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ORIGINAL ARTICLE

Microstructure and mechanical properties of Ti/Ta/Cu/Ni alloy laminate composite materials produced by explosive welding

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Abstract Ti/Ni alloy-based laminate composite materials were produced by explosive welding with two thin intermediate layers of tantalum and copper placed between Ti and Ni alloy layers. The influence of the thickness of the Cu interlayer (0.1–0.7 mm) on the structure and mechanical properties of the explosively welded composites was examined. Investigations carried out by optical and scanning electron microscopy showed the formation of an inhomogeneous structure in the vicinity of the interfaces with zones of local melting and cavities within these zones. The wavelength and the amplitude at the interface between the copper and tantalum interlayers changed with the thickness of the copper layer. In order to evaluate the mechanical properties of the composites containing copper interlayers of different thicknesses, microhardness, tensile, and bending tests were performed. As the thickness of the copper layer was decreased to 0.3 mm, the tensile and bending strengths of the laminate composites increased.

Keywords Welding · Composites · Mechanical properties · Fracture

1 Introduction

In recent years, welding technologies, including welding processes of dissimilar materials significantly differing in physical, chemical, and mechanical properties, have attracted a lot of attention. Examples of dissimilar materials are titanium and aluminum [1], titanium and steel [2], aluminum and magnesium [3], and niobium and stainless steel [4]. Normally, welding of these materials occurs through the formation of a layer at the interfaces, which mainly consists of solid solutions and chemical compounds—intermetallics. The latter are usually undesirable, as they embrittle the welding joints and deteriorate the mechanical properties of the composites [5–9].

One of the most efficient technological solutions solving the problem related to the formation of brittle intermetallic compounds in the welding joints is the introduction of intermediate layers acting as barriers and preventing the formation of brittle phases. It was shown that the use of barrier layers at the boundaries of welded materials increases the strength of the laminate composites [10–15]. The enhancement of mechanical properties was possible, as undesirable reactions in the weld zone were prevented. The use of intermediate layers leads to increased strength of the welded materials that are further processes using annealing [16] and or tested without any post-welding heat treatment [17].

The materials of the intermediate layers and their thickness play an essential role in the improvement of the mechanical properties of the composites. Normally, intermediate inserts as thin as possible are preferred. At the same time, a clear relationship between the interlayer thickness and the value of the ultimate strength of the joints has not been established. This is evidenced, for example, by the data obtained during fusion welding of dissimilar materials [18–21]. It was found that, with increasing the thickness of the intermediate layers up to a certain value, the mechanical properties of the joint improve,

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as the volume content of brittle intermetallic compounds in the weld zone is reduced. However, upon a further increase in the thickness of the barrier layer, the mechanical properties of the laminate composite material deteriorate, which is caused by the formation of intermetallic-rich zones and structural defects, such as pores filled with gas and shrinkage voids.

In the joints welded without the formation of a liquid phase, the dependence of the strength on the thickness of the intermediate layer has a different character [22–29]: the thinner the insert, the higher the mechanical strength. As thicker inserts were used, the strength of the composite decreased due to the formation of many melting zones at the interfaces containing brittle intermetallic phases.

The literature overview shows that the influence of the thickness of the intermediate layers on the mechanical properties of composites welded from dissimilar materials is not fully understood. Therefore, in this study, laminate composite materials consisting of layers of commercially pure titanium and nickel alloy were obtained by explosive welding using barriers made of thin plates of tantalum and copper. The influence of the thickness of the copper layer on the microstructure and mechanical properties of explosively welded Ti/Ta/Cu/Ni alloy composites was examined.

2 Experimental procedure

Figure 1 shows the scheme of explosive welding realized in Lavrentyev Institute of Hydrodynamics SB RAS. The EI698VD nickel alloy plates (wt.%: Al 1.95; Si 0.32; Ti 2.84; Cr 14.84; Fe 0.54; Nb 2.31; Mo 3.96; Ni balance) 5 mm thick were used as a base. On the Ni alloy plate, foils of commercially pure M1 copper, TVCh tantalum 0.1 mm thick, and VT1-0 titanium 0.2 mm thick were placed (EVRAZ company) with a purity of 99.9, 99.9, and 99.7%, respectively. The thickness of the copper plate ranged from 0.1 to 0.7 mm. Copper and tantalum were selected as intermediate layers because of their mutual insolubility and the absence of chemical compounds in the Cu/Ta, Ti/Ta, and Cu/Ni systems. All workpieces used in the experiments were cleaned mechanically and subsequently washed with acetone. A charge of 6ZhV ammonite type explosive (waterproof ammonium nitrate 79 ± 1.5% and trinitrotoluene 21 ± 1.5%) was placed on blind-plate 1 mm thick, to which a flyer plate made of titanium was attached. The detonator was placed in the corner of the explosive, as is shown in Fig. 1. The distance between the plates in all samples was 2 mm.

