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Original scientific paper

Quality Parameters of Explosively Welded Spring Steel and Carbon Steel

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Abstract: Explosive plating, or welding, is a process where part of the kinetic energy of the detonation of a certain amount of civil explosive material is used to accelerate the plate, which will form a welded joint upon an oblique impact on a stationary plate. The conditions that must be met to achieve a good weld are determined by welding criteria. Today, the most commonly used welding criteria are based on the speed of the collision point and the collision angle. In this paper a research is presented on explosion welding of two different steels and on quality of the obtained welded joint. Carbon steel and spring steel were welded using Amonex 4 explosive in different quantities. Basic characterization of the explosive was carried out: bulk density and detonation velocity were determined. Quality of the welded joint was inspected using the ultrasonic method. Possible intermetallic zones at the joint site created by the effect of increased temperature were examined by optical and scanning electron microscopy. Fracture toughness of the welded plates was determined, as well as hardness. The achieved experimental results were compared to theoretical predictions.

Keywords: carbon steel; detonation wave; explosion welding; intermetallic zone; melting zone; spring steel; ultrasound

1 INTRODUCTION

Explosion welding is one of the most useful high-energy methods for obtaining new or widely used materials with improved properties. It is most often used for welding dissimilar materials [1-4]. Its main advantage is that there is no limit to the surface area of the plate that can be welded as with other welding methods.

The development of new materials and production processes that use unconventional energy sources is the result of scientific and technical-technological progress of human society. The application of explosion welding to obtain bimetallic and multi-layer [5-9] compositions of materials is gaining more and more importance. Therefore, this method itself as well as all the phenomena that occur during it are increasingly attracting the attention of both scientists and its users.

Explosion welding is a unique process in terms of its practical application. It is known that the processing of materials requires equipment, tools and a source of energy. The technological process of making a new part requires new tools, which additionally increases work and time costs. On the other hand, explosion welding is much simpler, because explosives [10] are both a source of energy and a tool. In recent years, an ultrasound source has also been used in the explosive welding process [11-14]. Designing and making the necessary tools and controlling new work operations do not require much time, which enables more flexible production, but also the possibility to replace one material with another. This is very important for small-scale production.

2 WELDING CRITERIA

Explosion welding of different materials is possible under specific conditions, i.e. properties of the material and conditions of the process.

The area of welding (Welding window) is limited by straight and curved lines as shown in Fig. 1. In order to define it, a relationship must be established between the initial conditions - angles α, β and the characteristics of the explosive. It is limited by 7 parameters: α (the initial angle of inclination for the plates), β (the dynamic angle of collision), V_d (the detonation velocity), V_p (the impact velocity), V_f (the flyer plate velocity), V_c (the collision point velocity) and material properties [15].

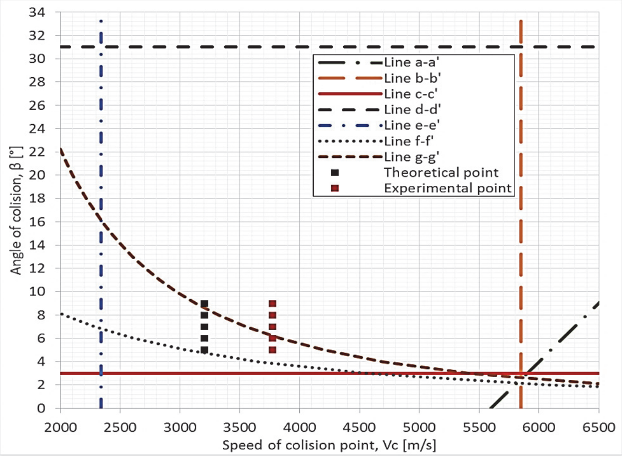

Figure 1 Weldability window of explosive welding

The usual form of displaying a welding window diagram is in V_c-β plane as it is represented in Fig. 1.

