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Influence of Laser Surface Remelting on Al-Si Alloy Properties

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The paper treats Al-Si alloy after laser surface remelting by the changes in microstructure and micro-hardness of a modified surface layer. Laser remelting of the thin surface layer was carried out with different energy inputs into the as-cast specimen surface. The remelting conditions were varied by application of different laser beam pulse duration. After solidification of surface remelted layer a fine-grained microstructure is formed. Such a microstructure increases micro-hardness of Al-Si alloy by about 60 to 80%. The variation and size of mainly tensile residual stresses in surface remelted layer greatly depends on the cooling rates i.e. laser pulse duration. Precipitation annealing after the process of laser surface remelting additionally influences the reduction of residual stresses.

Keywords: Al-Si alloy, laser surface remelting, residual stresses, microhardeness, precipitation annealing

0 INTRODUCTION

Hardening of thin surface layers of aluminium alloys by laser remelting has become valued due to the economy of the process and its applicability, in comparison with other processes, to both small- and large-series manufacture [1]. With a selected laser beam power, the energy input may be adapted to individual needs by changing the degree of defocusing and the laser beam travel rate. In the engineering practice the aluminium alloys are often used for parts which are to be built in, after machining, into functional assemblies; therefore, it is often required that their surfaces and surface layers are of good quality, which is defined as surface integrity. Laser remelting of the thin surface layer is one of the surface-hardening processes which produce higher material hardness levels, and consequently improve wear resistance of machine parts [2] to [4]. With numerous alloys, which show no phase transformations up to the melting temperature, this is the only process for alloy hardening. By selecting a suitable energy input, rapid local heating of the material over the melting temperature could be achieved, followed by rapid cooling and solidification. Thus, a thin remelted layer consists of a solid phase finely distributed in the basic matrix. Properties of the remelted layer are dependent on the chemical composition of the alloy prior to remelting, partly also on the microstructure of alloys prior to the remelting process and on the magnitude of energy input into the sample surface causing thermal stress field [5].

In the technical literature results of numerous investigations on hardening of the thin surface layer by remelting of different aluminium alloys with silicon and other alloying elements may be found. Increasing the hardness of surface could also be achieved by dispersion of hard particles into the material surface as was studied by Anandkumar et al. [6]. It has been proved that the efficiency of hardening depends on cooling rates at the liquid/solid boundary and concentrations of alloying elements in the alloy [2] and [5].

Luft et al. [7] also studied aluminium alloys with particular regard to microstructure, i.e. the size and distribution of individual phases. Vollmer and Hornbogen [8] investigated various Al-Si alloys, i.e., two hypoeutectic alloys, one eutectic and one hypereutectic alloy. With different energy inputs, which were ensured by different power densities and different interaction times, hardening of the solid solution of aluminium with individual alloying elements was determined. Conquerelle et al. [4] also investigated Al-Si alloys in terms of the size of crystal grains of the solid solution with different energy inputs with regard to constant power density and different laser beam travel speeds. Wear resistance of these alloys was determined in terms of the size distribution of silicon particles in the solid solution of aluminium and silicon as well as of different degrees of overlapping of laser traces. Wear mechanisms in terms of micro plastic deformation of the soft base and catastrophically failure of silicon crystals were explained by means of micro structural and micro chemical analyses. Rapid heating and cooling, i.e. rapid solidification, result in formation of metastable microstructures which are carriers of important technological properties such as vastly improved material hardness, improved wear resistance and often also improved corrosion resistance [9] to [11]. Rapid solidification is achieved by heat removal into the remaining cold part of the material, which has a much greater mass. The influence of graphite absorber coating thickness during laser surface hardening on a modified layer depth was analyzed by Kek et al. [12]. The optimum coating thickness was determined in a range around 0.03 mm. In their earlier research, Šturm

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et al. [13] described the influence of alloying elements in Al-Si alloys on the CO_2 laser remelting process.

The aim of this study was to define changes in the microstructure of the remelted surface layer after Nd:YAG laser remelting followed by precipitation annealing.

