

LASER SHOCK PROCESSING: AN EMERGING TECHNIQUE FOR THE MECHANICAL AND SURFACE PROPERTIES ENHANCEMENT OF METALLIC MATERIALS

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Abstract

Laser Shock Processing (LSP) is as an effective technology for the improvement of surface and mechanical properties of metallic alloys and is an emerging technology in its way to production engineering in direct competence with other well established technologies as, i.e. shot peening. The technique is based on the application of a high intensity pulsed laser beam on a metallic target forcing a sudden vaporization of its surface into a high temperature and density plasma that immediately develops inducing a shock wave propagating into the material.

The main advantage of this technique consists on its capability of inducing a relatively deep compression residual stresses field into metallic alloy pieces allowing an improved mechanical behaviour, explicitly, the life improvement under cyclic load connected with improved wear and corrosion resistance. The laser shock effects achieved by this method are comparable to those of shot-peening: that is, a local material compression linked to the generation and displacement of defects, surface state modification and, most important, a compressing residual stress field whose magnitude and depth into the material is generally associated with large improvements in fatigue resistance.

Along with a description of the theoretical/computational and experimental methods developed by the authors for the predictive assessment and experimental implementation of LSP treatments, experimental results on the residual stress profiles and associated surface properties modification successfully reached under different LSP irradiation conditions in typical high strength materials will be presented in this paper.

Keywords: laser shock processing; residual stresses; mechanical behaviour; surface properties; fatigue life.

1. Introduction

Laser Shock Processing (LSP) was initially developed as an alternative technology to classical treatments for the improvement of surface properties of metallic alloys involving the fatigue life of critical components. Especially wear resistance, stress corrosion cracking susceptibility and crack propagation rate seem to be material properties specifically improved by LSP treatments (see Fairand et al., 1972; Yang, 1974; Fairand and Clauer, 1979; Sano et al., 1996).

In the most recent years, and profiting by the availability of laser sources able to provide intensities exceeding the GW/cm² level, the LSP technology is aimed to be developed from an industrial point of view for the improvement of the fatigue cracking resistance and other surface properties of materials used in the aerospace, nuclear, automotive and biomedical applications, such as Al and Ti alloys and different types of stainless steel (see Dane, 1998; Sano et al., 1997).

Although, as a consequence of the inherent physical complexity of LSP processes, specifically stemming on the coexistence of different material phases (including plasma) developing and interacting under the action of the high-intensity laser beam, very limited attempts have been developed in the way of full comprehension and predictive assessment of the characteristic physical processes and material transformations, previous contributions by the authors (see, i.e. Ocaña et al. 2000, 2004a, 2006; Morales et al., 2010) have been able to

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correlate laser incidence and interaction material-geometry parameters to final thermo-mechanical effects resulting in treated specimens, thus providing a valuable tool for the technique parametrization and penetration at the industrial level.

In this paper, after a short description of the experimental implementation of LSP treatments conducted at the UPM Laser Centre (CLUPM), experimental results on the residual stress profiles created in AISI 316L stainless steel (taken as reference material) under different irradiation conditions are presented along with the associate effects on characteristic material surface and mechanical properties, namely microhardness, wear resistance and fatigue life.

2. Experimental implementation of LSP processes

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 by means of a robotized arm needed for the irradiation of extended areas of material following a pre-defined pulse overlapping strategy.

The laser beam (Q-switch Nd:YAG, 2.8 J/pulse, 9.4 ns FWHM pulse length, 10 Hz repetition rate) is conducted to the interaction area (typically circular spot 1.5 mm diameter to provide a peak laser energy density on target in the range of several GW/cm^2) through a water confining layer and without any protective coating by means of a reflecting mirror and a focusing lens. The control of the purity of the confining medium is important in order to avoid the possible effect of impurities resulting from material ablation following the laser irradiation.

