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Explosive and thermochemical treatment of multi-layer metallic composites
Obróbka wybuchowa i cieplno-chemiczna wielowarstwowych kompozytów metalicznych

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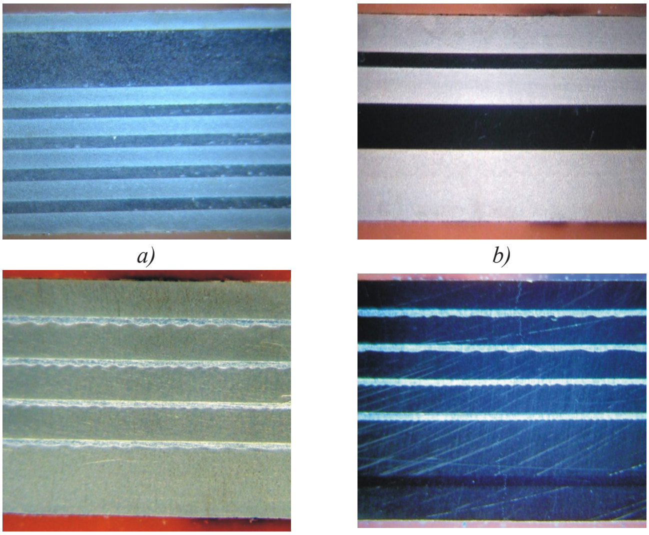
Abstract: *The paper describes methods for the explosive hardening of metals which were performed with a view to increasing the hardness of previously obtained composites, as well as treatment of their surface layers to increase the efficiency of further thermochemical treatment. Typical systems for explosive hardening of metals and the construction of current systems, are discussed. The resulting effects of explosive hardening are illustrated with before and after diagrams of microhardness distributions in cross-sections of the processed composites hardening. In a further processing stage, the tested composite samples were subjected to ion nitriding. As a result of this process, in addition to the typical increase in hardness of the individual layers, an intermediate phase with a distinctly higher hardness was observed in the junction zone. Preliminary analysis of the photographs and the results from a scanning electron microscope (SEM) with an energy dispersive spectroscopy (EDS) attachment suggests that the particularly beneficial properties of the composites are attributed to the presence of the intermetallic layer.*

Streszczenie: *W pracy opisano sposoby wybuchowego umacniania metali, które wykonywano w celu uzyskania wzrostu twardości otrzymanych wcześniej kompozytów, a także dla zdefektowania ich warstw wierzchnich, aby zwiększyć skuteczność dalszej obróbki cieplno-chemicznej. Omówiono typowe układy do wybuchowego umacniania metali oraz konstrukcję układu stosowanego w praktyce. Uzyskane efekty wybuchowego umacniania zilustrowano wykresami rozkładów mikrotwardości, w przekrojach poprzecznych obrabianych kompozytów, przed i po umacnianiu wybuchowym. W dalszym etapie obróbki badane próbki kompozytów poddano jarzeniowemu azotowaniu. W wyniku tego procesu, oprócz typowego wzrostu twardości poszczególnych warstw, zaobserwowano występowanie w strefie złącza fazy pośredniej o wyraźnie wyższej twardości. Wstępna analiza zdjęć i wyników ze scaningowego mikroskopu elektronowego z przystawką EDS pozwala przypuszczać, że jest to warstwa międzymetaliczna., której obecność nadaje kompozytom szczególnie korzystne właściwości.*

Keywords: *explosive welding, explosive hardening of metals, ion discharge nitriding*
Słowa kluczowe: *zgrzewanie wybuchowe, umacnianie wybuchowe metali, azotowanie jarzeniowe*

1. Processed composites

Multi-layer composites combining titanium plates with 1H18N9 steel or aluminium plates were produced using an explosive welding technique [1-3]. These metals were chosen as a consequence of the expectation that an intermetallic phase would be formed at the junction of the selected metal pair with appropriate properties in terms of hardness [4, 5]. Following the positive results, it is expected that the composites will be used in the construction of armour for military vehicles. The composites were obtained by the initial selection of a thicker titanium plate and subsequent alternating additions of aluminum or steel plates. Using this technique, it was possible to create packages with any number of layers. In Fig. 1 microscopic images of cross-sections of some samples of these composites, illustrating the nature of the contact of individual metal layers: titanium (Ti), steel (St) and aluminum (Al), are presented.



