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PROPERTIES OF ALUMINIUM-STEEL PLATES EXPLOSIVELY WELDED USING AMONEX

OSOBINE EKSPLOZIVNO ZAVARENIH PLOČA ALUMINIJUMA I ČELIKA UPOTREBOM AMONEX EKSPLOZIVA

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Keywords
- explosion welding
- steel
- aluminium
- non-destructive testing
- indentation hardness

Abstract

The aim of this study was to investigate the possibility to use the industrial explosive Amonex, which belongs to a group of low-to-middle detonation velocity explosives, for welding of metallic materials. It consists of ammonium nitrate and TNT as energetic components and other inert ingredients and has a powdery consistency, easily applicable in a desirable layer over the metal plates to be welded. Within this research, Amonex was applied to weld plates of aluminium Al 2024 and steel 1.0216 (according to EN 10027-2). The procedure of welding was carried out in the configuration of parallel plates, and afterwards the welded joint was examined. Ultrasonic method and infrared imaging were used as non-destructive techniques, and then the samples were cut from the welded plate using water-jet, in order to perform microscopic analyses of the cross-section in the joint area. It was observed that a good-quality welded joint was obtained, and that the selected explosive may find further application in this area. However, certain non-welded area was observed, encouraging future modification of the welding procedure set-up.

Ključne reči
- eksplozivno zavarivanje
- čelik
- aluminijum
- ispitivanje bez razaranja
- tvrdoća utiskivanjem

Izvod

Cilj ove studije je ispitivanje mogućnosti upotrebe industrijskog eksploziva Amonex, koji pripada grupi eksploziva male-do-srednje brzine detonacije, za zavarivanje metalnih materijala. Ovaj eksploziv se sastoji od amonijum nitrata i TNT-a kao energetskih komponenti i drugih inertnih sastojaka, ima praškastu strukturu i lako se nanosi u željenom sloju preko metalnih ploča koje se zavaruju. U okviru ovog istraživanja, Amonex je primenjen na zavarenim pločama aluminijuma Al 2024 i čelika 1.0216 (oznake prema EN 10027-2). Postupak zavarivanja izveden je na paralelno postavljenim pločama, nakon čega je izvršen pregled zavarenog spoja. Kao metode IBR korišćene su ultrazvučna metoda i termovizijsko ispitivanje. Primenom vodenog mlaza iz zavarene ploče su isečeni uzorci u cilju ispitivanja mikrostrukture poprečnog preseka zavarenog spoja. Uočeno je da je dobijen kvalitetan zavareni spoj, te da odabrani eksploziv može naći dalju primenu u ovoj oblasti. Međutim, takođe su uočene i određene površine nezavarenog područja, što je nametnulo potrebu za izmenama postavke ovog postupka zavarivanja.

INTRODUCTION

Besides their application in munitions and armaments, explosives have a significant role in industrial applications, such as cladding or welding of metal plates. In the process of explosion welding, the energy of explosive detonation is used to achieve a metallurgical bond between two metal components which are metallurgical compatible, but also those that are non-weldable by conventional methods. Explosion welding is a solid-state process that produces a high velocity interaction of dissimilar metals by a controlled detonation. This method makes possible joining two metal plates with dissimilar metallurgical properties, regardless of the differences in their physical and chemical properties. In this process, the high pressure released by the explosion is used to accelerate one metal plate over the other to form the bimetallic product, achieving inter-atomic bonds. With this process, not only that the metals are joined without losing their pre-bonded properties, but even the bond strengths are higher than the strength of the weaker among the two materials, /12/.

There are numerous advantages of explosion welding: very large work pieces can be welded, many dissimilar, normally non-weldable metals can be bonded, melting temperatures and thermal expansion coefficient differences do not affect the final product, backing plate has no size limits, the strength of the welded joint is equal to or greater than the strength of the weaker of two metals joined, there is no heat-affected zone (HAZ), etc. /5/. However, explosion welding has also certain disadvantages: the metals must have high enough impact resistance and ductility, the geometries welded must be simple - flat, cylindrical, or conical, the cladding plate cannot be too large, and the explosion generates the noise and carries certain risks, so the process can require worker protection. Most important applications of explosion welding have been found in cladding of base metals with thinner alloys, welding of flat plates, joining of pipes in socket joints, seam and lap welds, and reinforcing aerospace materials with dissimilar metal ribs, heat exchangers, tubular transition joints, cutting tools, special corrosion resistant tanks, etc.

