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ТЕХНОЛОШКОГ РАЗВОЈА И ИНОВАЦИЈА

11th International Conference on Renewable Electrical Power Sources

PROCEEDINGS

Editor Dr Milica Vlahović

Belgrade, November 02-03, 2023

P R O C E E D I N G S

11th International Conference on Renewable Electrical Power Sources

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on Renewable Electrical Power Sources

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FOREWORD

The conditions created by the development of technologies in which modern man lives have led to a complex and paradoxical effect: that by removing obstacles on the way to a more comfortable, simpler, faster and more efficient life and way of working, man also generates numerous misfortunes, attracting dark clouds of threats to the survival of the planet and humanity. The question that concerns and affects all of us - all people, all living beings, systems in which life takes place, large and small, strong and weak - boils down to the problem of the negative impact of man on the environment; this issue invites us to an urgent solution by looking at the causes, proposing solutions, evaluating them, changing approaches and ways of thinking, as well as drawing correct conclusions. Simply put, by adapting nature to one's own needs, man threatens and damages it. That is why, with the joint efforts of all of us, individuals, organizations and states, it is necessary to take all possible measures to immediately prevent the negative effects that are ahead of us.

The importance of renewable sources of electricity, which this international conference focuses on, is noticeable from two angles: the first - it is certain that fossil fuels as a resource will disappear and it is necessary to find alternative sources, the second - the use of renewable energy sources by its essence implies "clean" technology that significantly contributes to reducing CO_2 *emissions and thus mitigating climate change and reducing pollution, while encouraging social and economic development in all spheres of life.*

The 11th International Conference on Renewable Electrical Power Sources is organized by the Society for Renewable Electrical Power Sources (DOIEE) at SMEITS, with co-organizers: The Institute of Architecture and Urban & Spatial Planning of Serbia (IAUS) and the Chamber of Commerce and Industry of Serbia, with the support of the Ministry of Science, Technological Development and Innovation of the Republic of Serbia.

The registered participants designed their papers according to the given conference topics:
- Energy sources and energy storage;
- Energy efficiency in the context of use of renewable energy sources (RES);
- Environment, sustainability and policy;
- Applications and services.

Eminent authors - scientists, teachers, experts in this field from fifteen different countries: Algeria, Belgium, Bosnia and Herzegovina, China, Croatia, Greece, Hungary, India, Portugal, Saudi Arabia, Serbia, Slovenia, Spain, the United Arab Emirates, and Ukraine, contributed to the conference through sixty-nine papers that were reviewed by the Scientific Committee of the Conference, and after the review process were accepted for presentation at the conference and for publication in the proceedings.

At the end of this short message and at the beginning of the proceedings I believe that it can be proudly said that scientists, researchers, policy makers and industry experts gathered in one place, in order to exchange experiences and knowledge with the aim of promoting scientific and professional ideas and results of research, technology improvement for the use of RES, promoting the rational use of electricity, affirming and proposing inventive solutions in the field of sustainable sources of electricity.

Belgrade, *Milica Vlahović*
November 2023

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ISPITIVANJE KVALITETA EKSPLOZIVNO ZAVARENOG SPOJA RAZNORODNIH METALA ZA POTENCIJALNU PRIMENU U OBNOVLJIVIM IZVORIMA ENERGIJE

