LASER SHOCK PROCESSING AS A METHOD FOR SURFACE PROPERTIES MODIFICATION OF METALLIC MATERIALS

2005/26

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ABSTRACT

Laser shock processing (LSP) has been proposed as an effective technology for improving surface mechanical and corrosion properties of metals, and has been developed as a practical process amenable to production engineering

The main acknowledged advantages of the laser shock processing technique (LSP) consist in its capability of inducing of a relatively deep compressive residual stress field into metallic materials resulting in improved mechanical behaviour against fatigue crack initiation and growth, mechanical wear properties and stress corrosion without any recursion to any other subsidiary mechanical treatment.

From the metallurgical point of view, laser shock processing may have various significant effects on the microstructure of processed materials. Beside more or less known effects like compressive residual stress profiles and improved fatigue resistance, some other effects on micro-scale might be found.

During investigation of standard AISI 304 steel after laser shock processing, measurements of residual stress states near surface, microhardness as well as optical and electronic micrography were performed. The results showed the substantial effects of laser shock processing in every measured aspect to several 100 μm. As compared to classical shot peening, those effects are substantially different and enable users to better use the material.

I. INTRODUCTION

Laser shock processing has been proposed as a competitive alternative technology to classical treatments for improving fatigue and wear resistance of metallic materials, and has more recently been developed as a practical process amenable to production technology [1-3].

The technique was initially developed specifically for the improvement of the fatigue cracking resistance of materials used in the aeronautic applications. Up to now, many materials such as aluminium and titanium alloys and different types of stainless steel were extensively investigated but the unavailability of powerful laser sources able to provide the needed intensities made any industrial application impossible.

More recently, on the basis of the commercial availability of new powerful laser sources able to provide intensities exceeding the GW/cm^2 level, a new intense research effort has been started aiming to develop the LSP technology from an industrial point of view [4-7].

In this paper, experimental results on the residual stress profiles created in typical materials under different irradiation conditions are presented. In particular, the induction of residual stress fields and associated microstructure and material properties modification are analyzed for the case of AISI 304 stainless steel.

II. EXPERIMENTAL SETUP AND PROCEDURES

The practical irradiation system used for the experiments reported in this paper is schematically and photographically shown in Fig. 1. Using purified water as confining medium, the test piece is fixed on a holder and is driven along X and Y directions by means of a computer controlled stage needed for the irradiation of extended areas of material following a pre-defined pulse overlapping strategy.

The laser light is then conducted to the interaction area by means of a reflecting mirror and a focussing lens. The control of the purity of the confining medium is important in order to avoid the formation of water bubbles or increasing concentration of impurities resulting from material ablation following the laser irradiation.

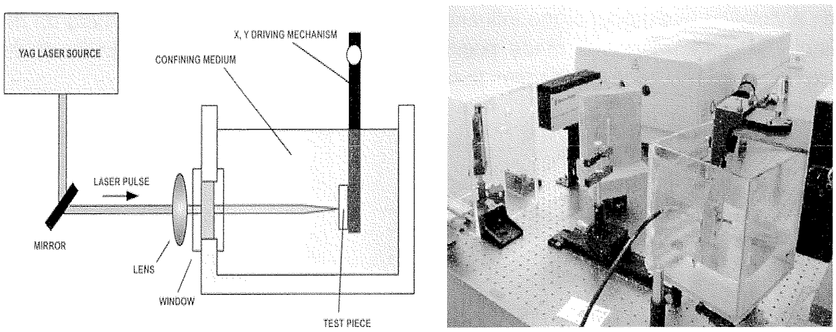

Figure 1: Schematic representation and photographic view of the LSP irradiation experimental setup used in experiments.

The LSP experiments reported in this paper were performed at 1064 nm wavelength using a Q switched Nd:YAG laser operating at 10 Hz and providing 8 ns FWHM, 1,2 J pulses. A convergent lens was used to deliver the laser energy over a 1.5 mm spot diameter. The confining layer was provided by a water jet delivered at 2 bar.

III. EXPERIMENTAL RESULTS

Under the referred experimental conditions, the effects induced by the laser on the mechanical properties of the treated material have been characterized. In particular, the analysis of induced residual stress fields, associated microstructure and analysis of materials properties, have been performed.

The test piece geometry used for the investigations is displayed in Fig. 2 together with a photograph of the resulting aspect of the work piece after the application of the LSP treatment and subsequent residual stresses field determination by hole drilling method. In this test piece, the varying experimental parameter is the so-called "overlapping pitch", d, a direct measure of the distance between both adjacent laser shots and parallel processing tracks which, in the defined geometry, implies a given number of pulse density according to table I for the chosen representative values.

