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STRUCTURAL ANALYSIS OF THREE-METAL EXPLOSION JOINT: ZIRCONIUM-TITANIUM-STEEL

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The influence of applied explosion joining parameters on the structure and strength of three-metal joints: Zr-Ti-Steel is analysed in this paper. Zirconium was explosively clad on steel over an inter-layer of titanium. Zirconium-titanium-steel joint is produced during simultaneous cladding operation using a single cladding shot and plan parallel joining scheme. The metallographic analysis of interfaces Zr/Ti and Ti/Steel structures and microhardness measuring are performed. Mechanical testing of bond strength is performed on both interfaces by shear strength examinations.

Key words: structural analysis, explosion welding, zirconium-titanium-steel, mechanical properties

Strukturna analiza eksplozijski spojenog trosloja: cirkonij-titan-čelik. U radu je analiziran utjecaj primijenjenih parametara spajanja eksplozijom na strukturu i čvrstoću troslojnog spoja: Cirkonij/Titan/Čelik. Čelik je eksplozijski platiran cirkonijem preko međusloja titana. Troslojni spoj: Zr/Ti/Čelik, proizveden je istovremenim postupkom platiranja- uporabom jedne detonacije i plan-paralelne sheme spajanja. Provedena je metalografska analiza struktura graničnih površina Cirkonij /Titan i Titan/Čelik, te mjerenje mikrotvrdoća. Čvrstoća spoja na obje granične površine je utvrđivana mjerenjem smičnih čvrstoća.

Ključne riječi: strukturna analiza, zavarivanje eksplozijom, cirkonij-titan-čelik, mehanička svojstva

INTRODUCTION

Explosion metal welding is high-speed angle oblique collision of two or more metal plates caused by detonation. The metal is joined – welded under high dynamic pressure creating by plastic deformation the waves on the bond interface, accompanied by local adiabatic heating [1].

The explosive metal cladding process can be divided into three stages: a) generation of explosion energy through the detonation of explosive charge, b) acceleration and deformation of the cladding plate and c) collision of the cladding plate with the base plate.

A schematic illustration of explosive metal welding is given in Figure 1 [2, 3]. After the initiation of the explosive charge, the detonation wave "travels" at a constant velocity V_D which depends on the explosive material characteristics and explosive charge density. The detonation wave is transformed into a shock wave in the metal (position 1 in Figure 1). The clad plate, driven by detonation products, accelerates, bends twice and hits the lower fixed plate. The explosion energy generates very high pressure (approximately 100 GPa) and the collision point travels gradually along the base plate at velocity V_C. Under the influence of the "surface" cumulative flow, oxides and other impurities on the two surfaces are decomposed, and partly removed from the bonding area.

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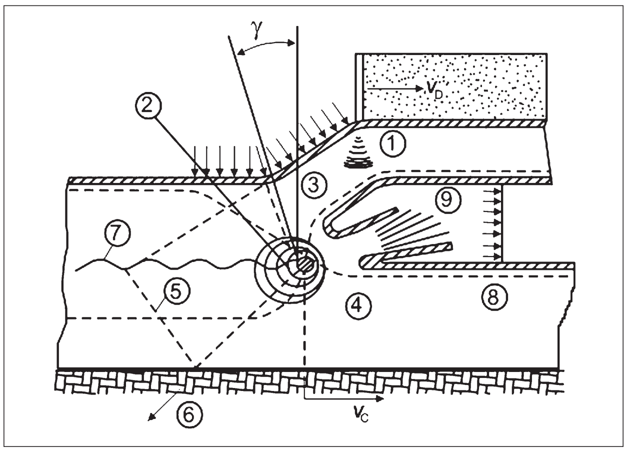


Figure 1. Schematic illustration of explosive metal welding mechanisms

1. shock wave in the metal caused by detonat. wave V_D
2. plastic deformation caused by dynamic pressure
3. shock wave caused by collision with clad plate
4. forming of surface cumulative jet
5. reflected shock wave
6. passing shock wave
7. waves at bond interface
8. air shock wave and its effects on the plate
9. surface cumulative jet