TESTING THE QUALITY OF EXPLOSIVELY WELDED JOINTS OF DISSIMILAR METALS POTENTIALLY APPLICABLE IN RENEWABLE ENERGY SOURCES

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Apstrakt

Eksplozivno zavarene metalne ploče velikih površina ili specifične geometrije nalaze primenu u opremi za proizvodnju električne energije iz obnovljivih izvora. U eksplozivnom zavarivanju koristi se energija kontrolisane detonacije da bi se ostvario spoj, kada se jedan metalni deo sudara sa drugim velikom brzinom formirajući spoj talasastog profila. Eksplozivno zavarivanje se koristi u proizvodnji specijalnih komponenti za obnovljive izvore energije, kao što su delovi vetroelektrana ili turbina, jer omogućava čvrste i sigurne spojeve između različitih vrsta metala. Ova tehnika se može primeniti i u izradi specifičnih komponenti za solarnu industriju, kao što su nosači solarnih panela koji zahtevaju snažne i pouzdane veze, neretko između raznorodnih materijala koje je teško zavariti konvencionalnim postupcima. Osim toga, eksplozivno zavarivanje može biti korisno u proizvodnji baterija za skladištenje obnovljive energije, gde je ključno osigurati da su spojevi mehanički i električki pouzdani. Za primenu u takvim konstrukcijama važno je da se može vršiti in situ kontrola primenom nedestruktivnih tehnika kako bi se proverila uspešnost izvršenog zavarivanja celih komada ili proizvoda dobijenih na ovaj način. U ovom radu prikazana je primena nedestruktivnih i destruktivnih tehnika za ispitivanje kvaliteta eksplozivno zavarenih spojeva dva različita seta metalnih ploča: aluminijumska legura-čelik i ugljenični čelik-alatni čelik, sa dva eksploziva, Amonex i Demex. Ispitivanje kvaliteta ostvarenih spojeva vršeno je površinskim metodama i zapreminskim metodama bez razaranja i sa razaranjem. Primenjene su sledeće tehnike bez razaranja: vizuelna metoda, ispitivanje tečnim penetrantima, radiografija i ultrazvučno ispitivanje. Kako bi se rezultati nedestruktivnih tehnika potvrdili, izvšena je i mikrostrukturna analiza poprečnog preseka zavarenog spoja. Primena tehnika ispitivanja bez razaranja u ispitivanju kvaliteta eksplozivno zavarenih spojeva doprinosi smanjenju troškova kada se vrše destruktivna ispitivanja. Ovim tehnikama može pratiti uspešnost samog procesa i na taj način poboljšati tehnološki proces izrade bimetalnih spojeva eksplozivnim zavarivanjem.

Ključne reči: *ispitivanje bez razaranja, eksplozivno zavarivanje, ultrazvučna defektoskopija, ispitivanje tečnim penetrantima*

Abstract

Explosively welded metal plates of large surfaces or specific geometries are used in equipment for the production of electricity from renewable sources. In explosive welding, the energy of a controlled detonation is used to create a joint, when one metal part collides with another at high speed forming a weavy bonded interface. Explosive welding is used in the production of specialized components for renewable energy sources, such as parts of wind farms or turbines, because enables strong and secure connections between different types of metal or material. This technique can also be applied in the production of specific components for solar industry, such as solar panel supports that require strong and reliable connections, often between dissimilar materials that are difficult to weld with conventional methods. In addition, explosive welding can be useful in the production of batteries for renewable energy storage, where it is crucial to ensure that the connections are mechanical and electrically reliable. For such structures it is important to be able to perform in situ monitoring using nondestructive techniques to check the success of the performed welding on the whole pieces or products made this way. This work considers the application of non-destructive and destructive techniques to examine the quality of explosively welded joints of two different sets of metal plates: aluminum alloy-steel and carbon steel- highly wear resistant alloy steel, with two explosives, Amonex and Demex. Inspection of the joints was carried out using surface methods and non-destructive volumetric methods. The following techniques were applied: visual method, liquid penetrant testing, X-ray and ultrasound defectoscopy. To confirm the results of non-destructive techniques, a microstructural analysis of the cross-section of the welded joint was performed. The application of non-destructive testing techniques in testing the quality of explosively welded joints contributes to the reduction of costs that would be caused by destructive tests, since these techniques can be used to monitor the success of the process itself and thus improve the technological process of producing bimetallic joints by explosive welding.

