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HEAT TREATMENT INFLUENCE ON CLAD DISSIMILAR JOINTS WEAKNESS

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Original scientific paper

The dissimilar specimens (ASTM A387 Gr.12 + ASTM A240 TP 304L) clad by different procedures (explosion welding, submerged arc welding–surfacing using strip electrode (SAW) and hot rolling) were heat treated (650 °C through 2 hours). The shear strength testing of clad joints and Charpy impact energy testing were performed. The statistical analysis of testing results was elaborated, and the significance of heat treatment influences on the clad joints weakness was established.

Keywords: *clad joints, heat treatment, shear strength*

Utjecaj toplinske obradbe na slabljenje platiranog raznovrsnog spoja

Izvorni znanstveni članak

Raznovrsni uzorci (ASTM A387 Gr.12 + ASTM A240 TP 304L) platirani različitim postupcima (eksplozijskim zavarivanjem, elektrolučnim postupkom navarivanja pod prahom elektrodnom trakom (EPP) i toplim valjanjem) toplinski su obrađivani (650 °C tijekom 2 sata). Provedena su ispitivanja smične čvrstoće platiranog spoja i Charpy udarne radnje loma. Rezultati ispitivanja su statistički obrađeni te je utvrđena značajnost utjecaja postupka toplinske obradbe na slabljenje platiranog spoja.

Ključne riječi: *platirani spojevi, smična čvrstoća, toplinska obradba*

1 Introduction

The clad products are used in the manufacture of process equipment for the chemical, petrochemical and petroleum industries, where corrosion resistance of an expensive metal is combined with the strength and economy of another. The cladding layer that will be in contact with the corrosive media is made of the corrosion resistant alloys, whilst the less expensive base steel covers the strength and toughness required to maintain the mechanical integrity [1 ÷ 3]. The explosion welding, weld overlaying and hot rolling can produce clad plates. One of the most widely used applications of explosion welding has been in the cladding of base metals with thinner alloys.

The explosion welding is a solid-state welding process, in which the coalescence is the effect of high-velocity movement together of the parts to be joined, produced by a controlled detonation. Even though the heat is not applied in making an explosion weld, it appears that the metal at the interface is molten during welding [4 ÷ 6]. This heat comes from several sources, i.e. from the shock wave associated with the impact, and from the energy expended in the collision. The heat is also released by the plastic deformation associated with the jetting and ripples formation at the interface between the parts being welded. When a cladding plate collides with a base plate, a jet, which cleans the surface of plates, is formed. It is formed from the surfaces of both materials. The joint is formed continuously according to the movement of the detonation wave of the explosion with the displacement of high pressure point behind the collision region. Due to the unstable plastic flow of metal in the surroundings of the point of incipient flow, a wavy interface is formed, which is characteristic for the explosion welded metals. Plastic interaction between the metal surfaces is especially pronounced when the surface jetting occurs. It is found necessary to allow the metal to flow plastically, in order to provide a quality weld [7 ÷ 9].

As the source of necessary and controlled amount of high density and action rate energy, the explosives are used mainly in powder form. As oxygen atoms bearer, almost exclusively at commercial explosives, ammonium nitrate is used. Ideally, ammonium nitrate, during the explosion process, decomposes in acc. with expression (1)

$$NH_4\,NO_3 \rightarrow N_2 + 0{,}5\ O_2 + 2H_2O + \text{heat}, \tag{1}$$

and by this, the explosion temperature around 1200 °C is produced.

In the explosion cladding of large plates, it is necessary to use a commercial explosive with a detonation velocity less than the sonic velocity in the metals being welded, which implies a detonation velocity less than 4 km/s, or even less for some combinations of metal [10, 11].

2 Materials and plan of experiment

The experiment consisted of plate bonding by different cladding procedures (explosion welding, submerged arc welding-surfacing using strip electrode (SAW) and hot rolling). Afterwards, the clad plates were heat treated by annealing (650 °C through 2 hours).

