UDK 621.771

Sibirskii Gosudarstvennyi Aerokosmicheskii Universitet
imeni Akademika M. F. Reshetneva. Vestnik
Vol. 18, No. 1, P. 205–210

STUDIES OF NONEQUILIBRIUM PHASES FORMED AT EXPLOSION WELDING OF TITANIUM AND ALUMINUM

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The work is devoted to the study of physical and chemical processes occurring in the contact zone of titanium and aluminum at the joint plastic deformation caused by explosion welding. One of the most effective ways to solve problems of materials science is the development of composite materials. An important advantage of the materials used in aircraft, is their low density, providing the possibility to receive the result composites with high specific strength. This study supports the development of composite materials based on Ti–Al, which can be used for the manufacture of gas turbine blades, and ribbed hollow weldments for the aircraft industry.

Explosion welding is a high-energy process, allowing high quality joining dissimilar metal materials including various combinations of materials used for the composite metal–intermetallic compound.

Ti–Al system was studied extensively enough, but there remain a number of unclear issues, namely which can form intermetallic phases with the explosion welding. conditions for the formation of a number of intermetallic phases Ti–Al: Al_5Ti_2, $Al_{11}Ti_5$, Al_2Ti, $AlTi_3$, Al_3Ti, including in the framework of one formula unit of different types of structures (stable and metastable, virtual) can be implemented. During the mechano-chemical reactions in the contact zone between titanium and aluminum are formed during explosion welding nonequilibrium intermetallic phases: Al_2Ti, Al_5Ti_3, $Ti_{3.3}Al$.

To study the transition zones of the samples structure used a scanning electron microscope JEOL 6390LV. The phase analysis was performed on the X-ray diffractometer company "Bruker" in the emission of copper.

It is shown that the mass transfer titanium aluminum atomic clusters directional flow at a rate of at least 35 m / s occurs. Intermetallic phases formed in the contact zone during mechanochemical reactions occurring at the interface of Ti and Al. Processes of structure formation under explosion welding are explained from the standpoint of an abnormally rapid directional mass transfer under conditions of stress, creating a lattice curvature.

Keywords: explosion welding, mass transfer, Mechanochemistry, intermetallic phases, the curvature of the crystal lattice.

Вестник СибГАУ
Том 18, № 1. С. 205–210

ИССЛЕДОВАНИЕ НЕРАВНОВЕСНЫХ ФАЗ, ОБРАЗУЮЩИХСЯ ПРИ СВАРКЕ ВЗРЫВОМ ТИТАНА И АЛЮМИНИЯ

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Представлено исследование физико-химических процессов, происходящих в зоне контакта титана и алюминия при совместной пластической деформации, вызванной сваркой взрывом. Один из наиболее эффективных путей решения задач материаловедения заключается в разработке композиционных материалов. Важным достоинством материалов, используемых в летательных аппаратах, является их малая плотность, обеспечивающая возможность получать в итоге композиты с высоким уровнем удельной прочности. Данное исследование способствует разработке композитных материалов на основе Ti–Al, которые могут быть использованы для изготовления лопаток газовых турбин, пустотелых и ребристых сварных конструкций для авиационной промышленности.

Сварка взрывом представляет собой высокоэнергетический технологический процесс, позволяющий с высоким качеством соединять разнородные металлические материалы, в том числе различные комбинации материалов, используемых для композитов металл–интерметаллид.

Система Ti–Al исследована достаточно широко, однако остается ряд неясных вопросов, а именно, какие интерметаллидные фазы могут образоваться при сварке взрывом. Условия образования ряда интерметаллидных фаз Ti–Al: Al_5Ti_2, $Al_{11}Ti_5$, Al_2Ti, $AlTi_3$, Al_3Ti, среди которых в рамках одной формульной единицы могут быть реализованы различные типы структур (стабильные, метастабильные, виртуальные). В процессе механохимических реакций в зоне контакта титана и алюминия при сварке взрывом формируются неравновесные интерметаллические фазы: Al_2Ti, Al_5Ti_3, $Ti_{3,3}Al$.