Key words: *non-destructive testing, explosive welding, ultrasonic defectoscopy, liquid penetrants testing*

1 Introduction

Explosive welding is used in the production of specialized components for renewable energy sources. It can be used to join dissimilar materials in wind turbine components, such as the bonding of aluminum to steel in the rotor blades or the tower structure. Explosive welding can be employed in the fabrication of heat exchangers used in concentrated solar power systems, where it's crucial to ensure efficient heat transfer. It can be used to create strong, corrosion-resistant connections in underwater components like turbine blades, ensuring their durability and efficiency. In geothermal systems, explosive welding can help in the construction of heat exchangers, which are essential for transferring geothermal heat to the surface. Also, it can be used to join materials in underwater structures and components used in wave and tidal energy systems, where corrosion resistance and durability are paramount. Explosive welding offers the advantage of creating robust, metallurgically bonded joints between dissimilar materials, enhancing the performance and longevity of renewable energy components.

Non-destructive testing (NDT) represents any form of testing or inspection that can verify the structural integrity of a component without affecting its functionality. NDT methods have become indispensable for checking the quality of welded joints or monitoring corrosion damage in exploitation [1,2]. On the other side, 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 metallurgically compatible, but also those that are non-weldable by conventional methods [3-5]. Explosion welding is a solid-state process that produces a high velocity interaction of dissimilar metals by a controlled detonation and the advantages and disadvantages of explosive welding are summarized in Table 1.

Principle of explosion welding includes several phases. The ideas listed below [6-8] are the foundation of the explosive welding process:

- the explosive material is distributed across the top of the cladder metal plate, which can be positioned parallel to or at an angle to the base plate;
- a single blasting cap can be used to ignite the explosive;
- upon explosion, the cladder plate collides with the base plate and creates a weld;
- wavy joint is formed along the mechanical bonding that occured.

Potential use of aluminum-steel explosively welded joints is for connecting aluminum roofs, masts and antennas to steel structures which would reduce the weight and increase the stability of the structure. Secondly, this kind of joints might be used as a cryogenic joint and for connections to liquid gas storage containers, as well in shipbuilding for making ship's formwork [9-11]. On the other side, welding metallic materials - plates of highly wear resistant alloy steel X160CrMoV121 and low-carbon steel S355J2 have potential application for specialized cutting tools [12,13].

Table 1 – The advantages and disadvantages of explosive welding

Advantages	Disadvantages
Very large work pieces can be welded,	Metals must have high enough impact resistance and ductility,
Can bond many dissimilar, normally unweldable metals,	The geometries welded must be simple - flat, cylindrical, conical,
Material melting temperatures and coefficients of thermal expansion differences do not affect the final product,	The cladding plate can't be too large,
Process is compact, portable, and easy,	Noise & blast can require worker protection, vacuum chambers, buried in sand/water.
Welding can be achieved quickly over large areas,	Metals must have high enough impact resistance and ductility.
No need for surface penetration,	
Backer plate has no size limits,	
Inexpensive,	
The strength of the weld joint is equal to or greater than the strength of the weaker of two metals joined,	
No heat-affected zone (HAZ).	

In this paper, non-destructive techniques were applied to examine the quality of explosively welded joints of two different sets of metal plates: aluminum-steel and carbon steel- highly wear resistant alloy steel, with two explosives, Amonex and Demex.

2 Experimental part

2.1 Explosive welding

For both sets of metal plates: aluminum alloy-steel and carbon steel- highly wear resistant alloy steel the same experimental set-up for explosive welding was followed. The base plate was 8 mm thick S355J2 steel, whereas the flyer plate (EN AW 2024 (AlCu4Mg1) or X160CrMoV121) was 3 mm thick. The plates size was 150 mm x 200 mm. Small poly(methyl methacrylate) squares were used as spacers at the plate corners in a parallel plate design with a 4 mm gap between the plates. The upper plate was covered with an even layer of powder explosives due to the a wooden frame (Figure 1).

a) Plate before welding, experimental set-up with Amonex explosive, and welded plate Al/Steel

b) Lleft: steel plates in parallel configuration with wooden spacers; right: wooden frame placed over the plates with DEMEX explosive and blasting cap placed in a holder

Figure 1. Experimental set-up for explosive welding

Quantity of 200 g of explosive Amonex 4 was used, equivalent to the mass of 196 g of TNT, while quantity of 540 g and 640 g of explosive Demex was used. The industrial explosive Demex consists of ammonium nitrate (~95.5%) and TNT (2%) as energetic components, and other inert constituents. Wooden frame was used to enable pouring an uniform layer of the powdery explosive onto the top plate [14]. The mass of the explosive was calculated according to theoretical approach, to meet the criteria of a quality welded joint [15-17].