Explosives used in explosion welding are usually taken from the two groups: higher velocity, 4570-7620 m/s (trinitrotoluene, cyclotrimethylenetrinitramine, pentaerythritol tetranitrate, Datasheet, Primacord) and mid-low velocity, 1520-4570 m/s (ammonium nitrate, ammonium perchlorate, amatol, nitroguanidine, dynamites, diluted PETN), or special industrial mixtures developed for this purpose /8/. Nowadays, special plastic explosives might find application in tailorable detonating properties (Bajić et al. 2022). Most often explosives of lower detonation velocities are used, to avoid severe damage to the processed metal plates. Detonation velocity is an important parameter when it comes to explosion welding, and especially when the selected explosive is of powdery consistency, there are several factors affecting the detonation velocity: explosive type, composition of explosive and the thickness of explosive layer, /13/.

The aim of this study was to investigate the possibility to use the industrial explosive Amonex, a low-to-middle detonation velocity explosive, for welding of dissimilar metal plates, aluminium Al 2024 and steel 1.0216.

MATERIALS AND METHODS

Within the experimental part of the research, two dissimilar metallic materials were selected to be welded: aluminium plates Al 2024 and steel 1.0216. A configuration of parallel plates was selected, with a spacing of 4 mm between plates where small squares of poly(methyl methacrylate) were used as distancers inserted at plate corners. Flyer plate was Al 2024 with a thickness of 3 mm, and base plate was steel 1.0216 with thickness of 8 mm. Both plates had dimensions 150×200 mm. A wooden frame was used to enable pouring a uniform layer of the powdery explosive onto the top plate (Fig. 1). Industrial explosive Amonex, produced by TRAYAL Corporation was used, that consisted of ammonium nitrate (86.5 %) and TNT (4.5 %) as active components, and the rest of inert ingredients and additives, /16/. Declared detonation velocity is minimum 3200 m/s, density is 0.96-1.04 g/cm^3 and declared apparent (bulk) density is 0.5 g/cm^3. The quantity of Amonex explosive used in the experiment was 200 g, which is equivalent to a mass of 196 g of TNT. The necessary quantity was determined based on a theoretical approach, defined by Blazynski and Radić /4, 11/. Namely, explosion welding is possible if specific conditions are satisfied, regarding the properties of the material plates to be welded and the process conditions, which define the limits of the so-called welding window. According to Blazynski /4/, there are 7 factors that affect the explosion welding process which should be considered when defining the welding window for selected materials to be welded: initial angle of inclination for the plates, dynamic angle of collision, detonation velocity, impact velocity, flyer plate velocity, collision point velocity and material properties.

Figure 1. Plate before welding, experimental set-up, and welded plate after the process.

Characterization of Amonex explosive

Prior to the experiment, Amonex explosive was examined regarding its basic characteristics (Fig. 2). The bulk density of Amonex was determined using a standard brass container of defined exact volume of 100 cm^3 and 200 g mass, with a plastic funnel, by pouring the powdery explosive into the container under gravitational free fall, Fig. 2. This way we may obtain the density of explosive poured onto the metal plates during explosion welding, when the explosive powder takes the volume of the particles free package, without compression /9/. Detonation velocity was measured with optical probes and a photodetector connected with a time counter (Pendulum CNT-91 Timer/Counter/Analyzer) and an oscilloscope - Tektronix Digital Mix Oscilloscope MSO2022B), according to the method defined by Andjelić et al. /1/.

Figure 2. Determination of the bulk density of Amonex.

Quality inspection of the welded joint

The quality of the obtained welded joint was first inspected by non-destructive techniques of ultrasonic defectoscopy and infrared imaging, and afterwards, microstructural analysis of the welded joint was performed.