Для исследования структуры переходных зон полученных образцов использовали сканирующий электронный микроскоп JEOL 6390LV. Фазовый анализ проводили на рентгеновском дифрактометре фирмы Bruker в излучении меди.

Показано, что массоперенос титана в алюминий происходит направленными потоками атомных кластеров со скоростью не менее 35 м/с. В зоне контакта Ti и Al формируются интерметаллические фазы в процессе механохимических реакций, протекающих на интерфейсе. Процессы структурообразования при сварке взрывом объясняются с позиций аномально быстрого направленного массопереноса в условиях напряжений, создающих кривизну кристаллической решетки.

Ключевые слова: сварка взрывом, массоперенос, механохимия, интерметаллидные фазы, кривизна кристаллической решетки.

Introduction. In aviation and space there is an urgent need to provide a strong, light and wear-resistant designs. One of the most effective ways to solve problems of materials science is the development of composite materials. An important advantage of the materials used in aircraft, their low density, providing the possibility to receive the result composites with high specific strength. For example in [1; 2] developed composite materials based on Ti–Al, Ni–Al, which can be used for the manufacture of gas turbine blades, and ribbed hollow weldments for the aircraft industry. It is known that titanium and aluminum, can react with each other to form intermetallic compounds such as $TiAl_3$, characterized by high hardness and friability. It is known [2] that the formation of intermetallic compounds leads to a drastic reduction of mechanical characteristics of welded structures. However, in [3], the specific rigidity Ti–$TiAl_3$ twice the specific rigidity steel. In [4] a detailed study of the structure and properties of multilayered composite Ti–Al, produced by explosion welding. It is shown that intermetallic compound $TiAl_3$ greatly improves the mechanical properties of the composite. In [5] states that the operation of the intermetallic alloys based on Ti–Al at temperatures below 600 °C is ineffective in connection with the destruction of the fragile material. Heating in the range from 600 °C to 750 °C contributes to a sharp increase in ductility intermetallics while maintaining its strength. This allows their use in the aerospace industry.

In recent years, explosive welding has proved to be an effective method of creating a multi-layered composite materials. explosion welding is a high-energy process, allowing high quality joining dissimilar metal materials including various combinations of materials used for the composite metal – intermetallic laminated (MIL) [4]. Pressure developed during the explosion welding, providing excellent contact between the surfaces of the welded metal. The cumulative flow generated during the welding process, cleans the plate from the oxide films and impurities that could reduce the rate of solid-phase processes [6]. Subsequent annealing is proposed as an alternative method of creating a multi-layer metal – intermetallic laminated (MIL) [4]. Annealing may be conducted at temperatures above and below the melting point of aluminum, local melting can occur due to the exothermic nature of the reaction between Al and Ti [7].

Currently, solid-state processes that may occur during the plastic deformation actively studied [3–9]. Mechanical impact can initiate mechanochemical reactions occurring at high speeds during the passage of plastic deformation waves [10]. The possibility of formation of intermetallic compounds due to the energy expended on the plastic deformation of the metal heat affected zone [11].

The ultra-high pressure and shear strain can increase the mass transfer rate by 15 orders of magnitude compared to the conventional diffusion [12; 13]. The usual mechanisms of a new phase with the emergence and growth of embryos in plastic deformation wave can not work because of the short duration of the process. For the formation of new phases in the static experiments, the time required several seconds or more. In the waves of plastic deformation of these processes will be completed within the order of 10^{-5}–10^{-7} c [14]. In practice, particle sizes of the new phase can reach several tenths of a millimeter and more [14]. The study of the processes occurring in the metal contact zone with intense dynamic loads, is of considerable interest for the production of composite materials with new properties.

Ti–Al system was studied extensively enough, but there remain a number of unclear issues, namely which can form intermetallic phases with the explosion welding. In [15] identified a number of conditions for the formation of intermetallic phases Ti–Al: Al_5Ti_2, $Al_{11}Ti_5$, Al_2Ti, $AlTi_3$, Al_3Ti, including in the framework of one formula unit of different types of structures (stable and metastable, virtual) can be implemented.