2.2 Non-destructive methods for welded joint quality inspection

The quality of the obtained welded joint was examined using different non-destructive methods.

First method used for inspection joint quality is visual testing according to the standard SRPS EN ISO 17637. Visual testing (VT) is the oldest and most common method for testing materials without destruction. The main features of this method are that it is simple, easy to perform and belongs to relatively cheap methods. It is preferable that the visual examination is performed before some other method, and therefore visual control is an important part of complex examinations by non-destructive methods. This method is based on the observation of surface parts of products and tested samples in order to detect and analyze irregularities, as well as drawing relevant conclusions. It is carried out in the appropriate phase of the production process [18]. Visual inspection can be done before, during and after welding. The VT method allows the detection of some major damage on the surface of the material, which can automatically reduce the scope of other types of testing that require more time and are much more expensive. In case of explosion welding, this method is not applicable during the welding, due to safety procedures, and also having in mind that the process is very fast so the visual insight would not change the outcome of the procedure. This method is applied after the welding procedure, to observe eventual major defects or non-welded zones.

Next method for examination quality of joint is surface method-liquid penetrant testing (PT). Testing with liquid penetrants of the explosively welded steel plate was performed with the penetrant system IIEd according to the standard SRPS EN ISO 3452-1 and it is shown in Figure 2 [19]. The test temperature was 23 °C, while the illumination of the test surface was 750 lx. Before testing with liquid penetrants, the surface of the samples was cleaned and dried. After that, penetrant was applied to the test surface and left to penetrate into the open surface irregularities. After the time required for penetration, the excess penetrant was removed from the surface and then a developer was applied, which has a role to absorb the penetrant left in the irregularities and to give a visible indication.

Figure 2. Penetrant system IIEd according to the standard SRPS EN ISO 3452-1 [19]

The third non-destructive method applied is ultrasonic defectoscopy. The welded steel plates with aluminum alloy were ultrasonically tested with the "Phasor XS" device / ultrasonic probe over the entire surface, by the pulse-echo method [20]. Explosively welded plates of steel (carbon/tool) were examined with an ultrasonic flaw detector "UCD-50" manufactured by Kropus. An ultrasonic SE probe with a frequency of 10 MHz was used to scan the entire surface of each plate (Figure 3). Tapetol glue was used as a contact agent, and the test was performed in accordance with the SRPS EN 16809 standard [21]. Considering that different materials with different ultrasound speeds were joined, calibration was performed on the base materials. For steel, the calibration was done on a 20 mm thick plate with a speed of longitudinal waves of 5860 m/s, while for aluminum the speed was 6320 m/s.

Figure 3. a) Ultrasonic thickness measurement of Explosively Welded joint b) SE probe

The fourth non-destructive technique used to examine the quality of the welded joint was radiography. Radiographic examination is a process in which, based on the use of X-ray radiation, the parts to be examined are irradiated. It belongs to the group of conventional methods used for testing, most often welded structures. X-ray testing enables examination of internal, hidden material defects based on the ability of X-rays to penetrate different materials of different thickness and density. Penetrating radiation passing through the material can be detected by radiation-sensitive film (film radiography). Radiographic control in the dissection was performed with the "TELEDYNE ICMCP300D" device, according to the SRPS EN ISO 17636-1 standard [22] (Figure 4).

Figure 4. "TELEDYNE ICMCP300D" device and X-ray testing.