a) *b)*

c) *d)*

Figure 1. Examples of cross-sections of multilayer composites:
(a) Ti/St/Ti/St/Ti/St/Ti/St/Ti/St/Ti = 1.5/3.0/1.5/0.7/1,5/0.7/1,5/0.7/1,5/0.7/1,5 mm – 11 layers,
(b) Ti/St/Ti/St/Ti = 1.5/0.7/1.5/2.0/3.0 mm – 5 layers,
(c) Ti/Al/Ti/Al/Ti/Al/Ti/Al/Ti = 1.5/0.3/1.5/0.3/1.5/0.3/1.5/0.3/3.0 mm – 9 layers,
(d) Ti /Al/Ti/Al/Ti/Al/Ti/Al/Ti/St/Ti = 1.5/0.3/1.5/0.3/1.5/0.3/1.5/0.3/3.0/0.7/1.5 mm – 11 layers

2. Explosive hardening of test composites

Explosive hardening was performed with a view to increasing the hardness and altering the structure of the composites to achieve better effects in further thermochemical treatment, which was ion nitriding. Thin, layered 2-3 mm plastic explosive charges were used for the explosive hardening. The main component of the explosive material was fine-crystalline pentrite (PETN).

Explosive hardening can be carried out in several ways, depending on the value of the pressure pulse which needs to be imparted to the item being strengthened, in other words, depending on how much it needs to be hardened. Fig. 2 shows schematics of four basic variants of explosive hardening of metals. The first diagram illustrates the simplest and most commonly used method hardening, in which action of the detonation products of a thin strong explosive charge directly on the un-strengthened surface, is performed. The effect of hardening is the smallest with this method, which is often referred to as the method of hardening by an «oblique wave” entering the metal. The second approach hardening involves using a metal plate as a so-called liner which, due to a much higher density than the detonation products, generates a much higher pressure pulse at the moment of impact with the strengthened surface. Nonetheless, it is a variant of the “oblique wave”. The third diagram illustrates the most effective method for explosive hardening which uses an indirect explosive material charge, generating a flat wave. As a result, the entire metal surface is simultaneously loaded with a so-called “flat pressure pulse”, which penetrates the deepest into the metal and has the longest duration. This method hardening is rarely used due to the enormous destructive power of the detonation products resulting from prolonged contact with the surface. The fourth diagram shows the effect of a pressure pulse generated during a metal plate impact; however, thanks to the appropriate alignment of the impacting plate and the specific detonation of the explosive charge, a similar effect to the third method is obtained, but with a much shorter duration of the loading pulse which does not have such a destructive effect as in the previous option. During the studies, two of the above hardening methods were used: the first and the fourth.

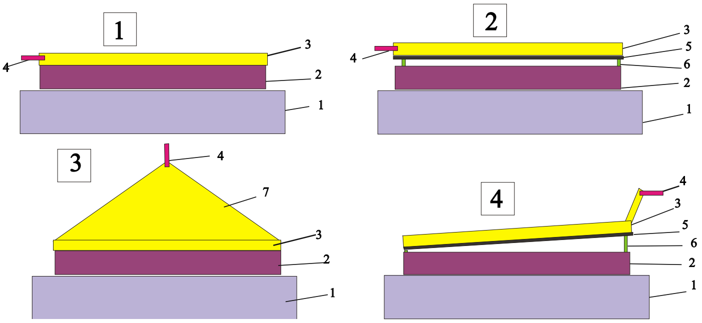


Figure 2. Schematics of the systems used for explosive metal hardening: **[1]** – hardening with explosive material detonation products directly adjacent to the metal; **[2]** – hardening by impact with a metal plate driven by the explosive material detonation products; **[3]** – hardening of the explosive material charge activated by the plane wave generator; **[4]** – hardening by a metal plate driven by a quasi flat pressure wave: 1) metal base, 2) strengthened plate, 3) explosive material charge, 4) electric igniter, 5) metal liner plate, 6) distance, 7) flat wave generator

3. Composite micro-hardness measurements

The changes in hardness of multilayer composite samples were determined by micro-hardness measurements using the Vickers apparatus. To illustrate these changes (Fig. 3) a sample containing five Ti/St layers (sample No. 3) and a sample consisting of nine Ti/Al layers (sample No. 4) were selected from a large number of composites.

