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Formation of intermetallics at the interface of explosively welded Ni-Al multilayered composites during annealing

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Abstract. The Ni-Al multilayer composite was fabricated using explosive welding. The zones of mixing of Ni and Al are observed at the composite interfaces after the welding. The composition of these zones is inhomogeneous. Continuous homogeneous intermetallic layers are formed at the interface after heat treatment at 620 °C during 5 h. These intermetallic layers consist of $NiAl_3$ and Ni_2Al_3 phases. The presence of mixed zones significantly accelerates the growth rate of intermetallic phases at the initial stages of heating.

1. Introduction

Development of multilayered composites with a high complex of mechanical and performance properties is one of the most significant problems of the advanced materials science. There are many special requirements such as high specific strength, stiffness and low density that are imposed on the materials used in aircraft, rocket building and power engineering [1-2]. Some types of intermetallic compounds meet these requirements and may become a promising basis for manufacturing of the details applied in critical conditions at high load and temperature. A special attention is given to chemical compounds such as aluminides. These materials have unique properties that allow their use in the advanced aerospace industry. At the same time, their extensive use is limited by increased brittleness, especially at low temperatures [2]. Reliable utilization of the products manufactured of these materials is only possible under such conditions that enhance ductility, for example, heating [3].

One way to solve this problem is to form laminated composites, which consist of alternated plates of dissimilar alloys that are inclined to form intermetallics. The growth of intermetallic layers occurs during the heat treatment of such composites at the boundaries of dissimilar metals [4]. High mechanical properties of the material are provided by a combination of hard and stiff intermetallic layers and ductile metallic layers [5, 6].

Processes frequently used for production of the composite materials with intermetallic layers are reaction sintering of metal sheets [7, 8] and roll bonding of sheets with subsequent heat treatment of obtained multilayered samples [9, 10]. Furthermore, a lot of researchers experimentally showed that explosive welding is an effective method of connecting similar and dissimilar metals [11-13]. Features that are distinctive to the explosive welding process, in particular, local heating of workpieces to high temperatures (up to the melting point), high pressure during the interaction between welded plates, promote intensification of the chemical compounds formation [13]. It should be noted that the published data on the problem of intermetallic compounds formation during explosive welding are fragmentary. Many features of this process are still not investigated. The subject of this research is to study the processes of intermetallic compounds formation during explosive welding of metal plates and subsequent heat treatment of welded multilayer samples. Ni – Al systems were chosen as objects of the study.

2. Materials and methods

Ni-Al composites with intermetallic layers were produced by explosive welding and subsequent heat treatment. Explosive welding of alternatively stacked 4 plates of commercially pure (cp-) nickel (100 × 50 ×1 mm) and 3 plates of cp-aluminum (100 × 50 × 0.5 mm) was carried out according to the scheme with parallel orientation of workpieces. The distance between the plates during explosive welding was 1 mm. Ammonite 6GV was used as an explosive material. The chemical composition of initial metals is shown in Table 1.

Table 1. Chemical composition of initial materials, % wt.

	Fe	Cr	Ni	V	Si	Cu	Al
Cp-aluminum (alloy A5)	0.32	0.002	–	0.006	0.14	0.002	rest
Cp-nickel (alloy NP2)	0.029	–	rest	–	0.03	0.142	0.029

The intermetallic interlayers were fabricated by annealing of explosively welded Ni–Al composites at 620 °C. The duration of annealing varied from 5 min to 5 h.

The samples for characterization of the structure were prepared by the standard procedure including mechanical grinding and polishing. Metallographic studies were carried out using light microscopy (LM) and scanning electron microscopy (SEM). The elemental composition of the local zones was studied using energy dispersive X-Ray spectrometry (EDX). The phase analysis of metallic – intermetallic composites was performed using X-ray diffractometer ARL X'TRA by means of CuKα radiation in a step mode with $\Delta 2\theta = 0.02°$. The dwell time was 5 s.