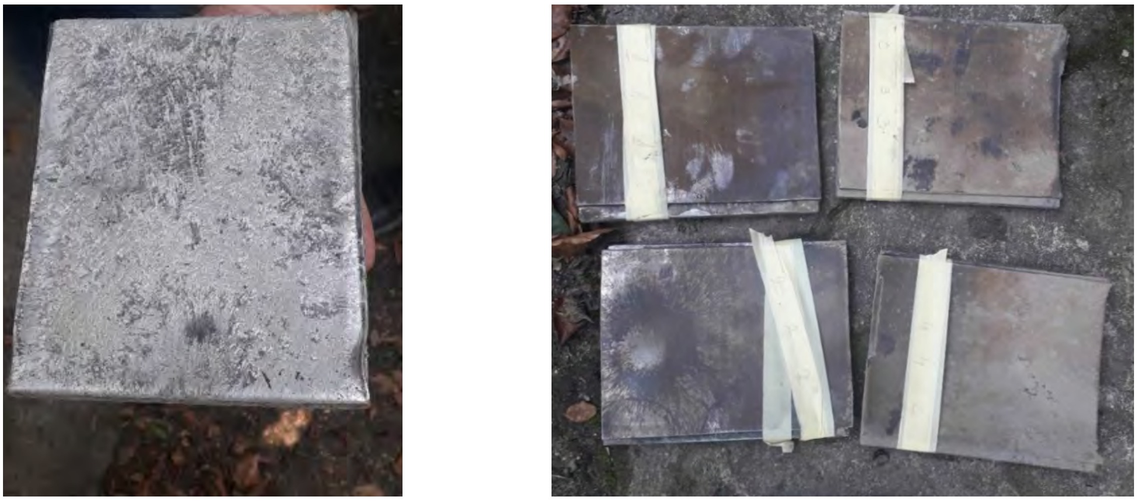
At the end, one destructive technique was applied to control the obtained results from non-destructive techniques: microstructural analyses of the cross-section of the welded joints. In order to prepare the samples for metallographic examination, the welded plate was cut with a water jet, with the following working parameters: the speed of the jet was 50 mm/min, pressure 3800 bar, and consumption of abrasive material 250 g/min and 1.5 l/min of water. Standard metallographic preparation techiques, grinding and polishing, applied for specimens preparation. Specimens cross-sectional of welded plates steel/steel were etched with 3% nital. Microstructures were observing by light „Leitz“ optical microscopy equipped with a DFC 295 camera (Figure 5).

Figure 5. Optical microscope Leitz equipped with a DFC 295 camera.

3 Results and discussion

3.1 Visual examination

After explosive welding, the plates were visually inspected in order to check whether the welded joint was achieved over the entire surface. Figure 6 shows the appearance of explosively welded structural steel/aluminum alloy and structural steel/tool steel plates.



Al alloy/steel Steel/steel

Figure 6. Explosively welded joints of two different sets of metal plates: aluminum alloy-steel and carbon steel- highly wear resistant alloy steel, with two explosives, Amonex and Demex

Visual inspection revealed that there was no successful connecting of materials on the edges and the corners of the plates, where the spacers were inserted. Also, due to the detonation effect, plastic deformation of the plate occurs. After the visual examination, it can be concluded that a satisfactory welded joint has been achieved on a large part of the surface of the steel/aluminum alloy and steel/steel joints.

3.2 Liquid penetrant testing

In order to see if the welded joint is consistent and without irregularities, samples were cut from the plate and a standardized surface method was performed using liquid penetrants. The parameters during the test are given in Table 2.