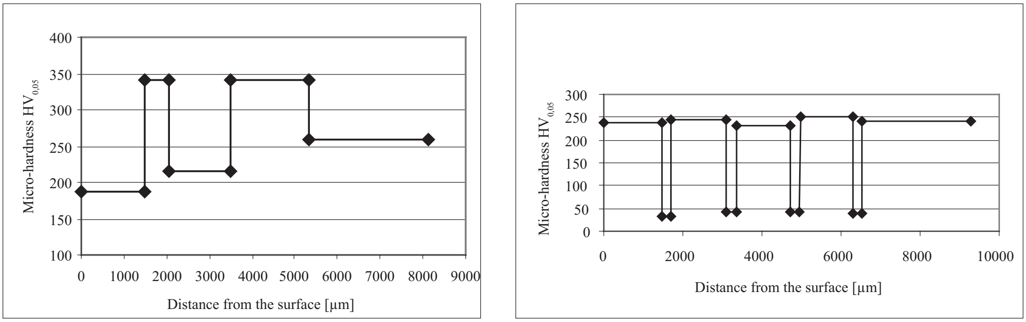


Figure 3. Charts of micro-hardness distributions in cross-sections of tested composites: (a) sample 3 – Ti/St composite, (b) sample 4 – Ti/Al composite

3.1. Micro-hardness distributions after explosive welding

Explosive welding of individual layers of composites was performed with layered ammonium or slurry explosive charges. Both explosive materials can be termed as not very powerful. They did not contain any explosive ingredients, but were sensitised with flaked aluminum dust. Their detonation speed did not exceed 3 $km \cdot s^{-1}$, and the bulk or the loosened gel density was approximately 1 $g \cdot cm^{-3}$.

The results of the measurements are shown in Fig. 3. It is noteworthy that the micro-hardness of the titanium layers of sample 3 increases, as the subsequent layers are welded. The initial hardness of the titanium plates was approximately 200 $HV_{0.05}$, with the chart showing that, following application of subsequent layers, the micro-hardness of the bottom titanium layer increased to the value of 260 $HV_{0.05}$, while the middle layer increased to the value of approximately 220 $HV_{0.05}$. No significant increase in the micro-hardness of the other steel plates was observed.

3.2. Micro-hardness distributions after explosive hardening

The explosive hardening was initially conducted using methods 1 and 4 (Fig. 2), and, after concluding that method 4 is more effective, research was restricted to this option. The velocity of detonation of the explosive was 7.5 $km \cdot s^{-1}$, its density was 1.4 $g \cdot cm^{-3}$, and the thickness of the layer was 2.5 mm. To distinguish explosively strengthened samples, they were marked with a (!) symbol. The results of the measurements are shown in Fig. 4. Both composites clearly show an increase in micro-hardness compared to the distributions in Fig. 3. The highest increase was achieved in the case of the Ti/St composite titanium top plate, which is understandable as it was acted on by the largest pressure pulse. The initial micro-hardness value was 180 $HV_{0.05}$, and after hardening it was 320 $HV_{0.05}$. The hardness of the steel plates also increased: from 340 $HV_{0.05}$ to 415-450 $HV_{0.05}$. An increase in micro-hardness after explosive hardening was also observed for the Ti/Al composite; however, it was smaller than in the previous example. The micro-hardness of titanium increased from 230-250 $HV_{0.05}$ to 270-295 $HV_{0.05}$. The micro-hardness of aluminum remained practically unchanged.

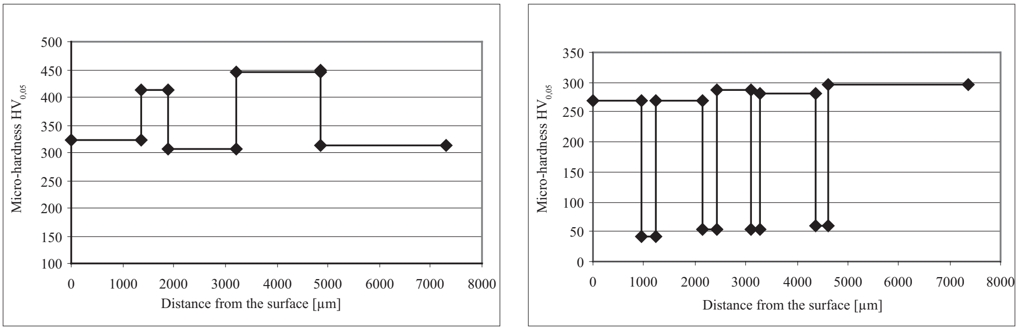


Figure 4. Charts of micro-hardness distribution in cross-sections of samples subjected to explosive hardening: (a) sample 3! – Ti/St composite, (b) sample 4! – Ti/Al composite

3.3. Micro-hardness distributions after ion nitriding

Ion nitriding of both types of composites resulted in unexpected and surprising results (Fig. 5). The useful effects of explosive hardening of titanium and steel plates disappeared, and even the micro-hardness of aluminum fell below the initial value (approximately 50 $HV_{0.05}$). Only the surface layers of composites, the titanium plates, increased significantly in microhardness; however, for the Ti/St composite this value was higher (up to 950 $HV_{0.05}$) than for the Ti/Al composite, which only increased to 600 $HV_{0.05}$. These differences are believed to result from varying degrees of structural defects of these composites following explosive hardening. The characteristic increases in the micro-hardness of the Ti/Al composite at the junction of these plates, inside the composite, indicate the formation of an intermetallic phase in those parts.