3. Results and discussion

3.1. The structure of explosively welded samples

The cross section of the explosively welded composite is shown in Figure 1a. Continuous mixing zones are observed at the interface between dissimilar plates. The formation of these zones during explosive welding is known and described in many researches [18-20]. The thickness of the interlayer depends on the interface location in the composite. Two types of the interfaces can be distinguished in the composite, namely ‘Ni/Al’ type and ‘Al/Ni’ type (Figure 1b). If during collision the nickel plate is above aluminum plate the ‘Ni/Al’ interface is formed, otherwise, when the aluminum plate is above the nickel plate the ‘Al/Ni’ interface is formed (Figure 1a). The average thickness of mixing zones at ‘Al/Ni’ interfaces is in the range of 20…70 μm. At the ‘Ni/Al’ interfaces this value is in the range of 7…25 μm. A typical peculiarity of explosively welded materials is formation of the wavy interface. However, no waves are observed at interfaces of both types. ‘Ni/Al’ interfaces are nearly flat, while at the ‘Al/Ni’ interfaces a periodic variation of the mixing interlayer thickness is observed.

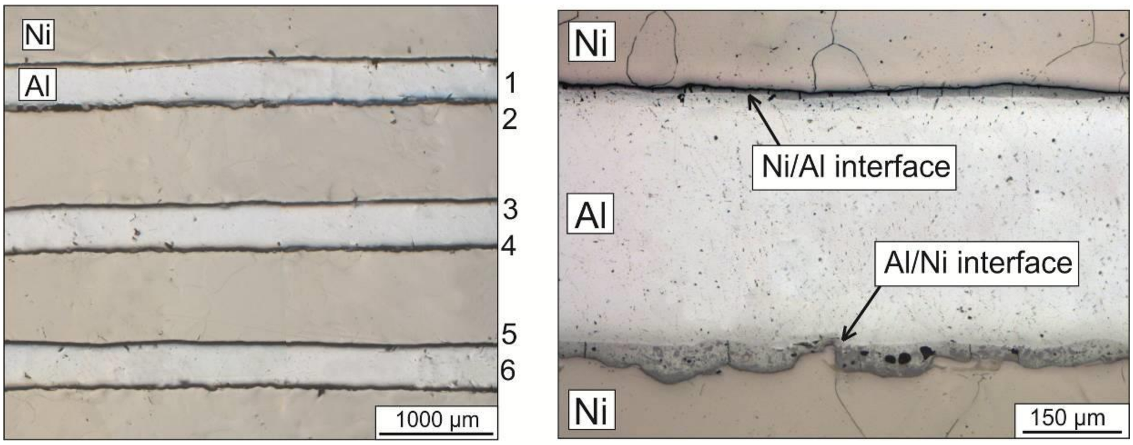

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Figure 1. A structure of explosively welded multilayered Ni-Al composites.

Characterization of Ni–Al interfaces, performed by means of LM and SEM revealed that mixing zones possess a complicated non-uniform structure. Multiple dendrites with dimensions of 0.5…3 micrometers are observed (Figure 2a), which indicates that the mixing zones appear from the liquid state. Some particles have a complex fragmental shape with the size exceeding 10 μm. Results of the EDX analysis of the mixing zone, corresponding to Figure 2b are presented in Table 2. Different chemical composition within the intermixing regions evidences that the solidification rate of the material in the mixing zones is very high since homogenization does not have time to occur. A detailed TEM research revealed that such mixing zones contain metastable intermetallic compounds based on nickel and aluminum [13].

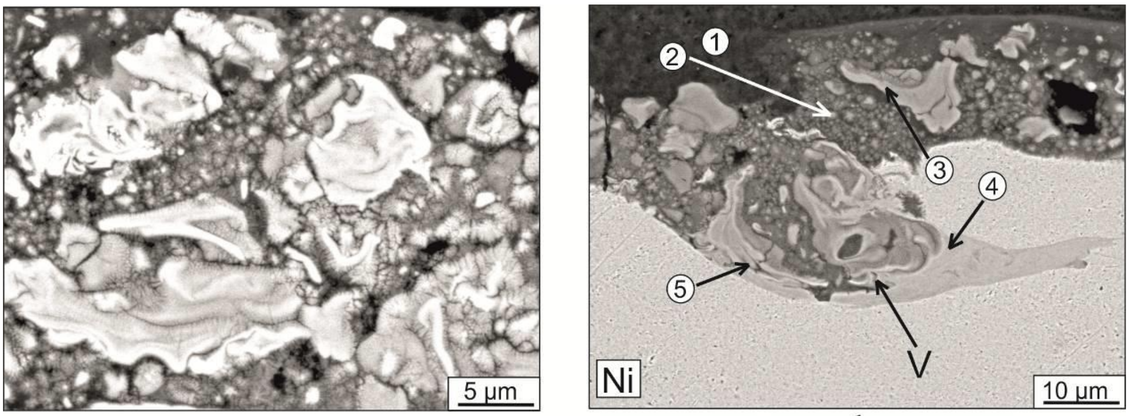

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Figure 2. Mixing zones at the Ni–Al interfaces.