The distance between the plates must be such that the moving plate can accelerate to the desired impact speed. The minimum gap is determined empirically by half the thickness of the moving plate Eq. (1). The empirical formula for calculating the required spacing between plates from [15, 16] is given by:

$$S = 3kh_e \frac{C}{M} \tag{1}$$

where S represents mutual distance between the plates, k is dimensionless constant, M is the mass of moving plate, C mass of the explosive, and the thickness of the explosive. The value of k is in the range between 0,4 and 0,7 and depends on the impact speed, (70% and 100% V_p, respectively).

The most important condition for welding is the formation of a jet, which is represented by the line a-a' in Fig. 1. This must happen at the point of contact for successful welding. From the theory it is known that the V_c must remain subsonic while the other criteria of optimal pressure must be satisfied simultaneously. In order to meet both criteria the minimum angle β [17, 18]. Jet formation will be successful if the conditions on the left side of the line *a-a'* are met. Abrahamson [19] suggests the following relationship between β and V_c Eq. (2):

$$V_C = 10^3\left(\frac{\beta}{10}+5,5\right) \tag{2}$$

Covan [15, 20] defined the lower limit V_c (line *e-e'*) of Eq. (3), according to the fluid hypothesis as follows:

$$V_C = \sqrt{\frac{2\left(H_F + H_A\right)R_e}{\left(\rho_F + \rho_A\right)}} \tag{3}$$

where R_e is Reynolds number, H is hardness according to Vickers, indexes F and B represent the moving and stationary plates respectively.

The lower limit of V_c (line *f-f'*) can be determined at the transition limit that occurs at $R_e = 10,6$. Eq. (4) to show the lower limit for welding [21].

$$V_C = \frac{k_1}{\beta}\sqrt{\frac{HV}{\rho}} \tag{4}$$

where β is impact angle in degrees, HV hardness according to the Vickers scale, ρ is the density and k_1 is a dimensionless value between 0,6 and 1,2 depending on the surface roughness of the plates.

In the available works, the coefficient k can have different values [22, 23]. This indicates that the most important parameter is the impact velocity of the plate V_p. However, V_p is very difficult to measure directly due to the speed of the process. Some measurement procedures are described in papers [16, 24, 25].

To determine the upper limit (line *g-g'*) Wittman [26] proposes this experimental formula:

$$V_C = \frac{\left(T_m C_b\right)^{\frac{1}{4}}}{\sqrt{2N\sin\frac{\beta}{2}}}\left(\frac{kC_pC_b}{\rho h}\right)^{\frac{1}{8}} \tag{5}$$

The formula also takes thermal effects into account [27]. They can affect the hardness of the welded joint, especially in the zone close to the joint [28]. In Eq. (5), the parameter N is not specified precisely. Depending on the works, its values vary between 0,037 and 0,11 [22].

Eq. (6) is an experimentally determined formula that connects the mass of the explosive and the mass of the moving plate [21, 29].

$$\frac{e}{m} = \frac{4\sin\frac{\beta}{2}}{\left(k - 2\sin\frac{\beta}{2}\right)} \tag{6}$$

where e is the amount of explosives, m mass of explosives, k dimensionless constant, $k = 0,612$ in [21], $k = 0,578$ from [29], and $k = 0,55$ in accordance with [30].

3 MATERIALS AND METHODS

3.1 Main Properties of Steel and Explosive

The mechanical characteristics of steel 51CrV4 and S355J2, necessary for the calculation of explosive welding, are shown in Tab. 1.

