Nano-indentation hardness and modulus of laser surface modifications for outer-penal forming moulds & dies

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ABSTRACT The mechanical properties of the laser metal surface hardening, especially obtained with certain temporal and special intensity distributions of laser beams for cast iron in automobile industries, have been investigated with use of a Nano-indentation Testing Technique (NTT). In comparison with the traditional micro-hardness tests, the NTT can be employed to measure the real-time loads on laser surface modification layers of specimens. Moreover, the hardness and modulus vs. displacement into the surface with different microstructures of the laser hardening samples of cast iron can be also obtained.

KEY WORDS: Laser surface hardening, nano-indentation testing technique, hardness and modulus

1. INTRODUCTION

Advanced manufacturing technologies including flexible, agile, intelligent and virtual processes play a very important role in industrialized and imformationalized activities nation-wide. Especially, on the basis of principle of laser-material-interaction, manufacture technology and information technology, the research of integrated laser intelligent manufacturing and flexible machining has become one of the most attractive areas in this multi-discipline field.

In manufacturing industry, the modification of the mechanical properties of traditional materials is the key factor for the quality and lifetime of products. Until recently, many methods and attempts are available to be applied in materials processing to improve their mechanical properties. Among these, laser surface treatment of metals has been proved in both research and application as one of the most practical techniques[1] to enhance the surface hardness, wear resistance, anti-corrosion and strength-ness of base metals in particular used in high temperatures. Therefore, exploring deeply the phenomenon of laser-material-interaction becomes one of the fundamental researches in materials processing. In this paper, we describe in details of experimental and theoretical research on surface hardening of working moulds and dies used for automobile industries (outer-penal forming process), and emphasize on interaction of temporal and special distributions of high intensity laser beam with materials of moulds and dies in order to obtain an evaluation system of both micro and macro mechanical properties and metallic structures during the modification processes.

2. MODELING OF LASER MATERIAL INTERATION

Melting and evaporation are encountered in almost all laser materials processing, particularly in those of laser industrial applications. A two-dimensional time-dependent model, employing an easily applied implicit finite-difference scheme of an enthalpy method to simulate the transient material behavior during laser processing, is developed[2,3]. In modeling, the spatial and temporal intensity profiles of an impact laser beam and the temperature-dependent target material properties including absorption, heat capacity and thermal conductivity are considered for the calculation. At both the

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laser-material interaction boundary and the inner phase-change boundary, the energy losses by ways of absorption, reflection, conduction, convection, radiation, and evaporation are thoroughly taken into account.

For convenience and to clarify the applicability and limitation of the model, the following assumptions are mainly made: (1) classical heat conduction theory is applicable to laser-material interaction process; (2) density variations of the solid with temperature are negligible; (3) evaporated material does not interfere with the incoming laser beam; (4) melting and evaporation occur at their constant temperatures respectively; (5) flow in the melting pool and molten liquid ejected from the melting pool, due to the ablation pressure are neglected.

A cylindrical coordinate frame has been established, where the z-axis is the incident laser beam direction and the r-axis the radical direction, as shown in figure 1. Since the complete solution requires the identification of the melting and evaporation interfaces and their propagation velocities simultaneously with the temperature computation, the weak solution method is used and solved simultaneously with the temperature-enthalpy relation *T-h* equation, whereby the governing equations may be written[3]3] in term of the specific enthalpy *h*,

$$\rho \frac{\partial h}{\partial \tau} = \nabla[k(\nabla T)] \tag{1}$$

here ρ, h, τ, T, and k are density, enthalpy, time, temperature, and thermal conductivity respectively. The boundary conditions state that the irradiation absorbed at the surface is used up both by conduction losses into the solid and by evaporation,

$$\alpha \cdot P_s + k_l\left(\frac{\partial T_l}{\partial n}\right)_w = L_v \rho \upsilon_w \tag{2}$$

here α, P_s, n, L_v, and v_w are surface absorption, spatial distribution of laser irradiance, unit surface normal, latent heat of vaporization, the surface recession velocity respectively, and w and l stand liquid-vapor interface and liquid phase.

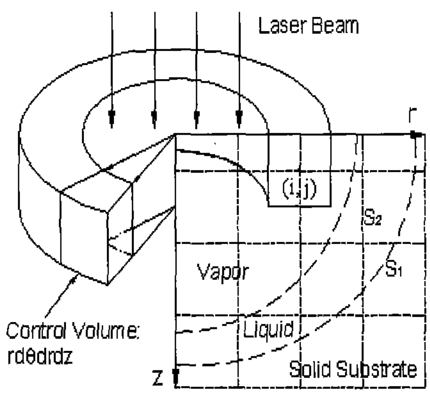


Figure 1. Schematic diagram illustrating the coordinates and grid system for the model.