The microstructure of the composites with intermediate copper layers of different thicknesses was studied by optical microscopy (Axio Observer Z1m, Carl Zeiss) in the bright field mode, scanning electron microscopy (EVO 50 XVP, Carl Zeiss) with a detector for energy dispersive spectroscopy (EDS) (X-act, Oxfords Instruments) to determine the chemical compositions at welded interfaces, and transmission electron microscopy (Tecnai 2G, FEI). Microstructural features of copper were revealed by means of etching with the $FeCl_2$ + HCl solution.

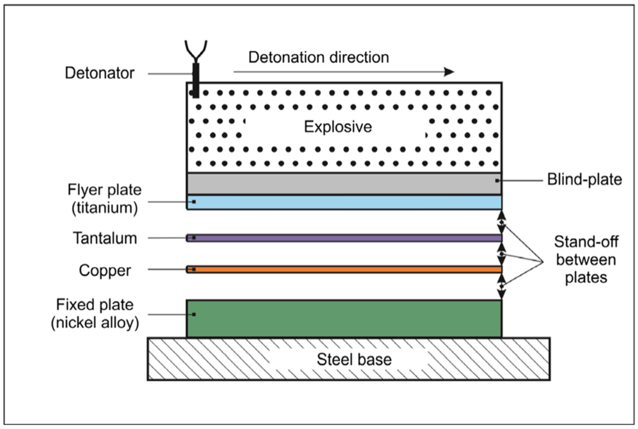


Fig. 1 The scheme of explosive welding of Ti/Ta/Cu/Ni alloy laminate composites

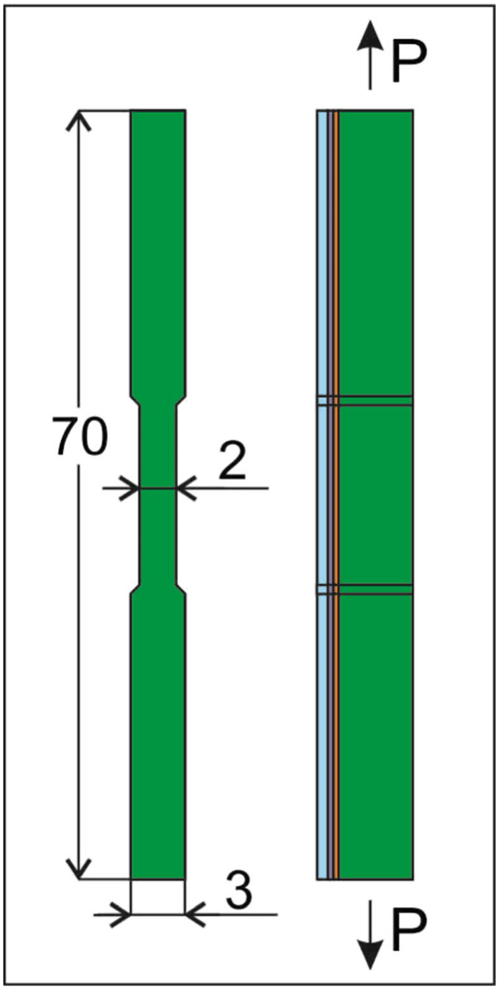


Fig. 2 Loading scheme of the composites in tensile tests. The *numbers* correspond to the dimensions of the samples in millimeters

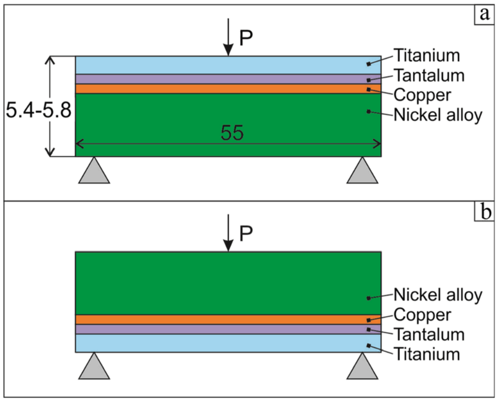


Fig. 3 Loading scheme of the composites in bending tests: titanium plate on the top (**a**), titanium plate on the bottom (**b**). The *numbers* correspond to the dimensions of the samples in millimeters

Vickers microhardness (402 MVD, Wolpert Group) was measured on metallographic samples cut along the direction of the detonation wave. The load on the diamond indenter was 0.245 N. The distance between the indentations was 25 µm. The tensile strength of the composites was determined using a versatile testing machine (Instron 3369) with a crosshead speed of 5 mm/s. The layers in the composite materials were parallel to the direction of tensile loading (Fig. 2). Samples for the tensile test were prepared in accordance with ISO 6892-1:2016 standard [30]. In order to evaluate the ability of the welded materials to deform without cracking, three-point bending tests were performed in accordance with ISO 5173:2009 standard [31] using the versatile testing machine (Instron 3369). The bending tests were carried out using two schemes. In accordance with the first test scheme, the VT1-0 titanium plate was placed on the top and subjected to compressive stresses (Fig. 3a). In accordance with the second scheme, the titanium plate was on the bottom and was subjected to tensile stresses (Fig. 3b). The samples were bent to the destruction moment. Fracture surfaces after the tensile and three-point bending tests were examined using scanning electron microscopy.