Table 1 Mechanical characteristics of steel 51CrV4 and S355 J2

Variable	Units	Flyer plate	Base plate
C_b - Bulk sound speed	m/s	$4,5\cdot10^4$	
Re_{cr} - Reynolds Critical		10,6	
HV_f, HV_p - Vickers Hardness	Pa	$2,20\cdot10^9$	$1,84\cdot10^9$
ρ_f, ρ_p - Density [31]	kg/m^3	$7,80\cdot10^3$	$7,85\cdot10^3$
k_1 - Empirical constant [22, 34]		0,6	
N - Empirical constant [22]		0,062	
T_m - Melting temperature	°C	1454	
C_p - Specific heat	J/kgK	500	
k - Thermal conductivity	W/mK	21,4	
h - Flyer plate thickness	m	0,003	0,010
σT_f, σT_p - Ultimate Strength [32, 33]	Pa	$7,0\cdot10^8$	$6,3\cdot10^8$
σ_f, σ_p, -Yield Strength [32]	Pa	$5,5\cdot10^8$	$3,55\cdot10^8$

For the realization of the experiment it was ordered five kilograms of explosives Amonex 4, produced by the company Trayal from Kruševac, Republic of Serbia. The Amonex 4 explosive was chosen, as the weakest of the same group. Its characteristics are presented in Tab. 2.

Table 2 Characteristics of explosive Amonex 4 [35]

Property	Unit	Amonex 4
Density	g/cm^3	0,96 - 1,04
Apparent density	g/cm^3	0,5
Velocity of detonation, min	m/s	3200
Gas volume	dm^3/kg	1004
Oxygen balance	%	+0,17
Heat of explosion	kJ/kg	3892
Temperature of explosion	K	2661
Pressure of detonation	kbar	27
Initiation		KD-8

3.2 Chemical Composition of Steel

The chemical composition of steel 51CrV4 and S355J2, in mass percentages, is given in Tab. 3.The test was done with the device "Spectrometer Spectro Lab LACM12", according to the standard SRPS C.A1.011:2004.

Table 3 Chemical composition of steel 51CrV4 and S355J2

Unit of measure	% / m/m													
Element	C	Si	Mn	P	S	Cr	Ni	Mo	Cu	N	Ti	Nb	V	Al
Content51CrV4	0,491	0,257	0,816	0,0134	0,0052	0,988	0,194	0,051	0,250	0,012	< 0,001	0,003	0,128	0,015
Content S355J2	0,160	0,033	1,382	0,0132	0,0052	0,027	0,028	< 0,001	0,029	0,007	0,008	0,029	0,004	0,038

3.3 Characteristic of Explosive Amonex 4

The chemical composition of Amonex4 declared by the producer is shown in Tab. 4.

Table 4 Chemical composition of explosive Amonex 4 [36]

Type of explosive	Percentage of chemical composition
Ammonium nitrate - NH_4NO_3	86,5%
TNT - $(NO_2)C_6H_2CH_3$	4,5%
Wooden beech shavings without resins	7,0%
Carboxymethyl cellulose	0,7%
Calcium stearate - $C_{36}H_{70}CaO_4$	0,3%
Base paraffin oil	1,0%

The bulk density of Amonex 4 explosive was determined as follows: the equipment used consisted of a stand, a brass container of 100 cm^3 volume and a mass of 200 g when empty, a funnel, and a brass spatula. Powdered explosive was poured by free fall through the funnel into the specified container of defined mass and volume, without any compression, pressing or vibration that might affect the powder packaging. Then the funnel was removed and the explosive in the container was levelled with the top of the container using a brass spatula. The mass of the container filled with explosive was measured and the mass of the empty container is subtracted from the measured value. Tab. 5, shows the results of determining the bulk density of powder explosives obtained as the mean value from three measurements.

Table 5 Chemical composition of explosive Amonex 4 [36]

Measured value of bulk density / g/100 cm^3	Average value of bulk density / g/dm^3	Standard deviation / g/dm^3
79,75	762,4	39,1
72,03		
76,94		

It can be concluded that the powder explosive is of uniform quality, i.e. uniform granulation, given that the results of all three measurements are similar. The deviation is about 5% (39,1 g/dm^3) which may be considered as very good, since Amonex 4 is industrial powder explosive.