The significance of cladding procedure and heat treatment influence on the mechanical properties were investigated.

The explosion bonding of metals was performed using the explosive material - ammonite [85 % ammonium nitrate as oxidiser + 12 % explosive trinitrotoluene (TNT) + 3 % Al as fuel] in the powder form is frequently used [5 ÷ 8]. As the base material, low alloyed ferritic-pearlitic steel, the quality of which was in acc. with ASTM A387 Gr.12 thickness 14 mm, and as the cladding material, austenitic high alloyed corrosion resistant steel, the quality of which was in acc. with ASTM A240 TP304L thickness 2 mm, were selected.

The base material was delivered in the normalised condition, while the cladding material was in the quenched condition (Tabs. 1 and 2). The bonding by hot rolling was performed on the identical combination of materials and thicknesses as at the samples plated by the explosion welding in acc. with the producers patented procedure at the temperature above 1100 °C.

Table 1 Mechanical properties of clad materials

Material	Properties			
	R_e / MPa	R_m / MPa	δ_5 / %	KV / J
ASTM A 387 Gr. 12	421	598	26	169
ASTM A 240 TP304L	218	591	63	210

The submerged arc welding (SAW)-surfacing was performed using the strip electrodes (Tab. 3). The strip electrodes quality selection was performed using WRC-1992 diagram with the intention to avoid overlaying brittleness [12, 13]. The surfacing was performed in two beads. In such a way, it was possible to obtain the joint chemical homogeneity, as well as to prevent the under-cladding cracks appearance (reheat cracking) by the normalisation of previous bead with the next bead deposit (Tab. 4) [14 ÷ 16].

If the weld deposit is austenite, then an FN of around 4 or 5, minimum, usually suffices to prevent the hot cracking. The tendency of welds solidification cracking decreases at Cr_{eq}/Ni_{eq} ratios 1,5 ÷ 2,0 for the equivalence determined by WRC-1992 calculations (Fig. 1). During overlaying, in order to prevent the plate distortion, a stiffening device was used. Afterwards, the clad plate was tested by a dye penetration method, in order to detect the surface errors. The ultrasound method tandem-technique with 70°-angle probes frequency of 2 MHz was used to discover the possible under-cladding cracks caused by the heat affected zone (HAZ) reheating. The control of δ - ferrite content at the surface bead was performed using the measuring device "dr. Foerster", and 5,4 % was measured.

The Charpy impact energy was tested in acc. with EN 10045/DIN 50115, with the notch positioned in thicknesses direction (Fig. 2) on the device RPSW30 with the energy capacity of 300 J.

The shape and dimension of shear strength tested specimen is shown in Fig. 4.

The shear strength testing was performed on the testing equipment MWM, type EU40, with a measuring range of 100 kN according to ASTM A264, using a special stiffening device (Fig. 6) [17]. All the results were statistically analysed using the F-test [18].

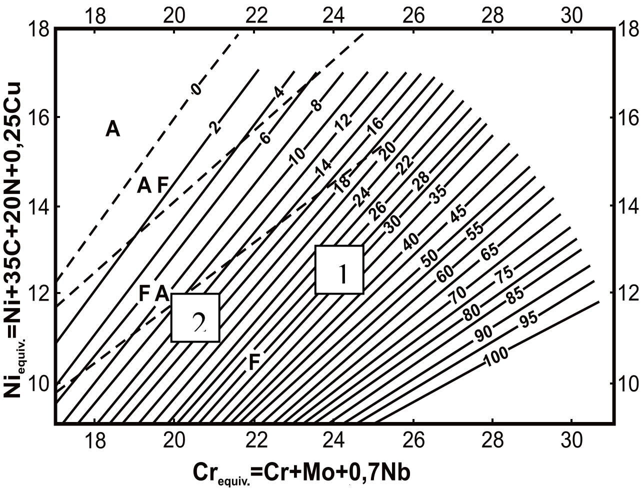


Figure 1 WRC1992-diagram with ratio Cr_{eq}/Ni_{eq}-s position of beads deposits of selected filler strip materials

