Laser shock peening of welded joints

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Abstract. The effect of laser shock peening (LSP) process on the mechanical characteristics of aluminum and titanium welding joints was investigated. Since LSP requires special ablative and transparent coatings, efficiency of different coatings was analyzed. It was shown that highest LSP effect was obtained by using aluminum foil attached with adhesive tape as an ablative layer and water as a transparent overlay. Several laser peening conditions with different intensities, durations, and number of shots were tested to determine the applicability of the method for an aluminum and titanium alloys. Surface microhardness of observed materials was increased up to 70 %. It was shown LSP of welded joints of Al-6Mg aluminum alloy allows to change tensile residual stresses in the weld zone, on compressive stresses.

1. Introduction

Laser shock peening (LSP) is a cold process of surface modification by using Q-switched laser radiation [1 – 4]. This method is based on modification of mechanical properties and microstructure in various materials by means of the shock waves that generates with the pulsed laser radiation [5, 6].

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 [7]. The strain rate reaches about 10⁶ s⁻¹. Thereby, the number of dislocations and transfer speed increases leading 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 [8]. Shock wave causes residual compressive stresses maximum at the surface and decreasing deep in material. The larger the magnitude of the shock pressure, the deeper the plastic deformation develops [9].

LSP can replace shot or ultrasonic shot peening [9, 10]. The advantage of this method is the possibility of complex form surfaces processing due to great varieties of radiation delivery to the processing site [11]. While a complete contact of a tool with a surface is necessary in the ultrasonic method. Despite the traditional methods, LSP allows a local areas processing, for example, welded joints.

Welded joints have some negative affect on the reliability of manufactured products. The weak areas of welded joints are fusion zone (FZ), transition zone (TZ) and heat affected zone (HAZ) [12]. One of the main reasons of the decrease in operational properties are residual tensile stresses in welded joints. In particular, fatigue life is mainly determined by magnitude and distribution of tensile residual stresses. For example, in aluminum alloys tensile residual stresses lead to a fatigue decrease resistance under varying loads [13]. Fatigue strength can be improved by surface plastic deformation with compressive residual stresses creation. One way to do this is LSP.

The aim of this work is to study the technological features of LSP and to improve the properties of welded joints of aluminum and titanium alloys.
2. Experimental procedures

The process of laser shock peening is schematically shown in Fig. 1.

It is necessary to perform the following procedures for laser shock wave generation. Target surface is covered with an absorbent (ablation) coating. 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 absorbent layer also prevents base metal from meting and laser ablation. Energy transparent overlay (tamping layer) is applied for effective transformation of laser energy to shock wave. It prevents plasma from surface expansion thereby increasing the intensity of the shock wave.

Ablative layer allows to increase absorption coefficient of incident laser radiation and also protects surface from melting. The transparent overlay with high acoustic impedance is required to redirect the shock wave energy. It is important to say that laser ablation can be considered as one-dimensional model on LSP conditions, which leads to a high directivity and high depth of the effect.

Ablative and transparent layers have a significant influence on the efficiency of the LSP process. In addition the final result of absorption coefficient or acoustic impedance can also be affected by their technological features, for example, their adaptability to the processing of complex form surfaces. One of the main goals of this work was to investigate the effectiveness of certain coatings.

Black paint and 50 μm thick aluminum foil were used as ablative coatings [8]. The effect of irradiation with overlaps was investigated by a single or multiple laser shots. Transparent overlay was chosen on the base of the acoustic impedance value. In this paper, the following materials were used: water \( Z=0.15 \times 10^6 \text{ g/cm}^3 \text{s} \), glycerol \( Z=0.24 \times 10^6 \text{ g/cm}^3 \text{s} \), isopropyl alcohol \( Z=0.09 \times 10^6 \text{ g/cm}^3 \text{s} \), glass \( Z=1.44 \times 10^6 \text{ g/cm}^3 \text{s} \).

A study to determine the effectiveness of the ablative coating and the transparent overlay was carried out by LSP of Al-6Mg aluminum alloy samples. The best combination of an ablative coating and a transparent overlay was selected in accordance with the values of micro hardness results of the sample surface.

LSP effect on welded joints was investigated on arc welded samples of Al-6Mg aluminum alloy and Ti-7Al-3Mo titanium alloy. Since the goal of LSP of welded joints - the alignment of the microstructure in different areas of the joint and the treatment were carried out at the following zones: FZ, HAZ and base metal (BM). Overlap factor was 0.7. Effect of LSP was measured by microhardness value of treated areas.

To determine the residual stresses, an X-ray method was used. This method based on measuring the deformation 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. The diameter of laser spot was 1 mm (FWHM).
For titanium alloy was used 1060 nm solid state laser with pulse energy up to 10 J, wavelength 1064 nm, pulse duration 4 ms, frequency 2 – 15 Hz and treatment speed 60 – 200 mm/min.

