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ANALYSIS OF INTERFACE AT EXPLOSIVE WELDED PLATES FROM LOW-CARBON STEEL AND TITANIUM

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On the basis of experimentally obtained data, it was established that a very thin layer of a melt is generated at the explosive welding of two metals at the bond interface within which impurities flow at the bond during melting. Rapid cooling after the collision generates an alloy of different structure and very small grains of an average thickness approximately 1 to 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 welding of metals. Using the metallographic analysis, the development of the vortices which were formed by the explosive welding of low-carbon steel and titanium plates is described in the paper.

Key words: *explosive welding, plate, composite material, low-carbon steel, titanium, vortex, melt*

Analiza međupovršine eksplozijski zavarenih ploča iz niskougljičnog čelika i titana. Na osnovi eksperimentalnih rezultata utvrđeno je da pri eksplozijskom zavarivanju dvaju metala na međupovršini spoja nastaje veoma tanki sloj rastaljenog metala unutar kojeg dolazi do istjecanja nečistoća tijekom taljenja. Velika brzina hlađenja nakon sudara dovodi do nastanka sitnozrnate legure drugačije strukture s projećnom veličinom od 1 do 2 μm. Zapaženo nastajanje amorfnog sloja na području spoja kod različitih kombinacija metalnih materijala predstavlja temeljni mehanizam eksplozijskog zavarivanja metala. Primjenom rezultata metalografske analize u radu je opisan razvoj vrtloga koji su nastali eksplozijskim zavarivanjem ploča iz niskougljičnog čelika i titana.

Ključne riječi: *eksplozijsko zavarivanje, ploča, kompozitni materijal, niskougljični čelik, titan, vrtlog, talina*

INTRODUCTION

Explosive welding is an effective technical engineering solution method in joining plates, of very different or similar metals, which are from technological and economical aspect not suitable for any other joining in the composite material [1, 2].

Very different metals, such as copper, aluminium and their alloys, different steel grades, and metals with high melting point are joined with the explosive welding, too [3, 4]. They must fulfil the conditions of minimal ductility and impact toughness. The explosives are the source of necessary and controlled amount of high density and action rate energy [5]. Thus tight metallurgical joints between very different or very similar metals without any additional materials or external thermal effect are formed. When a flyer plate collises with a parent 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 unstable plastic flow of metal in the surroundings of the point of incipient flow a wavy interface is formed which is characteristic for the explosive welded metals [6].

In this paper the characteristics of the vortex [7], which is the most significant section of the wave, are presented. The kinetic energy of the flyer plate is transformed into a heat. The amount of this energy rises the temperature in the vortex over the melting points of both metals. Thus melt of both metals is formed in the vortex. By stirring, diffusion, and solving of solid fragments, alloying of both liquid metals occurs. Homogenisation of the melt takes place also simultaneously. Due to high cooling capability of the surroundings, the solidification of the melt is immediate. Heat removal to cool surroundings with high heat conduction efficiency is so fast, that solidification occurs at high cool-

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ing rate. The cooling rates in the molten zones in vortices have been calculated. Their values are of the order 10^5 to 10^7 K/s during or immediately after the solidification [8].

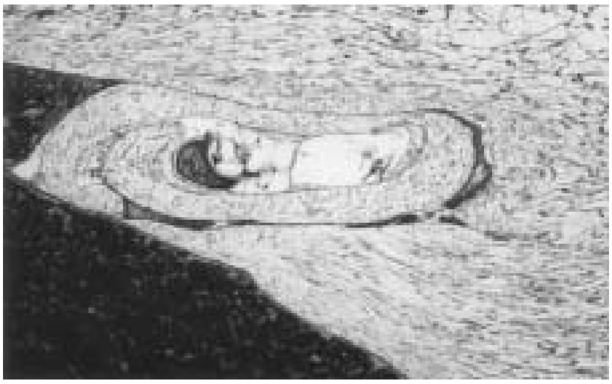

Figure 1. **Vortex. Spiral like lamella is composed of high deformed low-carbon steel. White core areas with cracks are part of remelted vortex core, dark core area is titanium, etched area is low-carbon steel. OM. Magnification 200 ×**

Slika 1. **Vrtlog. Spiralna lamela sastavljena od visokodeformiranog niskougljičnog čelika. Bijela područja jezgre s pukotinama su dio pretaljene jezgre vrtloga, tamno područje jezgre je titan, nagriženo područje je niskougljični čelik. OM. Povećanje 200 ×**

Typical defects in vortices which are formed during the solidification are: shrinkage, cracks and gas porosity. The inhomogeneous chemical composition in vortices was discovered by scanning electron microscopy (SEM) [9].