1 EXPERIMENTAL PROCEDURE

1.1 Selection of Al-Si Alloy

Table 1 shows the selected Al-Si alloy EN AC-48000-K-T6. The microstructure was analyzed in as-delivered state, i.e. as-cast state, and after laser remelting of the thin surface layer.

Table 1. *Chemical composition and mechanical properties of EN AC-48000-K-T6 Al-Si alloy*

a) Chemical composition of AlSi12CuNiMg alloy [wt. %], Al balance

Si	Fe	Mn	Mg	Cu	Ni	Ti
12	0.01	0.01	1.04	0.93	0.9	0.01

b) Mechanical properties of AlSi12CuNiMg alloy

$HV_{0.2}$ [MPa]	Rm [MPa]	$Rp_{0.2}$ [MPa]	A_5 [%]
100	280	240	1

The selected alloy AlSi12CuNiMg is hypoeutectic and contains inter-dendritic network of eutectic silicon with different intermetallic compounds which improve alloy micro-hardness. Intermetallic compounds are Mg_2Si (black script), Al_6Cu_3Ni (light-gray script) and Al_3Ni (dark-gray script). The alloy AlSi12CuNiMg shows micro-hardness of around 100 $HV_{0.2}$. The selected hypoeutectic alloy AlSi12CuNiMg shows tensile strength of around 280 MPa. The microstructure is shown in Fig. 1.

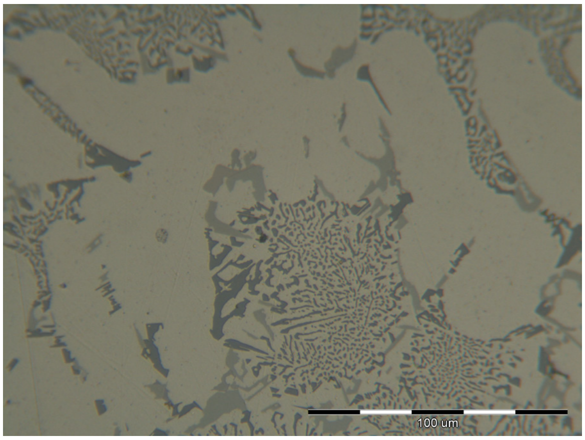

Fig. 1. *Microstructure of as-cast AlSi12CuNiMg*

1.2 Selection of Laser Remelting Conditions

Tests of laser hardening by remelting of the thin surface layer were carried out with a Nd:YAG laser system OR-LASER with laser source maximum power P = 80 W. Based on the previous research, the following laser parameters were selected:

Laser source power	$P = 40$ W
Mode structure	multimode – top hat
Pulse duration	$t_b = 4$, 6 and 8 ms
Pulse frequency	$v = 7$ Hz
Laser beam travel speed	$v_b = 150$ mm/min
Beam diameter on the specimen surface	$D_b = 1.4$ mm
Beam overlapping	0.9 mm, 40% of D_b

1.3 Preparation of Specimen Surfaces by an Absorbent

Absorptivity of the aluminium or its alloys for laser light of Nd:YAG radiation ($\lambda = 1.06 \mu m$) is poor (0.07) [14]; therefore, the surface of the aluminium alloys should be suitably prepared prior to laser remelting. This can be done by surface treatment or by deposition of a suitable absorbent [9] to [13]. Absorptivity is defined as the relationship between the absorbed and the incident energy flows. It also increases with an increase in the energy at the specimen material surface [15]. For our experiment of laser surface remelting of Al-Si alloy colloidal graphite as an absorbent with very high absorbtion coefficient in the range of 60 to 80% [16] was used.

2 EXPERIMENTAL RESULTS

2.1 Size of the Remelted Layer

When applying laser hardening by remelting the thin surface layer of the material some basic conditions should be satisfied if a machine part is to operate in a machine or installation efficiently. They are as follows:

- Such a high energy input should be ensured that melting of the thin surface layer is guaranteed in the required depth, min. of 0.2 mm.
- A significant size of the remelted surface area is obtained by overlapping of laser remelted traces.