Table 2 – Testing parameters

No.	*Portable sprayers:*	*Batch No.:*	*Time(min)*
1	*MR68C - Penetrant*	*68C/1092 A*	*20min*
2	*MR70 - Developer*	*70/1292 A*	*15min*
3	*MR79 - Remover*	*79/1298 A*	*/*
Measuring equipment:		*Calibration certificates No.:*	
1	*LUX Metar AH6384*	*057/021 LK_03 from 08.06.2021.*	
Drying:	Ambient	*Penetrant system remover:*	Water, remover

Before liquid penetrants testing, the surface must be cleaned and dried. After that, a *MR68C* penetrant is applied to the test surface to enter the open surface irregularities. After the time required for penetration, the excess penetrant is removed from the surface, and then a developer is applied which absorbs the penetrant left in the irregularities and gives a visible indication.

The cleaned samples were sprayed with colored penetrants and after a penetration time of 20 min, the excess penetrant was removed from the surface with a lint-free cloth and the samples were allowed to dry in ambient air before applying the liquid developer (Figure 7).

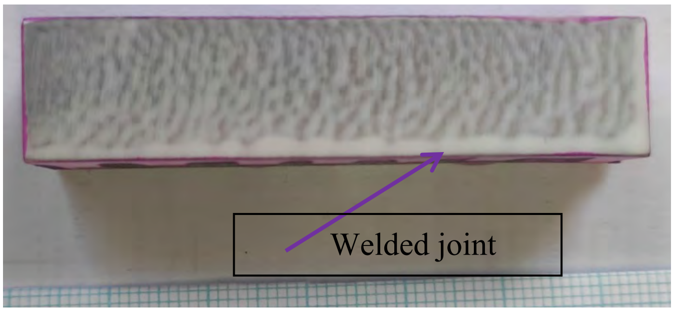


Figure 7. Steel/steel sample after 20 min application of wet developer

As seen from Figure 7, the penetrant did not show any irregularity along the welded joint, so the procedure of explosive welding may be considered successfully performed. All samples of explosively welded plates of structural steel with aluminum alloy and structural steel with tool steel showed that there are no cracks, porosity or other irregularities at the joint.

3.3 Puls-echo method

The Pulse-echo method was used with only one probe in contact with the prepared basic part of the material. The device emits very short pulses. After emitting a short pulse, the transmitter is turned off, and the receiver is turned on, so that it is ready to "catch" those waves that are generated by the reflection of waves from the surface that limits the observed element. In the case of poor contact between the plates, the emitted pulse will be reflected from them and thus travel a shorter distance than it would be if there was a homogeneous connection, *i.e.* if the plates were metallurgically connected. With this method, the places where welding errors were observed, *i.e.* where they were not joined, were recorded. Application of the Pulse-echo method [20] requires a special type of ultrasonic apparatus, in which there is only one probe that is in contact with the material.

With this method, the places where the errors of the welded joint were observed, that is, where they did not join, were recorded. A more suitable method for testing is Phased array-based ultrasonic testing [23]. The test results are shown in Figure. 8 for aluminum alloy-steel welded by Amonex and in Figure 9 for carbon steel- highly wear resistant alloy steel welded by Demex explosive.

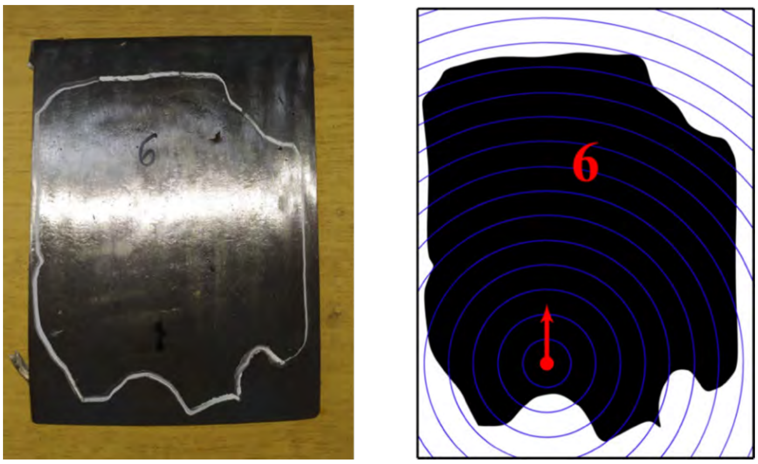


Figure 8. Result of explosively Al/steel welded joint testing with ultrasound defectoscopy.

