Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science. 2022 vol. 24 no. 3 pp. 103–111
ISSN: 1994-6309 (print) / 2541-819X (online)
DOI: 10.17212/1994-6309-2022-24.3-103-111

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Structural features and technology of light armor composite materials with mechanism of brittle cracks localization

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ARTICLE INFO

Article history:
Received: 04 July 2022
Revised: 13 July 2022
Accepted: 21 July 2022
Available online: 15 September 2022

Keywords:
Composite metal material
Explosion welding
Reinforcement
Crack resistance
Bullet resistance

Acknowledgements
Research were partially conducted at core facility "Structure, mechanical and physical properties of materials".

ABSTRACT

Introduction. Monometallic armor traditionally used in military and special equipment armaments has a number of key disadvantages that have a significant impact on the tactical and technical characteristics of the products, namely, significant weight and thickness. At the same time, composite non-metallic armors, which have been widely used recently as an alternative, in turn, are not able to withstand multiple hits in local areas of the structure due to its complete destruction or delamination. **The purpose of the work:** to develop the technology of obtaining a new class of multilayer metal armor materials based on light metals and alloys by explosive welding, combining high indicators of bullet resistance and structural strength along with low specific gravity. **The work presents** a new scheme for reinforcing the composite using explosive welding technology, which allows localizing the development of brittle cracks along interlayer boundaries with external ballistic impact on the object. **Results and discussion.** Reinforced composite material based on titanium and aluminum alloys is obtained by explosive welding. Rational modes of shock-wave loading, which ensure production of composite material of required quality are determined; evaluation of strength of composite is carried out. In order to improve the tactical and technical characteristics of the composite, it was proposed to form high-solid intermetallic layers in its structure due to heat treatment. Rational modes of high-temperature annealing are defined, which ensure formation of intermetallic layers of preset thickness in composite structure. The phase composition of intermetallic pro-layers is studied. Structural features of the composite material are investigated. Mechanism of brittle cracks localization in composite structure at ballistic impact on it is described.

For citation: Kryukov D.B. Structural features and technology of light armor composite materials with mechanism of brittle cracks localization. *Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science*, 2022, vol. 24, no. 3, pp. 103–111. DOI: 10.17212/1994-6309-2022-24.3-103-111. (In Russian).

Introduction

Traditionally used in armour systems, steel and composites have its own highly specific applications. Armored products made of high-strength steel have proven itself as the basis for heavy armored vehicles, while armor based on composite materials is widely used for light armored vehicles, aviation equipment, combat robots and personal protective equipment [1–4].

Composites are most often used in cases where the weight of the armour is of critical importance. According to a number of experts [5–8], when replacing steel with a composite, it is possible to achieve a reduction in the weight of the product by about half, which in turn will increase equipment and improve the tactical and technical characteristics of the machine or product.

Today, aramide, carbon and glass fibers, ceramics, as well as polyethylene with a complex of various binding materials are widely used as a basis for light composite armor. At the same time, the technology

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of manufacturing armored elements based on such materials requires the use of rather complex technical solutions and expensive equipment. The armor elements itself based on the above composites having ballistic characteristics comparable to monometallic armor do not compete with it at the requirement of multi-impact, i.e. are not able to withstand multiple hits in local areas due to complete destruction or delamination [7, 9, 14–16]. The development of a new class of composite armor materials that combine high bullet resistance and structural strength along with low specific gravity is an urgent task.

The Department of Welding, Foundry and Materials Science, FSBEI HE Penza State University has developed a unique technology for the manufacture reinforced composite armor materials based on light metals and alloys that does not have analogues [10, 11]. The metal base of these materials is proposed to use an armored aluminum alloy (*V95*), and as reinforcing layers of titanium alloy (*VT1-0*).

The metal composite is made using explosive welding technology, which allows obtaining high-quality welded joints of materials and alloys that cannot be welded by traditional methods, which include the above materials. Permanent metal joints obtained by the explosive welding technology are formed at the inter-atomic level without significant thermal embedding in the contact zone of materials. The strength of the welded joint itself is higher than the strength of the least strong metal of the composition [19].

The purpose of this work is to develop a technology for obtaining a new class of multilayer metal armor materials based on light metals and alloys by explosive welding, combining high rate of bullet resistance and structural strength along with low specific gravity. This position will significantly improve the tactical and technical characteristics of the armoured military weapons and special-purpose products.