V_C collision point velocity / m/s
V_D velocity of detonation wave / m/s
γ dynamic collision angle / °

On the basis of experimentally obtained data, it was established that a very thin layer of melt is generated at the bond interface, within which impurities flow out of the bond during melting. Rapid cooling after the collision generates an alloy of different structure and very small grains, of average thickness 1-2 μm. The generation of such an amorphous layer in the bond area has been noticed with various metal combinations and represents a fundamental mechanism of explosive metal cladding [4, 5]. The explosives as the source of necessary and controlled amount of high density and action rate energy, mainly in the powder form are used. As oxygen atoms bearer almost exclusively at commercial explosives, ammonium-nitrates are used. Ideally, ammonium-nitrates, during explosion process, decompose in acc. with equation:

$$NH_4NO_3 \rightarrow N_2 + 0{,}5\,O_2 + 2H_2O + heat \quad (1)$$

and the explosion temperature round 1200 °C is produced [6]. The previous researchers have noticed that vortex heterogeneity and defects on the interface of two different materials have no significant influence on strength of the joint [1, 2, 5]. During the solidification of the melted vortices core, the alloys rich in titanium crack, which was not the case with ferrite [7]. This paper deals with the influence of applied explosion joining parameters on the structure and strength of three-metal joints: Zr-Ti-Steel.

EXPERIMENTAL WORK

Zirconium was explosively clad to steel over an inter - layer of titanium. The resulting three

- metal Zr702 - TiGr.1(SB265Gr.1) - steel (StE355), obtained from starting sheets and plate sizes □460 ×1460 × (8+2+90) mm, was used for fabrication of three-metallic clad rounds ϕ1200 × (8+2+90) mm, from which the heat exchanger tube-sheets were fabricated. Before the process of joining, the purchased materials are chemically and mechanically tested according to ASTM B265, ASTM B551 and DIN 17102 (Table 1, Table 2).

Zirconium-titanium-steel joint is produced during simultaneous cladding operation using a single cladding shot and a plan parallel joining scheme. The distance between the flayer and the fixed plate was 10 mm with 30 mm thick explosive powder layer. Explosive materials - ammonite [85 % ammonium nitrates as oxidizer + 12 % explosive trinitrotoluene (TNT) + 3 % Al as fuel] in the powder form is used with a standard commercial blasting cap no.8 instantaneous as the activator to detonate the explosives. Bond integrity is verified using the straight-beam ultrasonic inspection procedures. The specifications typically provide several acceptance criteria depending upon the customer's needs, the more stringent being 25 mm maximum length of any indication and 99 % minimum sound bond area. In the structure analysing, the optical microscopy was used by Leitz- and Jenaert-optical microscopes. Ti- and Zr-structures are etched by Kroll's reagent, i.e. (HF+HNO_3+H_2O).

Table 1. **Mechanical properties of materials**

Materials	Yield strength / MPa	Tensile strength / MPa	Elongation A_5 / %
Ti Gr.1	191	373	29
Zr 702	223	391	21
TStE 355	419	566	27

Carbon steel structures are etched by Nital [8]. The bond micro-hardness HV0,1 was cross-section tested using micro hardness-tester PMT–3. Bond strength was analysed through shear strength testing using a special stiffening device and a shear strength testing device MWM, type EU40 with measuring range 100 kN.

Metallographic and mechanical properties joints analysis

Metallographic analysis

A metallographic structure review of the explosion-joined three-metal joint: Zr-Ti-Steel is shown in Figures 2-4. The rear vortices mainly contain the surface of the cladding plate while the front vortices contain the base plate surfaces (Figure 2).

