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Laser Welding-Soldering of Titanium Alloys with Aluminum Alloys Using Microplasma Pre-Coating

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ABSTRACT

The research is aimed at improving the technology of laser welding-soldering of titanium and aluminum alloys widely used in the aerospace and automotive industries. Welding is difficult due to the formation of a brittle layer of intermetallides ($TiAl_3$), worsening the strength of the joints. To reduce the formation of intermetallides it was proposed to use preliminary microplasma spraying of METCO 54NS-1 aluminum powder coating (fraction 0-40 μm) on titanium edges of 1 mm thickness (OT4 alloy (analog ST-A90)). The coating thickness was 50 μm. Laser welding-soldering was carried out using a CO_2 laser with a power of 2-4 kW, at a speed of 16-30 m/h, a defocus value of +10...+15 mm and a flow rate of shielding gases (helium – 10 l/min, argon – 14 l/min). Samples made of titanium and aluminum (AMg6 (analog AA 6061)), thickness 1.2 mm) were joined overlapping with an overlap of 6-12 mm. The results showed that microplasma coating does not provide a quality joint. Residual porosity, aluminum oxides and air gaps prevented the formation of a continuous weld, which led to non-melting and burn-through. The presence of oxides on aluminum and titanium nitrides formed by interaction with air impaired metal wetting and bonding. The results indicate the need for further improvements in technology, including reducing air gaps, improving surface preparation, and utilizing alternative joining methods such as hybrid technologies and new types of intermediate layers. This will minimize the formation of intermetallides and improve the performance of welded joints.

Keywords: laser welding-soldering, aluminum, titanium, plasma spraying, intermediate layer, defects.

INTRODUCTION

In the manufacture of structures with high performance and mechanical characteristics, combined welded assemblies made of dissimilar metal materials are widely used. This makes it possible to maximize the advantages of each of them and reduce costs [1]. Welding of aluminum with titanium is an urgent task of modern materials science and engineering. These metals are widely used in aerospace, automotive, shipbuilding and other high-tech industries due to their unique properties [1, 2]. Aluminum is characterized by low density, high ductility, and good corrosion resistance, while titanium is characterized by outstanding strength, heat resistance, and biocompatibility [3, 4]. Combining aluminum and titanium in one structure allows achieving an optimal ratio of weight, strength, and resistance to external influences. However, differences in their physicochemical properties, such as density, thermal expansion coefficients and melting point, create significant difficulties in welding [5]. For example, when fusion welding titanium alloys with aluminum alloys, it is difficult to avoid the formation of intermetallic layer of considerable thickness, embrittlement of the weld. One of the widely used technological methods to create a welded joint with satisfactory mechanical characteristics when welding dissimilar joints is the use of intermediate layers. These interlayers help to avoid the formation of intermetallides in both fusion welding and brazing [6]. The composition of interlayers is selected for specific dissimilar metals and structures. The correct choice of interlayers can not only eliminate the occurrence of intermetallides, but also provide relaxation of welding residual stresses at the interface of dissimilar materials.

For the pair "titanium-aluminum" is known method of argon-arc welding with tungsten electrode, before which the edges of titanium are cleaned from α-layer and contaminants and alitized in pure aluminum at a temperature of aluminum 800...830 ° C for 1...3 min. In this case, the period of formation of the compound between aluminum and titanium is shorter than the retardation period, and brittle intermetallides along the compound line do not have time to form [7].

In this connection, the development of alternative methods of joining this and other pairs of dissimilar metals, allowing to avoid the formation of intermetallic layer or to minimize its thickness, is of great importance. Currently, one of such promising methods is solder welding [8, 9]. This method of welding is used when joining metals that form chemical compounds, or when welding metals that differ sharply in melting point, thermal conductivity, as well as having insignificant mutual solubility [8, 10]. This method is characterized by the fact that only one of the metals to be joined is melted, while the other (usually refractory) remains solid. When welding-soldering titanium with aluminum using laser radiation, it is necessary to take into account the temperature and time conditions of formation of the intermetallide layer [11]. The technology of laser soldering is chosen so that the thickness of the intermetallide layer was minimal, this layer had no defects in the form of cracks and pores, and the duration of contact between dissimilar metals at maximum temperatures did not exceed the latency period (the time required to reach the limiting concentration above which intermetallides are formed) (Fig. 1).

