Influence of post-processing on the strength of heterogeneous materials produced by the laser welding

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Abstract. The paper presents the investigation of the laser welding of the alloy Al-Cu-Li and titanium alloy Ti-Al-V, as well as the analysis of the post-processing on the strength properties of welded joints. Macro- and micro-structure of the joints have been studied. The resulting heterogeneous welded materials have been post-processed. The mechanical characteristics of the welded joints have been determined before and after the thermal processing.

1. Introduction
Titanium and aluminum alloys have a number of unique properties such as high specific strength, low density (comparing to steel) and high corrosion resistance. The properties of these materials make them be commonly used in aviation and rocket technologies \cite{1}. The need to combine the properties of titanium and aluminum alloys in one structure is often for a modern vehicle. Welding of heterogeneous materials is a challenge. First, the differences in the chemical and physical properties: the welded materials have different melting points, density, thermal conductivity, etc. The difference in the chemical composition may result in undesirable combinations during the welding and variation of the material properties in the near-joint zone because of the mutual diffusion of the materials. The difference in thermophysical properties causes the nonuniform heating of the materials, which in turn leads to the residual thermal stresses which can hardly be removed due to the different temperature of the thermal processing for the welded materials, as well as occurrence of brittle intermetallic compositions in the welded joint \cite{2, 3}. Today, high-strength aluminum alloys alloyed by lithium are developed. Lithium added into the alloy decreases the alloy density and increases the strength properties owing to the strengthening phases resulting from the thermomechanical processing. These alloys are promising for the welded constructions \cite{4}.

By now, there is no technology of connection of titanium and aluminum parts by the melting welding method (for example, fixation of titanium wings to the aluminum fuselage of an aircraft) because of the intermetallic compositions forming in the melt pool which make the joint brittle and undurable. Usually this task is solved with the aid of riveting which has a number of serious disadvantages such as growing weight of the construction, occurrence of stress concentrators (which rises the specific amount of metal in the structure), complexity of sealing, low process efficiency. Rivets can hardly be smoothed to have an aerodynamic shape. At the same time, the welded connection permits providing the sealing. The structure weight is much lower without rivets, and this connection can be polished for the needed shape.
In this paper we analyze the peculiarities of the laser welding of heterogeneous materials for the aluminum alloy of the system Al-Cu-Li and titanium alloy of the system Ti-Al-V, as well as the influence of the post-processing of the strength properties of the welded connections.

2. Experimental Technique
To weld heterogeneous materials, we chose the titanium alloy VT-20 and aluminum-lithium alloy 1461 (made in Russia). VT-20 alloy is characterized by high heat resistance and welds well. The alloy is intended for the manufacture of products operating for a long time at temperatures up to 500 °C. The aluminum alloy 1461 production Kamensk Uralsky Metallurgical Works (KUMZ in Russian abbreviation) is the promising Russian high-strength welded alloy of the third generation and is involved in the parts made by PAO “Sukhoi Company”. Table 1 gives the chemical composition of the studied alloys.

Table 1. Chemical composition of aluminum alloys.

| Alloy | Ti | Al | Cu | Mg | Mn | Li | Zr | Sc | Mo | V |
|-------|----|----|----|----|----|----|----|----|----|---|
| VT-20 | base | 5.5-7 | - | - | - | - | 1.5-2.5 | - | 0.5-2 | 0.8-2.5 |
| 1461 | 0.07 | base | 2.5-2.95 | 0.4-0.6 | 0.1-0.4 | 1.5-1.9 | 0.05-0.12 | 0.05-0.1 | - | - |

The titanium alloy VT-20 belongs to the titanium alloys of the system Ti–Al–V (the class by the pseudo α structure). This alloy is durable to hot cracks during the melting welding.

The aluminum-lithium alloy 1461 of the system Al-Cu-Li presents a solid solution based on Al with strengthening phases $T_1 (Al_2CuLi)$, $T_2 (Al_6CuLi_3)$, $S_1 (Al_2MgLi)$, $\delta' (Al_3Li)$, $\theta (Al_3Cu)$ [5].