Fine grained micro alloyed normalised (HSLA) steel StE355 has a normalised rolled ferrite-pearlite structure. Near the transition area with titanium, the HSLA steel grains are deformed. Due to greater difference in strength of Ti-Steel, interlayer's vortices are larger and melting of materials is more characteristic compared with vortices on Ti - Zr interlayer area (Figures 2-4). Elongated α-grains of Ti caused by high-rate cold deformation are shown in Figure 3.

It seems that transformation into α-martensite is present in the melted vortices core since all conditions for developing are present: very quick cooling, as well

Table 2. **Chemical composition of joining materials**

Chem. comp. of mat. / %	C	Cu	H	Fe	Mn	Nb	Ni	N	O	P+S	Si	Ti	V	Zr+Hf
Ti Gr.1	0,06	-	0,010	0,15	-	-	-	0,025	0,15	-	-	rem.	-	-
Zr 702	0,05	-	0,005	0,20	-	-	-	0,025	0,15	-	-	-	-	rem.
TStE 355	0,15	0,10	-	rem.	1,2	0,03	0,10	-	-	0,04	0,20	-	0,08	-

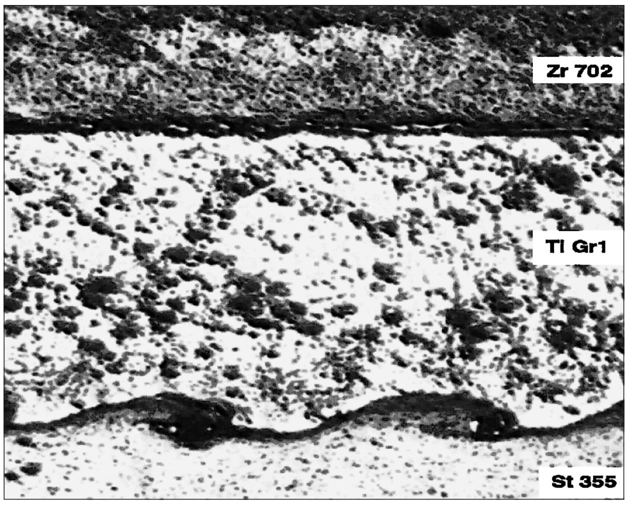


Figure 2. Steel/Ti/Zr joint. Magnification 15 ×

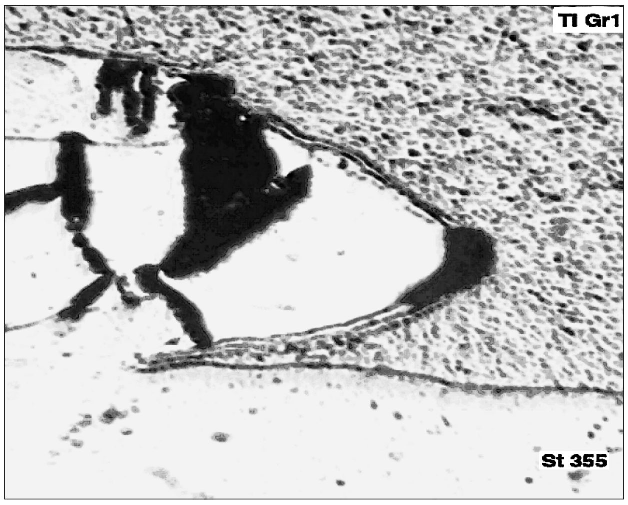


Figure 3. Transition area Steel/Ti. Magnif. 100 ×

as external stress applying (twinned martensite). This fact can explain the appearance of cracks only in the titan-part of the vortices core.

The microstructure of Ti Gr.1 consists of equiaxed α-grain structure with fine precipitates present within the grains and at grain boundaries. In Figure 4 the transition zone of Ti-Zr is shown. Due to smaller difference in strength between two materials, the possibility of martensite forming and cracks, as the consequence of it, is reduced. Thermal characteristics of Ti/Zr influence on martensite forming and crack appearance on Ti/Zr interface since the amount of melted Ti compared with melted Zr in vortices core is greater than in the previous case and its cooling is slown down. Zirconium is anisotropic and exhibits twins and slip lines in their large α-type grain microstructure when plastically deformed (Figure 4).