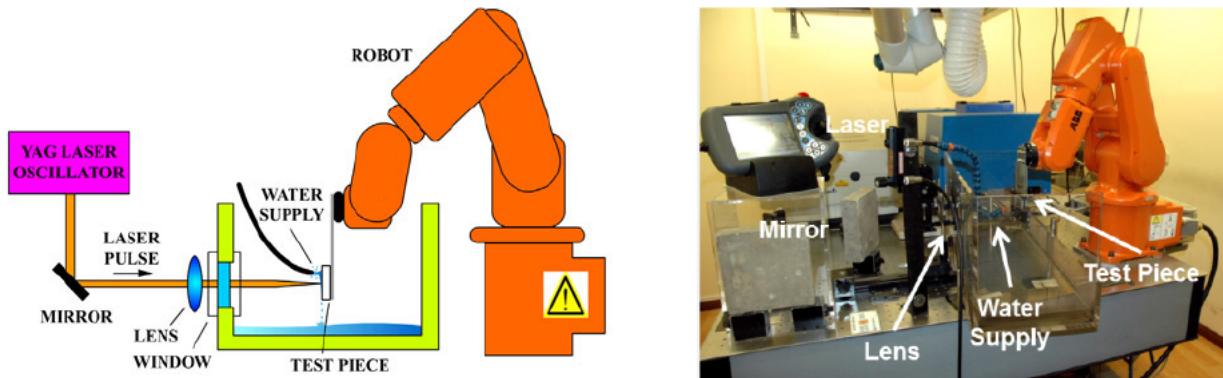


Figure 1: Schematic representation and photographic view of the LSP irradiation setup used in the reported experiments.

The LSP experiments reported in this paper were performed on AISI 316L steel (taken as reference material) with the composition shown in Table 1. The as-received material, in the form of 6 mm thick plates, had been previously hot rolled and solution annealed between 1050°C and 1100°C.

Table 1: Percent Composition of AISI 316L Steel Used in the Reported Experiments

Element	C	Cr	Ni	Mo	Mn	Si	N	P	S	Fe
% wt	0.018	16.815	10.086	2.044	1.294	0.458	0.047	0.032	0.003	Bal.

For the analysis of the surface properties modification induced on the material by LSP, 40 mm x 40 mm samples were one-side treated according to the experimental variable overlapping procedure originally defined by the authors (Ocaña et al., 2010; 2012). Two equally X-Y spaced overlapping schemes were selected implying respective equivalent overlapping densities (EOD's) of 900 and 1600 pulses/ cm^2 (respective overlapping pitches of $d=0.33$ mm and $d=0.25$ mm).

For the analysis of the fatigue life enhancement induced by the LSP treatment, both in pristine form and after thermal aging (in order to check the thermal stability of the treatment, as will be discussed below), standard dog-bone type specimens 150 mm long were used for normalized fatigue tests were machined in accordance with ASTM standard E466. For these specimens, the LSP treatment was applied on both sides over approximate areas of 35 mm x 20 mm in their central reduced zone following a sweeping strategy progressing transversally to the larger dimension.

3. Results on Surface and Mechanical Properties Enhancement by LSP

3.1. Microhardness

Vickers microhardness measurements were performed using a Matsuzawa MXT30 indenter with constant load of 50 g according to ASTM E384 standard up to depths of 1 mm into the as received and treated specimens. In figure 2 results corresponding to these 3 conditions (as-received + 900 pulses/cm² and 1600 cm²) are depicted. A clear increase in the microhardness, both at the surface level and in inner subsurface zones, is observed, what clearly indicates the generation of high densities of dislocations due to the LSP treatment. As it will be discussed below, the presumably irreversible character of these dislocations due to the high deformation rate achieved under the treatment (exceeding 10⁶ s⁻¹) will be an important argument to be considered when analyzing the thermal stability of the microstructure modifications induced by the treatment.

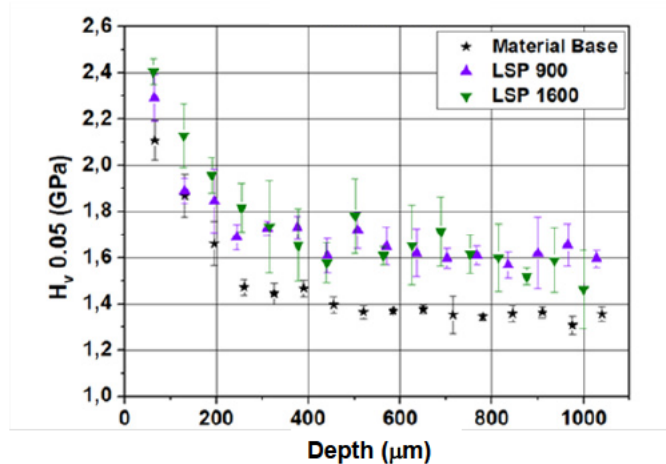


Figure 2: In depth profile of Vickers microhardness for as-received and LSP treated material with two characteristic EODs.

