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Effects of LSP on micro-structures and residual stresses in a 4 mm CLAM steel weld joints

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ABSTRACT

The effects of laser shock processing (LSP) on the distribution of residual stress and micro-structure of China Low Activation Martensitic (CLAM) steel weldment were investigated via neutron diffraction and optical microscope (OM). A pair of 4 mm CLAM steel plates joined by GTA welding. Special attention is paid to the generation of high level compressive residual stresses introduced by LSP. Residual stress in longitudinal, normal and transversal direction at weldment surface and longitudinal stress through thickness are evaluated via neutron diffraction. Compressive residual stress after LSP occurred at more than 90% areas within the weld joint, it is almost double the areas of compressive stress compare to weldment surface before LSP. The maximum compressive normal residual stress becomes to −183 MPa after LSP from −63 MPa before LSP. The Modification of surface micro-structures including weld zone (WZ), heat affected zone (HAZ) and base metal (BM) are also discussed. Results to date demonstrate that laser shock processing has been a great potential method for the improvement of mechanical performance of components.

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1. Introduction

China Low Activation Martensitic (CLAM) steel, a kind of RAFM steel with Chinese independent intellectual property rights, is presently recognized as one of the candidate structural materials for future fusion reactors due to its excellent thermophysical and mechanical properties [1,2]. Welding technology is a key method for the fabrication of many engineering structures using CLAM steel. A variety of welding methods have been investigated for the welding of CLAM steel, such as HIP welding, GTA welding, laser welding etc. [3]. CLAM steel is an essential material for the China-designed ITER test blanket module which has to suffer poor working conditions like surface thermal load from the plasma side, corrosion as well as irradiation at elevated temperatures [4]. However, the uneven distribution of micro-structure and residual stresses within the weld area make the weld zone more sensitive to these conditions, researches on corrosion of CLAM weldment at 550 °C for 500 h in liquid LiPb show that the corrosion rate of the weld zone achieve two times that of the base metal [3,5], the main reasons include the coarser and uneven micro-structure as well as tensile residual stress within the weld zone. Post-weld treatment is a convenient way to modify the micro-structure and balance the residual stress.

Laser shock processing has been a member of the most effectively and widely used surface enhancement methods to introduce compressive stress for the improvement of mechanical properties of engineering materials. Massive studies about the effects of LSP impacts on surface residual stress, micro-structure, and stress corrosion cracking (SCC) behaviors have been conducted. The effects have been demonstrated through actual applications as preventive maintenance against SCC in the operating nuclear power reactors. Experiments prove that after LSP, the austenitic steel materials exhibit a good capability to prohibit the SCC initiation and the propagation of small pre-cracks due to the fact that the surface residual stress was converted from tensile residual stress to the high-level compressive residual stress [6–8]. The influences of LSP on the pitting corrosion behavior in 316L steel also has been investigated and evaluated, and results showed that LSP has great potential as a mean of improving the mechanical performance of components [9]. All investigations are focused on either the corresponding experimental results or the improvement of residual stress induced by refined micro-structures during LSP. A series of researches were

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Table 1
Chemical composition of CLAM steel (wt%).

C	Mn	Cr	W	V	Ta	Al	Co	Cu	Nb	Ni	S	P	O	N
0.092	0.47	8.87	1.48	0.21	0.13	<0.01	<0.005	<0.10	<0.01	0.01	0.0023	0.0036	0.004	0.0092

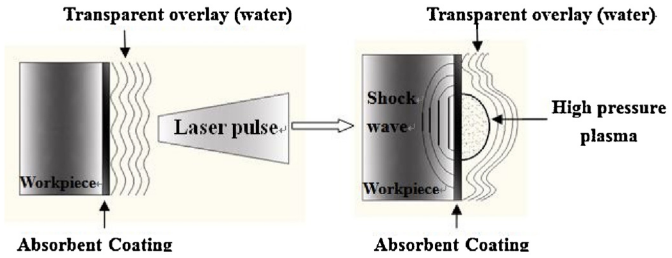

Fig. 1. The schematic diagram of LSP process.