Table 2. The content of the chemical elements at points marked in Figure 2b

Zone #	Al, % at.	Ni, % at.
1	93.5	6.5
2	75.8	24.2
3	62.1	37.9
4	43.2	56.8
5	30.5	69.5

3.2. Structural transformation occurring at the interfaces during annealing

During heat treatment the nonequilibrium interlayers at the interfaces are gradually replaced by continuous intermetallic layers. This process occurs due to a reaction between Ni and Al and is greatly intensified at elevated temperature. The intermetallic $NiAl_3$ layer grows near aluminum. The Ni_2Al_3 intermetallic compound layer adjoins nickel. After 5 hours of heating only two intermetallic layers $NiAl_3$ and Ni_2Al_3 are observed along the interface. This is evidenced by the EDX analysis (Figure 3a, Table 3) and X-ray diffraction results (Figure 3b).

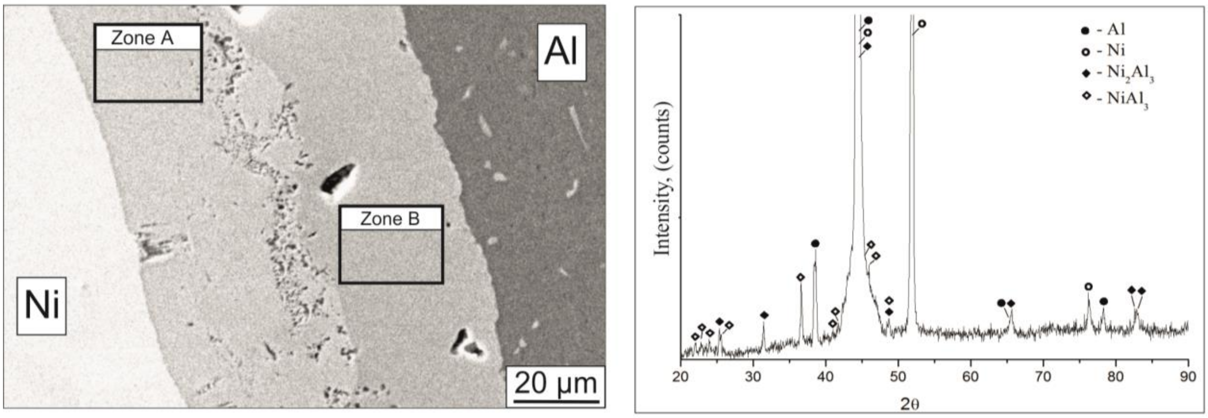

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Figure 3. Intermetallic layers formed at the Ni-Al interfaces of explosively welded samples after 5 h of annealing (a) structure (b) X-ray diffraction pattern.

Table 3. The content of the chemical elements in areas A and B, indicated in Figure 4.

one #	Al, % at.	Ni, % at.
Zone A	60.4	39.6
Zone B	75.2	24.8

The difference in thickness and morphology of mixing zones having interfacial types ‘Al/Ni’ and ‘Ni/Al’, which is described above, leads to different rates of intermetallic layers growth. That is seen in the structure of samples annealed during 3 hours (Figure 4). The dependence of intermetallic layers growth at ‘Al/Ni’ and ‘Ni/Al’ interfaces on time is demonstrated by the graph in Figure 5a.