Table 2 Chemical composition of clad materials

Base and cladding materials	Elements contents, wt. %							
	C	Si	Mn	P	S	Cr	Mo	Ni
ASTM A 387 Gr.12	0,13	0,28	0,78	0,008	0,010	1,07	0,52	-
ASTM A 240 TP 304L	0,026	0,48	1,33	0,030	0,030	18,7	-	10,8

Table 3 Chemical composition of used filler strip materials for SAW overlaying - surfacing

Filler material for overlaying		Chemical elements content, wt. %								
		C	Si	Mn	Ni	Cr	Mo	S	P	Fe
1 Strip: 60×0,5mm UTP 6824 LC Flux: UP flux 6824	AWS E 309LC$r_{eq.}/Ni_{eq.}$=1,77	0,013	0,29	1,68	13,05	23,92	-	0,003	0,013	Rem.
2 Strip: 60×0,5mm UTP 6820 LC Flux: UP flux 6820	AWS E 308L $Cr_{eq.}/Ni_{eq.}$=1,69	0,021	0,94	1,00	1,4	20,5	-	0,006	0,017	Rem.

Table 4 Review of base SAW strip overlaying characteristics

Parameters and characteristic of SAW overlaying	
Electrode strip and flux (1st bead 60 × 0,5 mm)	UTP 6824LC; UP Flux 6824
Electrode strip and flux (2nd bead 60 × 0,5 mm)	UTP 6820LC; UP Flux 6820
Equipment for SAW overlaying	LINCOLN WELD - NA-3S
Overlaying current strength, A	580 ÷ 600
Overlaying current tension, V	29 ÷ 30
Overlaying velocity, cm /min	≅ 20
Preheating temperature, °C	≅ 150
Interlayer temperature, °C	≅ 150
Beads overlapping, mm	3 ÷ 4
Total overlay elevation, mm	6 ÷ 7

3 Results and discussion

The post weld heat treatment is generally used for reducing the residual stresses, as well as for making low brittle structure. The heat treatment consists of three stages including recovery, recrystallization, and grain growth. The completion of these stages takes time. The recrystallization may occur during or after deformation. During the recrystallization, the density of dislocation also decreases considerably, thus the effect of strain hardening may be eliminated.

At the explosion welding, the plastic deformation occurred due to the impact of two sheet metals (low alloyed & stainless steel) during the process. In the first step of recrystallization, many of small grains occur due to the nucleation at a particular temperature. These small grains have longer grain boundaries and they are the barrier for dislocation movement. All clad samples, achieved by the explosion welding, show elongation in the explosion direction and heat treatment does not change the grain geometry. A high value of hardness near the interface of 304 type austenitic steel in the explosion bonded joint could be attributed to the high degree of deformation of stainless steel during the explosion welding process. When the austenitic stainless steels are deformed, there can be martensite formation, and the dislocation density growth occurs.

3.1 Charpy impact energy testing

The necessity of heat treatment application at the low alloyed ferritic-pearlitic steel joints was estimated by the value of Charpy impact energy, which was the material base indicator of brittle fracture. The used heat treatment at the clad materials had probably a favourable influence on the base low alloyed ferritic-pearlitic steel material, but it could have had damaging influence on the clad high alloyed austenitic corrosion resistant material. Therefore, the testing on specimens with a different volume share (10 %; 25 %) of clad austenite materials was performed. The results achieved by using the unadvisable high energy device capacity had a qualitative value (Tab. 5). The influence of cladding procedures and clad material volume share, as well as the applied heat treatment on the Charpy impact energy values, is graphically presented in Fig. 3. The Charpy impact energy testing results were statistically investigated by the analysis of variance of influencing factors using the F-test, and presented in Table 7. The statistical analysis of measured impact energy results indicated no significant influence of applied cladding procedures, as well as the volume share of cladding austenite corrosion resistant material (C2; C3). The mentioned conclusion is explainable with a small volume share (10 %; 25 %) influence of cladding austenite materials.