Ultrasonic testing was conducted using Phasor XS device, scanning over the entire surface of the welded plate with the ultrasonic probe, by the pulse-echo method.

Infrared imaging was carried out using IR camera FLIR SC620, with characteristics given in Table 1. The plate was recorded from both sides, aluminium and steel. They were recorded while heating: the plate was placed in a rack heated by a flow of warm air from the front side (recorded side); and while cooling down after being immersed in hot water during 5 min. IR imaging is a modern non-destructive technique, nowadays often applied in many fields, as well as in welding process monitoring, but also in quality control and inspection of defects in materials /7, 10, 14, 15/.

Table 1. PTA surfacing parameters.

Camera specification	FLIR SC620
FOV-field of view	24° horizontal and 18° vertical
Detector	640 × 480 pixels, uncooled, microbolometer
Minimum focus	0.3 m
Spectral range	7.5 μm – 13 μm
Accuracy	±2 °C or ±2 % of full scale
Operating temperature	-10 to 50 °C; 0 to 500 °C; 200 to 1600 °C

In order to perform microstructural analysis of the joint, the welded bimetal plate was cut with an abrasive water-jet parallel to the direction of detonation movement, polished to obtain a smooth cross-section and to be able to inspect the quality of the welded joint. Figure 3 shows a cross section of the welded material.

Figure 3. Cross section of the welded material.

RESULTS AND DISCUSSIONS

Quality of Amonex explosive

For the used Amonex explosive, the obtained values of bulk density and detonation velocity are given in Table 2, as mean values obtained from three measurements, along with the standard deviations.

Table 2. Bulk density and detonation velocity of Amonex.

Property	Mean value	St. dev.
Bulk density (g/100 cm^3)	76.18	0.63
Detonation velocity, D (m/s)	3769.8	19.5

The obtained detonation velocity is higher than declared by the producer, which is good from the point of view of the current application of this explosive. Also, it is important to notice that standard deviations for both measured characteristics are small, meaning that measurements were performed well, and the results are reproducible.

Ultrasonic defectoscopy results

Ultrasonic defectoscopy revealed welded and non-welded areas on the plate, while liquid penetrants confirmed the quality of welded surfaces. In Figure 4, the black area is the area where the material was joined. Outside of this area welding was not successful. The position of the explosive activation was marked with a red dot, its direction with a red arrow, and the front of the detonation wave with blue concentric circles. In the area of the initiation point the joint was not achieved, since there still was no stable detonation process developed. Maybe this could be avoided by implementation of some other initiation method, /2/. In the corners of the plates, where the spacers were positioned, non-welded areas can be observed as well.

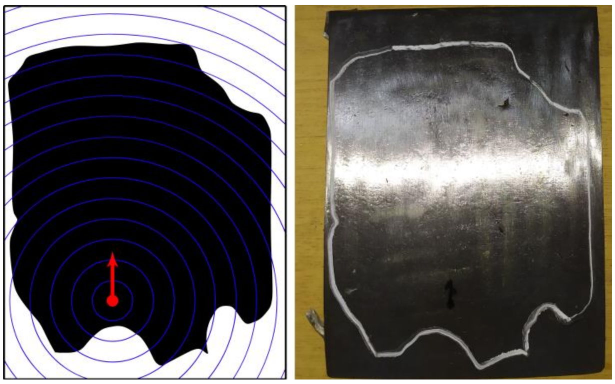

Figure 4. Zone of the weld detected by ultrasonic defectoscopy.

IR imaging results

The registered thermograms and diagrams of registered temperatures for the aluminium side of welded plate, heated with hot air, are presented in Fig. 5, as follows:

(a) welded plate in a rack and IR camera screen - experimental set-up;
(b) thermogram of the selected frame of recorded sequence of the weld sample (from the aluminium side);
(c) thermogram of the lower surface part of the aluminium plate at the beginning of heating;
(d) thermogram of the frame of the same sequence during heating;
(e) thermogram of the first frame of the same sequence, at the beginning of recording before heating.

