Post-treatment of arc-welded aluminum alloy joints by laser shock peening

A A Tareva¹, D M Melnikov¹ and M A Melnikova¹
¹Bauman Moscow State University, 105005, 2nd Baumanskaya str., Moscow, Russia
E-mail: Daenoor@gmail.com

Abstract. The possibility to improve aluminum alloy welded joints with laser shock peening was demonstrated. It was shown that microhardness of peened area in heat affected zone is higher than one without post-treatment. Also in this area the residual tensile stresses turns into residual compressive stresses. Laser peening process is proposed to carry out using low-energy lasers. In this case were analysed different types of ablative overlays.

1. Introduction
In recent years laser shock peening (LSP) became an attractive way to create a local plastic deformation for various implements [1]. LSP is a cold surface modification process that uses high power pulsed laser radiation [1 – 4]. This is an important post processing method for metal parts. Now it is extensively used to enhance the fatigue lifetime of jet engine fan, compressor blades and recently in aircraft structures [5]. LSP is the most suitable alternative process among the existed shot peening technology [6]. From that point of view, LSP can be put into commercially practice in the small industries by reducing a cost of the experiment. For this purpose, methods for LSP using low-energy kHz lasers have been recently developed [6].

The laser peening process is illustrated on Figure 1. It uses high power density laser pulses (5-10 GW/cm²) which are located at the metal surface, coated with an ablative film and transparent tamping layer (usually water). As laser beam passes through the transparent layer and hits the surface of the material, the thin layer of the ablative layer is vaporized. The vapour continues to absorb the remaining laser energy, heats up and then ionizes into plasma. A rapidly expanding plasma is limited in expansion due to water counterstand. It creates a high surface pressure, which propagates into the material as a shock wave [7, 8].

A shock wave that propagates deep into the metal is caused by a sudden pressure leap. Plastic deformation of the material occurs when shock wave pressure exceeds Hugoniot elastic limit [9, 10]. The strain rate reaches about 10⁶ s⁻¹. Thereby, the number of dislocations and transfer speed increases. That leads to changes in microstructure and mechanical properties (hardness and strength) of the material. The total amount of cold work is much lower than after shot peening despite the high strain rates [11]. Shock wave causes maximum of residual compressive stresses at the surface and decreasing deep in material. The larger the magnitude of the shock pressure, the deeper the plastic deformation develops [12].

LSP can be used for small-scale processing despite the traditional methods such as shot or ultrasonic peening, for example, micro dents [13], fatigue crack mouth [14] or welded joints [15].

Welded joints have negative effect on the reliability of manufactured products. One of the main problem is high residual tensile stresses.
The weak areas of welded joints are fusion zone (FZ), transition zone (TZ) and heat affected zone (HAZ) [15]. The compressive residual stresses after LSP can significantly increase fatigue life and fatigue strength by inhibiting the initiation and propagation of cracks [16]. The positive effect of LSP has been demonstrated in increase of fatigue life, wear resistance, etc. [17] for aluminum, steels, and titanium alloys.

The aim of this work is to study the technological features of LSP applied to possibility to improve the properties of welded joints of aluminum alloys.

2. Experimental procedures
Spot diameter, number of shots and laser intensity are parameters that influence LSP process. The process of laser shock peening is schematically shown in Fig.1.

![Figure 1. Scheme of laser shock peening.](image)

It is necessary to perform the following procedures for generation of laser shock wave. Target surface is covered with an ablation film. Evaporation of this layer leads to the formation of a plasma flame. The expansion of the flame leads to short-pulse pressure waves formation. An ablative layer also prevents base metal from melting and laser ablation. Energy transparent overlay (tamping layer) is applied to increase the pressure of the shock wave by inhibiting the expansion of the plasma.

The right choice of coatings is important for this purposes. Except the absorption coefficient, the ablative layer must be resistant to multiple shocks due to the specifics of low-energy lasers that require small spot size and, therefore high repetition rates, to maintain sufficient power density. It is impossible to update the ablative film after each shot with kHz frequencies.

Black paint and 50 μm thick aluminum foil were used as an ablative coatings, water – as a tamping overlay. The effect of irradiation with overlaps was investigated by a single or multiple laser shots. Effectiveness studies of coatings were carried out on pure nickel samples (as a model material).