The size of the remelted layer was defined in the cross-section of the remelted specimen. For metallographic analysis, the specimen was cut in the transverse direction, ground, polished and etched for observation with an optical measuring microscope. The depth of the remelted trace was then measured. The results of surface modified layer dimensions are shown in Table 2 as a function of laser pulse duration. The greatest depth of the remelted layer h_{RL}, is obtained with the laser pulse duration t_i = 8 ms and it amounts of 0.34 mm.

Table 2. *Laser modified layer dimensions*

Laser pulse duration t_i [ms]	Depth of laser remelted layer h_{RL} [mm]	Depth of laser modified layer h_{ML} [mm]
4	233 to 259	270 to 334
6	241 to 316	281 to 378
8	274 to 343	310 to 419

2.2 Macro and Micro Analysis of the Modified Layer

The metallographic preparation of samples and subsequent analysis of the microstructure of the modified surface layer of the studied AlSi12CuNiMg alloy helped us to assess the micro structural changes and to quantify them by measurements.

The as-cast hypo-eutectoid AlSi12CuNiMg consists of different intermetallic compounds, as Al_6Cu_3Ni and Al_3Ni were detected in the microstructure. These intermetallic compounds improve alloy micro-hardness to a level of 100 $HV_{0.2}$. Measurements of intermetallic compounds were made according to form factor defined in Equation 1, where parameters of *AREA*, D_{max} and D_{min} are defined in Fig. 2.

$$FORM \cdot FACTOR = \frac{AREA}{\pi/4 \cdot D_{max} \cdot D_{min}}. \qquad (1)$$

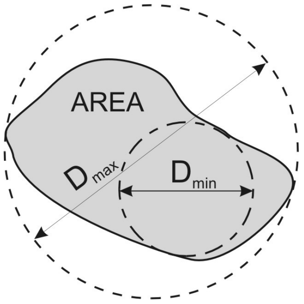

Fig. 2. *Definition of Form factor parameters*

The results of intermetallic compounds measurements are shown in Fig. 3. In both cases it can be seen that the majority of intermetallic compounds were small and round and that only few were long and massive. Laser heating indirectly provokes micro-structural changes in the specimen material. High heating and cooling rates lead to re-solidification of the melt in the melt pool, resulting in a very fine, homogeneous microstructure. By varying the laser pulse duration, changes of the melting rate are produced, which further produces changes in the morphology of the eutectic and thus also changes in the mechanical and technological properties of given alloys.

Laser remelting of the thin surface layer on the studied AlSi12CuNiMg alloy, using the chosen remelting conditions, creates a very fine and homogeneous microstructure with increased hardness or micro-hardness.

Based on the microstructure analysis, modified layer consists of two zones with different microstructure, i.e. remelted zone, and transition zone between the remelted zone and the base material.

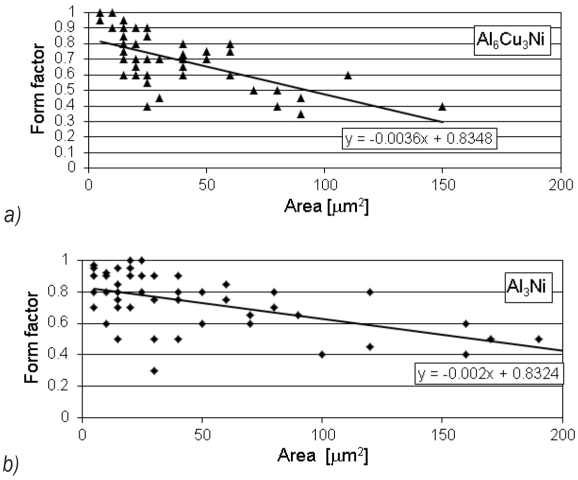

Fig. 3. *Dependance of Form factor and cross-section area of intermetallic compounds; a) Al_6Cu_3Ni, b) Al_3Ni*

2.2.1 Remelted Zone

By laser remelting of the thin surface layer it is possible to achieve local changes in the microstructure of the AlSi12CuNiMg alloy induced by the high heating and cooling rates. High cooling rates of the homogeneous melt gives us an important effect of formation of fine dendrite microstructure. Thus, formation of very fine and homogeneous microstructure of the solution crystals of silicon can be explained by thermo kinetic processes caused by high cooling rates (Fig. 4a).