This justified the standardised method of clad materials impact energy testing, which was performed only on the base-backing material. The used heat treatment had the main influence on the Charpy impact energy values of clad specimens. The cladding procedure, in the interaction with the applied heat treatment factor, exerted a significant influence on the Charpy impact energy property of clad specimens, as well. The interaction of cladding material volume share factor, and applied heat treatment as their significant effect on the Charpy impact energy, can be explained by the fact that the applied heat treatment had a beneficial influence on reducing the base low alloyed ferritic-pearlitic steel brittleness, but it was partly detrimental to the clad austenitic stainless steel.

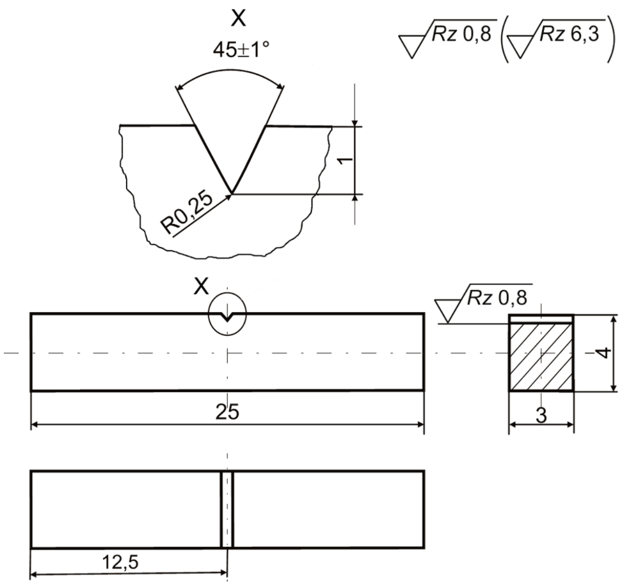


Figure 2 Dimensions and treatment quality of Charpy testing specimen

Table 5 Charpy impact energy testing results

Charpy impact energy / J	B1 No annealing		B2 Annealing 650 °C /2 h	
	C3 25 %	C2 10 %	C3 25 %	C2 10 %
A1 Hot rolling	5	5	3	5
	5	5	5	4
	5	5	5	5
A2 SAW overlayed	6	5	5	6
	5	5	4	4
	5	5	4	4
A3 Explosion cladded	6	5	3	3
	7	4	2	4
	6	6	4	5

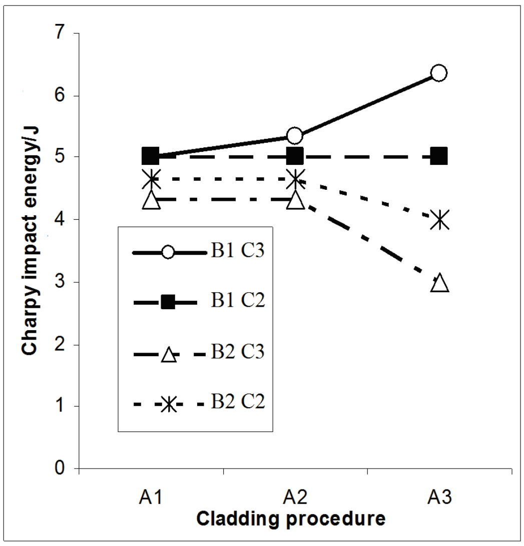


Figure 3 Influence of cladding procedures, clad material volume shares and applied heat treatment on Charpy impact energy

Due to the sensitiveness to applied heat treatment, the volume of delta-ferrite decreased, including the decomposition and transformation into carbides and intermetallic phases (σ-phase), causing the cladding brittleness and possible stress corrosion cracking. The most characteristic drop of Charpy impact energy values was noticed at the heat treated explosion clad specimens. Therefore, it could be concluded that for the explosion clad plates, the post heat treatment is not advisable.