The detonation velocity of Amonex 4 explosive was determined by the method with optical probes. With this method, the measurement is performed by installing or introducing two optical probes into the sample, in the zone of stable detonation, at a distance of approximately 1,5 diameters of the charge from the side where the activation is performed. The first is the "START" probe, and then at a certain distance the second, or "STOP" probe. The distance between them is the measurement base l (in millimetres), i.e. the distance that the detonation wave travels through the sample for a certain time, t (in microseconds). This distance is measured using an electronic counter or oscilloscope, by registering the light signal received from the optical probes through a photodetector, which converts the light signal into an electrical one [37]. In the experiment, a system with a time measurement accuracy of up to 1 ns was used. The distance between the probes was measured with a digital micrometre, with an accuracy of 0,01 mm. The detonation velocity D is calculated as the quotient of the distance and the time the detonation wave travelled from the "START" to the "STOP" probe, and is expressed in m/s or km/s:

$$D = \frac{l}{t} \tag{7}$$

Powdered explosives are poured into cartridge cases PVC pipes 200 mm long, with an outer diameter of 50 mm, on which openings for optical probes are positioned at a distance of 100 mm. The diameter of the probes is identical to the diameter of the openings in cartridges, which prevents their movement. In this way, it is ensured that inside the powder explosive is poured in the density in which it will be applied in the experiment with welding of metal plates. Three tests were performed.

Fig. 2, shows a cartridge with built-in probes, ready for the experiment.

Figure 2 The texts under figures [37]

Tab. 6, shows the results of determining the detonation velocity of the Amonex 4 explosive, obtained as the mean value of the results for three samples.

Table 6 Detonation velocity measurement results

Sample	Distance-measuring base, l / mm	Time, Δt / µs	Detonation velocity, D / m/s	Average value D_{avg} / m/s	Standard deviation / g/dm^3
1	100,02	26,442	3782,6	3769,8	19,5
2	99,83	26,640	3747,4		
3	99,43	26,308	3779,5		

The measured detonation velocity of the explosive is higher than the declared minimum, i.e. it was clearly confirmed that the explosives used met the quality criteria. Also, it should be noted that the achieved measurement results are uniform (the standard deviation is only 19,5 m/s, i.e. about 0,5% of the mean value), which confirms that the preparation and implementation of the experiment were carried out correctly.

3.4 Experimental Settings

The explosion welding was performed at the training ground of the "Technical Repair Institute" in Kragujevac, Serbia. A cross-section of the experimental setup is shown in Fig. 3.

For the tests, 200 × 150 mm plates made of two types of steel were used: 51CrV4 with a thickness of 3 mm and S355J2 with a thickness of 10 mm. All steel plates are cleaned and degreased. Box elements are made of wood, i.e. OSB boards. The dimensions of the wooden boards are 250 × 80 × 18 mm. The box is made so that its internal side dimensions are four millimetres smaller than the sides of the metal plate.