3.2. Wear

In clear correspondence with the shown increase in the surface and sub-surface microhardness provided by the LSP treatment, the wear resistance of the LSP treated samples has been found to be increased by both the parametric treatments applied. In figure 3, the comparative evolution of the wear behavior with the sliding distance of the as-received and the samples treated with the two parametric EODs is shown. The determinations were made with the aid of a Microtest® MT/30/NI/LIN tribometer working in the ball-on-disk mode with rolling ball of AISI 52100 steel, 10 N applied load and 0.063 m/s tangential speed according to the ASTM G99 standard. As it is clearly evident, the threshold sliding distance is increased as the LSP treatment intensity is increased and, in the long sliding distance limit, the worn material corresponding to the samples treated by LSP is considerably lower than that corresponding to the as-received condition, what clearly indicates an improvement in the overall wear behavior of these samples.

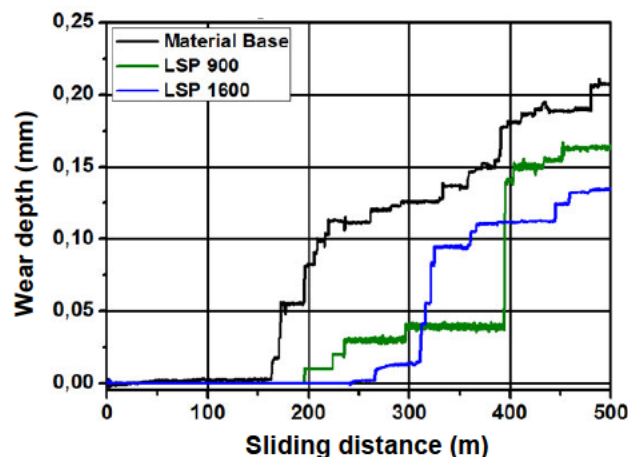


Figure 3: Wear depth vs. sliding distance according to ASTM G99 for as-received and LSP treated material with two characteristic EODs

3.3. Residual Stresses Fields and Their Stability

As a property directly associated to the fatigue behavior of the treated materials (see, i.e., Peyre et al., 1998), the residual stresses fields induced by the LSP treatment were especially analyzed, both with comparison to the as-received base material and considering their thermal stability. The investigation on the effect of thermal treatments on the residual stresses fields induced by LSP is motivated because in some critical industrial applications, materials are subject to repeated thermal stresses as a result of thermal gradients occurring during heating/cooling cycles close or directly in the creep range, what finally leads to an effective working life reduction due to creep-fatigue interaction regimes.

The study is considered to be relevant as the beneficial effects derived from induction of near-surface work-hardened nanoscale microstructures by thermo-mechanical treatments can prevail and result in an effective improvement of components fatigue life only if the induced residual stresses fields remain stable during in-service mechanical loading and/or exposure to high temperatures, and LSP has been identified as one of the treatments providing a higher degree of stability of these fields (Prevéy, 2000).

For the proposed analysis, the samples were LSP treated according to the two referred parametric conditions and subject to thermal aging in order to evaluate the RS's fields stability. According to the practical working conditions of a great proportion of AISI 316L components, a thermal aging temperature of 500°C maintained over 8 hours (considered as sufficient for pure thermal stresses release) was selected as testing reference. No experimentation beyond this temperature was made in view of the well known drop in tensile stress and creep onset starting at about 550°C for the considered material (see, i.e., Tjong et al. 1995 and Chowdhury et al 2005).

Residual stress distributions reached in the LSP treated specimens were determined according to the ASTM E837 Standard Test Method for Determining Residual Stresses by the Hole Drilling Strain Gage Method. Strain gage rosettes CEA-13-062UM-120 along with a Vishay Measurements® RS-200 milling guide were used.

Figure 4 shows the in-depth profiles obtained for LSP-induced Mohr principal maximum (i.e. minimum in absolute value) RS's with the two considered LSP treatment conditions before and after application of thermal aging.