It could be explained by the nature of explosion welding process, as a solid state process at high rate deformation after shock wave loading.

3.2 Shear strength testing

The successfulness of applied procedure, i.e. cladding procedure, is verified by the joint strength testing. The joint strength of dissimilar clad steel was estimated by the shear strength testing.

The shear strength testing results are shown in Tab. 6. The histograms of clad joint strength dependence upon the applied cladding and heat treatment procedures are presented in Fig. 5. The shear strength testing results were statistically analysed using the F-test, too (Tab. 8).

The results indicated 10 ÷ 15 % lower values of shear strength test of heat treated specimens compared to the non-treated specimens.

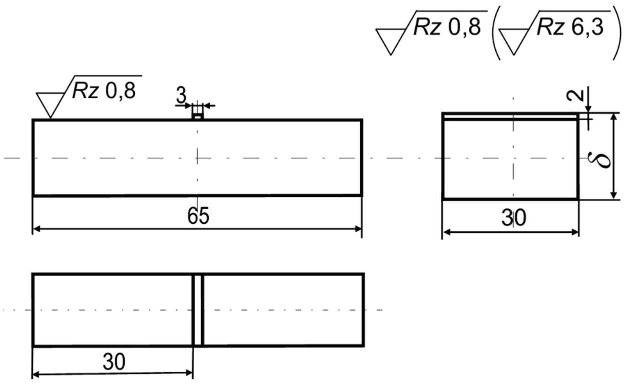
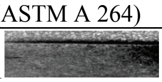
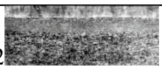
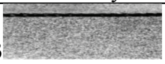


Figure 4 Dimensions and treatment quality of shear strength testing specimen

Table 6 Shear strength testing results

Shear strength, MPa (ASTM A 264)	B1 Non annealed	B2 Annealed
A1  Hot rolled	328	307
	394	298
	369	343
A2  SAW overlayed	405	361
	362	376
	401	301
A3  Explosion cladded	440	417
	528	432
	369	349

This fact was especially expressed at the specimens clad by hot rolling. These values were on average the lowest, but still above the standard limit (140 MPa). This fact could be explained by an assumption that all as-delivered status hot rolled clad specimens had a characteristic decarbonised zone. The formation of the bond in the hot rolled plate is dependent upon the diffusion between the cladding and base materials, which can result, in certain combinations, in hardening at the interface, due to the precipitation of intermetallic phases or carbides. In the cases where the initial slab was plated before hot rolling, or inserted metal was used, such intermetallic phases did not form, since the nickel or iron layer acted as a buffer. A careful control of the material chemistry, particularly the base steel carbon content, can also reduce the risk of precipitates at the interface in the absence of an intermediate nickel or iron layer (made by electroplating or inserting).

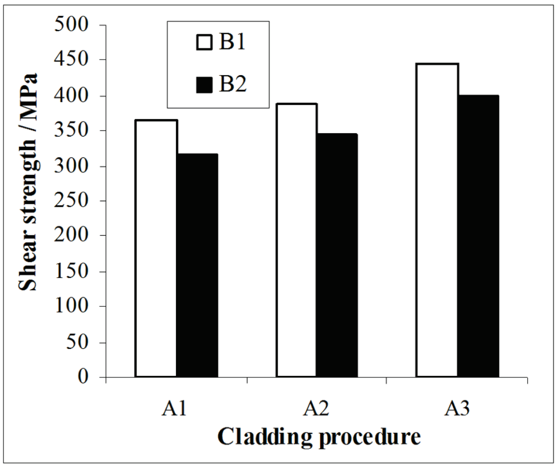


Figure 5 Clad joint strength dependence upon applied cladding and heat treatment procedures