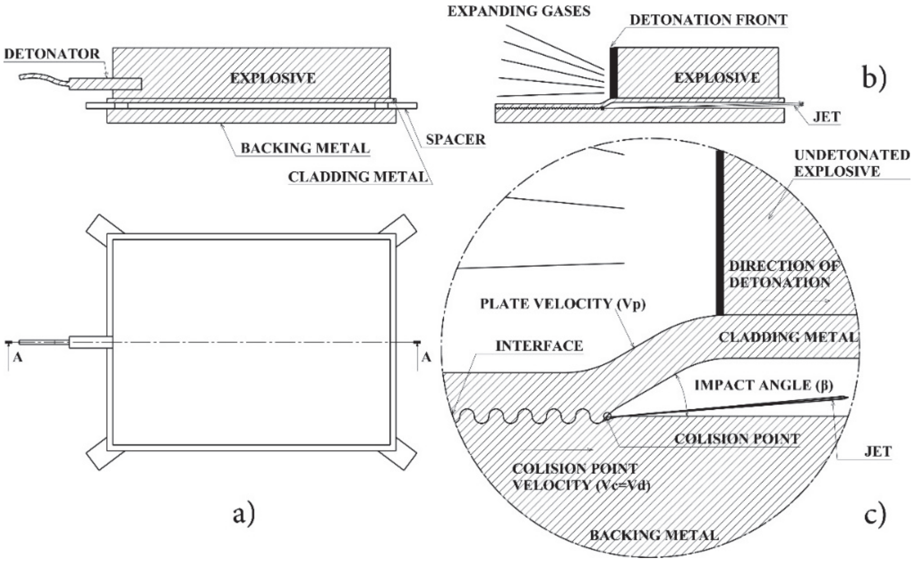

Figure 3 Experimental setting of explosive welding, parallel configuration. a) experimental setup, b) experimental setup at the time of the explosion, c) increase view [38]

They are intended to prevent the dissipation of powder explosives during the preparation of the experiment. On the inner sides of each box, a drawn line marked the height to which the explosives were to be poured. Also, the serial number of activation is written on certain passes. The appearance of the prepared steel plates and wooden boxes is shown in Fig. 4.

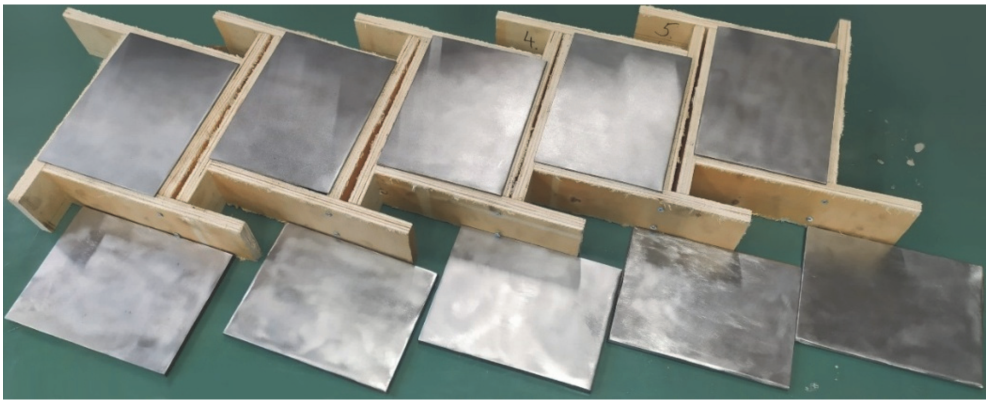

Figure 4 Metal plates and boxes for explosion welding

For the tests, 200 × 150 mm plates made of two types of steel were used: 51CrV4 with a thickness of 3 mm and S355J2 with a thickness of 10 mm. For the experimental welding of two steels 51CrV4 and S355J2, the distance between the plates was exactly 4 mm, due to the possibility of cracks. The distance between the plates is achieved with Plexiglas spacers placed under each corner of the top plate. The experiment was carried out on an earthen surface. The burst explosive was activated with a KD-8 detonator cap. The length of the slow-burning stick was 1,5 m, and the planned burning time was three minutes and ten seconds.

According to theoretical considerations (point 2), the mass of the explosive was calculated, which met the criteria of a quality welded joint. In order to confirm the theoretical results, two additional activations were performed, which partially met the explosive welding criteria (number of detonation 1 and 5). A total of five activation experiments were performed. The parameters of the experiment are shown in Tab. 7.

Table 7 Chemical composition of explosive Amonex 4 [36]

	Type of explosive Amonex 4				
Detonation speed of explosive	3769,8 m/s				
Number of detonation	1	2	3	4	5
Mass of explosive charge / g	200	267	333	400	467
Angle of collision / β	5°	6°	7°	8°	9°

3.5 Characterization of Explosive Amonex 4

Fig. 5, shows steel plates (from number 1 to number 5) obtained by explosive welding, as well as plate 6, a joint of aluminium and steel (supplementary experiment), which will not be considered. In the second photo, plate 5 is deformed due to the effect of the explosion.