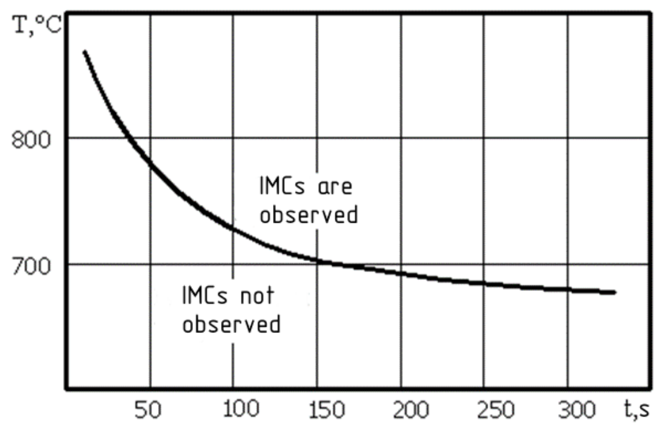

Figure 1. Temperature-time dependences of $TiAl_3$ compound formation at contact of titanium with liquid aluminum [12]

Based on the analysis of the titanium-aluminum state diagram, as well as the temperature dependence of the latent period of formation of $TiAl_3$ intermetallic layers in the surface contact zone of titanium and aluminum (Fig. 1), we can conclude that using the difference in melting temperatures of titanium and aluminum, the laser welding process can be carried out without melting titanium in the presence of a liquid aluminum bath. In this case, due to the short-term interaction of liquid aluminum with titanium during laser welding, the concentration of liquid aluminum will be insufficient for the formation of γ-phase, and the amount of $TiAl_3$ can be significantly reduced.

The purpose of this study is to reduce the formation of intermetallic interlayer during laser welding brazing of titanium alloys with aluminum alloys by preplasma coating using.

MATERIALS & METHODS

Instead of environmentally harmful, highly energy- and resource-consuming process of alitizing, the authors proposed a process of preliminary coating of technically pure aluminum on the welded edges of samples using microplasma spraying.

In E.O. Paton Electric Welding Institute the equipment and technology of coating with the help of microplasma method have been developed. Its advantages include: increased, in comparison with plasma coating, the coefficient of material utilization; low thermal effect on the part; relatively low power of plasmatrons (up to 2-3 kW); small size of the sputtering spot (2...5 mm); low noise level. This equipment has high mobility, relatively small weight and dimensions, is easy to operate. It consists of: power supply, microplasmatron, which generates a thin laminar jet of gas plasma, dispenser, which provides dosing and feeding of powders into the plasma jet. METCO 54NS-1 technical aluminum powder (0...40 µm fraction) was applied to 1 mm thick OT4 titanium alloy (analog ST-A90) plates using microplasma spraying (Fig. 2). The thickness of the coatings was about 50 µm. The process of microplasma coating on samples made of titanium alloy OT4 is shown in Fig. 3.