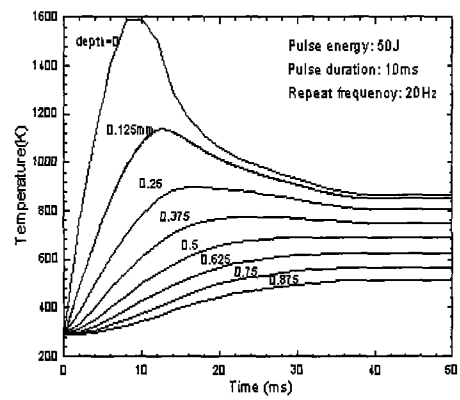


Figure 2. Development of temperature at different depth along with beam axis during pulsed laser process.

Typically, the calculated time dependent temperatures at different case depths of the material along the beam axis are shown in figure 2. It shows that short period laser irradiation on the target material results in a sharp increase in temperature at the surface with a change rate as high as $1.5\times10^5 K/S$, without affecting the surrounding areas. The sharp temperature gradient between the surface of sample and surrounding areas leads to self-quenching. The cooling rate is much higher than the critical rate 30-40*K/S*. At different depth locations along the incident beam propagation, the highest temperature reached T_{max} and times to this temperature t_{max} are all different. With increasing depth, T_{max} decreased sharply while t_{max} increased sharply. The rolling out in temperature development curves indicates that phase change has happened during this interval.

3. HIGH POWER LASER BEAM CONVERSION

In laser materials processing, particularly in metal surface modifications, high power laser beams are frequently required to be in a special shaping with determined intensity distributions. However this is difficult to be satisfied by employing only traditional optical focusing systems. According to our experimental results[4,5], it shows that the pre-determined intensity profiles of incident laser beams may be realized by using the Diffractive Optical Elements (DOE's), not only enhancing the performance of laser surface treatment but increasing the speed of processing as well. The application of the diffractive optics in surface processing with high power laser beams is an attractive method for improving the usage with a conventional lens system. It should notice that the strong zero order could induce the problem of localized melting and vaporizing of metal surface. Hence it becomes the most influenced factor in laser surface processing resulting a serious surface damage.

The simulated annealing algorithm method (SA) is employed to design DEO's. It can be concluded that the key steps are choosing the merit function and cooling it down. The merit function may have different structures for different application requirements. In our application the merit function of the designing process has two weight factors that need to be controlled, namely the diffraction efficiency and the relative distribution of all the spots. The common choice is to select a high starting temperature, a criteria for stopping the optimum loop and a function of decreasing temperature.

In general, any output intensity distributions produced by DOE's are obtainable by using the SA method. Figure 3 shows examples of profile patterns formed on the metal surface by using DOE's, (a) and (b) are grid arrays, (c) is a spot array. The original incident beam is a Gaussian one, the actual pattern size converted by using DOE's is related to the design and the focal length of the focusing system, in our case it is about 4 by 4 mm. The cross-section view of metal surface treatment of these patterns is presented in figure 4. It is clear seen that there is no surface damage incurred, and the periodical phase change area has been formed.

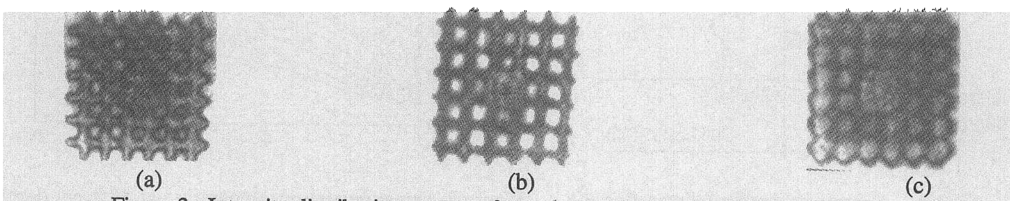


Figure 3. Intensity distribution patterns formed on metal surface by using DOE's.

4. NTT RESEARCH ON LASER METAL SURFACE STRENGTHENING

Nano-indentation Testing Technique (NTT) is a newly developed method to measure the mechanical properties of target material by control of continuous loading and displacement with very high resolution, and it has been widely used in relative fields of scientific research and engineering. With help of NTT, one can obtain micro- even nano-scaled information (modulus and hardness for example) of target material surface directly from the loading-indentation database. By means of combination of micro-hardness tests and NTT, the mechanical properties of laser surface modifications for cast iron materials may be investigated thoroughly. The test material in experiments is from body forming moulds and dies containing cast iron, and cut into specimens with size of 9×9×15mm. In order to treat working surface of forming moulds and dies in automobile industry, a computer integrated 5-axis frame structured laser robotic processing equipment with flexible beam deliveries has been built up[6,7], almost suitable for any type of outer-penal moulds.