LSP effect on welded joints was investigated on arc welded aluminum alloy samples of Al-6Mg. There used two measurement methods. X-ray method was used to determine the residual stresses. This method is based on deformation measuring of the crystal lattice from the displacement of the diffraction lines. The microhardness studies were carried out on an EmcoTest Durascan 20.

The laser source for aluminum samples was a solid-state laser "Solar LQ 829" with a wavelength of 532 nm, pulse energy up to 250 mJ, pulse duration 20 ns (FWHM) and a repetition frequency of 10 Hz.

3. Results and discussion
The LSP results with different ablative films are shown in the Fig. 2. Measurements were carried out in the center of dimples that are formed after LSP. In cases where the coating was damaged after laser shots, microhardness measurements were carried out beside the spot center in non-melted area. The best results were obtained for aluminum tape attached with adhesive tape. This ablative layer does not
disintegrate even after 4 shots and provides high microhardness results. Black paint is an effective coating, but it can withstand only one laser shot and then it is necessary to replace it. The same happens with glue and foil combination.

![Microhardness graph](image)

**Figure 2.** Distribution of external microhardness of Ni sample after LSP with different coatings (1 – Al foil and adhesive tape; 2 – Al foil and adhesive tape (2 shocks); 3 – glue with Al foil; 4 – black dye. Energy pulse 180 mJ, spot diameter – 200 μm.

The photos of coatings are shown in Figure 3. The tape carbonizes after one or two shots, does not transmit laser radiation and is able to withstand up to 4 laser pulses. This is an important advantage since the treatment of the welded joint involves overlapping and coating needs to be renewed constantly.

![Coatings photos](image)

**Figure 3.** Photos of adhesive tape with aluminum foil (left) and adhesive tape (right) after multiple laser shot

In this work we obtained the increase of hardness for aluminum alloys. We reached hardness values 70% higher than on untreated samples with the same parameters 1,8 GW/cm², four repetitions of penning and 0,5 mm spot diameter. Figure 4 shows the distribution of internal hardness across the sample. The character of the curve is sufficiently stable: microhardness decreases with the raise of
distance from surface. The maximum of microhardness is at the 50 μm depth and the minimum effect is at the value of 500 μm.

![Microhardness profile](image_url)

**Figure 4.** Microhardness profile of aluminum alloy after LSP (laser intensity of 1.8 GW/cm² and spot diameter of 0.5 mm).

Fig. 5 shows the microhardness profiles obtained before and after LSP of aluminum arc-welded joint. Laser intensity was 1.8 GW/cm² and spot diameter of 0.5 mm. There are two characteristic zones in welding joints indicated in Fig.5: heat affected zone and fusion zone. The results of microhardness before and after LSP are shown on the figure 5 by two curves. The increase of microhardness up to 70% is peculiar for peened surface in transition and fusion zones. This could be explained by structural changes or residual stresses that occurs after the LSP.

![Microhardness profiles](image_url)

**Figure 5.** Microhardness profiles of aluminum arc-welded joint before and after LSP.

Residual stresses measurements were performed with the standard X-Ray diffraction method on arc-welded aluminum alloy samples in heat affected zone before and after LSP. The results of the study are shown on Fig.6. It can be observed that residual tensile stresses of 15 MPa magnitude forms after welding in transition zone. Transformation from residual tensile stress to residual compressive...
stress occurs after LSP treatment (the magnitude was 50 MPa). From [12] it is obvious that the change of stress sign leads to fatigue strength increase in welded structure.

![Figure 6. Average residual stress values determined at the surface in the HAZ before and after LSP of aluminum arc-welded joint.](image)

4. Conclusion
Laser peening process of arc-welded aluminum samples has been discussed. The efficiency of ablative coatings for LSP has been studied. We have found that aluminum foil attached with adhesive tape is the best choice for complex geometries in LSP with multiple overlapping strategy. This coating is able to withstand the repeated irradiation. The results of microhardness for this coating is comparable to other coatings. It provides tight flexible contact and it is suitable for LSP of welded joints.

We also demonstrated the increase of microhardness up to 70 % after LSP for Al alloy. In addition, a change of residual stresses sign from tensile to compressive after LSP of aluminum welded joint was shown. The results allow us to conclude that laser shock peening is a promising method for post-processing of welded joints.

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