Objective. To investigate the products of solid state reactions, occurring in the contact zone of titanium and aluminum at the joint plastic deformation caused by explosion welding.

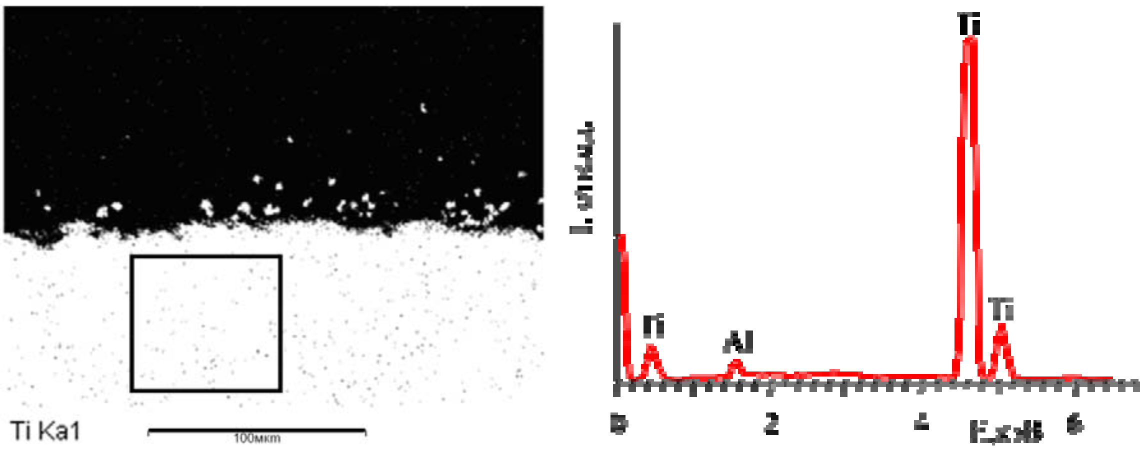
Methods of experiment. Samples of the composite obtained by explosion welding multilayer stack wafers commercially pure titanium VT1-0 (IMI125) and A5 (ENAW-1050A) thick aluminum 0.5 and 1 mm, respectively. Package 11 of alternating titanium and aluminum plates 12 are welded one explosion of the explosive charge ammonite 6GV as described in [16]. The thickness of the explosive was 45 mm, is made up of plates dimensions 80×80 mm. Detonation velocity estimated at 3600 m / s collision angles were set by 24o (upper plate) to 6,2o (for the lower plate). We studied the structure of the transition zone in the cross-sectional plane (perpendicular to the layers of aluminum and titanium) and aluminum contact area structure and titanium after mechanical separation of the layers of the composite.

To study the transition zones of the samples structure used a scanning electron microscope JEOL 6390LV. The phase analysis was performed on the X-ray diffractometer company "Bruker" in the emission of copper.

Experimental results. Fig. 1 shows image of the contact area in the transverse cut plane aluminum and titanium obtained by X-ray microanalysis. We see what happened titanium penetration into aluminum, and the process is not a continuous front of the diffusion zone, was the formation of discrete particles at a considerable depth of the contact zone.