The laser welding (LW) was performed on the automated laser technological complex “Sibir-1”. The ALTC consists of a gas-discharge CO$_2$-laser equipped with a SFUR-resonator [6,7]. The characteristics of the generated radiation are the following: the radiation wavelength $\lambda = 10.6$ μm; the maximal radiation power up to 8 kW; the beam quality $BPP = 4.7$ mm*mrad. The laser wave guide includes the following components: flat mirrors and the phase-shifting mirror, which permits transforming the flat radiation polarization into the circular polarization. The two-coordinate spanning technological table moves the welding heading in respect to the welded sheet. The values of the major table characteristics are: the working area is 1.5 x 2.5 m; the maximal motion rate is 50 m/min; the positioning accuracy is 0.1 mm.

The welding head includes the focusing ZnSe lens, the gas-dynamic nozzle protecting the welded connection from oxidation, plus the mechanism permitting the motion of the lens position along the beam axis. Figure 1 shows the photo of the laser welding process. Thermal processing of the welded connections was carried out in a tube vacuum furnace equipped with the temperature controller. The pressure in the vacuum furnace was 1 mm Hg.

Figure 1. Laser welding diagram.
The strength of the welded joints was measured at the static extension on the electro-mechanical test machine Zwick/Roell Z100.

3. Results and Discussion

3.1. Laser welding of homogeneous welded joints
At the early stage, the laser welding of the titanium alloy VT-20 and aluminum alloy 1461 was studied. The laser radiation was focused on the alloy surface with the aid of the ZnSe lens, its focal distance was 254 mm. Helium, the inert gas, was used to protect the welded joint and joint core. The gas was supplied through the nozzle which was included at the angle of 45° to the welded plate, the gas flow rate was 5 l/min. prior to the test, the samples were polished with a sand paper and washed in petroleum in order to remove impurities from the surface. The titanium alloys samples (50x100x2 mm) were set on a multi-purpose table with special clamps.

Experiments gave the optimal conditions for the laser welding of titanium VT-20 sheets at which the qualitative defect-free welded joints are produced. The optimal energy conditions of the welding are: the laser radiation power is 1.2 kW, the welding rate is 1 m/min, the focus position about the upper sheet boundary is -3 mm.

Welded joints aluminum alloy 1461 without any surface defects such as hot cracks or poor fusion were obtained with the following welding mode parameters: laser beam power 3.3 kW, welding speed 4 m/min, and depth of focus in the material – 2 mm, with keyhole penetration.

Figure 2 shows an optical photograph of the cross section of the weld of a titanium and aluminum alloy, showing the difference between the microstructure in the fusion zone and the heat-affected zone (HAZ) from the base alloy.

The structure of the welded joint titanium alloy is typical for the cast condition: equiaxed poliendric grains are in the center, and from them the grains elongated along the heat release toward the base. The average size of the base alloy is 5 µm, the thermal effect zone size is 20 µm.

The weld microstructure is fundamentally different from that of the aluminum alloy (see figure 2, b). The microstructure of the central fusion zone exhibits an equiaxed dendrite zone in the weld center. The heat affected zone consists of columnar dendrites. The same structure of the Al-Li alloy weld was observed in other studies.

![Figure 2](image-url)

**Figure 2.** Optical photo of the weld microstructure cross section, HAZ and base alloy. (a) weld titanium alloy, (b) alloy aluminium alloy (magnification 5x and 100x).

