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THE CONCEPT OF IMPROVEMENT HIGH-STRENGTH ALUMINUM ALLOYS FSW JOINT PROPERTIES VIA POST-WELD EXPLOSIVE TREATMENT

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Summary. *The study describes the theoretical background and technological aspects of the post-weld explosive treatment of high-strength aluminum alloy FSW joints. Although FSW allows to effective join high-strength aluminum alloys, the heat generated during the process causes undesirable changes in the strengthening phase, giving a joint efficiency of about 80%. The load-carrying capabilities of these joints can be increased via post-weld treatment (e.g. shot peening, laser shock peening). The new, potential post-weld treatment that is presented in this paper is based on the affection of the welded joint by a shock wave generated during the detonation of explosive material. Such post-weld explosive treatment would result in the hardening of the low-hardness zone, which often determines the mechanical properties of precipitation-hardened aluminum alloy FSW joints. Studies show that explosive welding of annealed aluminum alloys increases their microhardness by about 25% as the result of a high-velocity collision. If a similar effect can be achieved in explosive hardening, the microhardness of the low-hardness zone will increase entailing an improvement of entire joint mechanical properties. The variety of explosives materials used in metalworking (covering the values of detonation velocity from about 2000 m/s to 8000 m/s) and different systems for shock-wave affection gives many technological possibilities. In this work are discussed two different explosive hardening systems: with direct placement of explosive material on a treated welded plate and with an additional driven plate, which provides a higher pressure impulse. Considering that affecting of high amplitude shock wave introduces defects into the structure and decreases residual stresses in the welded joints, the application of an appropriate technological system creates a potential for improving the load-carrying capacities of discussed joints, especially in a condition of cyclic loading.*

Key words: *aluminum, friction stir welding, post-weld treatment, explosive hardening.*

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Statement of the problem. In recent years, friction stir welding (FSW) has become the subject of many research works due to a number of advantages of this joining technique, including the high quality of obtained joints, the possibility of joining aluminum alloys difficult to weld using conventional methods, low energy consumption and neutrality for the natural environment. Although in the case of pure aluminum and its non-precipitation hardened alloys, deformation and grain refinement in the thermo-mechanically affected zone (TMAZ) and in the stir zone (SZ) increases the strength in these areas, FSW of precipitation-hardened aluminum alloys is characterized by the dissolution of strengthening phases resulting in a decrease in strength in each zone: SZ, TMAZ, heat-affected zone (HAZ) [1,2]. These phenomena find their reflection in the distribution of microhardness on the welded joint cross-section (Fig. 1).

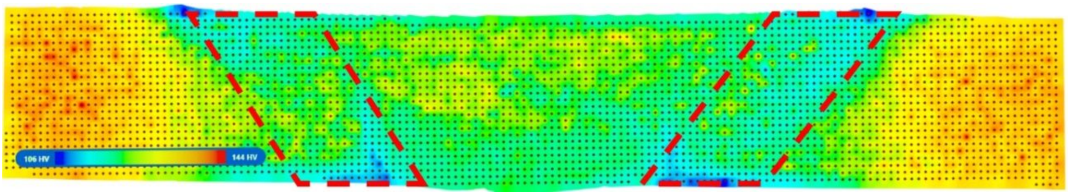

Figure 1. Microhardness contour map of AA2519-T62 FSW joint [3] with the marked low-hardness zone (red dashed lines)

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The zone, which determines the strength of a joint is the low hardness zone (LHZ), often localized on the boundary between the HAZ and TMAZ [1]. FSW joints of precipitation-hardened alloys tend to fail in this zone, which is characterized by low participation of the strengthening phase and coarse grains [4]. In conventional welded joints, the possible solution to this problem is post-weld heat treatment (PWHT) allowing for re-precipitation of the strengthening phases [5]. When it comes to the PWHT of FSW joints there are some problems e.g. in the form of abnormal grain growth, giving relatively poor fatigue properties [6].