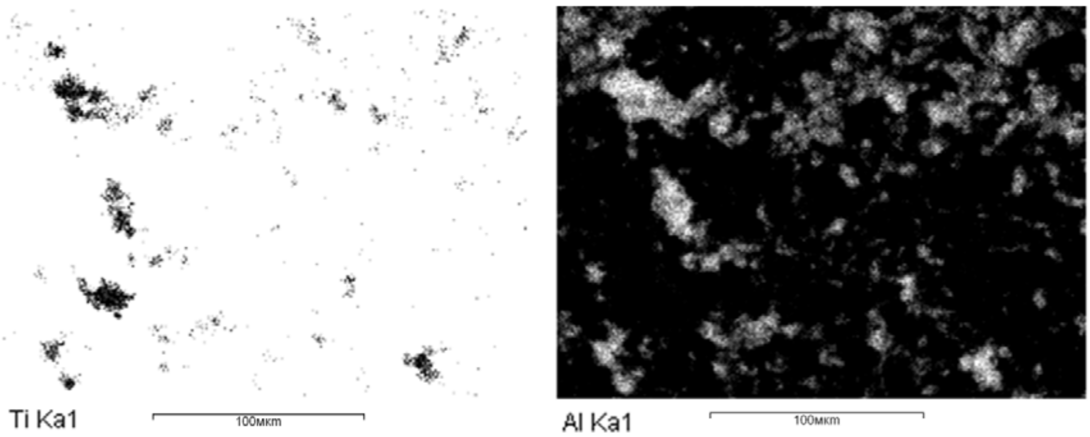
Aluminium also penetrates into the titanium, but in much smaller quantity than titanium in aluminum. Study of energy dispersive spectra (fig. 1), and X-ray diffraction spectra revealed that the aluminum to titanium from 10 to 70 microns in depth, formed intermetallic compound. Assuming that the distance that penetrates the titanium in aluminum is about 70 micrometers (fig. 1, *a*), and the reaction time is about 2 microseconds, then a simple calculation shows that the rate of mass transfer of titanium in aluminum is not less than 35 m / from. According to [17; 18], the coefficient of mutual diffusion of titanium and aluminum at a temperature of 1,123 K is about 10–16 m^2 / s, from the viewpoint of diffusion rate is 8.10 m / s. Therefore, in this experiment, the mass transfer titanium in aluminum (significantly at temperatures below 1000 K), at least eight orders of magnitude higher than the rate of diffusion. Similar results were obtained with other materials in the paper [19].

By method scanning electron microscopy and energy dispersive analysis was investigated the area contact aluminum and titanium after mechanical separation of the layers of the composite. Image of the surface of the titanium band gap in the X-ray of titanium and aluminum are shown in fig. 2, *a* and *b*, respectively.



a *b*

Fig. 1. Study contact zone Ti–Al: *a* – the image obtained in the scanning electron microscope mode in microanalysis X-ray of titanium; *b* – Energy-spectrum square area shown in fig. 1, *a*



a *b*

Fig. 2. Image Ti surface area in contact with the Al in the resulting SEM microanalysis mode in: *a* – X-ray of titanium; *b* – X-ray of aluminum