By visual inspection, it was observed that there was no joining of materials on the edge parts of all plates. In particular, there was no fusion in the places where the spacers were located.

Figure 5 Plates obtained by explosive welding

3.6 Ultrasound Testing

Ultrasonically welded steel plates were tested with the "Phasor XS" device in the laboratory in Obrenovac. The ultrasonic probe was used to cover the entire surface of each plate. Application of the Pulse-echo method [39] requires a special type of ultrasonic apparatus, in which there is only one probe that is in contact with the material. The device emits very short pulses. After the emission of 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 created by the reflection of the waves from the surface that limits the observed element. In case of a crack or poor contact of the plates, the emitted pulse will be reflected from them and thus travel a shorter distance than it would be with a homogeneous connection. 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 [40]. Fig. 6, shows the measurement procedure. The test results are shown in Fig. 7.

Figure 6 Welded joint testing with ultrasound

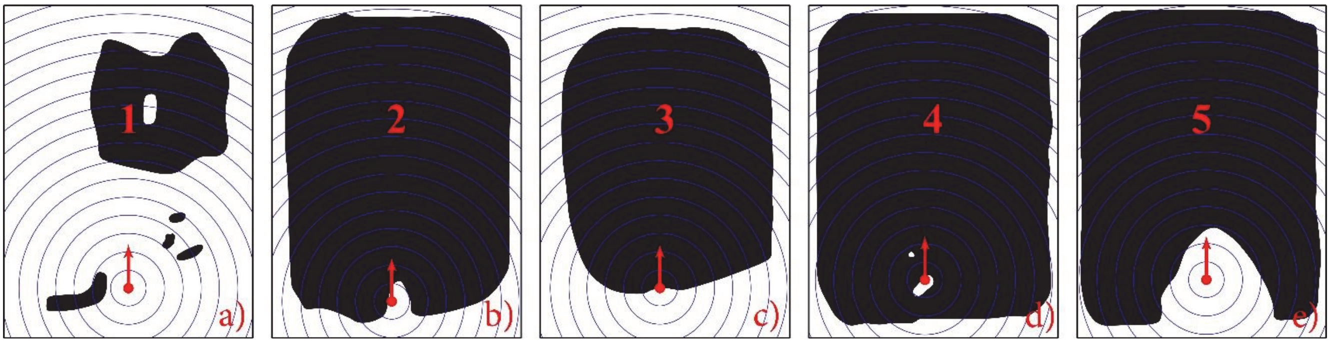

Figure 7 Result of welded joint testing with ultrasound

The black area in the presented images 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 numbers entered correspond to the numbering of the welded plates. It is clear that plate 1 is not even welded. A theoretical consideration established that in that case, at a thickness of approximately 15 cm of the explosive, the detonation wave was extinguished. Therefore, it will not be analysed further. At the point of activation of the detonator capsule, the material did not join, especially in plates 2 and 5. The reason for the unsuccessful joining in that zone is excessive impact energy and partial reflection of the energy back. The impact in that zone occurred at a right angle, so the conditions for the optimal value of the dynamic angle β were not created. After X mm from the place of detonation, a stable front of the detonation wave is established. A metal joint on a surface where a stable front is not established is considered to be poor, or no joint at all. That part is being removed.

3.7 Metallographic Examination

Cutting of the welded plate was performed with a water jet in order to prepare the samples for metallographic tests (Fig. 8). The speed of the jet was 50 mm/min, pressure 3800 bar, consumption of abrasive material 250 g/min and 1,5 l/min of water. The cut samples are marked with an alphanumeric code. The capital letter *P* is an abbreviation of the word "plates", while the numbers indicate: the serial number of the welded plate (first number) and the position of the cut sample (second number).

Fig. 9, clearly shows the change in wavelength proportional to the amount of explosive used. Increasing the amount of explosives affects the melting of the material and the formation of an intermetallic zone.