The objectives of the study are to develop a new reinforcing scheme for composite metal materials based on light metals and alloys; to determine rational modes of shock-wave loading, which ensure the production of composite material of the required quality by explosive welding; to describe the mechanism for brittle cracks localizing in the composite structure under ballistic impact on it.

Research methodology

In the composite reinforcing scheme special perforated layers made of titanium alloy are used (Fig. 1) [12].

The composite may contain two or more such layers. The perforations are arranged so that each subsequent layer does not coincide with the previous perforations and overlap is ensured. This nature of the arrangement of perforations in the composite structure does not allow a possible through passage of a ballistic object.

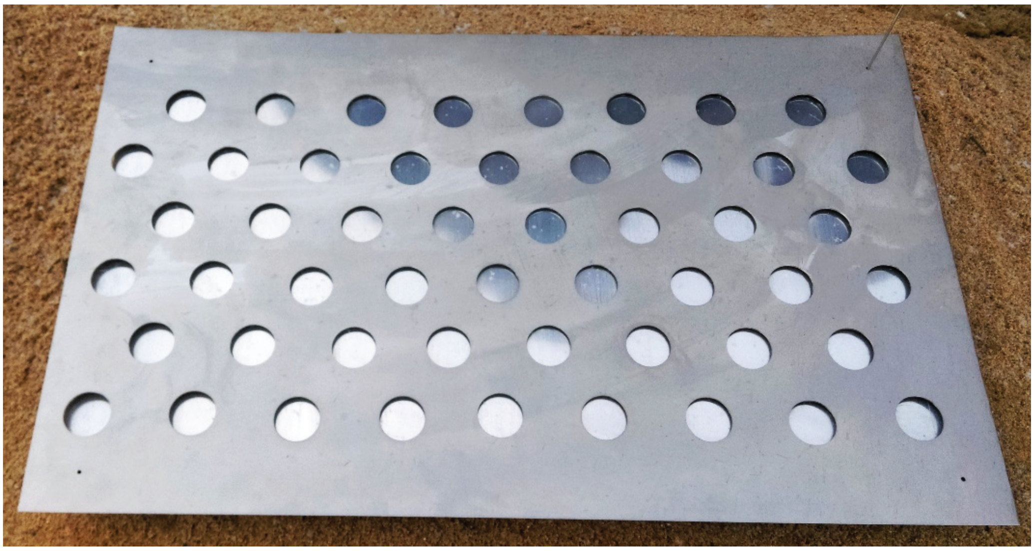

Fig. 1. Perforated reinforcing layer

Predicated on the analysis of technological schemes of composite metal materials formation using explosive welding (*V95* + *VT1-0* + *V95* + *VT1-0* + *V95*) the plane-parallel scheme of welding by explosion submitted in Fig. 2 was chosen.

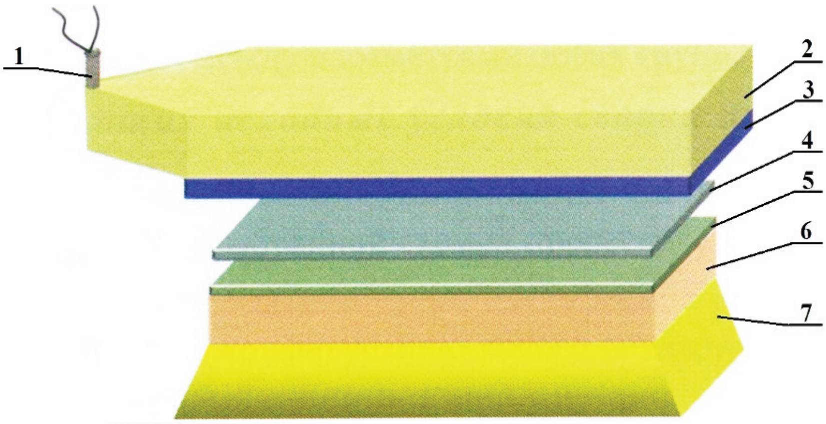

Fig. 2. Explosive Welding Diagram:
1 – electric detonator; *2* – container with explosive substance; *3* – driver plate;
4 – intermediate plate; *5* – fixed plate; *6* – metal base; *7* – ground

The thickness of the sheets being weld (*V95* + *VT1-0* + *V95* + *VT1-0* + *V95*) was 2 + 1 + 2 + 1 + + 10 mm respectively. An explosive «*Igdanite*» (96:4 mixture of ammonium nitrate and diesel fuel) was used for welding. Explosive welding was carried out in a wide range of contact point speeds from 1,800 m/s to 2,400 m/s.