2.2.2 Transition Zone between the Remelted Zone and Base Material

Fig. 4b shows the remelted area and the transition of the remelted zone into the basic microstructure. In the transition zone of the remelted layer into the base material α-dendrites of aluminium and silicon can be noted. In the transition of the modified layer extending into the base material, a narrow, non-uniform area has formed with a partially homogeneous microstructure presenting a solid solution rich with silicon.

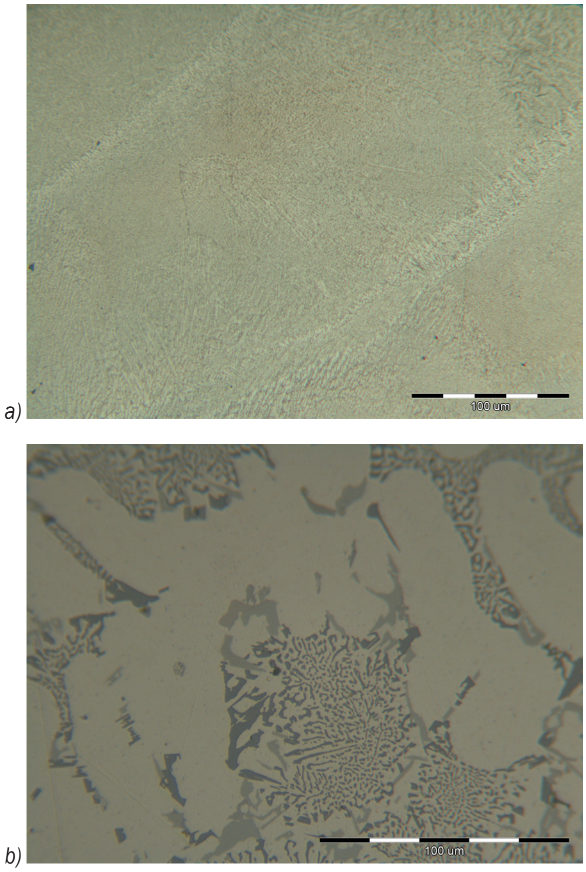

Fig. 4. *Microstructure of the laser surface modified layer of AlSi12CuNiMg alloy; a) remelted zone, b) transition zone*

2.3 Micro-hardness in the Remelted Layer

Micro-hardness was measured in accordance with the Vickers method, i.e. diamond pyramid hardness measurement, through the depth of the remelted layer. Micro-hardness was measured at a load of 2 N. Fig. 5 shows micro-hardness values through the remelted layer for different laser pulse durations. From the results shown in Fig. 5 the following may be concluded:

- Through-thickness micro-hardness variations in the remelted layers are very similar. The depth with increased micro-hardness is dependent on the energy input; therefore, with longer laser pulse duration a greater depth of the remelted layer is achieved, and consequently also a greater depth of uniform and increased micro-hardness.
- After remelting the surface layer of alloy AlSi12CuNiMg an average micro-hardness level of around 160 to 180 $HV_{0.2}$ was obtained.
- Micro-hardness gradually reduces in the transition zone from the remelted zone to the base metal.

