale greater than 65 corresponded to temperatures over 1650°C , the melt temperature of pure Ti. Calculation of the melt pool area thus involves counting the pixels with a grey scale over 65 and multiplying by the pixel size and a factor to correct for image magnification.

In order for the data generated by the imaging apparatus to be used for overall feedback control of the processing system, some mathematics is involved: first, a suitable dynamic process model must be identified (this describes the temporal relation between the desired and measured process outputs); and second, a controller



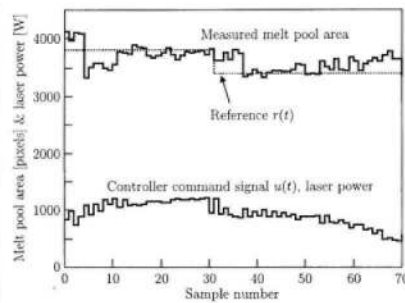
3 Schematic diagram of digital camera based laser surface alloying control system

must be designed that can be implemented to maintain the measured output at the level of the command (desired) output as closely as possible. Process identification is dealt with in standard texts¹⁵ and full details of the controller design and implementation for the system described here may be found in Ref. 16.

Performance of controlled system

Figure 4 illustrates the performance of a controlled laser surface alloying treatment of titanium with nitrogen. At sample 31 the command signal (melt pool area) is changed from 3800 to 3400 pixels, as a result of which the laser power is decreased by the controller. As can be seen from the graph, it takes 6 samples (which is three times as long as the inherent system communication delay) for the new reference value to be attained. There is also a slow increase in melt pool area from sample 52, attributable to thermal lensing of the focusing lens as well as the imperfect description of the process by the model for laser powers below 750 W. The startup time of the controlled process was reduced by starting processing at a higher power, and by accelerating the workpiece at some distance before the point at which processing should start, thus avoiding excessive melting.

Once the system had been tuned with these adjustments, the accuracy of control was tested by introducing temporary changes in the absorptivity and thickness of a workpiece. It was found that the control system could cope successfully with a change in absorptivity. In contrast, the workpiece with an area of reduced thickness caused the laser power to oscillate in an uncontrolled manner, and even when the laser had passed over the area of reduced thickness it took 15 samples before the power stabilised again at the original level. This poor performance can be attributed to the fact that the identified process model is not valid for a workpiece of reduced thickness. To overcome this unsatisfactory behaviour, adaptive control should be added to the control system: an adaptive controller consists of an online process identification algorithm which works at a relatively low sample rate, and a regular con-



4 Laser surface alloying of Ti with nitrogen: performance of controlled system

troller, acting at a high sample rate, which takes care of process disturbances.¹⁷ With this additional degree of enhancement, proper control of the melt pool surface area under all conditions will be achieved.

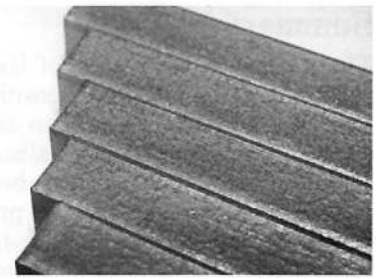
The vision system described above does have some disadvantages in terms of complexity and expense. An alternative system would involve a monochromatic (radiance) pyrometer, configured to measure the melt pool surface area by adjustment of the measurement spot so that it is larger than the area of the melt pool. This would have an additional advantage over the vision system in that sampling (and hence control) of the laser surface treatment process could be conducted at a higher rate. This system is as yet at an early stage of development at the University of Twente, but the indications are that it will prove to be an effective substitute for the digital thermographic camera based control system.

Laser cladding applications

A number of applications of laser cladding are currently being investigated at the University of Twente in parallel with the work on control systems. In laser cladding, a powder jet is injected into a laser melted pool of substrate material to produce a surface with improved hardness and/or wear and corrosion resistance. Two promising examples of laser cladding applications which could benefit from the process control discussed above are now described.

Magnetic brake for train carriage

Unlike conventional train carriage brakes, magnetic brakes operate by making contact with the rail, resulting in very high contact



5 Laser clad magnetic brake for train carriage

forces. Laser cladding can produce a protective layer with high resistance to this type of wear. Experiments have been performed using a high power CO₂ laser with Eutroloy 26001 cobalt powder injected into a 2 mm diameter melt pool on the mild steel substrate. Using various clad parameters, five layers were deposited on the substrate to form a 1.5 mm thick multilayer with a surface hardness of >600 HV after grinding (see Fig. 5).

Repair of corroded surfaces

Corrosion during production of oil gas can be largely prevented by proper material selection. Some parts, however, are subject to crevice corrosion, resulting in malfunction of sealing; parts affected in this way have either to be replaced or, if repair will cost less than replacement, repaired. Laser cladding has been investigated as a new repair technique for this application, as repair by thermal spraying often results in insufficient adhesion and conventional welding techniques involve too high a heat input and produce an extensive heat affected zone. Using a high power CO₂ laser, a Ni based powder with good anticorrosion properties has been successfully applied to a pre-machined surface (Fig. 6). Clad layers have been deposited with a thickness of 0.4 mm; heavily corroded surfaces are treated simply by applying multiple layers.



6 Repair of corroded surface by laser cladding (experimental setup)

Summary

The quality of the results of laser surface treatment is highly sensitive to unstable system parameters and process disturbances. A feedback control system has therefore been developed to ensure constant processing quality during laser alloying of Ti with nitrogen. Two versions of the system, which uses melt pool surface area as a quality parameter, have been investigated: the first uses a digital thermographic camera and the second a monochromatic pyrometer to provide online measurement of melt pool area. Both approaches can provide effective quality control of the process.

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Further information from: Professor Dr Aleksander Nakonieczny, Director, Instytut Mechaniki Precyzyjnej, Duchnicka 3, 00–967 Warszawa, Poland, tel. +48 22 6634335, fax +48 22 6634317, email nakon@imp.edu.pl.