Results and discussion

According to the results of visual and dimensional and ultrasonic examination of the welded composite samples, the mode with the following technological parameters was chosen as the rational mode of explosion welding: explosive height 55 mm, contact point speed 2,200 m/s, gap between sheets being weld 2 mm. The criteria for choosing a rational mode of explosive welding were the absence of edge and internal unwelded spots in the composite, as well as the external state of its surface. In particular, it was found by the above control methods that in explosive welding modes with a contact point speed of less than 2,200 m/s, there was no welding of the layers in the edge region of the composite with partial cutting of the driver elements. The state of the composite welded at a contact point speed of more than 2,200 m/s was characterized by partial destruction of its surface with a large number of internal unwelded spots.

Analysis of the macrostructure of the composite welded on the selected rational mode indicates a high quality of the material connection along the interlayer boundaries; the weld of the composite material along all interlayer boundaries is mainly wave-free.

The appearance of the reinforced composite macrostructure after explosive welding is shown in Fig. 3.

Fig. 3. Macrostructure of reinforced composite material based on light metals and alloys

The role of perforations in the proposed circuit solution consists in the formation of a viscous homogeneous layer of a metal base of an aluminum alloy composite matrix, which presents a welded joint through the perforation of the reinforcing element. Upon contact with the ballistic object **1**, brittle cracks arise in the composite, spread from the contact point **3** along the interlayer boundaries **2**, reaching the point of transition from the perforation edge to the welding zone of the composite viscous metal base **4,** stop on it and the development of the brittle crack stops. This makes it possible to localize the zone of ballistic destruction of composite armor within the local zone of welding of aluminum and titanium layers **2**, preserving the integrity of the product structure and its complex bullet resistance without obligatory replacement with a new armor element. Diagram of brittle crack localization in composite structure at contact with a ballistic object is given in Fig. 4.

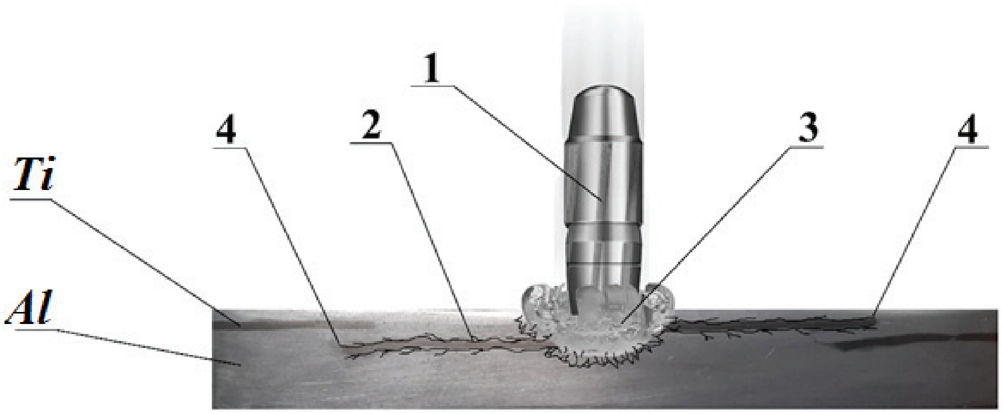

Fig. 4. Diagram of brittle cracks localization in the composite structure

In addition, the presence of thin perforated layers in the structure of the metal composite material also contributes to an increase in its strength indicators [17]. Evaluation of strength parameters and preparation of the test samples were carried out according to the standard method in accordance with *GOST 1497–84*. A set of studies has shown that the best combination of physical and mechanical properties, such as strength and elongation, is possessed by samples welded at the selected rational mode. Its relative elongation was from 3.1 to 3.7 %, and the strength value was in the range from 570.2 to 594.1 MPa.