Table I: Relation between overlapping pitch and equivalent density of pulses corresponding to the defined sweeping procedure.

$$\left(\text{Equivalent overlapping density} \equiv \text{eod} = \frac{\text{number of pulses}}{\text{treated surface}} = \frac{\frac{x}{\Delta x}\frac{y}{\Delta y}}{\Delta s} = \frac{\frac{x}{d}\frac{y}{d}}{xy} = \frac{1}{d^2}\right)$$

Overlapping pitch d (mm)	Equivalent overlapping density (pulses/cm^2)
0.4	625
0.285	1225
0.2	2500

This kind of experimental characterization is considered to be especially favourable as a detailed evaluation of the influence of the different process parameters on the final LSP performance is made possible in view of the direct amenability of the experimental results to comparison to numerical simulation results [8-9].

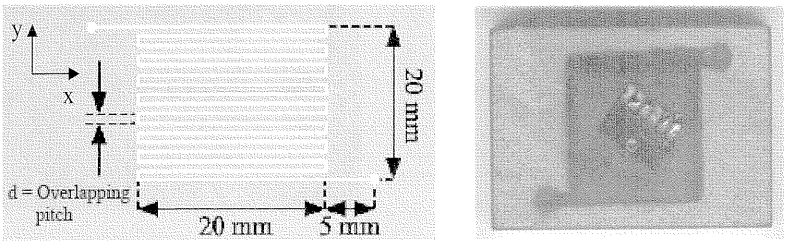

Figure 2. Schematic representation of the LSP track on the sample surface and photograph showing a real test piece after processing.

a) Residual stresses fields

Residual stress distribution was determined according to the ASTM E837-01 Standard test method for determining residual stresses by the hole drilling strain gage method [10]. Strain gage rosettes CEA-13-062UM-120 along with a Vishay Measurements RS-200 milling guide were used. AISI 304 steel specimens 8 mm thick were used for the experiments.

Fig. 3 shows, as an example of the experimental work performed in the field, the depth profiles obtained for LSP-induced residual stresses in y-direction for four representative values of effective pulse density.

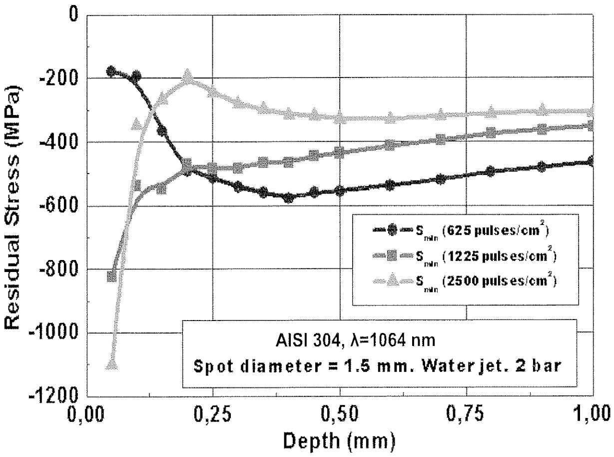

Figure 3. Comparative analysis of induced residual stresses along z-coordinate in AISI 304 steel for three representative pulse densities.

The new graph in Fig. 3 proves that compressive residual stresses can be introduced in the considered material with the applied laser intensity level of about 8 GW/cm^2.

The observed effect is predicted by previous modelling results published by the authors [11]. It clearly confirms the practical ability of the LSP treatment for the induction of compressive residual stress fields at an extent comparable with competing technologies like shot peening.

b) Microstructure and Mechanical Properties

Optical micrography on cross sections of the treated specimens (using Glyceregia, composition: 10 ml HNO_3 + 35 ml HCl + 30 ml glycerin as etching agent) has been performed showing, in addition to the external surface affection, a modification of the microstructure of the AISI 304 steel (see Fig. 4). The observed effect on microstructure can be attributed to increased dislocation density in the sub-surface layer.

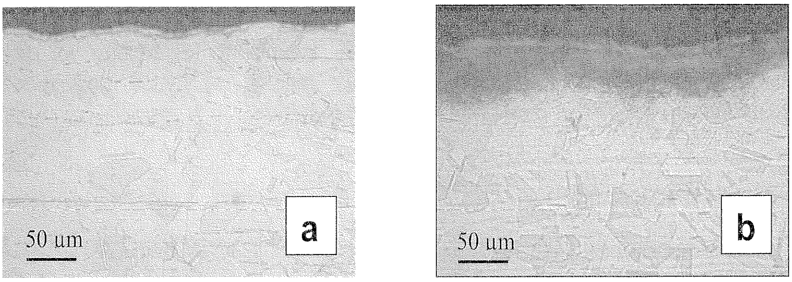

Figure 4: a) Microstructure of AISI 304 austenitic steel. Small individual phases are aligned in visible layers as a consequence of mechanical treatment (rolling).

b) Effect of LSP on the sub-surface under LSP treated area.