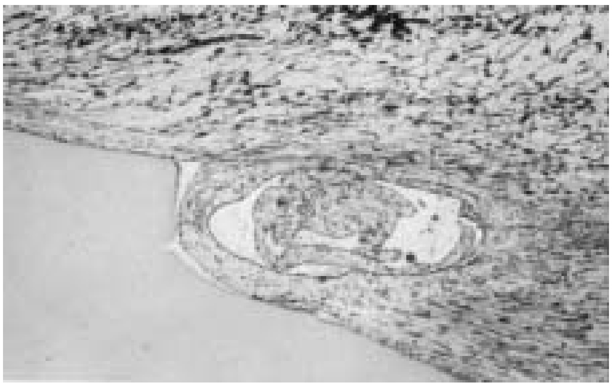

Figure 2. **Remelted alloy (white) and vortex with spiral like lamella of steel. Gray - titanium, etched - low-carbon steel. OM. Magnification 200 ×**

Slika 2. **Pretaljena legura (bijelo) i vrtlog sa spiralnom lamelom čelika. Sivo-titan, nagriženo-niskougljični čelik. OM. Povećanje 200 ×**

The microstructure changes near the interface, especially in the wave areas, are well illustrated in references [10, 11]. Plastic deformation, recrystallization, phase transformations in solid state, as well as the phenomena, connected to the melting and solidification in the vortices core, and the defects which occur during the solidification are also well known [12, 13]. The scope of our work is to examine to the phenomena which present in the vortices, which are part of the waves, and on the interface where the effect of explosion on material is the most intensive [14].

EXPERIMENTAL WORK

A composite material (plate) with a length of 800 mm and width of 75 mm was made by explosive welding of low-carbon steel plate with thickness of 24 mm, and titanium plate with thickness of 2 mm. Chemical compositions of both explosive welded metal materials are shown in Table 1.

Table 1. **Chemical compositions of explosive welded materials**

Tablica 1. **Kemijski sastav eksplozijski zavarenih materijala**

Element	Low-Carbon Steel/wt. %	Titanium /wt. %
Fe	99,11	0,17
Ti	-	99,64
C	0,10	0,05
Si	0,28	0,14
Mn	0,50	-
S	0,014	-
P	0,016	-

For metallographic analysis the specimens were prepared and etched separately or in the combination with nital and/or Keller's etching agent. In metallographic analysis of specimens of explosive welded metals an optical microscopy (OM) and electron scanning microscopy (SEM) equipped with the energy dispersive spectrometer (EDS) were used.

In liquid vortices the deformation of solid material is transformed into circular movement and stirring of molten materials, and this leads to intermingling of both metals. Generally, the basic metal of the vortex is deformed into a thin lamella, which is in form of a spiral (Figure 1.).

The area between the spiral lamellae contains melt and fragments of the other metal of the joint (Figure 2.). The formation of the melt is in connection with the formation

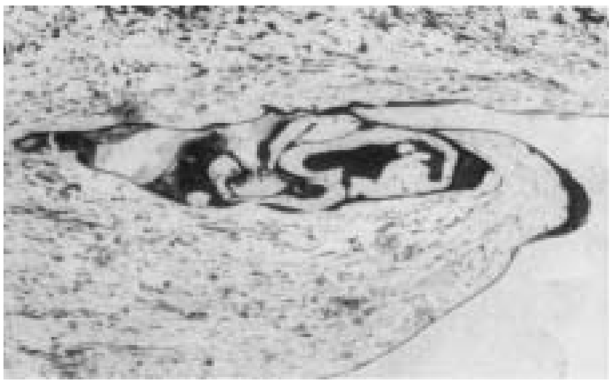

Figure 3. **Vortex with remelted metal in the core (dark) and titanium fragments in the remelted alloy at the periphery. White cores - titanium, etched - low-carbon steel. OM. Magnification 200 ×**

Slika 3. **Vrtlog s pretaljenim metalom u jezgri (tamno) i komadići titana na vanjskom rubu pretaljene legure. Bijele jezgre-titan, nagriženo-niskougljični čelik. OM. Povećanje 200 ×**

of vortices. The melt in the vortex core is stirred and rarely reaches the surface of the wave. Due to the high thermal source, which is created by the transformation of kinetic energy of the material into movement, the melt is formed. The solid metals which are in the contact with the melt are also dissolved.