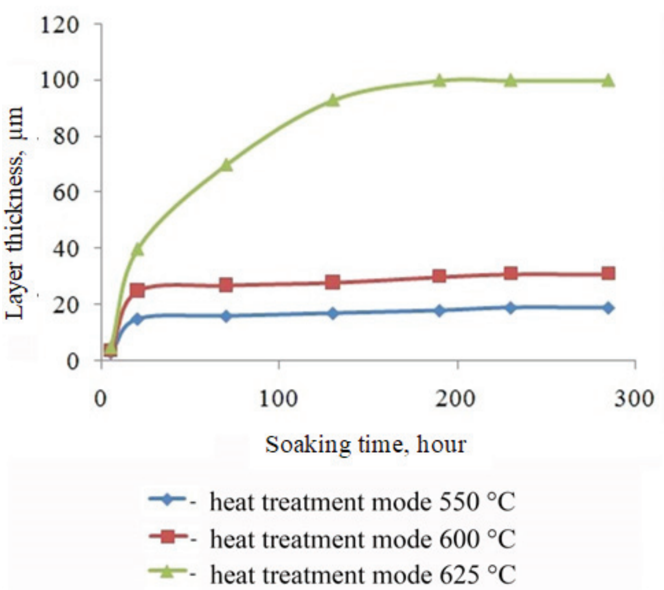

Fig. 5. Dependence of growth of intermetallic layer thickness on furnace holding time

Provided that the strength of the composite metal matrix base of similar thickness was in the order of 482.1–489.8 MPa, the total increase in the strength of the composite compared to it was 21.3 % [18, 20].

In order to improve the tactical and technical characteristics of the composite armor materials being developed on the basis of light metals and alloys, the authors proposed the formation of high-solid intermetallic layers in the composite structure due to heat treatment.

Intermetallic layers are formed due to mutual thermal diffusion of metals included in composite at interlayer boundaries. Maximum thickness of intermetallic layers is controlled by parameters of heat treatment, namely temperature and time of soaking during annealing. A set of studies made it possible to establish the dependence of the growth of the intermetallic layers thickness on the soaking time; the results are shown in Fig. 5.

Analysis of the obtained data indicates that the maximum thickness of the intermetallic layer is approximately 90–100 μm, while the holding time at a temperature of 625°C is approximately 300 hours.

The subsequent longer soaking of the material in the furnace does not lead to the growth of the intermetallic layer, which is apparently due to the ultimate extinction of diffusion processes.

The formation of intermetallic interlayers along the weld of the composite armored material after heat treatment is shown in Fig. 6.

X-ray phase analysis of intermetallic interlayers on a *DRON-3M* diffractometer showed its composition corresponding to intermetallic $TiAl_3$ [13]. The phase composition of the composite depending on the furnace holding time is shown in Fig. 7.

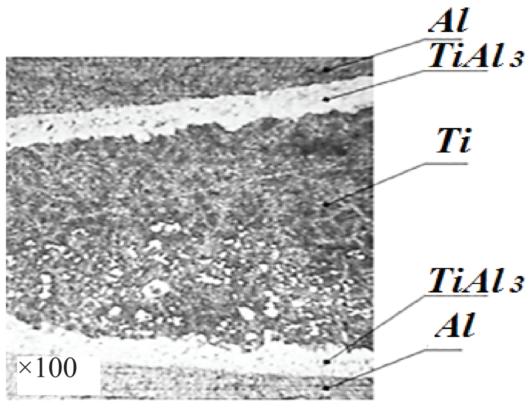

Fig. 6. Microstructure of reinforced composite material based on light metals and alloys after heat treatment

The highly solid intermetallic layers ($TiAl_3$) in the composite armor structure **2** contribute to the destruction of the ballistic object **1** into smaller parts, significantly reducing its kinetic energy, and the highly viscous aluminum layers of the composite effectively retain the formed fragments **5** of the ballistic object. The scheme of composite armor operation in the presence of intermetallic layers is shown in Fig. 8.

The mechanism of brittle cracks localization in the structure of a composite with intermetallic layers during ballistic impact on it is similar to that described above. Upon contact with the ballistic object **1**, brittle cracks arising in it are formed and developed mainly in high-solid intermetallic layers **2** located along the aluminum-titanium welding zone. Spreading from the point of contact with the ballistic object **3** and reaching the point of transition from the edge of the perforation to the welding zone of the composite viscous metal base **4**, the cracks stop on it, and its propagation stops (Fig. 8).

Evaluation of the strength of the composite in the state after heat treatment showed its increase in the range from 610.7 to 633.8 MPa, however, there is a slight decrease in plasticity, characterized by relative elongation in the range from 2.1 to 2.7 %.