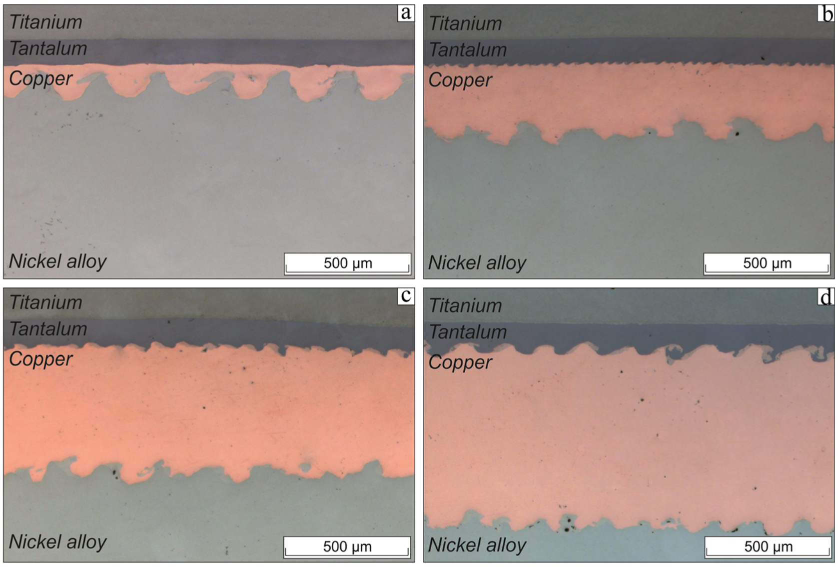
3 Results and discussion

3.1 Microstructure of composites with various copper interlayer thicknesses

The microstructure of the composites obtained using copper plates of different thicknesses is presented in Fig. 4. The interfacial contact between copper and tantalum as well as copper and the EI698VD nickel alloy had a wave structure that is typical for the explosive welding process. Mechanism formation and structure of wave-shaped interfaces between various materials were widely discussed [32, 33]. As the thickness of the copper layer increased, the amplitude and the wavelength of the bond increased. The quantitative parameters of the wave profiles at the copper/tantalum boundary are demonstrated in Fig. 5. Observations of the interface between the copper and the nickel alloy plates showed deviations from the periodic character, which did not allow drawing reliable conclusions on the geometrical parameters of these joints. For the welding joint between titanium and tantalum, a waveless interface profile was observed because the critical wave velocity was not reached.

A more detailed structural analysis of the welding joints between different metals in the obtained laminate composites indicated the formation of a continuous mixing zone at the Ti/Ta interface and local melting zones at the Cu/Ta and Cu/Ni alloy interfaces. In many cases, the wave formation process is accompanied by the formation of vortex zones consisting of mixed materials forming the welding joints (Fig. 6). The EDS

Fig. 4 Structure of Ti/Ta/Cu/Ni alloy laminate composites with copper plates 0.1 (**a**), 0.3 (**b**), 0.5 (**c**), and 0.7 mm (**d**) thick