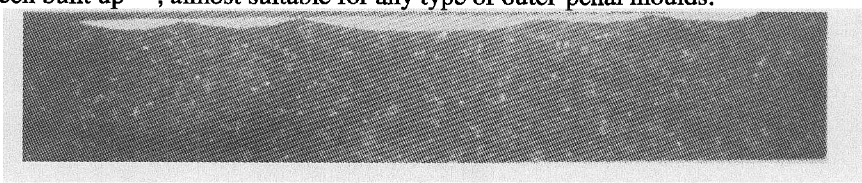


Figure 4. Cross-section view of the metal surface being hardened.

5. EXPERIMENTAL RESULTS AND DISCUSSION

As a comparison, NTT indentation experiments have been carried out firstly in the area of base material far away from laser treated zone, results are presented in figure 5 (a). It has to be pointed out that the hardness $H = P(d)/A(d)$, where P is the load, A is the project of the area size formed by the load, and d is the depth of indentation. This shows the loading capacity of the material. In table 1, H_A and E_A present an average hardness and modulus at distance of 400nm~1400nm, respectively. Where H_U and E_U are the hardness and modulus of maximum loading. Accordingly, the indentation positions of Test1 to Test5 are from lift to right, as shown in figure5 (b). Figure 5 (c) illustrates a cross-section picture of laser beam surface modification.

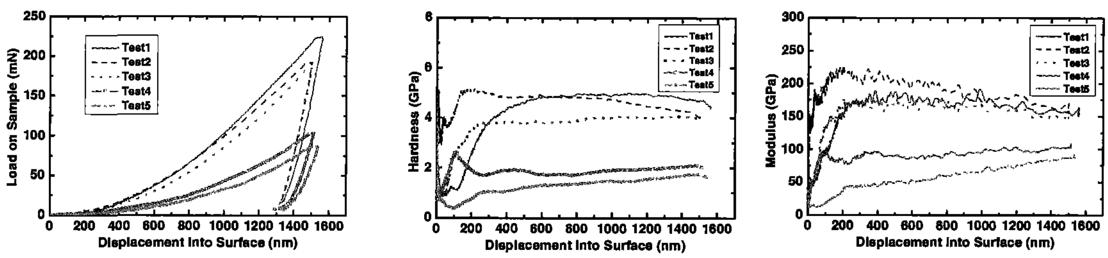


Figure 5. (a) Experimental results on base metal material.

With same test material few different laser beam parameters are chosen and applied to measure the optimum conditions, the treated area at cross-section may be divided into three zones, namely laser hardened zone (LHZ), heat affected zone (HAZ), and base material zone. Figure 6 shows the micro-structure and the indentation position of the laser modification zone. Under the observation of optical microscope and SEM, there exists a bright curve-like zone, as shown in figure 6 (d), consisting of fine structure of Marstine. It can be also seen the tremendous difference between phase change zone and heat affected zone, as shown in figure 6 (b). According to the indentation position in figure 6, experimental results of hardness and modulus from nano-indentation indicate various, as illustrated in figure 7. In figure 6 (a)~(c), point L1 stands the closed indentation to the surface, and L2 the second with the distance of 40μm from L1, and so on. Point G presents an indentation in HAZ, and S is the one on the boundary of phase changed zone and HAZ. It is obvious that hardness of target material increased by a factor of 3 roughly after the laser hardening, reaching a value of 11.307 Gpa comparing with 4.860 Gpa before treated. Since the mechanical properties of a traditional material has been improved a great amount by laser interaction process, the quality and lifetime of forming moulds and dies made from these materials may be also be improved.

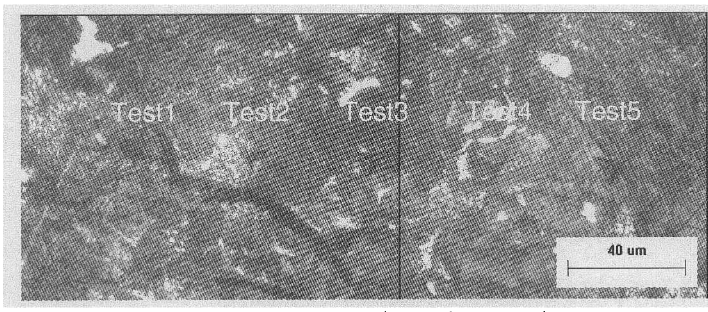


Figure 5. (b) Indentation Position on base metal.