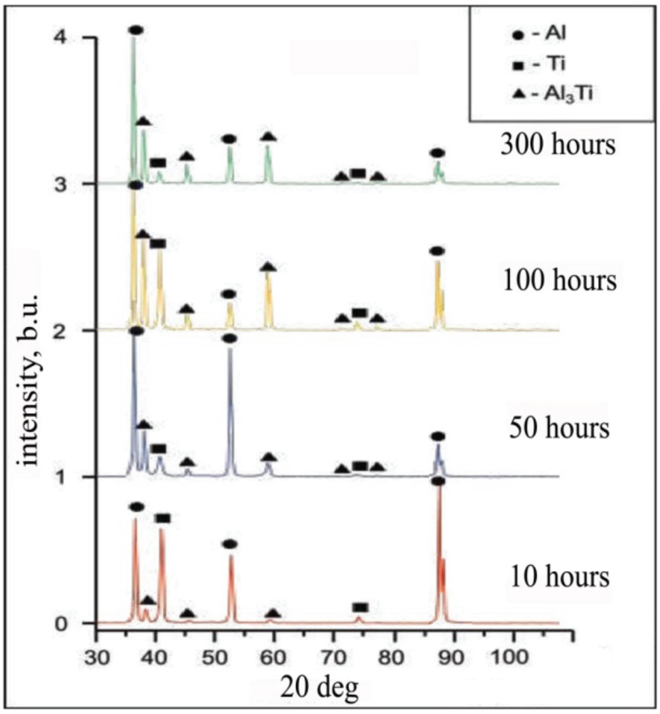

Fig. 7. The phase composition of the composite after annealing at a temperature of 625°C with different furnace holding time

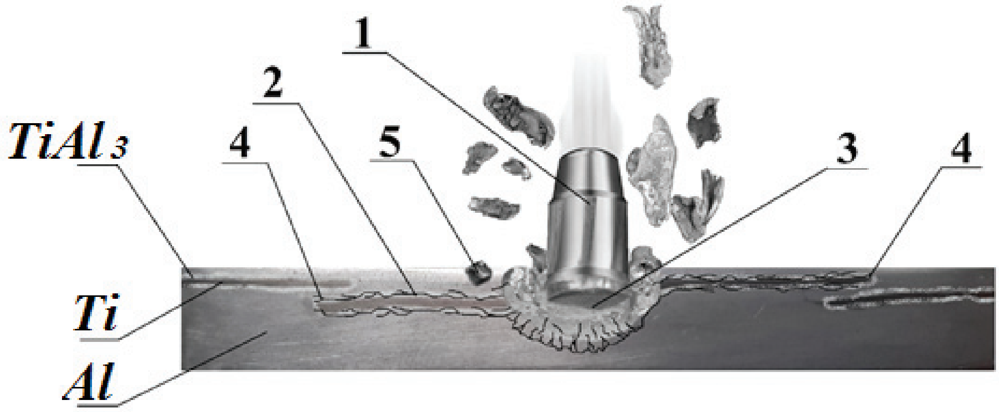

Fig. 8. Diagram of composite armor operation in the presence of intermetallic layers in it

Prototypes of new composite armor materials based on light metals and alloys developed by the authors of the work during ballistic tests confirmed the high level of properties declared by the authors and compliance with the high class of protective structure of the *EBP* according to GOST R 51112–97 and GOST 34282–2017.

Conclusions

1. An analysis of the scientific and technical literature showed that the traditionally used monometallic armor has a number of key disadvantages that affect the tactical and technical characteristics of the products, namely, significant weight and thickness. It is noted that composite non-metallic armor, in turn, is not able to withstand multiple hits in local areas of the structure due to its complete destruction or delamination.

2. A new scheme of composite reinforcing using explosive welding technology is presented, which allows localizing the development of brittle cracks along interlayer boundaries with external ballistic impact on the object.

3. Reinforced composite material based on titanium and aluminum alloys is obtained by explosive welding. Rational modes of shock-wave loading are determined, which ensure production of composite material of required quality; evaluation of strength of composite is carried out. In order to improve the tactical and technical characteristics of the composite, it was proposed to form high-solid intermetallic layers in its structure due to heat treatment.

4. Rational modes of high-temperature annealing are defined, which ensure formation of intermetallic layers of preset thickness in composite structure. The phase composition of intermetallic interlayers was investigated. Mechanism of localization of brittle cracks in composite structure at ballistic action on it is described.

The obtained results indicate the prospects of the proposed composite material reinforcing scheme using explosive welding and the manufacture of new types of armor materials based on it for a wide range of products, which combine high bullet resistance and structural strength along with low specific gravity.

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Conflicts of Interest

The author declare no conflict of interest.