Microprocesses at the brass surface after impact of scanning beam of pulse-frequency ultraviolet nanosecond laser

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Abstract. A mode of laser heat treatment of the brass surface prior to conducting of diffusion bonding is proposed. We used the frequency-pulse radiation of a nanosecond ultraviolet laser at a pulse energy density $W = 0.15 - 0.52 \, J/cm^2$. The metal sample was moved relative to a stationary laser beam along a raster trajectory ("snake") so that adjacent spots were overlapped with an overlap ratio of $\geq 99 \, \%$. The impact of radiation on brass was carried out in a subthreshold mode excluding crater formation. The process took place while the metal remained in a condensed state. A regular rough structure with a height of individual uplifts of the order of 1 micron was formed on the surface of the brass.

1. Introduction

Copper has properties, which are very important for industry. First of all, these are high values of thermal and electrical conductivity. However, the mechanical properties of copper are not always sufficient for a number of practical applications. These difficulties are largely corrected by alloying copper with other metals. One of the widespread copper alloys is brass, which is an alloy of copper with zinc [1, 2].

Laser technologies are widely used for various technological tasks [3, 4]. Recently, numerous publications have appeared on the effect of intense laser irradiation on such characteristic of metals surface as adhesion, which significantly affects the processes of diffusion welding of dissimilar materials [5-11]. There is data, that the diffusion coefficient in metals increases many times under impact of pulsed laser irradiation [12, 13].

The papers [14-16] report on our research devoted to the study of microscopic processes occurring in copper and its bronze alloys under the impact of an intense laser UV pulse focused into a spot with
a size of 100-200 µm. In these works, in particular, the features of plastic deformation of the near-surface layer of a metal impacted by a packet of 30 laser pulses of subthreshold intensity were investigated.

In this paper, we report on the features of heat treatment of a brass surface by a scanning beam of a frequency-pulse ultraviolet (UV) nanosecond laser.

2. Experimental technique
To improve the machinability of brass products with cutting tools, a small additive of lead (usually up to 0.5 %), which somewhat worsens the mechanical characteristics [1, 2], is added to the alloy. Lead also improves antifriction properties, and lead brasses are often used for frictional parts. Since lead is practically insoluble in solid copper (the solubility of lead in copper does not exceed 0.02 % [2]), then in the alloy it is in the form of dispersed particles of micron and submicron size randomly located both in the volume of grains and along their boundaries.

We have examined brass samples containing in addition to copper approximately 36 % zinc and insignificant amount of lead (< 0.3 %).

The laser heat treatment was performed with a solid-state Nd:YAG laser operating at the third harmonic. Wavelength was \( \lambda = 355 \text{ nm} \), pulse duration was 10 ns, pulse energy was up to 8 mJ, pulse repetition rate was \( f = 100 \text{ Hz} \). The experimental technique was described in detail in [14-19], but it had some very important change.

In this work only scanning impact mode was used. The radiation was focused into the spot up to a size of 100 - 200 µm by a quartz lens with a focal length of 250 mm. The sample mounted on a three-dimensional object stage was moved relative to a stationary laser beam along a raster trajectory ("snake") so that adjacent spots were overlapped with an overlap ratio of \( \geq 99 \% \). The length of the "snake" in this experiment was 4 mm, and the width was 1 mm, the distance between the horizontal lines was about 30 µm. The overlap coefficient \( k \) was determined as the ratio of the area impacted by two radiation pulses to the area of one spot:

\[
k = \frac{\left( \sum_{i} S_{i} \right) - \sum_{i} S_{i+1}}{\sum_{i} S_{i}} \times 100\%
\]

where \( S_{i} \) is the surface area impacted by pulse \( i \). In this case, the same area was exposed to 100 pulses.

Thermophysical calculations carried out in [19] showed, that under such regime the sample surface completely cools down to room temperature during the time between pulses. Such mode of heat impact is interesting, because with an extremely high specific heat load on the surface of the material being processed, the temperature of the total volume of the sample practically does not change, completely retaining its geometric parameters.

The use of UV radiation can significantly increase the dose of absorbed energy. If in the IR region the metal reflects up to 98 % of the incident radiation, then at a wavelength of 355 nm it reflects only 10 % [14, 20] (data are given for oxygen-free copper).

Before and after laser heat treatment, the samples were examined by Zygo NewView 7300 optical profilometer (Zygo, Middlefield, CT, USA, 2012) and a JEOL JSM 6610LV scanning electron microscope (SEM) (JEOL, Tokyo, Japan, 2011).

3. Experimental results and discussion
Figure 1 shows characteristic fragment of the heat-treated zone of a brass sample. At the pulse energy density \( W = 0.15 \text{ J/cm}^2 \), grain boundaries and dispersed lead particles, that do not dissolve in the alloy, are visualized.