3. Results and discussion

There are two common types of ablative layers: aluminum foil and black paint [8]. For overlapping treatment is important as far as the adhesion bonds of the coating and the surface of the target are firmly established. In this paper was investigated the efficiency of aerosol black paint, aluminum foil attached with adhesive tape and cyanoacrylate glue.

At a single-shot LSP there was no surface microhardness significant differences of treated Al-6Mg samples as shown on Fig. 2. However black paint and aluminum foil attached with cyanoacrylate glue were corrupted after double shots. The best result was obtained for aluminum tape attached with adhesive tape. This ablative layer withstood up to six shots without destruction. This is an important advantage since the treatment of the welded joint involves overlapping, and it is not convenient to permanently update of ablative coating.

![Figure 2. Microhardness values obtained after LSP of aluminum sample with different ablative layers with laser intensity of 0.98 GW/cm² and spot diameter of 1 mm.](image)

Transparent overlay was chosen among water, glycerol, isopropyl alcohol and glass. An aluminum Al-6Mg samples were peened with constant energy parameters, where as an ablative layer was used an aluminum foil attached with adhesive tape.

The highest microhardness values were obtained after LSP through glass. Liquid mediums such as water, alcohol or glycerol showed the similar effect, but lower 20 % than while using glass, as it shown on Fig. 3. The main flaw of glass as a transparent coating is that it can only be used for flat surfaces to make a hard adherence to the treating surface. For a rough surfaces, such as welded joint it’s necessary to use liquid mediums.
Foil attached with adhesive tape was chosen as an absorbent coating for further research. Water that used as a medium containing a transparent overlay was also chosen for further research.

LSP effect of aluminum alloy was studied under the varied parameters of laser intensity, spot diameter and number of shots. It was found that it is possible to obtain a hardness increase relative to the untreated material by 62 % with the intensity 1.8 GW/cm², spot diameter of 0.5 mm and 4 times irradiation repeating. The internal microhardness distribution of the peened sample is shown in Fig. 4. The maximum value of surface effects microhardness one has obtained at a depth of 100 μm, while valuable effect was observed at a depth of up to 500 μm.

Results of LSP welded joints are shown in Fig. 5. Peened surface in TZ and FZ demonstrates increasing in microhardness by 60-70 %. This microhardness increase may indicate a structural changes and residual stresses distribution in this zone.
Figure 4. Microhardness profile in aluminum alloy after LSP with laser intensity of 1.8 GW/cm² and spot diameter of 0.5 mm.

Figure 5. Microhardness profiles obtained before and after LSP of aluminum arc-welded joint with laser intensity of 1.8 GW/cm² and spot diameter of 0.5 mm.
The residual stresses were measured by the standard method of X-Ray diffraction in the TZ of aluminum arc-welded samples before and after LSP. Results is shown in Fig. 6. After welding in TZ residual tensile stresses of 15 MPa magnitude are formed. After LSP these stresses are transformed into residual compressive stresses. Their magnitude was about 50 MPa. The change in the sign of the stresses, as it is known [12], leads to a fatigue strength increase of the welded structure.

![Figure 6](image)

**Figure 6.** Average residual stress values determined at the surface in the HAZ before and after LSP of aluminum arc-welded joint.

After LSP of the titanium Ti-7Al-3Mo alloy, also was obtained valuable effect, that shown in Fig. 7. After LSP, the surface microhardness of the titanium alloy was increased by 55-58 %. This means that the structure of the material will change, the compressive residual stresses will form, static and fatigue strength will increase as well as in aluminum alloys.

The obtained results of the work indicate the possibility of using the method of laser shock peening to improve the welded joints characteristics of aluminum and titanium alloys.

![Figure 7](image)

**Figure 7.** Microhardness values obtained after LSP of titanium sample with 4 ms pulse width and spot diameter of 0.1 mm.
4. Conclusions
In this work efficiency of different transparent and ablative coatings for LSP process was investigated. It was found that aluminum foil attached with adhesive tape is the best choice for LSP of complex geometries and it is low sensitive to overlapping of the laser shots. The best choice for transparent overlay is water, but it was shown that glass with higher acoustic impedance value could provide better LSP effect. Glass still can’t be used for peening complex geometries, such as welding joints.

Microhardness of aluminum and titanium alloys can be increased up to 70% after LSP. It is known, that typical laser parameters for peening requires Q-switched radiation, but it was shown, that 4 ms pules could also lead to plastic deformation.

With LSP of welding joints tensile residual stresses can be transformed into compressive residual stresses that leads to fatigue life increase of the joints. In this work we succeeded in obtaining 50 MPa compressive stresses in TZ, while before LSP one had tensile 15 MPa residual stresses.

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