Hotter and colder areas can be seen on the thermograms with a temperature scale. The transmission method of heating a complex structure of two welded materials of different thermophysical properties was applied here, /14/. Aluminium has a higher temperature diffusion coefficient, responsible for the rate of heat transfer from a region of higher temperature to a region of lower temperature. If we assume that the rate of heat transfer in a well-welded region is better than in places with weld defects, conclusions can be drawn about the quality of the welded joint, that is, if we observe IR images of the aluminium surface, we expect higher temperature values in places of a bad welded joint, because in these places heat has not successfully transferred to the steel plate. Figures 5b and 5c show the thermal reflection on the aluminium side, while the sample is placed in a rack heated by a flow of warm air from the front side (recorded). Here, several areas need to be analysed. The colder dark region with the temperature at measuring point SP02 = 23.9 °C is highlighted, located in the centre of that surface, and the warmer region with a temperature at point SP01 = 26.0 °C, about 2.1 °C higher than the colder region at the moment of heating the steel plate opposite to this region. In Fig. 5d, it can be seen that the lower part of the surface of the aluminium plate is hotter due to the poor quality of the weld in this part of the tested material. In order to remove the doubt that these differences are the result of some previous state of the material, Fig. 5e shows the thermogram of the aluminium side before heating, where it can be seen that temperatures in all parts of the welded material are the same, i.e., the temperatures are the same in these areas, being logical since the aluminium and steel plates are in thermal equilibrium at room temperature.