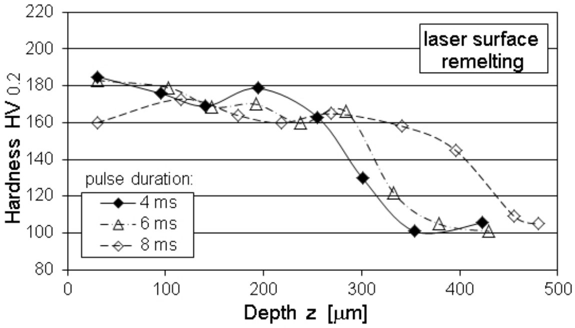

Fig. 5. *Micro-hardness measurements through the laser modified surface layer*

Hardening of the thin surface layer may be influenced by [3], [10] and [11]:

- Finest possible distribution of α-dendrites in the oversaturated solid solution of aluminium and silicon with other alloying elements.
- Finest possible and uniform distribution of intermetallic compounds such as Al_6Cu_3Ni, Al_2Cu and Ni_3Al.

Micro-hardness was measured in dependence of laser pulse duration. It can be noticed that laser pulse duration has almost no influence on micro-hardness achieved in the remelted zone. In the case of laser remelting with a pulse duration of 8 ms micro-hardness in the surface remelted region is a bit lower than in the case of pulse duration of 4 and 6 ms. Micro-hardness results confirm the difference measured in the depth of the remelted layers when laser operates with 4, 6 or 8 ms long pulses. The longer the laser pulse duration, the greater depth of the remelted zone is achieved.

2.4 Measurements of Residual Stresses

Strain measurements and calculations of residual stresses in the surfaced layer were based on the relaxation hole-drilling method in accordance with ASTM standards (ASTM Int., E 837-01, 1995 and ASTM Int., E 837-08, 2008) and were performed by using the CEA-06-062-UM measuring resistance rosettes and the RS-200 Milling Guide device, a product of Vishay Group. The residual-stress variation in the laser-surfaced specimens was obtained by implementing the integral method and the H-drill program [17]. The measurements of residual stresses were carried out on all specimens. Due to a relatively wavy and uneven surface of the surfaced layer, the resistance rosettes were glued by applying a two-component epoxy resin (Vishay, M-Bond, GA-2).

The graph in Fig. 6 presents the maximum residual stress profiles versus the depth of the modified layer of AlSi12CuNiMg alloy as a function of different laser pulse durations, defined by measurements of strain in a given direction and by calculating the directions of the main axes. From the results in Fig. 6 the following can be concluded:

- In all cases of different laser pulse durations residual stresses have a very similar profile differing only in absolute values. In the surface remelted layer, tensile residual stresses were found in a range between 45 and 67 MPa.
- The maximum tensile residual stresses were found in the lower part of the remelted layer, or in the transition zone between remelted zone and base metal.
- The maximum tensile residual stresses were achieved in the case of pulse duration of 6 ms, the minimum in the case of pulse duration of 4 ms.

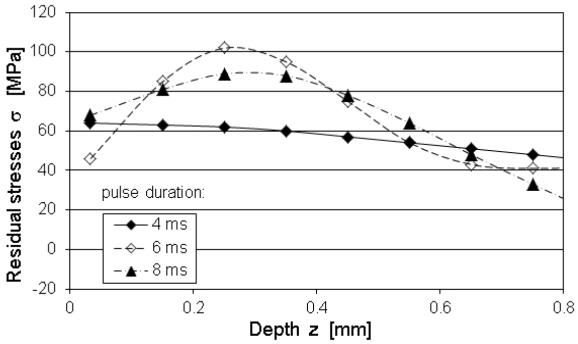

Fig. 6. *Residual stresses versus depth of the modified layer after laser surface remelting*

Residual stresses are a result of temperature and micro-structural stresses occurring in the specimen material directly after the process of remelting a thin surface layer. During the process of rapid cooling, when the process of solidification goes on, the volume of the sample contracts, resulting in temperature stresses. However, the variation and size of residual stresses in the remelted layer depends also on the composition and homogeneity of the melt and condition of cooling. The cooling conditions are very important since, at higher cooling rates, it is possible to achieve a fine distribution of α-dendrites in the matrix, i.e. in the solid solution of aluminium and silicon.