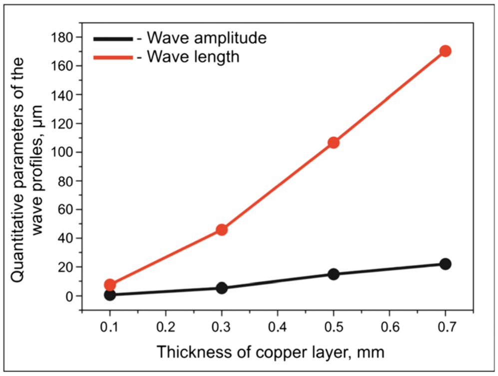


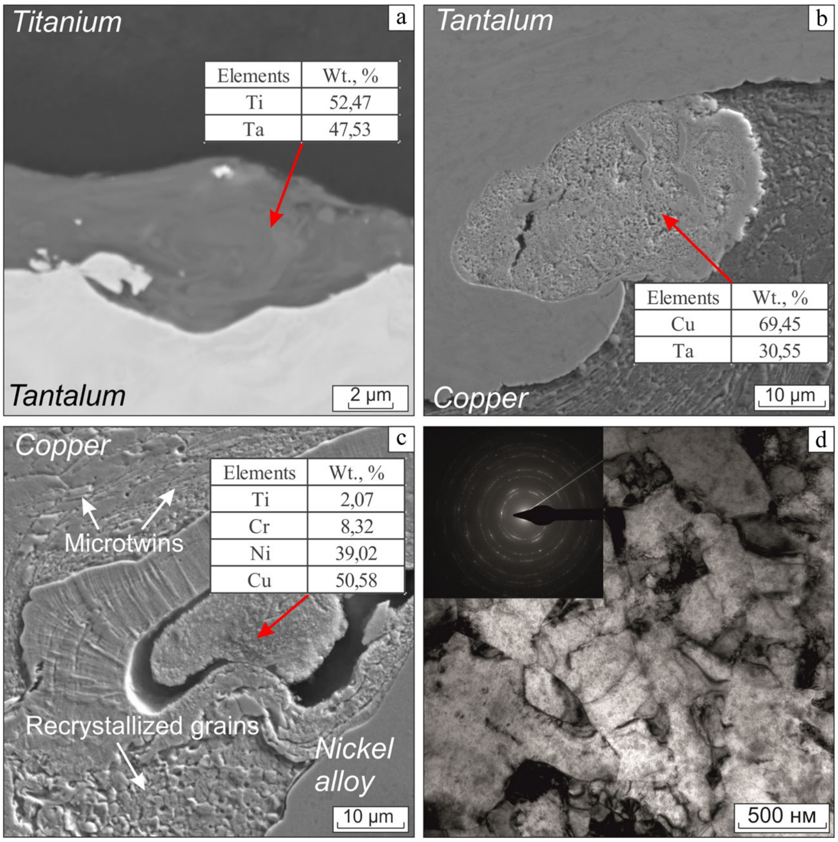
Fig. 5 Parameters of the wave-shaped copper/tantalum joints obtained by explosive welding of samples with tantalum plates 0.1 mm thick and copper plates of different thicknesses

results of the corresponding regions are specified in Fig. 6. With increasing thickness of the copper layer, the volume fraction and the size of vortices observed at the interface between the welding joints increased. The formation of vortices is associated with adiabatic heating caused by the formation of jets within the waves. These jets appear because of the density difference between the materials of the plates [34]. The vortex zones showed a cast structure with columnar crystals growing in the direction of heat dissipation. Local melting of materials within vortexes close to the weld interface induced by the high kinetic energy of the jet and the large plastic work of deformation.

Inside of many microvolumes that experienced melting, voids were observed. Their origin is mixing of the metals and shrinkage of the crystallizing melt (Fig. 6c). Other defects, such as microcracks and defects related to a lack of fusion, adversely affecting the strength of laminate structures, were not found in the composites obtained in this work. The elongated (sub) grains of copper, as well as the microtwins observed near the interface with tantalum and nickel alloys, clearly indicate that explosive welding is accompanied by severe plastic deformation. In the peripheral zones of the vortices (copper/tantalum interface), a fine crystalline structure formed. Its origin is dynamic recrystallization of the severely deformed materials as well as extremely high temperature followed by high cooling rates.

The signs of dynamic recrystallization, which occurs as result of high strain and high strain rates close to the bonding interface, were also confirmed by the TEM analysis (Fig. 6d). In Fig. 6d, the TEM structure of copper near the welding zone with tantalum is presented. Uniform equiaxial crystallites with an average size of 200–300 nm were observed, which is the result of dynamic recrystallization and subsequent recovery [35]. Microtwins that are typical for undeformed or slightly deformed copper have not been identified here (only randomly oriented subgrains and cells), suggesting that high degrees

Fig. 6 Structure at the interfaces between the explosively welded plates and EDS results of marked regions: mixing zone (**a**), local melting zone with fine crystals (**b**), local melting zone with columnar crystals (**c**), and copper structure near the welding zone with tantalum (**d**). SEM images (**a**–**c**). TEM image (**d**)