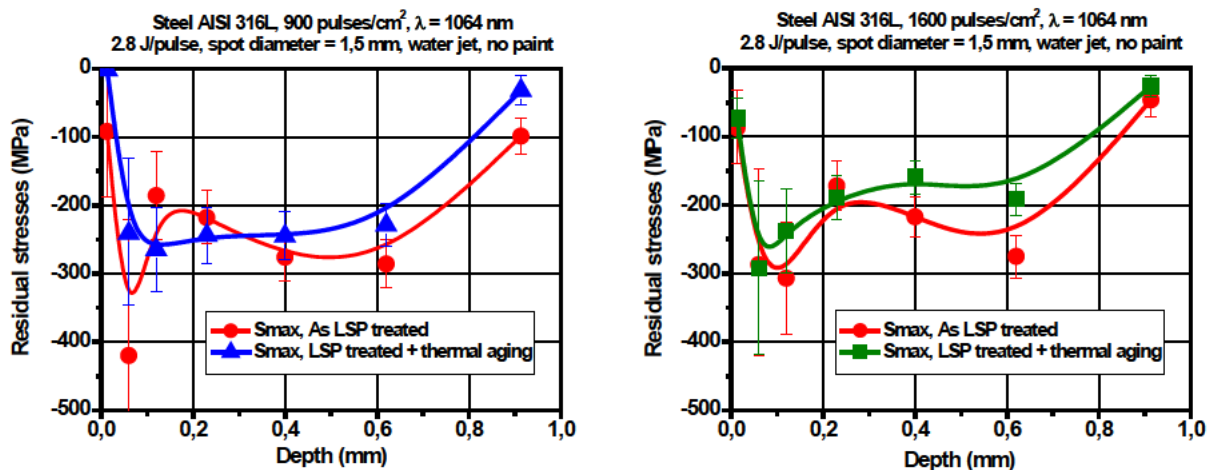


Figure 4. In-depth profiles obtained for LSP-induced Mohr principal maximum (i.e. minimum in absolute value) RS's with LSP treatment at EOD = 900 pulses/cm² (left) and EOD = 1600 pulses/cm² (right) before and after application of thermal aging at 500 C during 8 hours.

The effect of the applied heat treatment can be clearly observed in both cases, as both a decrease of the maximum compressive residual stress resulting in the treated material and a general softening of the level of compressive residual stresses available in the material depth explored by the RS's determination method are found. Both facts imply in practice a certain degree of compressive RS's relaxation that, undoubtedly, must have a certain effect on the material fatigue life, but it is also noticeable that the RS's release is by no means complete, what can be attributed to the special kind of thermally irreversible dislocations induced by the high deformation rates typical in the LSP treatment, as anticipated by Prévéy (Prevéy, 2000).

Additionally, in the case of EOD = 1600 pulses/cm² (a LSP treatment intensity considered as a certain threshold for AISI 316L in order to produce RS's fields deep enough to provide an effective protection against crack propagation), the effect of the applied thermal cycle is not enough to relax completely the minimum value of compressive residual stress induced by the treatment at the material surface, maintaining at the same time a reasonable level of compressive values through the material depth close to the surface (up to 1 mm according to

the determination method), a result that allows to anticipate a certain improved behaviour of the specimens treated under this condition in fatigue life tests.

3.4. Fatigue Life

Once the behavior of RSs fields assessed both in the pristine and thermally aged condition, fatigue tests of LSP treated specimens according to the two specified treatment conditions both prior and after thermal aging were conducted in order to evaluate the degree of permanence of the protective effect of the LSP treatments under such relaxation process. The corresponding tests were carried out on a MTS 810 servo-hydraulic system at room temperature in air. The loading axis was parallel to the rolling direction of the samples and the test was performed in load-control. A highly accurate loading of the specimen along its longitudinal axis with minimal bending strain was granted. The fatigue results were presented using the classic S-N fatigue (Wöhler) curve format with stress amplitude, S_a , plotted as a function of cycles to failure, N , establishing as fatigue limit the loading for which the material reaches 10^6 cycles without failure. The testing was limited to tension-tension loading with mean stress conditions described by $R=0.1$ and a sinusoidal waveform of 10 Hz.

In figure 5, the referred S-N curves corresponding to the two specified LSP treatment conditions are presented compared to the reference of the pristine AISI 316L material in the same experimental testing conditions, both after pure LSP treatment and after LSP treatment followed by thermal aging in the specified conditions.