The black area in the presented image is the area where the material was joined. Outside of this area welding was not successful. The position of the explosive activation is marked with a red dot, its direction with a red arrow, and the front of the detonation wave with blue concentric circles.

The detonation wave is extinguished at an explosive thickness of around 15 cm, according to theoretical analysis [8-10]. At the point of activation of the detonator capsule, the material is not connected. A failure merge in that area is caused by too much impact energy and incomplete energy reflection.

Conditions for the best value of the dynamic angle are not produced since the impact in that zone occurred at a straight angle. A stable forward detonation wave is established X mm from the point of detonation. Metal junction on a surface where no stable front has been established it is considered bad, or no joint at all. That part is being removed.

The hatched area in Figure 9 is the area where the material is joined. Outside of it, the joining of materials was not realized. Sample numbers of steel plates 1 and 2 correspond to different amounts of Demex explosives, namely 540 and 640 g, respectively. At the point of activation of the detonator capsule, the material did not fuse in all the steel plate samples as shown in the hatched surfaces of the real samples in Figure 9.

Figure 9. Explosively welded plates 1 and 2: area of weld, registered by ultrasonic method.

3.4 X-ray examination

The X-ray examination was performed on the "TELEDYNE ICM CP300D" device. Voltage, amperage and exposure time are adjusted for each plate. Thickness and material play a major role in obtaining quality radiographic images.

Radiography of the welded joints did not reveal significant joint defects. It is known that the X-ray is a reliable test for the detection of three-dimensional defects, but it is not able to show planar, two-dimensional defects and small defects (cracks) in the normal direction in relation to the direction of incident radiation [24]. Therefore, the detection of the lack of connection will depend on the orientation of the radiation. X-ray examination showed thinning of the material (moving plates) or deformation at the place of initiation of the explosive (Figure 10).

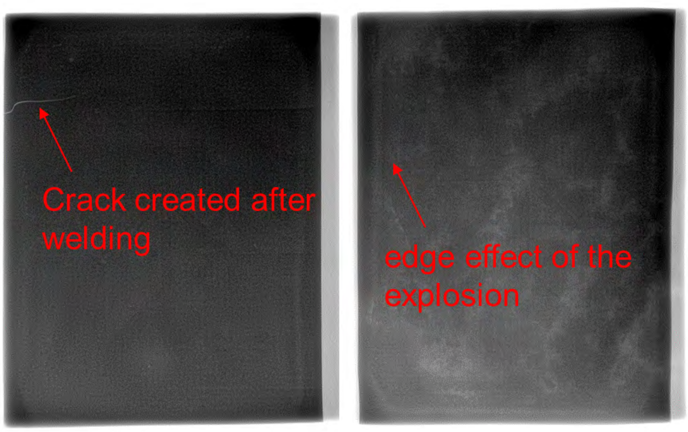


Figure 10. X-ray of explosively welded steel/steel plates with 540g and 640g of Demex

A crack was discovered on plate 1 welded with 540 g of Demex explosive (Figure 10a). Deformation was detected on all plates (on the edges of the plates) due to the presence of a wooden box that limits the volume of the explosives. There were no explosives in that place, and therefore insufficient pressure was achieved for joining. The radiographic examination technique enables reliable scaling of defects, but does not locate them completely. In order to compensate for the lack of radiographic testing, it is necessary to approach the implementation of tests using destructive methods.

3.5 Microstructural analysis

Optical images acquired from investigation of the welded joint microstructure, shown in Fig. 11, show that an intermetallic zone has developed between the two welded metals as a result of some melting of the Al alloy plate. A reduced amount of Amonex might be recommended for future welding because this might alter the plate's mechanical qualities. The wave-like appearance of the weld fusion line is typical of explosive welding.