Mechanical properties analysis

Metals with widely different properties: carbon steel, titanium and zirconium, show varying degrees of the increase in hardness and tensile strength, as well as

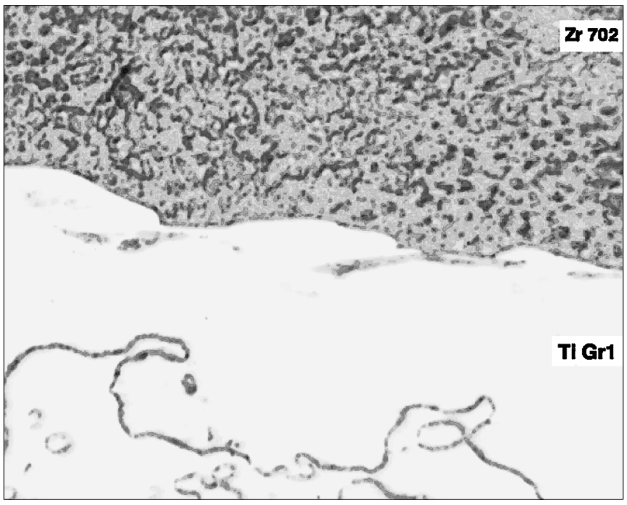


Figure 4. Transition area Ti/Zr. Magnif. 100 ×

reduction in ductility and impact strength when subjected to shock loading. Figure 5 shows the review of microhardness measurement of the bonded three-metal joint. The values of micro-hardness are much higher on the surface Ti/Zr than on the surface Ti/steel which indicates different rates of deformation. During qualification of explosion welding procedure, the method of bonding quality estimation is the shear strength test as the destructive method of inspection. Summary results of shear-strength tests on the three-metal joint are shown in Figure 6. The results show about 20 % stronger joint on the side of Ti/Steel compared with the joint Ti/Zr. In spite of the fact that cracks exist inside the vortex core on interface Ti/Steel, achieved shear strength i.e. bond strength is higher than on the surface Ti/Zr. These changes in properties occur with slightly higher deformation and not so visible grain distortion, so the change in properties cannot be related only to cold working. Obviously these changes have to be associated with the passage of intense compressive wave to which the materials are subjected or the reflected rarefaction wave. The diffusion across the bond during the process is generally negligible. In the welds between metals of very different densities, there is a greater possibility of the formation which consists of inter-metallic compounds with unfavorable mechanical properties. The vortex zones contain a mixture of the two component metals and due to the kinetic energy of the trapped jet, there is frequently a molten zone at the centre, which frequently contains metastable inter-metallic compounds.

CONCLUSIONS

The vortices formed on the interface Steel/Ti structure are greater with much more melted intermingled materials than on Ti/Zr interface which is caused by great strength as well as materials thermal properties difference.

Inter-layers defects on the interface Ti/Steel have no significant influence on strength of explosion