The result of microhardness of treated specimens was measured according to Vickers method using two different forces. Fig. 4 shows the measured values on a AISI 304 specimen treated with 625 pulses/cm^2. As expected, elevated microhardness is found near the surface down to the depth of about 0.2 mm.

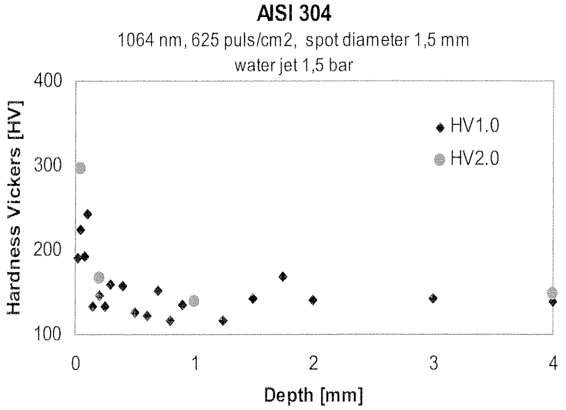

Figure 5: Hardness of AISI 304 specimen treated by LSP with 625 pulses/cm^2.

IV. DISCUSSION

According to the theoretical and experimental results obtained by the authors, the conclusion can be drawn that the LSP technology shows a potential of practical relevance for the improvement of mechanical surface properties. The treatment introduces compression residual stresses and increases the yield strength and hardness of the material in the effected surface layer by increasing the density of dislocations.

The results presented support and prove the findings of the authors presented in previous papers [8-9]. They also point out the high relevance of a suitable strategy for scanning the surface with the laser beam and of a well-defined pulse density for LSP treatment.

Consequently, LSP is considered as a really promising technology for the enhancement of the mechanical properties like fatigue resistance and stress corrosion cracking resistance (see [12]) of metallic materials.

ACKNOCWLEDGEMENTS

Work partly supported by MCYT (Spain; Project DPI2001-3669) and EADS-CASA (Spain).

REFERENCES

[1] FAIRAND, B.P. et al. J. Appl. Phys. Vol. 43 (1997) 3893-3896.

[2] YANG, L.C.: J. Appl. Phys. Vol. 45 (1974) 2601-2607.

[3] FAIRAND, B.P.; CLAUER, A.H.: J. Appl. Phys. Vol. 50 (1979) 1497-1502.

[4] SANO, Y.; et al..: "Underwater Laser Processing to Improve Residual Stress on Metal Surface". In: Proceedings of the 6th International Welding Symposium of Japan Welding Society, 1996, Nagoya, Japan, 501-506.

[5] DANE, C.B.: High Power Laser for Peening of Metals Enabling Production Technology. In: Lawrence Livermore National Laboratory, Report UCRL-JC-131104-Rev 1 (1998)

[6] SANO, Y. et al.: Nucl. Inst. Meth. Phys. Res., B Vol. 121 (1997) 432-436.

[7] BERTHE, L., et al.: J. Appl. Phys. Vol. 85 (1999) 7552-7555.

[8] OCAÑA, J.L. et al.: A Model for the Coupled Predictive Assessment of Plasma Expansion and Material Compression in Laser Shock Processing Applications. In: Phipps C.R.; Niino M. (Ed.): High-Power Laser Ablation II, SPIE Vol. 3885 (2000) 252-263.

[9] OCAÑA, J.L. et al.: "Predictive assessment and experimental characterization of the influence of irradiation parameters on surface deformation and residual stresses in laser shock processed metallic alloys". In: Phipps C.R.(Ed.): High-Power Laser Ablation IV, Taos, (NM, USA), April 2004.

[10] ASTM 2002 Annual book of ASTM Standards, v.03.01 No. E837-01 Standard Test Method for Determining Residual Stresses by the Hole–Drilling Strain Gage Method.

[11] OCAÑA, J.L. et al., Appl. Surf. Sci. 238 (2004) 242-248.

[12] RUBIO-GONZÁLEZ, C. et al.: Mat. Sci. Eng. A, 386 (2004) 291-295.