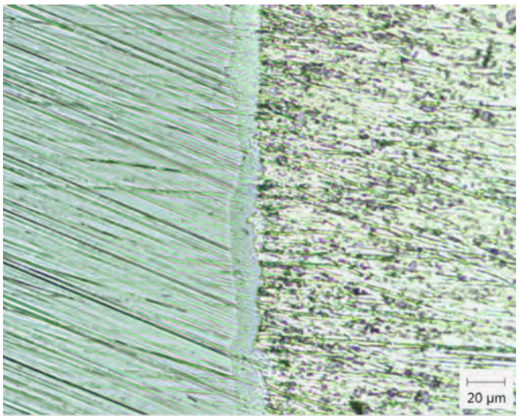


Figure 11. Microstructure in the zone of the welded joint Al alloy/Steel

Joint morphology is one of the more relevant indicators of joint quality. A wavy or transitional connection in the direction of action of the force caused by the explosion, without an intermediate layer, gives the desired properties. An important feature typical of high-speed impact welding is the formation of a liquid phase on the surface of the joint. When dissimilar materials are welded, it is often observed that formation of a wave-like morphology of the interfaces of the joining metals takes place within these areas, so such melting zones are often called vortex zone [17]. Optical images of the wavy interface of steel/steel plates with 540 g (left) i 640 g (right) of Demex are shown in Figure 12. This swirling is attributed to the mutual erosion of surface materials by the cumulative jet that occurs as a result of the collision.

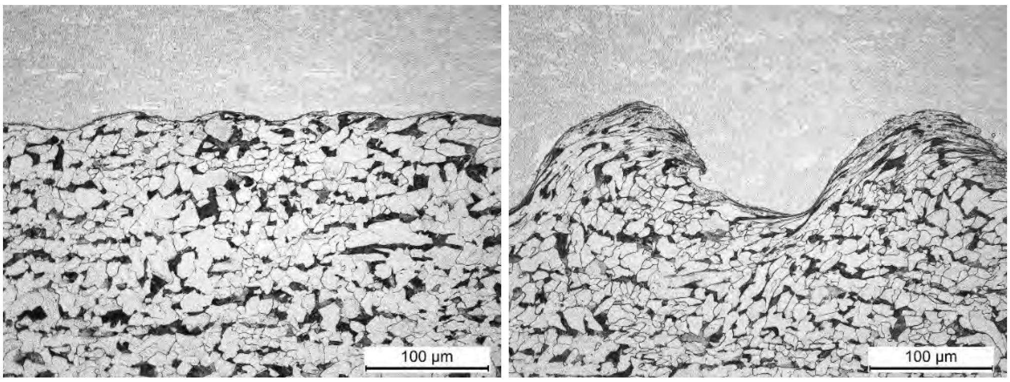


Figure 12. Microstructure of wave-shaped interface of the welded joints 1 (left) and 2 (right) steel/steel plates

As seen in Figure 12, the joint 2 has a much larger joining area between the two welded metal plates than the joint 1, which lacks the noticeable distinctive wave-like shape. This could imply that the 540 g of Demex selected for welding 1 is possibly close to the minimum amount of explosive required to provide the welded junction.

4 Conclusion

In this paper, we tried to point out the importance of non-destructive methods in testing the quality of explosively welded joints, as time, materials and energy saving methods. Surface procedures and non-destructive volumetric approaches were used to inspect the explosively welded joints. The visual testing method, liquid penetrant testing, X-ray, and ultrasound defectoscopy were all used. A microstructural examination of the cross-section of the welded junction was done to verify the findings of non-destructive methods. Since non-destructive testing techniques can be used to track the success of the process itself and thereby enhance the technological process of producing bimetallic joints by explosive welding, their use in evaluating the quality of explosively welded joints helps to mitigate the costs that destructive tests would otherwise incur. We can conclude that tested explosively welded joints can be used in the production of specialized components for renewable energy sources, such as parts of wind farms or turbines, or as specific components for solar industry, such as solar panel supports that require strong and reliable connections because these joints enables strong and secure connections between different types of metal.

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