Analysis of the available investigations. In the 70s of the last century, a number of research works showed a significant increase in the strength of welded joints subjected to explosive treatment, especially in terms of fatigue strength [7]. Research conducted on the process of explosive stress relieving of welded joints of 10G2S1 and M16S steels showed that as a result of treatment with explosive charges with a diameter of 4 mm, the fatigue strength of the samples increased from 3 to 5 times [8, 9]. Explosive treatment of welded joints of 14G2 steels not only reduced residual stresses in the weld but also changed their character from tensile to compressive [9]. The use of a post-weld explosive treatment may improve the strength of precipitation-hardened aluminum alloy joints as a result of introducing additional defects into the structure by the affection of a shock wave [7]. Considering the impact of the shock wave on the HAZ, an assumption can be made that the worst possible case is a complete overage of the precipitates after the FSW process, hence the HAZ would be in the annealed condition. Some works on the explosive welding of high-strength aluminum alloys can be useful to estimate the potential hardening of these alloys during explosive treatment. As an example the explosive welding of AA2519 in the annealed condition can be given, which causes the increase in microhardness from about 75 HV0.1 to 95 HV0.1 in the area affected by the high-velocity collision [10]. For the hardness of LHZ in friction stir welded AA2519-T62 is about 115 HV0.1, potentially it can be increased by a shock wave. It has to be noticed that a shock wave can be generated also by laser shock peening, but it affects only the near-surface area of the joint improving only the fatigue properties without affecting tensile properties noticeably. The generation of the high-amplitude shock wave can be achieved by the use of high-explosive material in the appropriate technological system (Fig. 2).

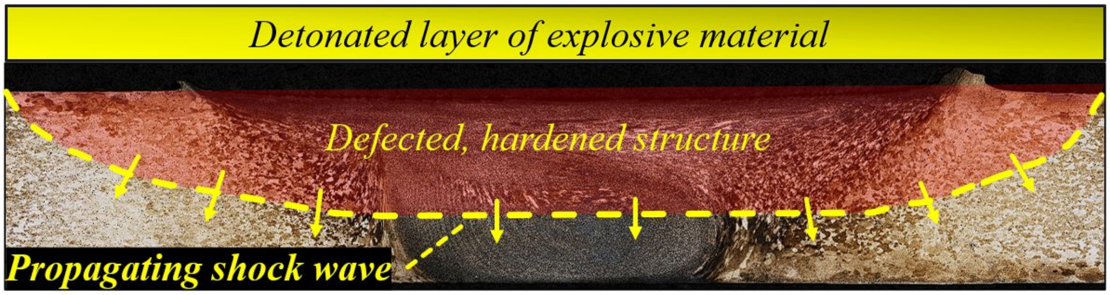

Figure 2. Scheme of FSW joint cross-section affected by a shock wave

The explosive hardening of FSW joints. Two factors determine the effect of explosive hardening: the detonation parameters of the explosive material and the used technological system used [11]. From the technological point of view, the post-weld explosive treatment is easiest to perform by «oblique wave», what can be achieved in two systems (Fig. 3 a, b).

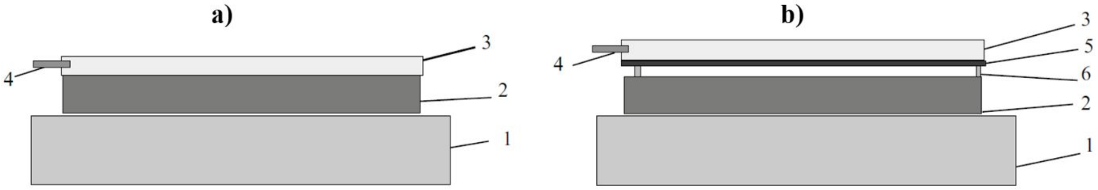

Figure 3. Explosive hardening systems: direct (a), and with intermediate plate driven by the detonation (b). 1 – base plate (anvil), 2 – hardened plate, 3 – explosive material, 4 – electric igniter, 5 – intermediate (driven) plate, 6 – distance [11]

In the first case, the shock wave is generated by the direct impact of detonation products (Fig. 3a). The basic parameter of explosive material is the value of detonation velocity. The common industrial explosives used in mining and metal treatment are ammonals, ANFO (ammonium-nitrate fuel oil), emulsion explosives, and plastic explosives, covering the values of detonation velocity from about 1800 to 8300 m/s [12]. It provides wide possibilities for selecting material that gives the highest value of hardening. Selected explosives materials used in metalworking together with their detonation velocities are set in Table 1.

Table 1

Selected explosive materials used in metalworking

Explosive	*Detonation velocity*	*Application*	*Ref.*
Ammonal (5%)	2400 m/s	Explosive welding of Hadfield steel to steel	13
ANFO-based mixture	2000 m/s	Explosive welding of aluminum to steel	14
Emulsion explosive	2800 m/s	Explosive welding of aluminum to steel	14
ANFO	2700 m/s	Explosive welding of Inconel to steel	15
RDX-based plastic	7600 m/s	Explosive hardening of Hadfield steel	16
C-2	5730 m/s	Explosive hardening of AA7075-T73651	17
C-4	7746 m/s	Explosive hardening of Cp-Titanium	18

An additional factor is the thickness of the explosive material layer, which can be optimized in terms of the highest hardening. From the technological point of view, the most suitable form of explosive for the post-weld explosive treatment would be a plastic explosive due to its easy forming and sticking to a welded construction. Nevertheless, plastic explosives are often characterized by a high value of detonation velocity, what can damage a treated element or lead to the generation high amount of heat during the treatment resulting in the overaging of aluminum alloy. The plastic explosives can be modified to severely decreased their detonation velocity by e.g. the addition of ZnO [19], what can be a compromise between accessible form and appropriate detonation parameters for post-weld explosive treatment.