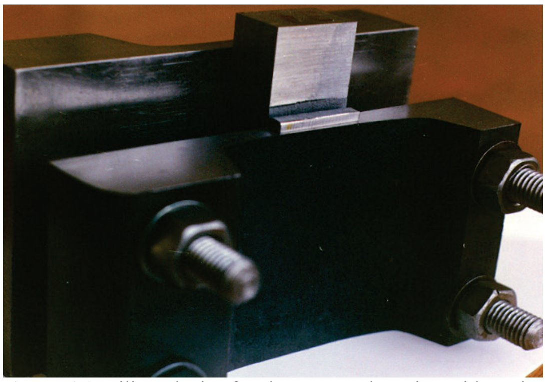


Figure 6 Auxiliary device for shear strength testing with testing specimen dimensions presented in Fig. 4

At the examination of influencing factors and their interactions with the shear strength properties of clad specimens, the statistical analyses indicated a significant influence of both factors: cladding procedure and applied post heat treatment. The influence of applied cladding procedure was somewhat more expressed, compared to the used heat treatment procedure (Tab. 8). Analysing the other results, it can be noticed that the highest values of shear strength testing were obtained for the explosion clad specimens. The explosion cladding process is a procedure of cold pressure bonding at high velocity, with practically no time for diffusion developing. The influence of cladding procedure and the applied heat treatment procedure were directly in connection with the heat inputting. The diffusion process at the bonding surfaces between two materials during the cladding process with heat treatment was intensified, and directly influenced the bond strength.

Table 7 Statistical analysis of Charpy impact energy testing results

Source of Variation (*SV*)	Sum of Squared Deviations (*SSD*)	Degree of Freedom (*DF*)	Mean Squared Deviations (*MSD*)	*F* Calculated	*F* tabular $\alpha = 0,05$	Effect of significance at risk $\alpha = 5$ %
A	77,0556	2	38,5278	0,660	3,37	
B	1356,6944	1	1356,6944	23,252	4,22	*
C	4,6944	1	4,6944	0,080	4,22	
AB	856,7222	2	428,3611	7,341	3,37	*
AC	18,0556	2	9,02778	0,155	3,37	
BC	318,0278	1	318,02778	5,451	4,22	*
Balance	1517,0556	26	58,348291			

* Significant effect of influencing factors: *F* calculated > *F* tabular, at affirmation risk of $\alpha = 5$ %

Table 8 Statistical analysis of shear strength testing results

Source of Variation (*SV*)	Sum of Squared Deviations (*SSD*)	Degree of Freedom (DF)	Mean Squared Deviations (*MSD*)	*F* Calculated	*F* tabular $\alpha = 0,05$	Effect of Significance at Risk $\alpha = 5$ %
A	21 093,444	2	10546,722	5,173	3,88	*
B	9800,000	1	9800,000	4,807	4,75	*
AB	2,33333	2	1,166677	0,001		
Balance	24 464,000	12	2038,6667			

* Significant effect of influencing factors: *F* calculated > *F* tabular, at affirmation risk of $\alpha = 5$ %

The post weld heat treatment by annealing increases carbonization on the side of plating of corrosion resistant steel, as well as the "depletion" zone in the base material with low strength values. The diffusion supported by the annealing temperature weakens the joint strength.

4 Conclusion

The Charpy impact energy and shear strength testing investigation was performed, since the cladding procedure and the applied heat treatment significantly influence the bond quality, as well as the mechanical properties of joining material.

The main influence on the Charpy impact energy values of clad specimens was exerted by the applied heat treatment. In the interaction with the applied heat treatment factor, the cladding procedure exerts a significant influence on the Charpy impact energy property of clad specimens.

The statistical analysis of measured impact energy results pointed to no significant influence of applied cladding procedures, as well as the volume share of cladding austenite corrosion resistant material. This justifies the standardised method of clad materials impact energy testing, which is performed only on the base-backing materials.