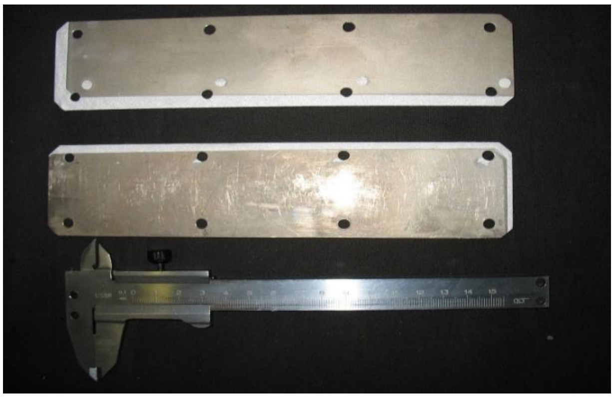

Figure 2. Samples made of titanium alloy OT4 with technical aluminum coating (METCO 54NS-1 powder)

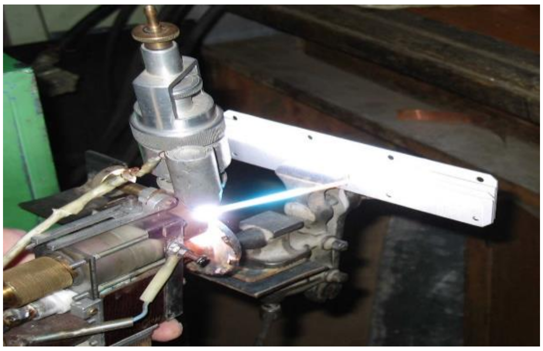

Figure 3. Process of microplasma coating of technically pure aluminum powder METCO 54NS-1 on samples made of titanium alloy OT4

For welding-soldering of joints from dissimilar alloys by CO_2-laser radiation, a technological post was developed on the basis of the laser unit "TRIAGON" (Fig. 4). In addition to the CO_2-laser, the unit included: a system of rotating mirrors to deliver laser radiation into the processing zone; a system of focusing laser radiation with a potassium chloride lens with a focal length of 300 mm; a system of protection of laser optics; a slide table with a clamp for fixing the sample; a laser processing head; a horizontal CNC axis used as a mechanism for moving the processing head relative to a stationary clamp with fixed samples.

Figure 4. Laser welding-soldering process of OT4 alloy with AMg6 on CO_2-laser "TRIAGON"

Samples from titanium alloy OT4 with sputtering and aluminum alloy AMg6 (analog AA 6061) in the form of plates 1.0 and 1.2 mm thick, respectively, were welded overlapping. In laser weld-soldering, a specimen of the more refractory material, OT4, was placed on top of a specimen of AMg6. The titanium alloy was heated with a defocused laser beam to a temperature below its melting point, but allowing the aluminum sample to be melted. Due to good contact between the titanium and aluminum alloys, the latter, due to heat transfer, was heated to temperatures above its melting point and wetted the surface of the unmelted titanium alloy.

The process of welding-soldering of titanium with aluminum alloys was carried out with the use of a special processing head, allowing to protect metals in the processing zone from contact with the atmosphere. Argon and helium were used as shielding gases. The design of the processing head allowed to supply separately gases directly into the processing zone and into the zone of the weld metal cooling down.

When conducting experiments on welding-soldering of titanium alloy OT4 with aluminum alloy AMg6, the laser beam was located exclusively on the titanium alloy. In order to reduce the cost of materials during welding-soldering of samples (and material intensity of products in the future), the minimum value of titanium alloy overlap on aluminum alloy was initially chosen, equal to the diameter of the spot of defocused laser radiation. Thus, the value of the overlap initially amounted to 6 mm, and the distance from the beam axis to the ends of the samples was 3 mm.

The amount of overlap of titanium alloy on aluminum alloy varied within 6...12 mm. Other parameters of the technological process of laser welding-soldering were varied in the following ranges: laser radiation power 2...4 kW; processing speed 16...30 m/h; defocus value +10...+15 mm; consumption of shielding gases - helium in the processing zone – 10 l/min, argon for protection of the cooling weld 14 l/min.

RESULT

As a result of experiments on laser welding-soldering of titanium alloys with aluminum alloys with the use of pre-applied microplasma-applied coating, a negative result was obtained and a conclusion was made about the impossibility of using this method for joining this pair of dissimilar materials.