In the second explosive hardening system, the wave is generated by the impact of the intermediate plate which is driven by the detonation products (Fig. 3 b). As a driven plate, a simple steel sheet can be used with a thickness of 1–2 mm. Generally, the most efficient hardening is obtained in this system, but there are problems that can limit its application in the post-weld explosive treatment of FSW joints. The system is relatively difficult to construct on the spatial welded structure and there is a risk of explosive welding of the hardened and driven plate. The explosive welding risk can be limited by the use of an additional, thin, protective layer (machine oil, plastic), what further complicates the construction. In both systems (Fig. 3 a, b), the appropriate base plate (anvil) should be used to limit the deformation of hardened welded plates, what is easy to achieve only in the case of flat, simple welded structures (e.g. butt-welded plate). In more complex welded structures the base plates should be temporarily installed as a part of post-weld explosive treatment or it can be skipped in the case when the welded plates have high enough thickness (e.g. 50 mm), the layer of explosive material is low and some deformations of construction are acceptable.

Conclusions. The post-weld explosive treatment may be a possible solution for increasing FSW joints' mechanical properties. Considering that affecting of high amplitude shock wave introduces defects into the structure and decreases residual stresses in the welded joints, the application of an appropriate technological system creates a potential for improving the load-carrying capacities of discussed joints, especially in a condition of cyclic loading. The variety of explosives materials used in metalworking (covering the values of detonation velocity from about 2000 m/s to 8000 m/s) and different systems for shock-wave affection gives plenty of technological possibilities. In the current state of the art, there is no research on this subject, but referring to studies on explosive welding, the conclusion can be drawn that an increase in precipitation-hardening aluminum alloys microhardness in the annealed condition by about 25% can be achieved. In order to verify the concept presented in this paper series of investigations will be carried out in the near future.

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КОНЦЕПЦІЯ ВИБУХОВОГО ЗМІЦНЕННЯ З’ЄДНАНЬ FSW ВИСОКОМІЦНИХ АЛЮМІНІЄВИХ СПЛАВІВ

Роберт Костурек

Військова Технічна Академія, Польща

Резюме. *У роботі представлено теоретичні основи та технологічні аспекти після зварювальної вибухової обробки з’єднань FSW алюмінієвих сплавів підвищеної міцності. Хоча FSW дозволяє отримувати якісні з’єднання алюмінієвих сплавів підвищеної міцності, тепло, що виділяється під час цього процесу, викликає небажані зміни у зміцнювальних фазах у самому з’єднанні, спричиняючи зниження ефективності з’єднання до 80%. Несучу здатність цих з’єднань можна збільшити за допомогою відповідної обробки після зварювання (наприклад, кулювання, лазерне ударне зміцнення). У статті представлена відносно нова методика після зварювальної обробки, яка опирається на впливі на зварне з’єднання ударною хвилею, що виникає під час детонації вибухового матеріалу. Така обробка вибухом після зварювання призведе до зміцнення зони низької твердості, яка часто визначає механічні властивості дисперсійно зміцнених з’єднань FSW з алюмінієвого сплаву. Дослідження показують, що зварювання вибухом відпалених алюмінієвих сплавів підвищує їх мікротвердість приблизно на 25%, що є результатом їх високошвидкісного зіткнення. Якщо подібного ефекту вдасться досягти при вибуховому зміцненні, мікротвердість зони низької твердості також збільшиться, що спричинить поліпшення всіх механічних властивостей з'єднання. Різноманітність вибухових матеріалів, які використовуються в металообробці (швидкості детонації приблизно від 2000 м/с до 8000 м/с), і різні технологічні системи ударно-хвильового впливу дають багато технологічних можливостей. Розглянуто дві різні технологічні системи вибухового зміцнення: з прямим розміщенням вибухового матеріалу на обробленій звареній пластині та з веденою додатковою пластиною, яка забезпечує вищий імпульс тиску. Враховуючи, що вплив ударної хвилі великої амплітуди вносить дефекти в конструкцію та зменшує залишкові напруження у зварних з’єднаннях, застосування відповідної технологічної системи створює потенціал для підвищення несучої здатності розглянутих з’єднань, особливо в умовах циклічного навантаження.*

Ключові слова: *алюміній, зварювання тертям з перемішуванням, післязварювальна обробка, вибухове зміцнення.*

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