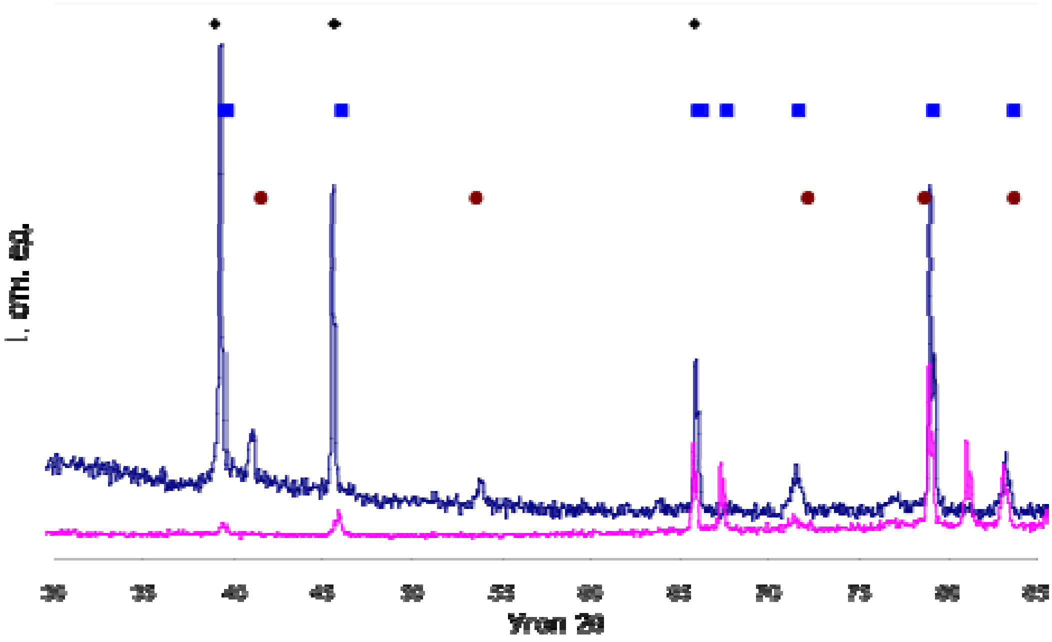


Fig. 3. X-ray diffraction spectra of the titanium surface (on the top) and aluminum (bottom) phase and reflexes: Al_2Ti (diamonds), Al_5Ti_3 (squares), $Ti_{3.3}Al$ (circles)

On the surface of titanium fig. 2, *a* you can see the dark specks – aluminum, and fig. 2, *b* light specks correspond to aluminum. Since the location of these inclusions in fig. 2, *a* and fig. 2, *b* substantially coincide, a coincidence indicates good adhesion of aluminum to titanium in the resulting samples. The concentration of aluminum in the inclusions on the surface of the titanium layer can be up to 20 at. %.

X-ray diffraction spectra from the surface of the titanium and aluminum layers after their separation are shown in fig. 3. On the surface of the titanium layer revealed the presence of intermetallic compounds and Al_2Ti $Ti_{3.3}Al$. On the surface of the aluminum layer revealed the presence of intermetallic compounds and Al_2Ti Al_5Ti_3.

The phase Al_2Ti existing in a very narrow concentration range presents at diagram of phase equilibria Al–Ti [20]. This phase is formed by explosion welding. Based on the state diagram, you can expect to see Ti_3Al phase having a wide field of existence, however, is not found in our experiment this phase. Phase Al_5Ti_3 and $Ti_{3.3}Al$ absent in the diagram of phase equilibria, but are present in the samples welded by explosion. Thus due to explosion welding we discovered the occurrence of non-equilibrium phases.

The discussion of the results. Mass transfer during explosion welding can be caused by gradients of stress, which are significantly higher than the yield strength of the material. Any excess of the yield stress gives rise to a wave of plastic deformation [12]. The waves of plastic deformation, according V. E. Panin theory, can create significant non-diffusion fluxes of mass propagating over long distances with the speed of sound in the material. An example of such speed of mass transfer is given in [21].

If explosion welding, significant curvature of crystalline lattice is appearing in the local contact zone of welded blanks [22; 23]. In the context of the local curvature of the crystalline lattice, in areas of increased interatomic distances special structural states are exist, which increase the degrees of freedom in a deformable solid. In [24] such states were called interatomic bifurcation structural states (IBSS). Due to occurrence in deformed metal IBSS possible to implement the directional mass transfer proceeding at a speed of switching of interatomic bonds, which in some cases can reach sound velocity in the metal [25]. The redistribution of atoms at the interface of the two materials may accelerate the formation of new phases, noted in [16].

Conclusion:

1. In the process of mechanochemical reaction at the contact zone of titanium and aluminum at explosion welding nonequilibrium intermetallic phases are formed: Al_2Ti, Al_5Ti_3, $Ti_{3.3}Al$.

2. During explosion welding mass transfer occurs by penetration flows of titanium atoms over distances of up to 70 microns from the interface at a rate of at least 35 m / s.

3. Processes of structure formation under explosion welding can be explained from the position of the crystal lattice curvature which appears in the conditions of stress gradient and leads to abnormally rapid directional mass transfer.

Acknowledgments. The authors thank A. K. Abkaryana (Siberian Federal University, Krasnoyarsk) and A. D. Gre-chanik (IRGETAS, Ust-Kamenogorsk) for help with the experiment.

Благодарности. Авторы благодарят А. К. Абкаряна (Сибирский федеральный университет, г. Красноярск) и А. Д. Гречаника (ІРГЕТАС, г. Усть-Каменогорск) за помощь в эксперименте.

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