Table 1 shows data on the elemental composition of the surface layer after laser heat treatment measured in 6 zones marked in the photograph (Figure 1). The studies were carried out using X-ray energy dispersive microanalysis attachment Oxford INCA Energy 350.
On the surface dark and light inclusions are observed, in which the lead concentration reaches a value of about 30 % and becomes comparable to the copper concentration. In the same zones the oxygen concentration is twice as high as in the areas, where the presence of lead is not registered. Light inclusions are assumed to be lead, while dark spots are lead oxides. Lead lines are absent in the X-ray spectra on the surface areas free from spots.

**Figure 1.** A spot on the brass surface after laser impact (Nd:YaG laser, $\lambda = 355$ nm, $f = 100$ Hz, $W = 0.15$ J/cm$^2$).

**Table 1.** Elemental composition of the surface of brass sample after impact.

| Zone  | C   | O   | Cu  | Zn   | Pb   |
|-------|-----|-----|-----|------|------|
| Zone 1| 0.82| 63.06| 36.12|      |      |
| Zone 2| 1.02| 63.21| 35.77|      |      |
| Zone 3| 0.97| 54.12| 44.91|      |      |
| Zone 4| 9.43| 1.13| 49.42| 40.03|      |
| Zone 5| 14.20| 1.99| 33.79| 21.21| 28.81|
| Zone 6| 17.36| 1.68| 29.08| 17.85| 34.04|

The problem of the formation of "carbon deposits" on the object under study due to the effect of an electron probe [21] is known in X-ray spectral analysis. "Carbon deposits" are formed during the decomposition of hydrocarbons, which are always present in the microscope chamber. It is mainly due to the action of secondary electrons and it increases with an increase in the primary impact dose. It is known, that after a short impact (a single accumulation of the X-ray spectrum at a point) when analyzing the composition, an excess amount of carbon appears, even in samples that do not contain it. This leads to errors in determining the elements in the investigated sample and necessity to adjust the analysis. In this case, since the presence of carbon in the alloy is not expected, the spectral analysis data were corrected.

The data on the elemental composition are in many respects qualitative, since the initial lead concentration was only about 0.3 % and error in measuring the elemental composition of an alloy by JEOL JSM 6610LV SEM, used by us, was 0.5 %.

Figure 2 shows three-dimensional images of various fragments of laser heat impacted zones on the brass surface. They were obtained by Zygo NewView 7300 optical profilometer. It can be seen, that
with an increase in the energy density, the size of the emerging defects reaches a level of 1 μm and higher (Figure 2f, Figure 2g).

![Figure 2a](image1.png) ![Figure 2b](image2.png)

![Figure 2c](image3.png) ![Figure 2d](image4.png)

![Figure 2e](image5.png) ![Figure 2f](image6.png)

![Figure 2g](image7.png)

**Figure 2.** Three-dimensional image of fragments of laser heat impacted zones on brass surface, obtained by profilometer: a) and b) fragments of the central zone at $W = 0.15 \text{ J/cm}^2$; c) and d) fragments of the edge zone at $W = 0.30 \text{ J/cm}^2$; e) edge of impacted zone at $W = 0.52 \text{ J/cm}^2$, f) central zone at $W = 0.52 \text{ J/cm}^2$; g) profilogram of the edge of impacted zone at $W = 0.52 \text{ J/cm}^2$. 
At an energy density in pulse of \( W = 0.15 \text{ J/cm}^2 \) (Figure 2a, b; Figure 3a) dispersed lead particles undissolved in the matrix and grain boundaries are visualized. Doubling the energy density leads to a noticeable change in the surface profile. Numerous hilly uplifts up to 1.0 \( \mu \text{m} \) in height appear.

![SEM micrographs of fragments of spots on the surface of brass after laser heat impact](image)

**Figure 3.** SEM micrographs of fragments of spots on the surface of brass after laser heat impact (Nd:YaG laser, \( \lambda = 355 \text{ nm, f = 100 Hz} \): a) \( W = 0.15 \text{ J/cm}^2 \), b) \( W = 0.30 \text{ J/cm}^2 \), c) \( W = 0.52 \text{ J/cm}^2 \), low resolution, d) \( W = 0.52 \text{ J/cm}^2 \), high resolution.

At \( W = 0.52 \text{ J/cm}^2 \), the uplifts in the region of grain boundaries become more embossed. In many grains traces of crystallographic sliding are observed, on some of them, point melting centers appear. They begin on inclusions of lead, which has a melting point of 327.3 °C, while in brass it is 932 °C [22].

### 4. Conclusion

Laser heat impact in the mode described in this work, in addition to cleaning the metal surface from oxides and other adsorbed impurities, creates developed surface with a regular structure, which should contribute subsequent diffusion welding. This mode seems to be more advantageous in comparison with the mode proposed in [5, 6]. The surface layer remains in the condensed state throughout the entire process. The impact of radiation on the metal surface is carried out without melting and evaporation, and there is no noticeable oxidation.
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