Table 2 contains data after mechanical testing about the ultimate tensile strength $\sigma_{UTS}$, ultimate yield strength $\sigma_{YS}$, and relative elongation $\delta$ of the alloys and welded joints.
Table 2. Mechanical properties of the alloys and welded joints.

| Mode                  | $\sigma_{UTS}$, MPa | $\sigma_{YS}$, MPa | $\delta$, % |
|-----------------------|---------------------|--------------------|------------|
| Alloy VT-20           | 1080                | 1000               | 12         |
| Welded joint VT-20    | 1050                | 980                | 5          |
| Alloy 1461            | 550                 | 470                | 10.1       |
| Welded joint 1461     | 341                 | 333                | 0.7        |

For a titanium alloy VT-20, the ultimate tensile strength of the weld is close to the ultimate tensile strength of the alloy. For aluminum alloy 1461, the weld ultimate tensile strength is 0.62 of the alloy ultimate tensile strength. In our work [6,7], it is shown that in order to increase the mechanical characteristics of the weld, it is necessary to apply post heat treatment of the weld.

3.2. Laser welding of dissimilar materials

The peculiarity of this research data is that the laser radiation is sheared in respect to the joint toward titanium for «0», «0.5», and «1» mm, where the solid titanium-based $\alpha$-solution would form with the minimum intermetallic compositions. The heterogeneous materials were welded in energy modes welding titanium alloy (the laser radiation power is 1.2 kW, the welding rate is 1 m/min, the focus position about the upper sheet boundary is -3 mm).

Figure 3 shows the values of the yield strength after the stretch tests for the initial alloys and resultant heterogeneous laser-welded connections at different shearing of the laser radiation.

![Figure 3](image_url)

**Figure 3.** Mechanical characteristics of the alloy and welded joint.

As is evident from figure 3, the strength increases versus the laser radiation position, remaining low comparing the initial alloys. Figure 4 shows a general view of a high-quality heterogeneous weld.

SEM images of the weld metal microstructure for the laser beam offsets «1» are presented in figure 5.
Figure 4. Photo of the laser dissimilar welded joint.

Figure 5. SEM image of cross-section of the welded joint.

Analyzing figure 5, three characteristic zones can be distinguished. The fusion zone «C» of titanium, the interface zone between aluminum and titanium «B», the fusion zone «A» of aluminum due to heat removal from molten titanium. In the interface zone there was a brazing welding.

In order to change the mechanical characteristics of the heterogeneous welded connections, the welded joints underwent the thermal processing.

This processing applied to the laser-welded connections of aluminum-lithium alloys of different systems results in the growth of the mechanical characteristics [6, 7]. In respect to the heterogeneous connections, this procedure can decrease the internal stresses remained after the welding.

The thermal processing was carried out by six modes. After the processing, the samples were cooled in air. The parameters were taken from recommendations of the references. We also preserved the control group of samples which did not undergo the thermal processing. The processed samples were tested for stretching. The test results are given in figure 6.
Figure 6. Results of stretch tests of the samples after the thermal processing produced at different shearing without laser beam a)«0», b) «0.5», c) «1» mm.

Figure 7 shows the changed zones «B» according to figure 5 depending on the temperature and time of heat treatment.

As can be seen from figure 7, the structure of the interface zone changes dramatically, with changes occurring both from the temperature at the same holding time in the furnace and from time at a constant temperature. There is a change in both the width of the interface zone and the structure. A change in the structure of agglomerates in color indicates a different chemical composition. According to the state diagram Ti-Al, various intermetallic phases (Ti$_3$Al, TiAl, TiAl$_2$ and TiAl$_3$) can occur, which affect the mechanical characteristics of heterogeneous laser welds based on titanium and aluminum alloy. For a more accurate determination of intermetallic phases, it is necessary to study the chemical composition of these phases using EDX analysis and transmission electron microscopy, which is planned in future studies.
4. Conclusions
The laser welding of heterogeneous materials based of titanium and aluminum alloys has been analyzed. It has been founded that the ultimate tensile strength of the produced welded connections depends on the laser radiation shear. The thermal processing of the connections produced with the sheared laser beam and without it results in the reduction of the strength. It is shown that as a result of heat treatment of the weld, the structure of the interface zone between the titanium and aluminum alloy changes its structure and size depending on both temperature and time. Apparently, as a result of heat treatment of the weld in the interface zone, intermetallic phases were formed. These intermetallic phases lead to a change in the mechanical characteristics of a heterogeneous welded joint based on titanium and aluminum alloy.

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