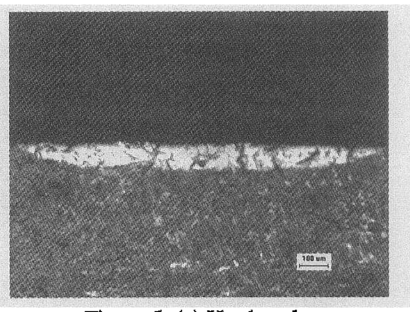
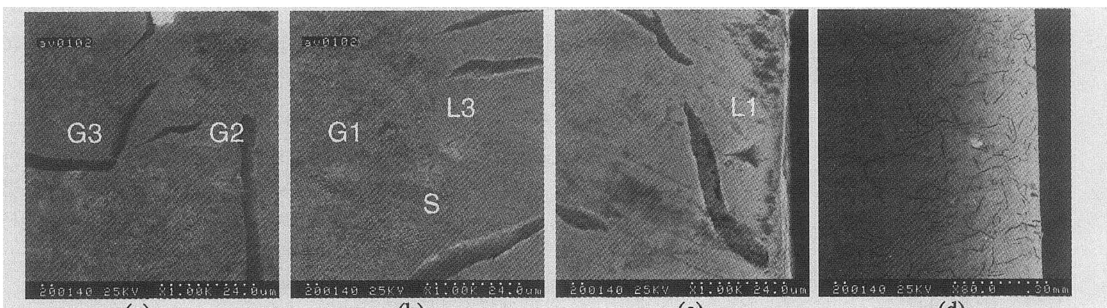


Figure 5. (c) Hardened area.

Table 1 Experimental results of hardness on base metal

	Test1	Test2	Test3	Test4	Test5
H_A	4.860	4.720	3.916	1.824	1.402
E_A	172.204	188.915	164.218	93.539	62.998
H_U	4.386	3.981	3.852	2.020	1.651
E_U	159.888	165.120	154.819	100.951	86.092



(a) (b) (c) (d)

Figure 6. Microscope pictures of structure and indentation of AV02X.

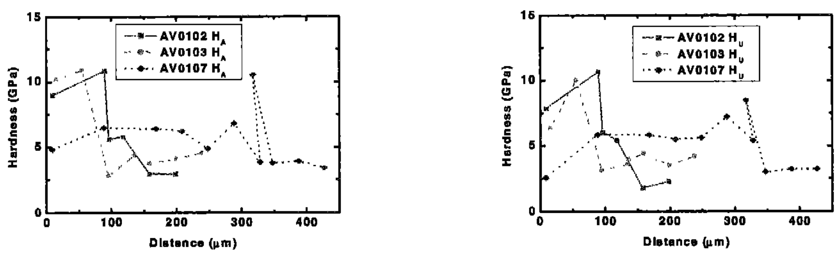


Figure 7. (a) Hardness distribution of three laser modification zones.

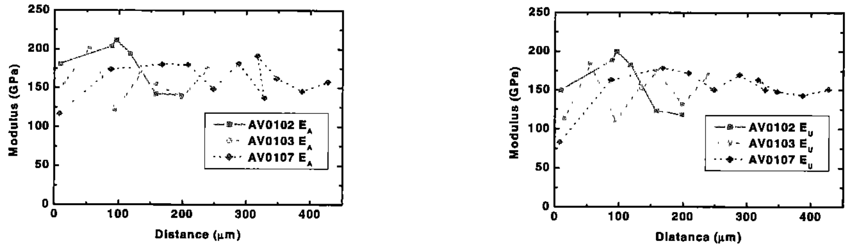


Figure 7. (b) Modulus distribution of three laser modification zones.

6. CONCLUSION

As demonstrated above, it can be concluded that the improvement of micro structure and mechanical property (hardness and modulus) takes place during the laser-material-interaction processes, and laser surface modification of traditional materials can be widely used in related industries including automobile manufactures to enlarge the quality and lifetime of products. By means of NTT and micro-hardness test, real-time mechanical properties can be obtained on scales of nano-meter to millimeter, theoretical and experimental research on these strong non-linear mechanical effects and understand the phenomenon of laser-material-interaction may lead to establish a general applied evaluation system.

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Prof. Gang Yu was born in 1958. He graduated form Southeast University, Nanjing, China, with B.Sc. in Electronic Engineering in 1982. Upon his graduation he was involved in research on rf-excited sealed-off wave-guide gas lasers and their applications in military uses for few years in Beijing. He moved to UK in 1987, and studied as postgraduate for higher degree in the field of high resolution infrared spectroscopy. He obtained his M.Phil. and Ph.D. degrees in Physics from Strathclyde University, Glasgow, UK in 1989 and 1992, respectively. From 1992 to 1995, he moved to Heriot-Watt University, Edinburgh, UK, and was involved in EUREKA Project EU113. During the period he engaged in research of high power compact CO laser system with rf-excitation and fast-axial-flow, as a postdoctoral research fellow. He returned to Beijing, was awarded a full professorship in 1995 at Institute of Mechanics, C.A.S., China. Since then, he has been in charge of projects funded by the CAS, NSFC and Industrial Sectors, including a present key project of innovation engineering from CAS. His research interests covers laser physics, laser technology, and laser industrial applications. He now is Ph.D. student supervisor and member of Chinese Optical Society.