The negative result was due to the characteristics of the obtained microplasma-applied coating. As with other methods of gas-thermal application, microplasma coating has a number of disadvantages due to the specificity of the application process. In our case, the most negative role played residual porosity and the presence of not only pure aluminum on the surface, but also its oxide, formed in the process of sputtering and cooling of the aluminum coating on the titanium alloy. Welding of this metal pair - titanium-aluminum requires the absence of an air gap between the welded materials. Otherwise, in case of insufficiently tight fit of titanium and aluminum alloy samples, during the laser welding process these metals interact with the air in the cavities. As a result of such interaction, a thin layer of oxide with a high melting point is formed on the surface of aluminum, and on the surface of heated titanium - a layer of titanium nitride, which leads to non-melting of the sample materials (Fig. 5).

Figure 5. Top view of the sample welded by CO_2-laser "TR100" at the allowance Δ=12 mm of titanium alloy OT4 (thickness δ=1mm) without coating (upper sample) and with pre-applied coating (lower sample), with aluminum alloy AMg6 (thickness δ=1.2mm)

The presence of oxygen in the pores and in the bound state in the form of oxide on the coating surface caused the presence of extended areas of non-melting along the entire length of the welded samples. Also a characteristic feature of the process of welding-soldering of titanium alloy OT4 with plasma-applied coating with aluminum alloy AMg6 was the presence of a large number of sparks flying from the welding zone during the process. The presence of such an effect, observed visually, indicated the presence of defects in the idea of burns and non-melting in these places, which was confirmed by further examination of the samples (Fig. 6).