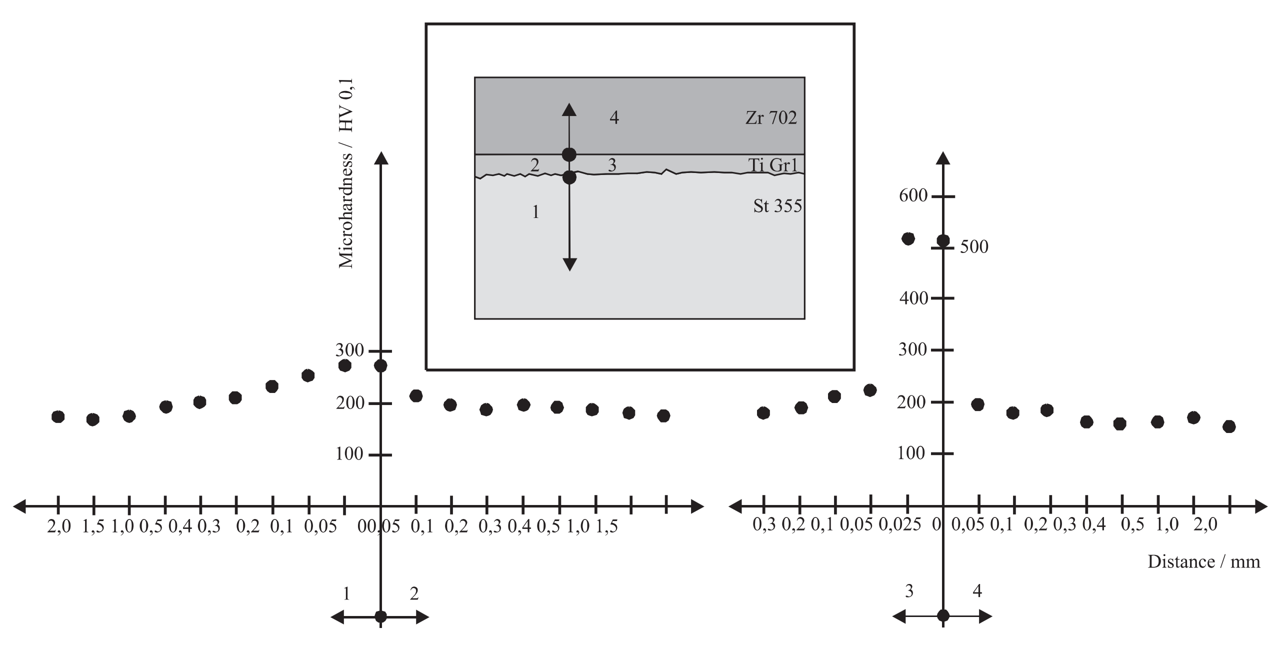
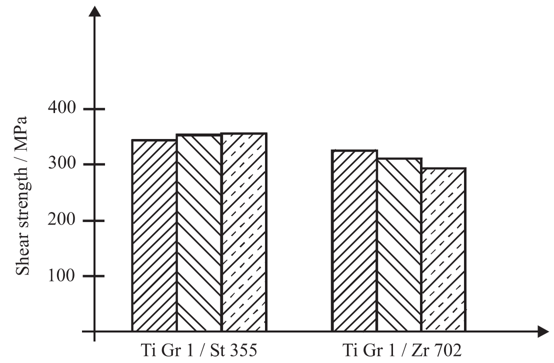


Figure 5. Review of microhardness measurement of bonded three-metal joint



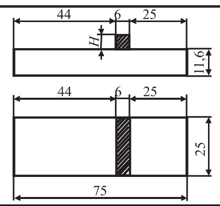
Specimen No.	Dimension / mm	Testing area / mm²	Force / N	Shear strength / MPa
1.1 Ti Gr 1/St 355		150,0	51500	343
1.2 Ti Gr 1/St 355		151,9	53500	352
1.3 Ti Gr 1/St 355		154,4	55000	356
2.1 Ti Gr 1/Zr 702		151,3	49000	324
2.2 Ti Gr 1/Zr 702		151,9	47000	309
2.3 Ti Gr 1/Zr 702		152,5	44500	292

Figure 6. Summary results of shear-strength tests on three-metal joint

three-metal: Steel/Ti/Zr joint made by specified explosion joining parameters.

The obtained results of all three-metal bond strength are very uniform with a difference of 20 % in favour of Ti/Steel bond.

Micro-hardness measurements indicate higher rate of deformation on the interface (Ti/Zr), i.e. between materials with quite similar strength, than at materials with great strength difference (Steel/Ti).

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