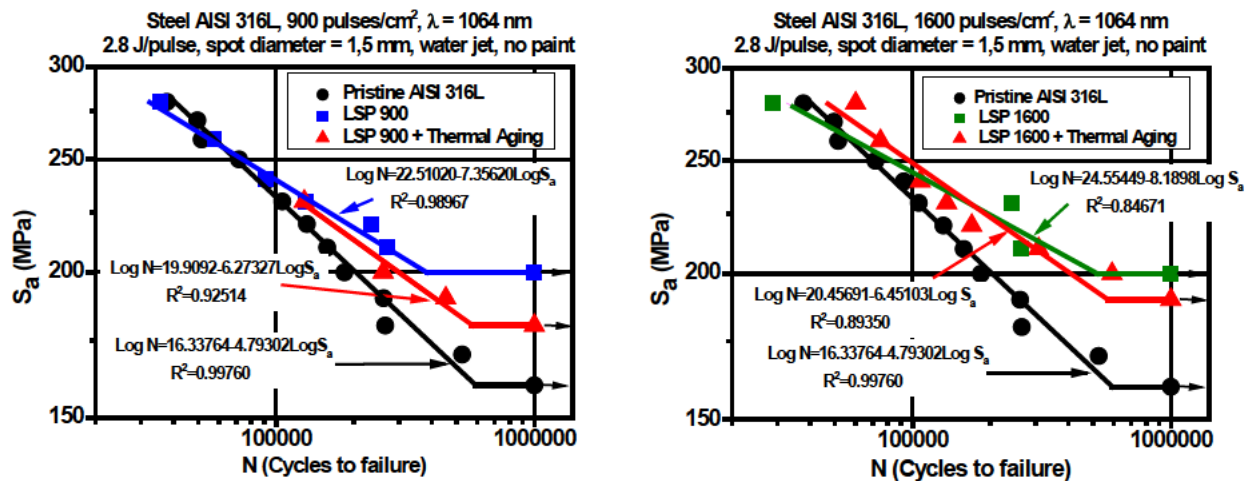


Figure 4. S-N curves corresponding to comparison to pristine AISI 316L material of LSP treated specimens and LSP treated specimens subject to ulterior thermal aging at 500 C during 8 hours. Results for EOD = 900 pulses/cm² (left) and for EOD = 1600 pulses/cm² (right).

In both curves, the improvement of fatigue life provided by the LSP treatment at both EOD's can be clearly observed (rise in runout amplitude from about 160 MPa to about 200 MPa in both cases) but, additionally and most important for the prospects of the present work, a maintenance of the protective effect provided by the LSP treatments after the application of the considered thermal aging cycle can be clearly observed also in both cases.

Within the limitations due to statistical factors in the performed tests, even in the case of EOD = 900 pulses/cm², an increase of about 12.5% (from 160 to 180 MPa in runout amplitude over the pristine AISI 316L) is still observed to be maintained after thermal aging and the increment is even higher (increase of about 18.75% in runout amplitude over the pristine material face to the 25% obtained without thermal aging) in the case of EOD = 1600 pulses/cm² treatment (in a consistent way with the observed better maintenance of the compressive RS's fields reported in the previous section).

4. Discussion

The application of LSP treatments to high relatively elastic limit materials (principally stainless steels and Al and Ti alloys) has shown the possibility of inducing joint significant improvements on their surface and mechanical behavior, namely wear resistance and fatigue life that justify their consideration as a firm alternative to present day well established treatments as "shot peening".

For both kinds of properties, the primary physical reason justifying such favourable macroscopic behavior enhancements is considered to be the induction of irreversible mechanical dislocations at the microscopic level following the extremely high deformation rate induced in the material by the shock waves typically launched by

the LSP treatment. These dislocations are considered to be, in turn, the responsible for the observed higher microhardness and high level of compressive residual stresses fields following the material deformation and, finally, the responsible for the integral enhancement of the surface properties (including corrosion resistance and crack initiation/propagation resistance) finally improving the overall fatigue resistance. The observed fact of the maintained stability of a noticeable level of residual stresses after aggressive thermal aging treatments strongly supports this hypothesis.

On the other hand, provided that the described LSP treatments are able to induce the described transformations over material depths generally higher than those typical corresponding to competing treatments (as, i.e. “shot peening”), it is considered that LSP arises as a powerful industrial technology for the treatment of high reliability components once the engineering aspects concerning process predictive assessment and design are addressed. Additionally, the essentially “clean” character of the technique (not involving residuals or material recycling needs) confers the LSP technique a clear character of sustainability-supporting technique as far as the whole life cycle of critical components is considered.