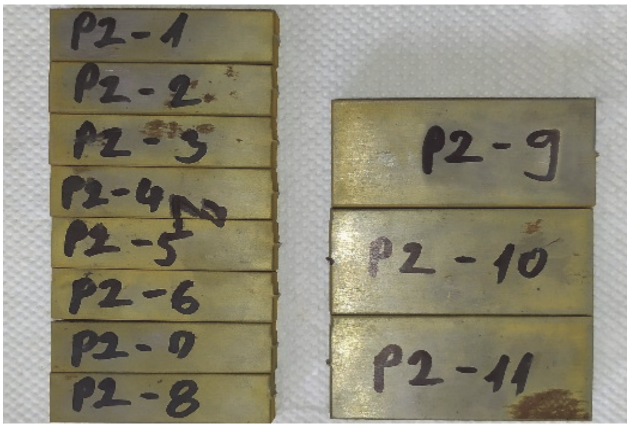

Figure 8 Cutting the plate with a water jet to prepare samples

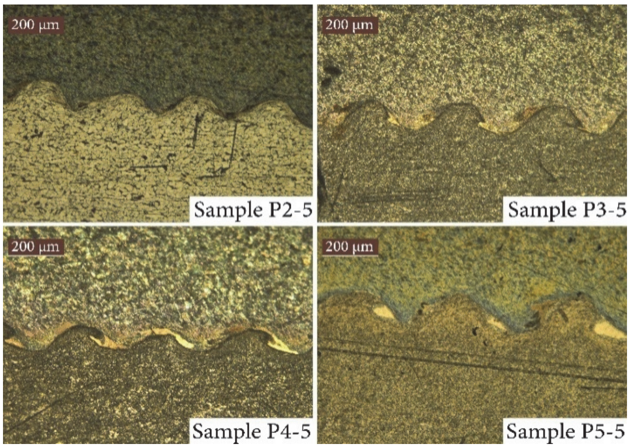

Figure 9 Change wavelength proportional to the amount of explosive used (200 μm)

3.8 Hardness Distribution in the Joint Zone

The examination of the microhardness of the welded joint was performed at the Faculty of Engineering Sciences in Kragujevac. The "Nanoindenter & Micro Scratch Tester" device, produced by CSM, was used. The measurement of the characteristics was achieved by pressing the indenter into the surface of the plate whose characteristics were to be determined. The hardness was tested by the Vickers method with the HV_{02} force.

A linear test was used. The direction of the line coincided with an angle of 10° in relation to the joint line. Two tests were performed at the joint: 1) a line test with a step of 0,1 mm and 2) a line test with a step of 0,05 mm closer to the joint. The microhardness values in the welded joint of 51CrV4 and S355J2 are shown in Fig. 10. The hardness of 51CrV4 is shown on the left side of the diagram, while the hardness of S355J2 steel is on the right. It is important to state that the experiment with plate P3 was done by mistake on a loose part of the soil, which significantly affected its hardness and which can be clearly seen in the diagram (P3-5)

Fig. 11 shows the impression of a four-sided pyramid on a welded joint with an indentation force of HV_{02}. A wavy border of the weld can be seen, with the upper, darker portion representing the 51CrV4 steel and the lower, lighter the S355J2 steel. By pressing a four-sided pyramid into S355J2 steel, a 35 μm print was created, while by pressing into 51CrV4 steel, a 30 μm print was obtained. In order to have a better overview of the achieved results, only the points in the zone close to the welded joint are presented.