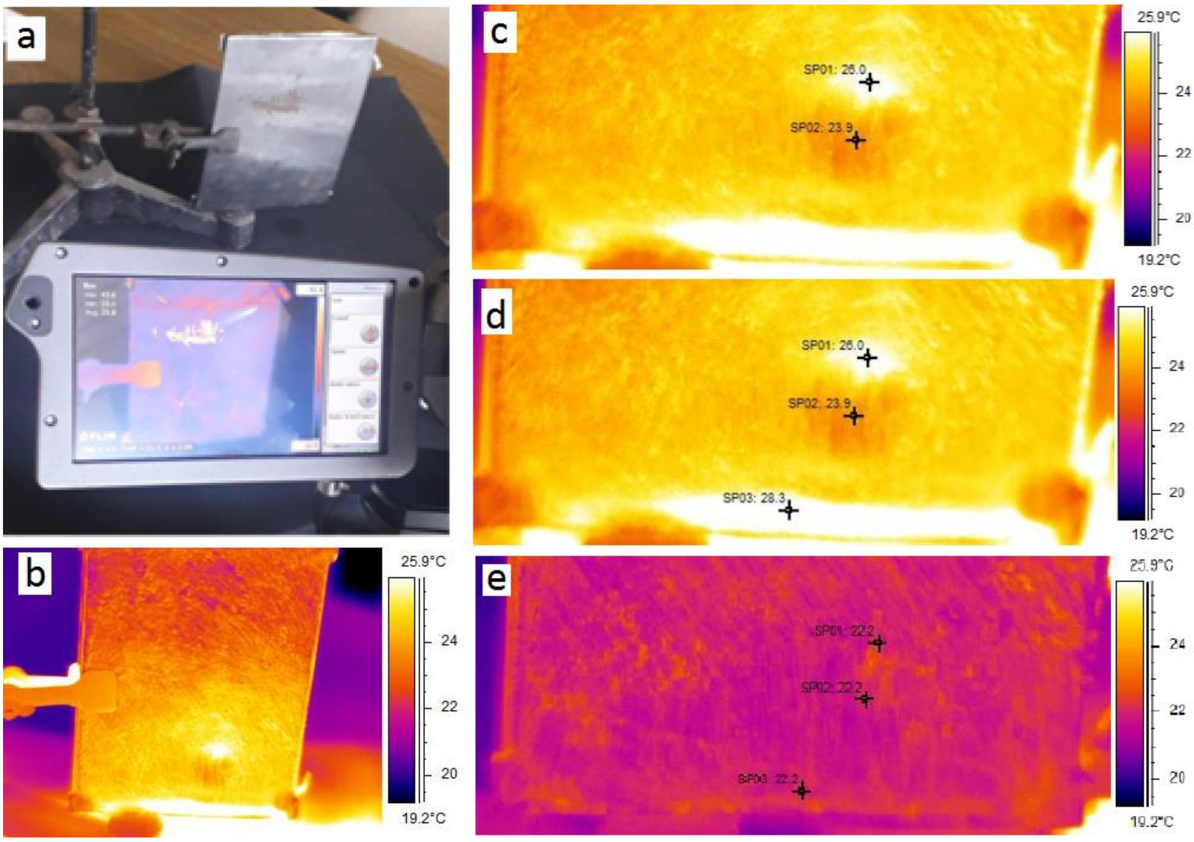

Figure 5. IR imaging results - aluminium side, heated with hot air.

These initial experiments showed that it is necessary to eliminate the appearance of the false ‘parasitic’ reflection of warm objects from the environment to the highly reflective surface of the aluminium plate. To overcome this, in the next step the aluminium side is pasted over with insulating tape and heating is done by immersing in warm water for 5 minutes. In the plate heated in this way, the thermograms show registered maximal and minimal temperatures T_{max} = 49.4 °C and T_{min} = 47.2 °C. This may indicate the existence of inhomogeneity in the welded joint, but analysis must also be carried out on the other side of the material. When observing the steel side of the welded sample, Fig. 6, an area with corrosion was noted.

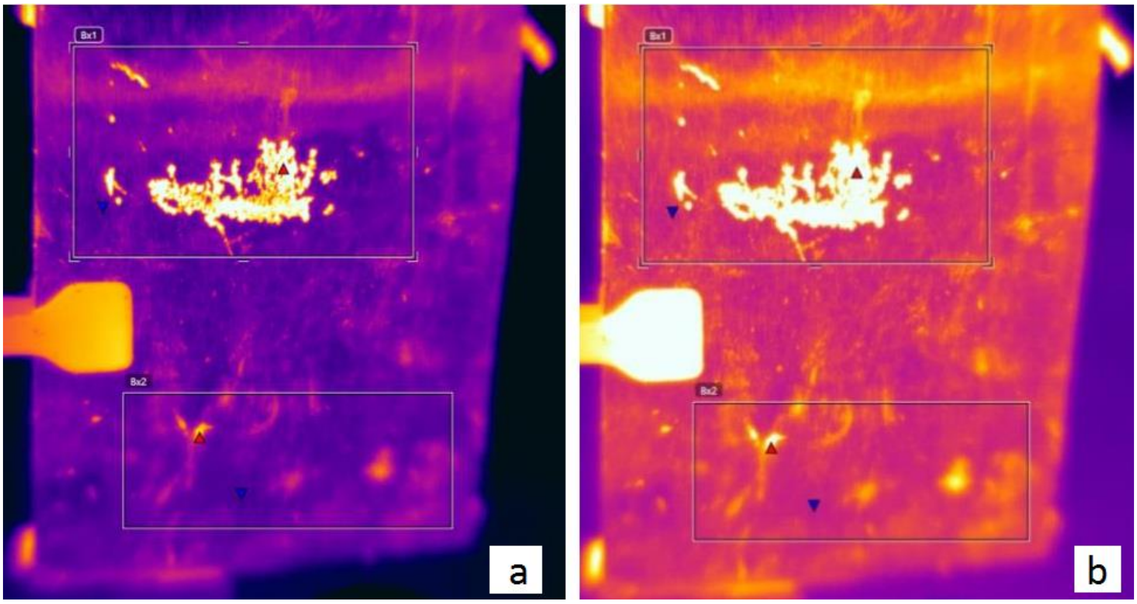

Figure 6. IR imaging results - thermogram of the steel side with marked measuring areas Bx1 and Bx2.

On the thermogram in area Bx1 the maximal registered temperature is T_{max} = 43.1 °C (blue arrow), and in the area with minimal temperature T_{min} = 23.1 °C, while the average temperature in that area is T_{avg} = 26.8 °C. The surface of steel with corrosion has a significantly higher radiation temperature due to a higher emissivity coefficient. In area Bx2, the maximal temperature is T_{max} = 36.2 °C, (red arrow), while the blue arrow is in the area of different emissivity compared to the minimal temperature T_{min} = 23.3 °C. The average temperature in that area is T_{avg} = 24.8 °C.