Elements	Wt., %
Ti	52,47
Ta	47,53

Elements	Wt., %
Cu	69,45
Ta	30,55

Elements	Wt., %
Ti	2,07
Cr	8,32
Ni	39,02
Cu	50,58

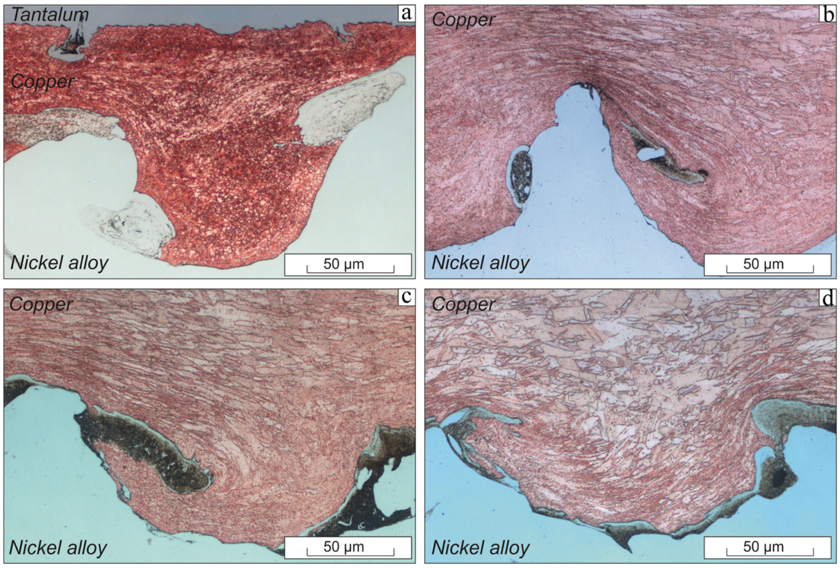


Fig. 7 Copper plates 0.1 (**a**), 0.3 (**b**), 0.5 (**c**), and 0.7 mm (**d**) thick deformed during explosive welding

of deformation lead to fragmentation and rotation of twins. The ring-like diffraction pattern also indicates uniform grains' distribution with high-angle boundaries.

Because of the nature of welded materials, namely the ability to form mechanical mixtures (tantalum/copper) or solid solutions (titanium/tantalum and copper/nickel alloy), there are no typical metastable phases in the local melting zones, such as intermetallic compounds and amorphous or glass structures, as well as quasicrystals. The formation of such structures depends not only on the parameters of welding, temperature, time, and cooling rate but also on the chemical composition of bonded metals. Examples of the metastable structure formation at the boundary of explosively welded materials are described in detail in [4, 36, 37].

The microstructure of the copper layers with minimum and maximum thicknesses observed using chemical etching is shown in Fig. 7. The structure of the copper layer 0.1 mm thick was the most homogeneous (Fig. 7a). Throughout its cross section, severely deformed and elongated grains were observed. In the copper plate 0.7 mm thick, the same structure was observed only in the areas adjacent to the tantalum and nickel alloy plates (Fig. 7d). The thickness of the severely deformed area was 40–50 μm. In the central region of 0.7 mm copper, indications of plastic deformation of the material were less pronounced. For copper plates 0.3 and 0.5 mm thick, the similar behavior of intensively deformed interface region and the non-deformed central region was observed (Fig. 7b, c). This conclusion can be drawn from the analysis of the shape of the copper grains. This shape indicates strong heterogeneity of the plastic deformation of the copper plates and the localization of the strain hardening mechanism of the material near the interfaces.

3.2 Microhardness of the composites with different thicknesses of the copper interlayer

The distribution of microhardness along the cross section of the composites with copper layers of different thicknesses is shown in Fig. 8. The distribution of microhardness in the four explosively welded composites had the same character. In all samples, the highest microhardness (700 HV) was found in the EI698VD nickel alloy microvolumes in the vicinity of the interface with copper that is explained by the high level of plastic deformation due to the high-speed impact of the plates. This zone is narrow, thereby, the hardness of nickel alloy decreased intensively as the distance from the interface increased. Microhardness of the copper layers 0.3–0.7 mm thick increased from 130 to 160 HV in the areas adjacent to the nickel alloy due to strain hardening of the material occurring during a dynamic collision of the plates. The microhardness of the copper layer 0.1 mm thick was 160 HV throughout the thickness, i.e., the degree of strain hardening was the same

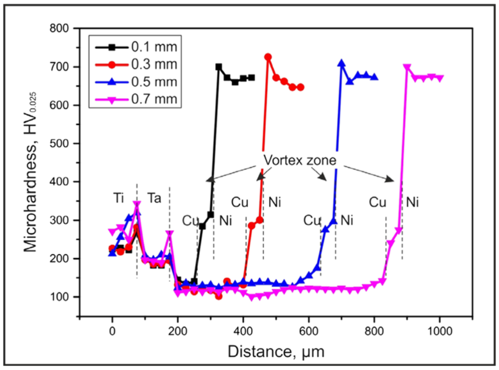


Fig. 8 The distribution of microhardness along the cross section of the Ti/Ta/Cu/Ni alloy explosively welded composites

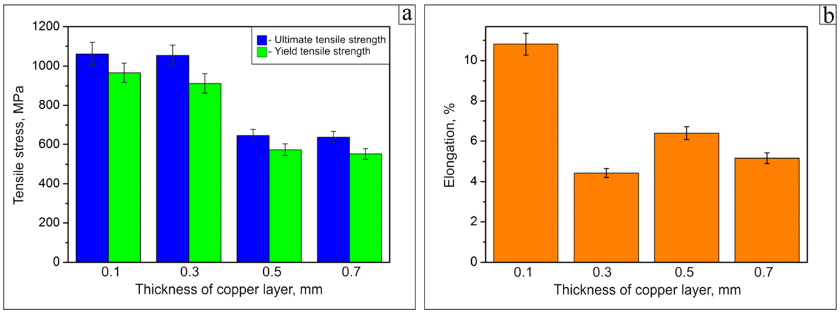


Fig. 9 Strength (**a**) and elongation (**b**) of the composite materials vs. thickness of the copper layer