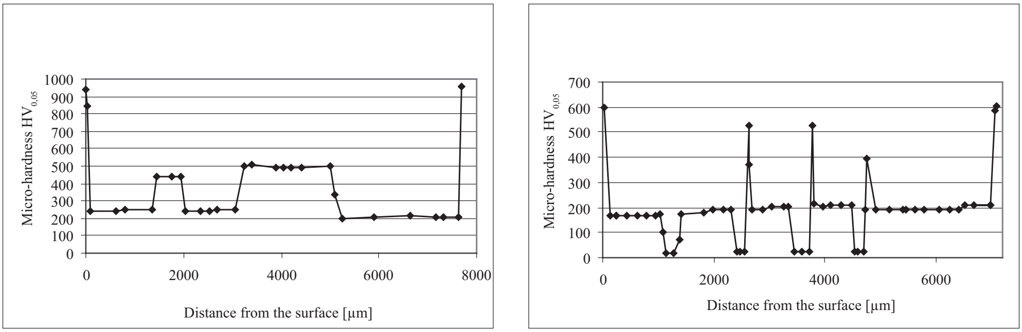


Figure 5. Charts of micro-hardness distributions in composite cross-sections after explosive hardening and ion nitriding: (a) sample 3! nitrided – Ti/St composite, (b) sample 4! nitrided – Ti/Al composite

To confirm the presence of the intermetallic phase formed inside the Ti/Al composite, on the border of the Ti-Al junction, a photograph was taken using a scanning microscope with an EDS attachment, allowing elemental analysis of the chemical composition of the intermetallic phase. Fig. 6 shows the area of this phase marked with a dotted line.

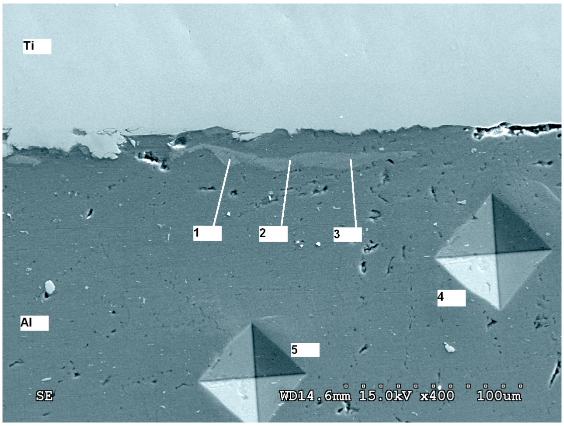


Figure 6. Ti/Al composite junction zone after ion nitriding: 1, 2, 3) measurement points using the EDS probe; 4, 5) Vickers's camera prints

The chart presented in Fig. 7, as well as Table 1 illustrate the results of elemental analysis of point 1 in Fig. 6. The results confirm the presence of Ti atoms inside the Al phase, which indicates the possibility of the presence of the Ti/Al intermetallic phase in this part. This is also indicated by the micro-hardness measured at points 1, 2 and 3, which are 525, 510 and 517 $HV_{0.05}$, respectively.

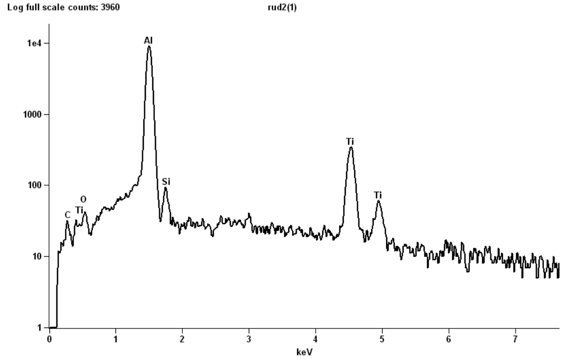


Figure 7. Elemental analysis at point 1 of the Ti/Al junction zone

4. Summary

Based on the conducted research, it can be concluded that the explosive hardening of multilayer composites improves their hardness not only on the surface, but the effects of the explosive load are also evident throughout the entire cross-section of the composite. Hardness increases are not large and are in the region of 20-30%.
Ion nitriding causes a significant increase in hardness on the surfaces and a withdrawing of the hardening effect inside the composite. The formation of the intermetallic phase at the Ti-Al junction border is mainly the result of long-term temperature impact and strong working of this area during explosive welding.

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