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References

- ASTM International (2004). ASTM G 99-04 Standard Test Method for Wear Testing with a Pin on Disk Apparatus.
- ASTM International (2013). ASTM E837-13 Standard Test Method for Determining Residual Stresses by the Hole-Drilling Strain Gage Method.
- ASTM International (2015). ASTM E466-15 Standard Practice for Conducting Force Controlled Constant Amplitude Axial Fatigue Tests of Metallic Materials.
- ASTM International (2016). ASTM E384-16 Standard Test Method for Microindentation Hardness of Materials
- Chowdhury, S.G., Das, S., De, P.K. (2005) ‘Cold rolling behaviour and textural evolution in AISI 316L austenitic stainless steel’. *Acta Materialia*, **53**, 3951-3959.
- Dane, C.B. (1998) High Power Laser for Peening of Metals Enabling Production Technology, Lawrence Livermore National Laboratory, Report UCRL-JC-131104-Rev 1.
- Fairand, B.P., Clauer, A.H. (1979) ‘Laser generation of high-amplitude stress waves in materials’, *J. Appl. Phys.*, **50**, 1497–1502.
- Fairand, B.P., Wilcox, B.A., Gallagher, W.J., Williams, D.N. (1972) ‘Laser shock-induced microstructural and mechanical property changes in 7075 aluminum’, *J. Appl. Phys.*, **43**, 3893–3895.
- Morales, M., Molpeceres, C., Porro, J.A., García-Beltrán, A. and Ocaña, J.L. (2010) ‘Numerical thermo-mechanical modelling of stress fields and residual constraints in metallic targets subject to laser shock processing’, *Mat. Sci. Forum*, **638–642**, 2682–2687.
- Ocaña, J.L., Molpeceres, C., Morales, M., García-Beltrán, A. (2000) ‘A model for the coupled predictive assessment of plasma expansion and material compression in laser shock processing applications’, in Phipps, C.R. and Niino, M. (Eds.): *High-Power Laser Ablation II*, SPIE Proceedings, SPIE, Osaka, Japan, Vol. 3885, pp. 252–263.
- Ocaña, J.L., Morales, M., Molpeceres, C., Torres, J. and Porro, J.A. (2004a) ‘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 V*, SPIE Proceedings, SPIE, Taos, NM, USA, Vol. 5548, pp.642–653.
- Ocaña, J.L., Morales, M., Molpeceres, C. and Porro, J.A. (2006) ‘A review of the physics and technological issues of high intensity laser shock processing of materials as a method for mechanical properties modification’, in Schuöcker, D. (Ed.): *XVI International Symposium on Gas Flow, Chemical Lasers and High-Power Lasers*, SPIE, Gmunden, Austria, Vol. 6346, 63461P.
- Ocaña, J.L., Morales, M., Porro, J.A., Iordachescu, D., Díaz, M., Ruiz-de-Lara, L., Correa, C. (2012) ‘Mechanical Properties Enhancement of High Reliability Metallic Materials by Laser Shock Processing’, *Mat. Sci. Forum*, **706–709**, 2565-2570
- Peyre, P., Berthe, L., Scherpereel, X., Fabbro, R. (1998) ‘Laser shock processing of aluminum-coated 55C1 steel in water confinement regime, characterization and application to high-cycle fatigue behaviour’, *J. Mat. Sci.*, **33**, 1421–1429.
- Prevéy, P.S. (2000) ‘The Effect of Cold Work on the Thermal Stability of Residual Compression in Surface Enhanced In718’. *Proc. 20th ASM Materials Solutions Conference & Exposition*. St. Louis (Missouri, USA), October 10-12, 2000.
- Sano, Y., Mukai, N., Sudo, A. Konagai, C. (1996) ‘Underwater laser processing to improve residual stress on metal surface’, *Proceedings of the 6th International Welding Symposium of Japan Welding Society*, Nagoya, Japan, pp.501–506.
- Sano, Y., Mukai, N., Okazaki, K., Obata, M. (1997) ‘Residual stress improvement in metal surface by underwater laser irradiation’, *Nucl. Inst. Meth. Phys. Res. B*, Vol. 121, pp.432–436.
- Tjong, S.C., Zhu, S.M., Ho, N.J., Ku, J.S. (1995) ‘Microstructural characteristics and creep rupture behavior of electron beam and laser welded AISI 316L stainless steel’. *J. Nucl. Mat.* **227**, 24-31.
- Yang, L.C. (1974) ‘Stress waves generated in thin metallic films by a Q-switched ruby laser’, *J. Appl. Phys.*, **45**, 2601–2607.