within the layer. The obtained microhardness values are consistent with results of the structural studies presented in Fig. 8. The microhardness of the vortex zones forming at the copper/nickel alloy interface ranged between the values corresponding to the contacting materials. At the titanium/tantalum as well as tantalum/copper interfaces, layers with microhardness higher than that of the contacting materials formed. This fact can be explained by the phenomenon of strain hardening and the formation of a fine-grained structure due to dynamic recrystallization [38]. The effect of work hardening is gradually decreased with increasing distance from the interface so thereby the hardness of materials also decreased.

3.3 Tensile strength of the laminate composite materials

The strength and elongation of the four-layer composites having copper interlayers of different thicknesses are shown in Fig. 9. Since copper had the lowest strength of all materials forming the laminate composites, it can be expected that the thickness of the copper layer will have a great influence on the mechanical properties of the composites. Composites having copper interlayers 0.1 mm thick showed the highest values of the ultimate tensile strength (1060 MPa) and yield stress (965 MPa). These composites also showed the maximum elongation (11%). The highest elongation relates to the more homogeneous microhardness distribution within the copper layer resulting in plastic deformation in all over the width. When the thickness of the copper layer was increased up to 0.3 mm, the values of ductility decreased significantly while the strength of the composites remained unchanged. A further increase in the thickness of the copper plate from 0.5 to 0.7 mm was accompanied by a decrease in the strength of the composite materials by 1.5 times. The elongation of these composites was 6.5 and 5%, respectively (Fig. 9b). A reduced elongation of the composites with increasing thickness of the copper layer is due to a highly localized plastic deformation taking place only in the areas adjacent to the tantalum and nickel alloy plates.

The results of the fractographic studies of the laminate composite materials after the uniaxial tensile tests are shown in Fig. 10. Based on the analysis of the fracture surfaces, it is possible to conclude that high-quality joining of the copper and tantalum plates occurred. The high-quality joining was associated with the formation of areas of local melting at the boundaries characterized by the elongated and fine-grained structures. Some of its features were reflected in [38]. The presence of a continuous defect-free interface indicated high-quality joining between the EI698VD nickel alloy and copper

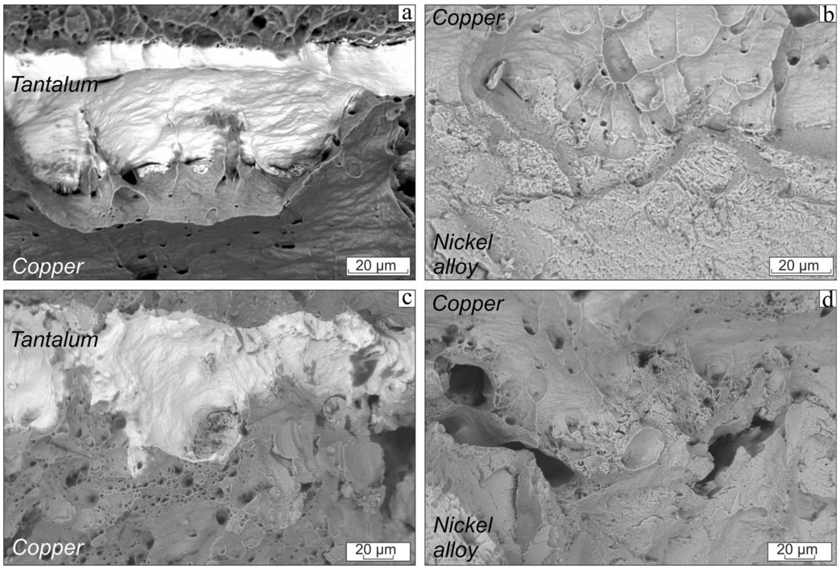


Fig. 10 Fracture surfaces of the composite materials with different thicknesses of the copper layers: 0.1 mm (**a**, **b**); 0.7 mm (**c**, **d**)

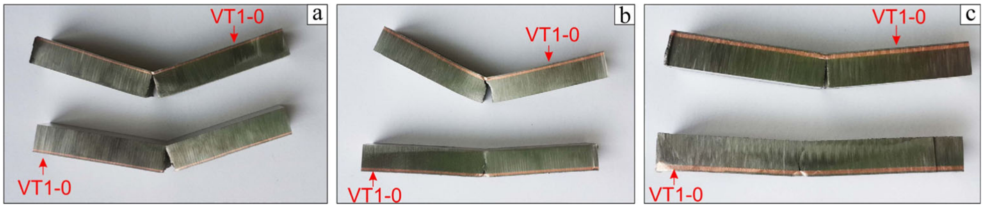


Fig. 11 Composites with copper layers 0.3 (**a**), 0.5 (**b**), and 0.7 mm (**c**) thick after three-point bending tests

plate 0.1 mm thick. With increasing thickness of the copper layer, strain hardening decreased resulting in the formation of discontinuities with the nickel alloy plate. This is also evidenced by defects in the forms of pores and delamination observed on the fractured samples. This behavior of the materials in the vicinity of the copper/nickel alloy interface is associated with weak strain hardening and low strength of the layers.