At the examination of influencing factors and their interactions with the shear strength properties of clad specimens, the statistical analyses indicated a significant influence of both factors: cladding procedure and applied post heat treatment.

The heat treatment of clad plates, with their influence on the mechanical properties - joint strength, had a direct effect on the clad materials designing rules, and on the clad materials construction reliability in exploitation.

Abbreviations and symbols

ASTM - American Society for Testing and Materials
AWS - American Welding Society
KV – Charpy impact energy, J
R_e – Yield strength, MPa
R_m – Tensile strength, MPa
SAW – Submerged Arc-Welding
δ_5 – Elongation, %
δ – Thickness of test specimen for shear strength testing, mm

5 References

[1] Knauschner, A. Oberflächenveredeln und Plattieren von Metallen, Deutscher Verlag für Grundstoffindustrie, Leipzig, 1983.
[2] Horn, E. M.; Korkhaus, J.; Mattern, P. Plattieren – eine kostengünstige Alternative für den Einsatz metallischer Werkstoffe in der Chemietechnik, Chem.-Ing.-Tech., 63, 10(1991), pp. 977- 985.
[3] Plattierte Bleche, Prospektmaterial, Voestalpine Stahl, Linz, 2000.
[4] Crossland, B. Explosive welding of metals and its application, Clarendon Press, Oxford, 1982.
[5] Ghosh, A.; Chattopadhyaya, S.; Hloch, S. Prediction of weld bead parameters, transient temperature distribution & HAZ width of submerged arc welded structural steel plates. // Tehnicki Vjesnik - Technical Gazette. 19, 3(2012), pp. 617-620.
[6] Simonov, V. A. Binding criterion for metals with explosion welding. // Combustion, Explosion, and Shock Waves. 27, 1(1991), pp. 127-130.
[7] Petrović, S.; Kosec, L.; Mateša, B.; Petrović, V.; Petrović, B. Industrial cladding of stainless steel to low carbon steel by explosion. // Strojniški Vestnik - Journal of Mechanical Engineering. 41, 11-12(1995), pp. 397-406.
[8] Petrović, S.; Pecić, V.; Mateša, B. Application of explosion welding process in industry. // Welding in the World (0043-2288). 51, (2007), pp. 509-518.
[9] Mateša, B.; Pintarić, A.; Stoić, M. Heat treatment by annealing use questionableness after dissimilar materials welding by explosion. // International Congress Eurojoin 8 – Proceedings / Pula, Croatia, 2012.
[10] Baum, A. Fizikavzryva, Fiz-mat., Moskva, 1975.
[11] Zukas, J. A.; Walters W.; Walters W.P. Explosive Effects and Applications. Springer Verlag, New York, 1998.
[12] Kotecki, D. J.; Siewert, T. A. WRC-1992 constitution diagram for stainless steel weld metals: a modification of

the WRC-1988 diagram. // Welding Journal. 71, 5(1992), pp. 171-178.
[13] Mateša, B.; Samardžić, I.; Dunđer, M. The influence of the heat treatment on delta-ferrite transformation in austenitic stainless steel welds. // Metalurgija. 51, 2(2012), pp. 229-232.
[14] Demuzere, R. Strip overlaying with SAW. S.A. Soudometal, No 930067 rev.3, N.V.B. – 1.7., Brussels, March 1984.
[15] Dhooge, A.; Vinckier, A. Reheat Cracking - A Review of Recent Studies. // Int. J. Pres. Ves. & Piping. 27, 4(1987), pp. 239-269.
[16] Welding Handbook, 8th Edition, Materials and Applications, Vol. 4/2, AWS, Miami, FL, 1998.
[17] Metals Handbook, Ninth Edition, Mechanical Testing, Vol. 8, ASM, Metals Park, Ohio, 1985.
[18] Pavlić, I. Statistical theory and application, Tehnička knjiga, Zagreb, 1988. (in Croatian)

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