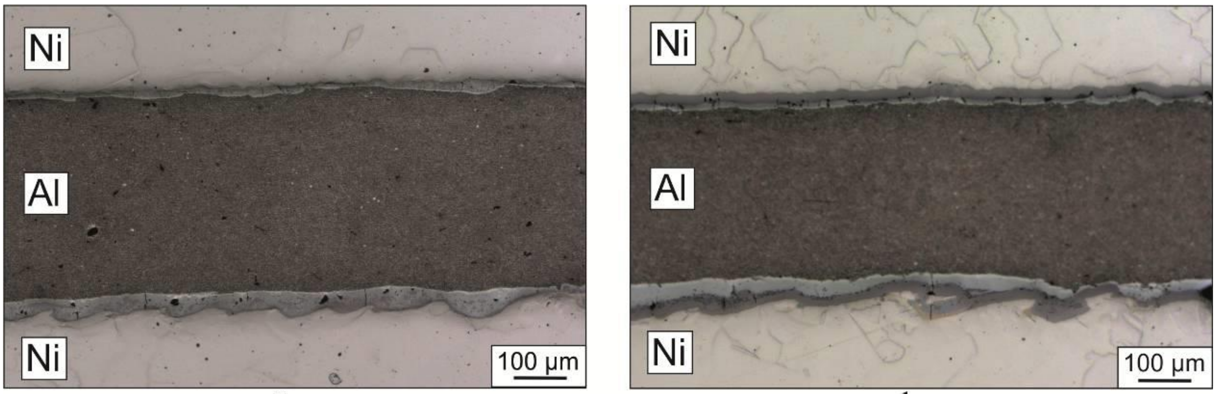

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Figure 4. Intermetallic layers formed at the interfaces of Ni-Al composites after heating during 5 min (a) and during 3 h (b).

The intermetallic layer growth rate in explosively welded composites was compared with that in casted composites, which were fabricated as it is described in [14]. The results of structural studies suggest that processes, which take place during explosive welding, promote active nucleation and growth of intermetallic compounds during subsequent annealing. The acceleration of intermetallic formation is caused by the presence of the above-mentioned mixing zones. Another important factor that facilitates fast growing of intermetallic layers is removing of oxides and impurities from the surfaces during explosive welding. Comprehensive studies of the annealed samples confirmed that the explosively welded structure enables faster intermetallic growth than that in the composites produced by means of the casting technique (Figure 5b).

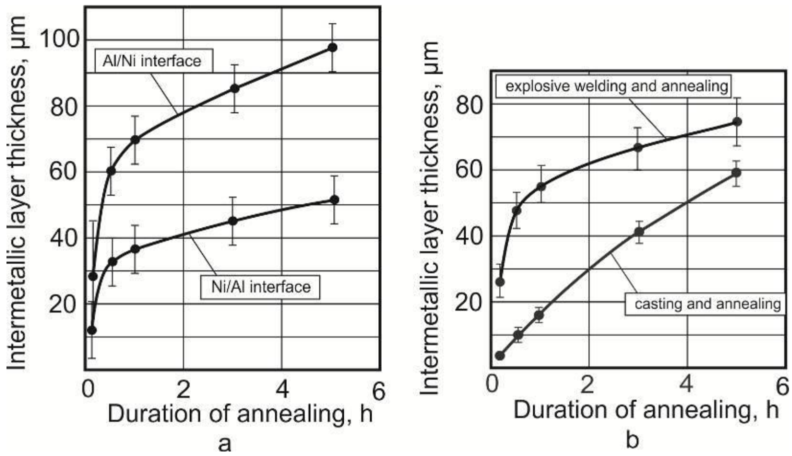

Figure 5. *a* – intermetallic layers growth in explosively welded composites at interfaces Al/Ni and Ni/Al, *b* – comparison of intermetallic growth during annealing at 620 °C in the samples produced by different techniques (explosive welding and casting).

4. Conclusion

The Ni-Al multilayered composite was successfully welded using the explosive welding technique. Zones of materials mixing were observed at the interfaces between Al and Ni. The mixing zones had a non-uniform chemical composition due to the nonequilibrium processes of explosive welding.

The $NiAl_3$ and Ni_2Al_3 intermetallic layers were synthesized at the interface after heat treatment of the composite at 620 ^{o}C. The intermetallic growth rate in the explosively welded composite was faster in comparison with that in the casted composite. The factors that accelerated the formation of intermetallic layers in explosively welded Ni–Al multilayered composites during annealing were purification of the surface of the plates from contaminations and oxides by a cumulative jet and formation of zones with intensively mixed Ni-Al.

Acknowledgements

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