Thus, the strength variation of multilayered composites is controlled by the strain hardening as well as the geometry of welding interface. In explosive welding process, the collision of plates is accompanied by pressure impact, localized plastic deformation that resulted in strain hardening at the interfaces between materials. As was shown in "Section 3.1," this action originates severe grain deformation, including its plastic elongation and refinement. Furthermore, with the increase of copper thickness, the uniformity of plastic deformation through the layer is decreased and structural changes have occurred only near the interfaces with tantalum and nickel alloys. Thus, the work hardening is the dominant strengthening mechanism.

Another possible reason for strength and elongation reduction with copper thickness is the geometry of welding interface. As the thickness of copper layer increased, the wave amplitude and length between copper and tantalum increased. As a consequence, the volume ratio of the local melting zone and vortices on the wavy-weld geometry was raised. Like every cast structure, these areas might contain solidification defects, such as shrinkage and voids that drop the strength of the cladded plates [39]. Moreover, Hokamoto and co-authors [27] were shown that formation of the local melting zone is directly related to the energy given to the welded interface and the thickness of interlayers. With the increase of the thickness of the intermediate plate, the energy dissipated by collision also increased and the thickness of the molten layer would increase.

3.4 Three-point bending test of the composite materials

In order to evaluate the strength and ability of the laminate composites to plastic deformation, the three-point bending test was performed. The bending strain (strain at fracture) was used as an indicator characterizing the mechanical behavior of the composite materials. The criterion for evaluating elongation was the bending angle, at which cracks initiated in the tension zone [31]. Figure 11 shows images of the samples fractured under bending. The analysis has shown that the bending angle of the samples was greater in those cases when the titanium plate was subjected to compressive strain. Under loading using the second scheme, samples containing copper layers 0.5 and 0.7 mm thick broke down almost immediately after load application. It should be noted that the EI698VD nickel alloy is brittle and cannot be deformed plastically at room temperature. The experiments showed that independent of the testing scheme, with increasing thickness of the copper layer, the bending strength and elongation of the composites decreased (Fig. 12). A decrease in the bending strain of the composites with a copper layer 0.7 thick is related to delamination and crack propagation along the welding joint between the copper and nickel alloys. The highest strength and elongation were observed in the composites having a copper layer 0.3 mm thick (Fig. 12a).

Figure 13 shows the fracture surface of the composites with copper plate 0.3 mm thick tested using two loading schemes. The fracture of the VT1-0 titanium mainly occurred through the ductile mechanism, as evidenced by the typical cup fracture topography. In the areas of bonding between titanium and

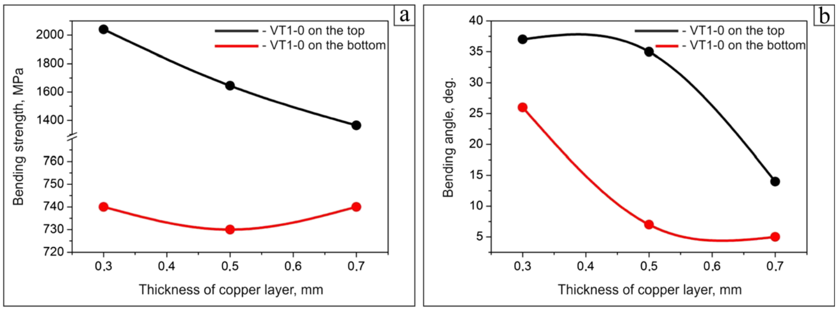


Fig. 12 The dependence of the bending strain (**a**) and angle (**b**) at the fracture of the composite materials having copper layers of different thicknesses