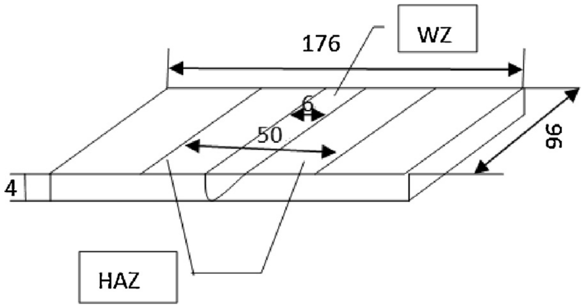

Fig. 2. Schematic diagram of the weldment.

conducted on the effects of LSP on the engineering materials including weld joints [10–13]. LSP has gone through a rapid development stage for its excellent effect on surface treatment process. Studies show that LSP can obviously strengthen the weldment surface, especially the weld fusion zone, increase grain refinement, as well as rebalance residual stress within the weld area [14]. Hundreds of MPa compressive stress was generated in the weldment after LSP, which effectively improve its mechanical properties such as fatigue life and corrosion cracking resistance.

The schematic diagram of LSP was illustrated in Fig. 1. Water was used as a transparent overlay in most practical applications because of its uniform and stable effects on the laser peened surface. To protect the workpiece surface and increase the shock wave intensity, absorbent coating such as aluminum foil or black paint is usually utilized in LSP experiment. Researchers investigated the stresses introduced by LSP with absorbent coating are compressive stress, however, stresses introduced by LSP without absorbent are generally tensile stress [15–17]. As shown in Fig. 1, when the high density laser pulse hits the absorbent coating, the absorbent coating begin to absorb the high power energy from laser pulse until it was vaporized and the electron was ionized from the steam, finally high pressure plasma was generated. High pressure plasma between the transparent and base metal introduces shock wave, and plastic deformation caused by the shock wave while propagating into the metal result in residual compressive stresses [18,19]. Various methods have been utilized to determine residual stress values in welds including destructive technique such as hole drilling, contour method and indentation technique, and non-destructive technique such as laboratory X-ray, X-ray synchrotron and neutron diffraction methods.

Neutron diffraction measurement is a well-established measurement for determination of residual stress in a wide range of components, which benefit from its unique deep-penetration, three-dimensional mapping capability measurements characteristic of the scattering neutron beam. Furthermore, special measurements characteristic of three-dimensional, especially in thick direction makes neutron diffraction measurement more available to fully identify the effect of LSP on weld area.

The main purpose of this paper is to investigate the effects of LSP on residual stress and micro-structure in a 4 mm CLAM weldment. Residual stress before and after LSP in longitudinal, normal and transverse direction at weldment surface and longitudinal stress through thickness are evaluated via neutron diffraction. Two groups of stress value across weld centerline and through thickness were measured and analyzed, respectively. The refinement of micro-structures by LSP are also observed and discussed.

Table 2
Mechanical properties of CLAM.

Temperature (K)	Tensile strength (MPa)	Yield strength (MPa)
298	680	514

2. Experimental procedures

2.1. Sample preparation

The material subjected to LSP was CLAM steel with chemical composition listed in Table 1. Parent steel plates of 96 × 88 × 4 mm^3 (as shown in Fig. 2) were cut from a casting CLAM steel plate which was hot rolled and then machined. Two CLAM steel plates with a thickness of 4 mm were chamfered to a V groove of 60°. The plates were polished with different grades of sandpaper from 1200 to 400, and then cleaned in deionized water. Ultrasonic cleaning was utilized to decrease the sample surface in ethanol. The mechanical properties of the CLAM steel are shown in Table 2.

2.2. Experimental

Two CLAM steel plates were welded by Gas Tungsten Arc Welding (GTAW) in two passes with a welding current of 96 A. The shielding gas was argon, with a purity of no less than 99.95%. The parameters of welding process were shown as Table 3. The filler wire has the same composition as the base metal. The size of the weld zone is shown in Fig. 2.

After welding, laser shock processing was carried out using a Q-switched Raymax GAIA-RNd:YAG laser (wavelength $\lambda = 1064$ nm), as shown in Fig. 3(a). The fundamental parameters of LSP are summarized in Table 4. The pulse energy was set as 10 J in 10 ns pulse width, with 5 Hz repetition-rate. The laser beam was focused on the sample surface to be treated with a spot diameter of 3 mm. During LSP, the sample plate to be treated was completely covered by a uniform water layer with a thickness of 1–2 mm, which was identified as the transparent overlay. Aluminum foil was served as an ablation medium for plasma initiation to protect the sample

Table 3
The parameters of welding process.

Groove angle (°)	Current (A)	Shielding gas
V/60	96	99.95% Ar

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