From the thermographic analysis, it can be concluded that there is a part on the rim/bottom of the plates where the welding is not successful, and in the larger part of the plate welded joint quality is satisfactory. Also, the area with an unevenness of the sample/indentation, suspected to be a defect, is nevertheless well welded, and the higher values of registered temperatures are a consequence of the emissivity of the material.

Microstructure of the welded joint

Images obtained from microscopic analysis of the welded joint microstructure, given in Fig. 7, reveal that between the two welded metals, a certain degree of melting of the Al plate occurred and an intermetallic zone has appeared. This may affect mechanical properties of the plate, so maybe for future welding, a smaller quantity of Amonex could be considered. The weld fusion line has a shape of waves characteristic for explosive welding.

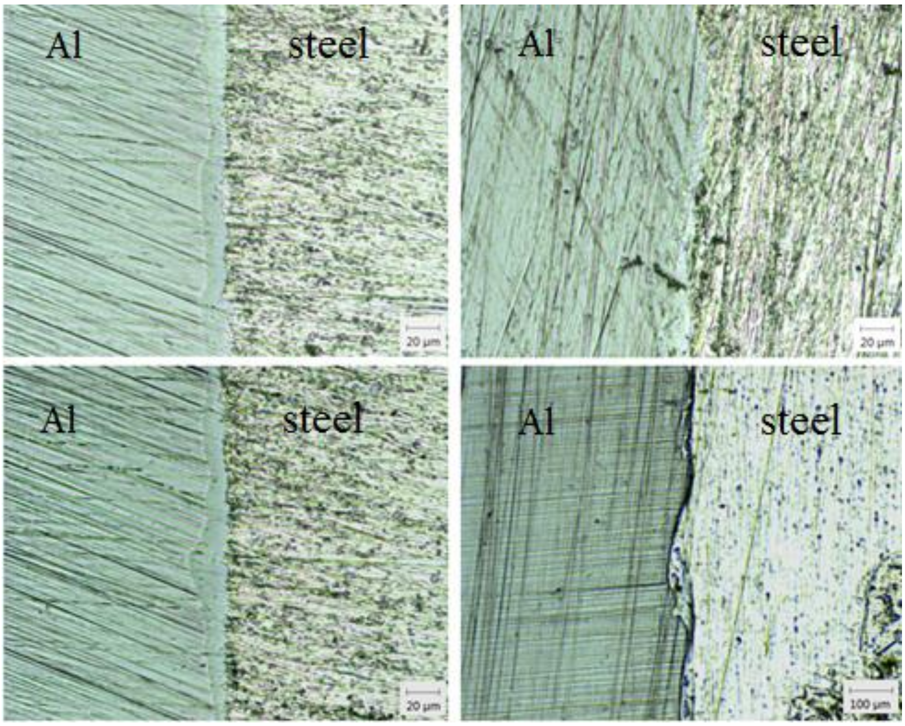

Figure 7. Microstructure in the zone of the welded joint.

CONCLUSIONS

Explosion welding procedure was applied to obtain a welded joint of Al 2024 and steel 1.0216 plates. Initial quality control has shown that Amonex explosive satisfies the requirements for this application regarding the bulk density and detonation velocity. First, non-destructive tests were performed and revealed good quality of the welded joint, but also existence of non-welded areas. Ultrasonic testing showed that there was a good joining of plates, with an unwelded zone near the explosion activation spot and on the edges of the plates. IR method confirmed these results.

For microscopical analyses the plate was cut using water jet and metallographic tests have shown that a certain degree of melting of the Al plate and an intermetallic zone appeared. This may be an indication that the applied quantity of Amonex could be reduced in future work. Future research should be based on different quantities of Amonex explosive in order to find the optimum, as well as on larger plates for more detailed research and confirmation of the obtained quality. Also, other non-destructive techniques should be applied in the quality control of the welded joint.

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