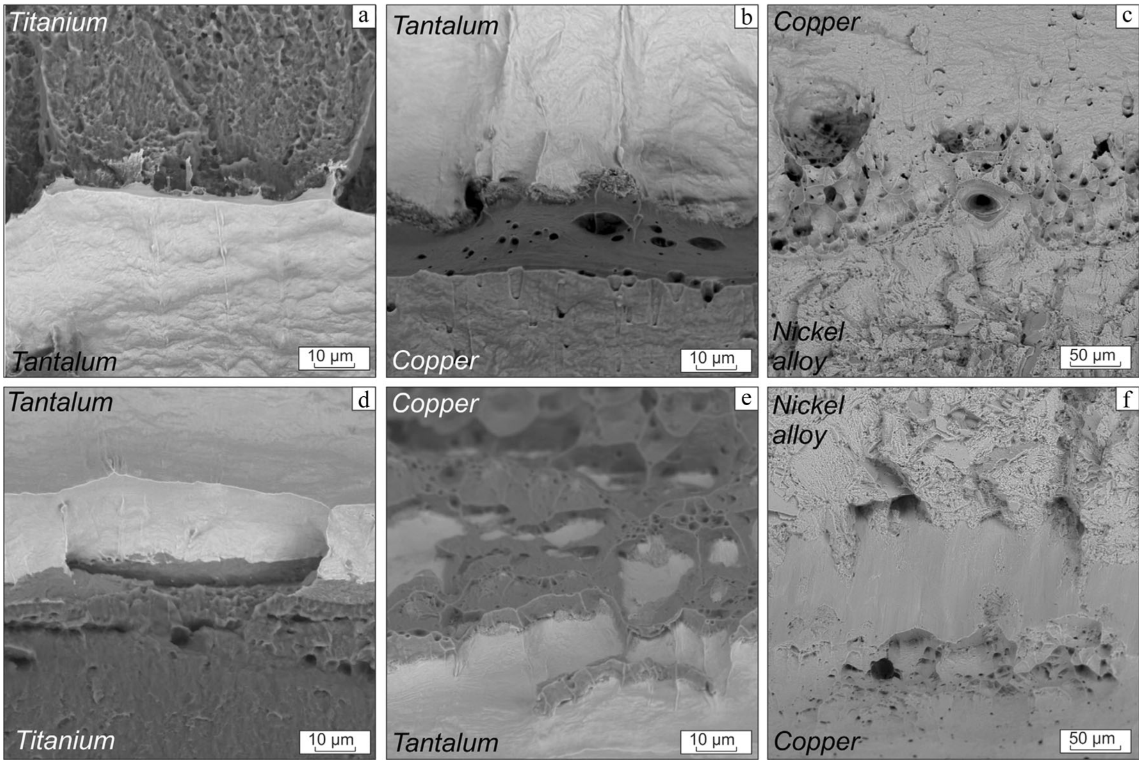


Fig. 13 Fracture surfaces of the composite materials with copper plate 0.3 mm thick after the three-point bending tests. The titanium plates were subjected to tensile (**a**–**c**) and compressive (**d**–**f**) loads

tantalum, no major defects were observed. The copper/tantalum interface revealed high adhesion between the materials. The most defective boundary was formed between the copper and nickel alloy plates. At the interface between the materials, melting zones with voids were clearly visible (Fig. 13c). The fracture surface of copper had a dimpled structure. Near the welding zone, the dimples were much smaller, indicating higher strength of the copper plate in this area as compared to that in the central region. With distance from the interface, the size of the dimples became larger and their density per unit area decreased. These signs indicated the gradient character of plastic deformation with the maximum deformation in the weld-adjacent zones. At a certain distance from the interface with the Ni alloy, dimples could be observed in the copper plate. This can also be explained by the low strength of the material located at a distance from the weld zone.

Three-point bending tests led to a conclusion that copper plates with a thickness that does not exceed 0.3 mm should be used in the assembly. In particular, the loading configuration providing compressive stresses to the titanium plate is preferable.

4 Conclusions

Using explosive welding, VT1-0 commercially pure titanium and EI698VD nickel alloy were efficiently joined to each other by explosive welding using intermediate layers of copper and tantalum. Based on the results of the studies, the following conclusions can be drawn:

1. Welding joints of a wave configuration formed between tantalum and copper as well as between copper and nickel alloys during explosive welding. Geometrical parameters of the wave joints changed with the thickness of the copper layer. The titanium/tantalum interface had a waveless structure in all analyzed samples.
2. The copper layer 0.1 mm thick had elongated grains in the direction of the shock front propagation, indicating severe plastic deformation. A structure of this type was found in the copper plate 0.2 mm thick adjacent to the tantalum and nickel alloy plates.
3. The microhardness measurements in the explosively welded samples with copper layers of different thicknesses have shown that the microhardness of the areas adjacent to the interface was higher than that of the initial materials. A higher microhardness was also observed in the regions of local melting at the titanium/tantalum and tantalum/copper interfaces. The main reasons for increased strength were strain hardening of the colliding plates and the formation of mixing zones with intensively deformed fine-grained structure.
4. The static tensile tests of the composites have shown a significant decrease in strength and a decrease in ductility

with increasing thickness of the copper layer. Results of these measurements could be explained by the strain hardening mechanism of the intermediate layers with various thicknesses as well as weld geometry of formed interfaces.

5. The three-point bending tests conducted using two schemes showed that a copper plate 0.3 mm thick is preferable. Herein, a flyer plate of the VT1-0 titanium is recommended to use under compression load.

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