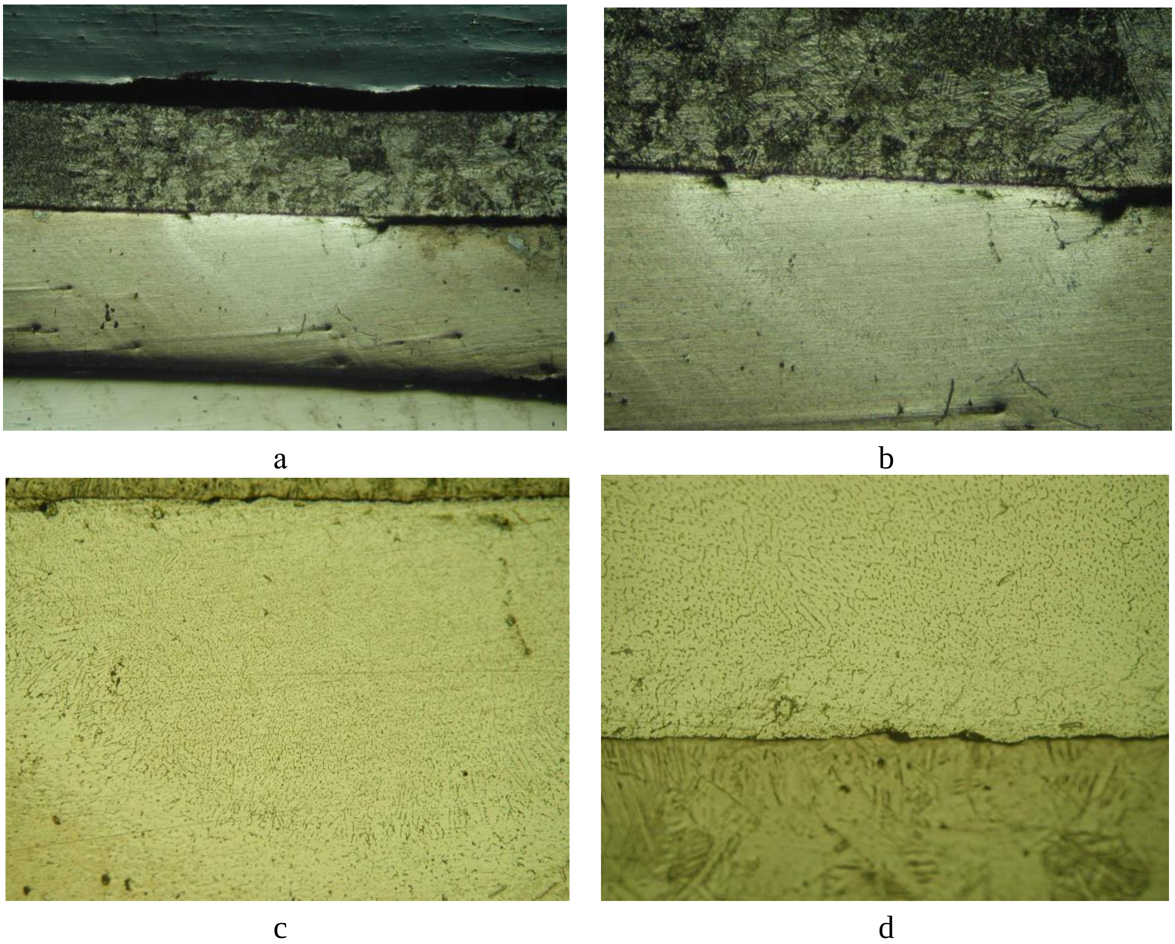

Figure 6. Cross-section of the seam welded by CO_2-laser "TR100" with overlap Δ=12 mm, titanium alloy OT4 with pre-coating, on aluminum alloy AMg6, at magnification: ×25, b) ×50, c) ×100, d) ×200

DISCUSSION

To reduce the formation of brittle intermetallides during welding of aluminum and titanium, various technologies and approaches based on the optimization of heat exposure and design features of joints are used [6]. One of the techniques is the displacement of the laser beam relative to the weld. For example, displacement towards titanium allows limiting the melting of aluminum due to heat transfer through heat conduction, which leads to a decrease in the thickness of the intermetallide layer. A 0,3 mm beam offset produced a joint with a minimum $TiAl_3$ layer thickness (2 μm) and a strength of 200 MPa [13, 14]. An alternative approach is to offset the beam towards aluminum, which prevents titanium melting and the formation of brittle intermetallides. This method is particularly effective when using a split laser beam and filler materials such as Al-Si wire. For example, the use of Al-12Si in a 45° V-shaped edge cutting process provided a joint strength of 278 MPa with an intermetallide layer thickness of less than 2 μm [15, 16].

Additional measures include the use of high welding speeds (>4 m/min), which limits the interaction time between aluminum and titanium and minimizes the formation of intermetallides. In some cases, the addition of intermediate layers such as Nb promotes the formation of more ductile phases (e.g., Al_3Nb), which improves the strength characteristics of the joint and reduces the likelihood of cracking [13, 17].

The use of laser-arc hybrid welding, such as with Cold Metal Transfer technology, also improves metal wetting and stabilizes the weld, providing strengths up to 213 MPa [17, 18]. Design modifications such as V-shaped edge cutting or U-shaped grooves in the aluminum component improve wettability and heat distribution uniformity, which minimizes intermetallic thickness and consequently increases joint strength. These approaches show high potential for improving joint reliability under service conditions.

CONCLUSION

As a result of the conducted experiments it was found that the use of microplasma coating for joining titanium alloys with aluminum alloys by means of laser welding-soldering showed negative results. The main causes of non-melting were the residual porosity of the coating, the presence of aluminum oxide and air gaps between the joined materials, which led to the formation of layers of oxides and nitrides that prevent reliable bonding. Defects in the welded joint, such as unmelted areas and burn-throughs, indicate the insufficient technological suitability of this approach.

Thus, the joining process of titanium and aluminum alloys requires further optimization of technological modes, including reduction of air gaps, selection of materials with minimal tendency to oxidation, as well as the use of new approaches such as combined welding methods, surface modification and the use of intermediate layers. This will improve the quality of welded joints and ensure their operational reliability.

Declaration by Authors

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Conflict of Interest: The authors declare no conflict of interest.

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