Regarding the nature of the laser remelting process, in which there is a melt pool that mixes due to hydrodynamic and electromagnetic forces, around the laser beam, a rather homogeneous melt, and, after a rather rapid cooling, quite uniform micro-hardness in the remelted specimen layer may be established. The nature of the residual stresses in the surface remelted layer is tensile. The maximum value is around 70 MPa, which is still low enough to select the process of laser surface remelting as apropriate procedure for surface hardness improvement.

2.5 Precipitation Annealing

After the process of laser surface remelting, additional heat treatment procedure was carried out. Precipitation annealing of laser surface remelted layer was carried out at a temperature of 150°C for 6 and 12 hours. In Fig. 6 it was found that the lowest residual stresses in the remelted surface layer were obtained in the case of the shortest laser pulse duration of 4 ms. The influence of precipitation annealing on residual stresses in laser surface remelted layer is shown in Fig. 7. It can be noticed that after 6 hours of annealing tensile residual stresses at the surface increased from 64 to 114 MPa. After 12 hours of precipitation annealing, tensile residual stresses at the surface of the remelted layer decrease extensively to a level of 36 MPa. We assume that the quantity and largeness of precipitates, as Al_6Cu_3Ni, Al_2Cu and Ni_3Al, in the laser surface remelted layer directly influences on presence of residual stresses. The influence of laser pulse duration, i.e. the remelting time, after 12 hours of precipitation annealing on residual stresses is shown in Fig. 8. In the remelted surface area tensile residual stresses decrease, when laser pulse duration is increased. In the case of pulse duration of 8 ms residual stresses at the surface get even compressive character of –9 MPa. Maximum tensile residual stresses of 81 MPa were observed in the transition zone in the depth of 0.4 mm. Such a big difference from compressive to tensile residual stresses in a very small dimension of 0.4 mm is not favorable course of residual stresses through thin surface remelted layer.

In addition to residual stress measurements the precipitation process was evaluated also with micro-hardness measurement through the surface remelted layer (Fig. 9). In the case of laser pulse duration of 4 ms micro-hardness in the remelted layer reduced for about 10 $HV_{0.2}$ when we performed precipitation annealing for 6 hours. In the case of precipitation annealing for 12 hours micro-hardness increased with respect to initial remelted microstructure in a range of 5 to 20 $HV_{0.2}$.

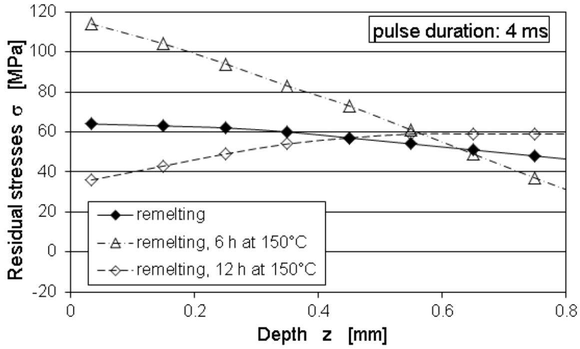

Fig. 7. *Residual stresses versus depth of the modified layer after laser surface remelting and additional precipitation annealing at 150 °C*

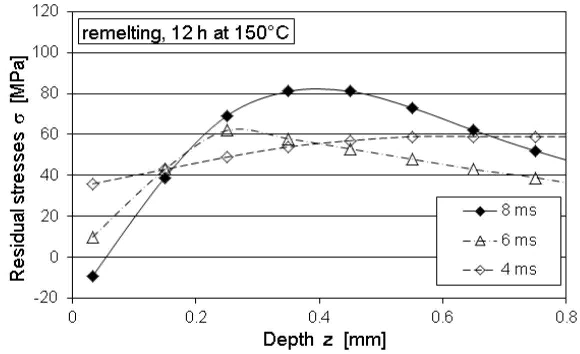

Fig. 8. *Residual stresses versus depth of the modified layer after laser surface remelting and additional precipitation annealing at 150 °C at different laser pulse durations*