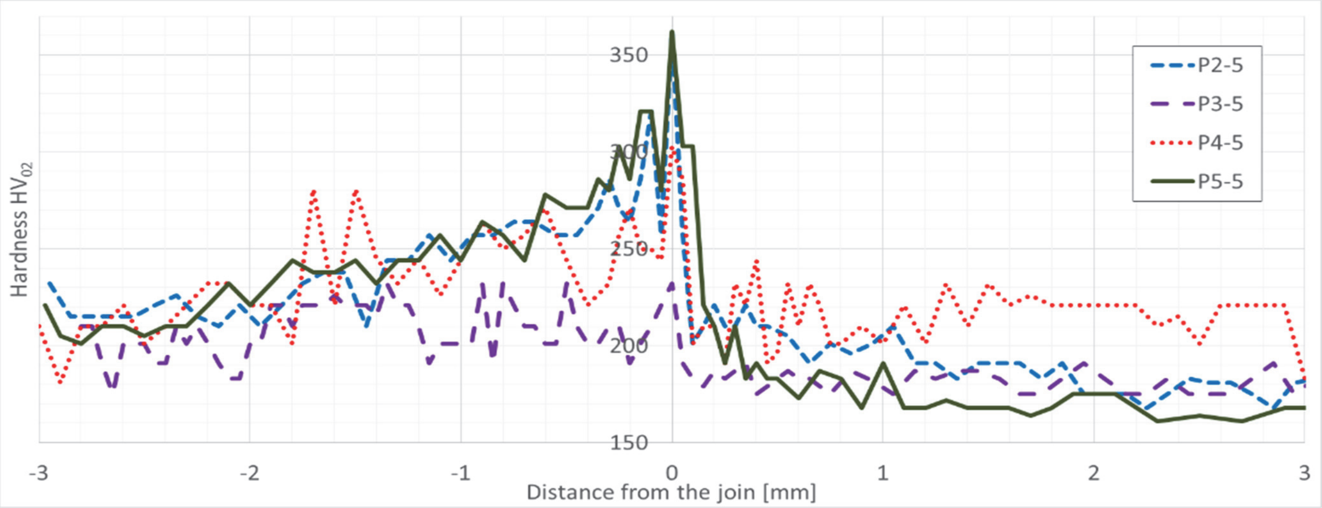

Figure 10 Hardness distribution in the joint zone (HV_{02})

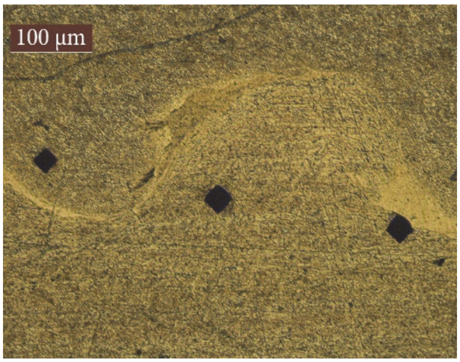

Figure 11 Imprint of a four-sided pyramid (junction) sample P5-5

4 CONCLUSION

Explosion welding belongs to the high-energy methods of processing materials, in which the energy of the explosive and the generated pressure are used to accelerate the metal plates, in order to join two or more metal plates. The selection of welding parameters is not a simple process, taking into account the complexity of processes that take place in a microsecond time interval.

On the example of spring and carbon steel, the calculation and procedure of obtaining a welded joint is demonstrated. Ultrasonic testing showed that there was a joining of plates numbered 2, 3, 4, and 5. In plate 1, there was no welding, so the plate could be separated mechanically, with a screwdriver. The quality of the welded joint was tested with a hardness tester and metallography. An increase in hardness of about 150% was observed at the joint. Metallographic tests show that the plates 3, 4, and 5 have melted and an intermetallic zone has appeared. The wavelength of the wave junction and the size of the intermetallic zone increase in proportion to the amount of explosive.

By checking the explosive welding parameters, it was shown that Amonex 4, with certain modifiers, can give an acceptable quality of the welded joint and the possibility of its application in the field of metal explosion welding was confirmed.

Such materials can find potential applications for the production of industrial cutting tools.

The quality of the knives made by the explosive welding process takes on the characteristics of the higher quality metal used, while the cost of production is closer to the cheaper metal.

Future research will be based on larger plates for more detailed research and confirmation of the obtained quality.

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