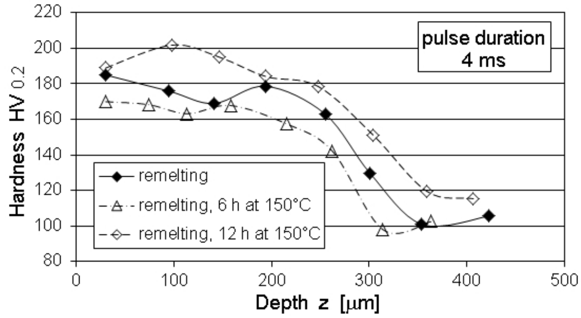

Fig. 9. *Micro-hardness versus depth of the modified layer after laser surface remelting and additional precipitation annealing at 150 °C*

The influence of laser pulse duration, i.e. the remelting time, after 12 hours of precipitation annealing on micro-hardness is shown in Fig. 10. It can be noticed that laser pulse duration had no significant effect on micro-hardness of laser surface remelted layer after precipitation annealing of 12 hours at 150 °C. The main difference is in comparison to initial remelted microstructure. The new annealed microstructure indicated higher micro-hardness as it was in the initial remelted microstructure, for 20 $HV_{0.2}$, and reached level of 180 to 200 $HV_{0.2}$.

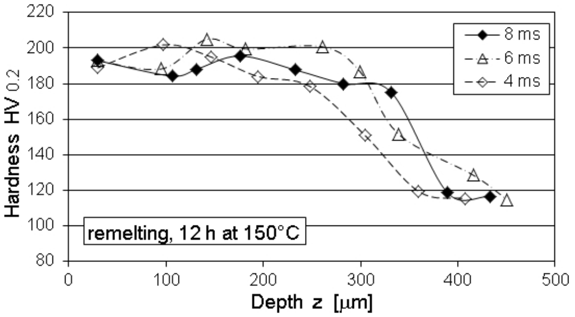

Fig. 10. *Micro-hardness versus depth of the modified layer after laser surface remelting and additional precipitation annealing at 150 °C at different laser pulse durations*

3 CONCLUSIONS

Traveling of laser light across the sample surface produces rapid heating and, consequently, melting and further solidification of the material. In addition to material hardening due to rapid solidification, there are several other advantages of the process, i.e. it is a clean, simple, practical and cheap process in comparison to the other processes of thermal surface treatment. The following findings confirm the efficiency of laser surface remelting process of AlSi12CuNiMg alloy:

- After solidification of surface remelted layer a fine-grained microstructure was formed.
- With the given remelting conditions the depth of the remelted layer h_{RL} varied between 0.27 and 0.42 mm.
- The process of laser remelting caused improvement of micro-hardness in the remelted surface layer. High quantities of Si in the alloy which were additionally modified with other alloying elements causing the micro-hardness increase from 100 $HV_{0.2}$ in base alloy to 160 to 180 $HV_{0.2}$ in laser surface remelted layer. Such a micro-hardness increase of the remelted layer represents 60 to 80% increase in micro-hardness regarding to the base alloy.
- Measurements of residual stresses were made on the specimen on which laser beam was led at a 40 % overlapping of the remelted layer. After laser surface remelting, tensile residual stresses of a magnitude of 45 to 105 MPa were identified

into a depth of 0.25 mm. In the depth greater than 0.25 mm from the sample surface, tensile residual stresses gradually decreased. The variation and size of residual stresses depends on the cooling rates or time necessary for the remelted layer to cool down to the ambient temperature.

- High cooling down rates in the remelted material caused formation of small α-dendrites, which influenced formation of higher internal stresses of tensile character.
- Additional precipitation annealing of 12 hours at 150 °C caused a reduction of tensile residual stresses at the surface of the remelted layer to level around zero. At the same time an increase of micro-hardness of 20 $HV_{0.2}$ occurred. The reason for this lies in a precipitation growth of intermetallic compounds in the remelted microstructure.

In the future, a detailed analysis of the precipitated intermetallic compounds in the laser surface remelted layer shall be undertaken to characterize the dependence between quantity, distribution and largeness of precipitates, as Al_6Cu_3Ni, Al_2Cu and Ni_3Al, on residual stresses and micro-hardness.

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