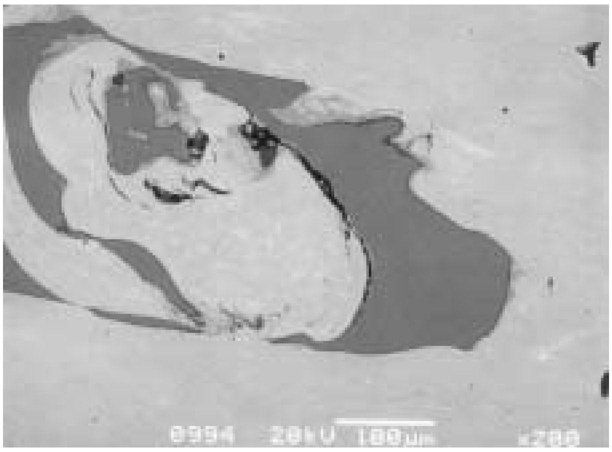

Figure 4. **Vortex. Due to deformation intermingled low-carbon steel and titanium. Remelted core with pores and cracks. SEM. Magnification 200 ×**

Slika 4. **Vrtlog. Izmiješani niskougljični čelik i titan zbog deformacije. Pretaljena jezgra s porama i pukotinama. SEM. Povećanje 200 ×**

Inside the vortex the diffusion zone around the solid segments of titanium is well indicated. The interface of low-carbon steel with the titanium is rounded which is characteristic for the solid - liquid interface when the solid phase is dissolving. The alloys in the vortex core in the low-carbon steel - titanium joint exhibit heterogeneity of the chemical composition. Examples of formed waves and vortices are shown in the Figures 3. and 4.

In the vortex, eddying of narrow strips, metal fragments and molten areas can be distinguished. The phase compositions of remelted part in vortices are well revealed by back scattered electrons (BSE) in SEM.

The black and white areas inside or in the surrounding of the vortex (Figure 5.) are primary metals low-carbon steel and titanium [15]. The rest are alloys which were formed by melting, stirring and alloying due to the solubility of solid metals in the melt. The chemical composition inside the remelted vortex was analysed at some characteristic points (Figure 5., Table 2.) and it is inhomogeneous.

Table 2. **Chemical compositions of the alloy in some characteristic points in the vortex in the low-carbon steel - titanium joint determined by the quantitative EDS analysis (Figure 5.)**

Tablica 2. **Kemijski sastav legure na nekim karakterističnim točkama vrtloga u spoju niskougljični čelik-titan određen kvantitativnom EDS analizom (Slika 5.)**

Point	Fe / wt. %	Ti / wt. %
A	89,6	10,4
B	31,5	68,5
C	98,7	1,3

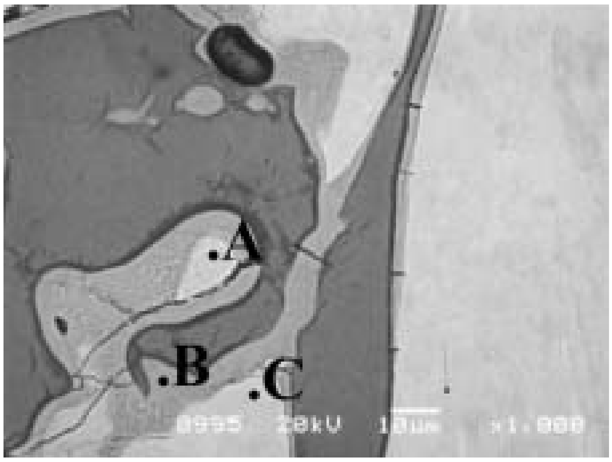

Figure 5. **Detail of the vortex core. Cracks and pores in the remelted vortex core. SEM. Magnification 1000 ×**

Slika 5. **Detalj jezgre vrtloga. Pukotine i pore u pretaljenoj jezgri vrtloga. SEM. Povećanje 1000 ×**

Remelted part of the vortex is microstructurally inhomogeneous, too. Two phases can be well distinguished, the first is rich in iron (ferrite) at the points A and C, and the second is rich in titanium (at point B). According to the chemical composition, the normal microstructure should be eutectic, but this morphology is occurred only partially. Highly varying chemical composition of the alloy shows that both alloy components (low-carbon steel and titanium) have been melted inside the vortex. Solidification rate was so high that both melts were only partially alloyed and were not homogenised. During the solidification, the alloys rich in titanium crack, what was not case for ferrite.

CONCLUSIONS

The results of metallographic and the in situ microchemical analysis showed that at explosive welding of low-carbon steel and titanium both metals are molten.

At the beginning the melts of both metals are separated. Further, the melts are due to intensive motion stirred by rotation and turbulent stirring action. Stirring and diffusion cause alloying and homogenisation of the melts. Alloying takes place also with dissolution of the solid surrounding, but this phenomenon occurs more slowly than the previous two.

In the vortex core varies the chemical composition of the alloys. The concentration of each metal in the remelted vortex core differs from area to area.

Cooling rate in the vortex core is very high (10^5 to 10^7 K/s) and therefore solidification is inequilibrial. Thus the microstructure of the remelted areas is essential by different from that which is predicted from the chemical composition and from the equilibrium phase diagram. In the remelted part of the low-carbon steel - titanium joint two phases were identified, ferrite with different concentrations of titanium, which is according to the chemical composition close to intermetallic phases in the iron-titanium system.

In this work we wish to point to simultaneous forming of melts of both metals inside the vortex core, to their intensive stirring, to the phenomena of alloying with stirring, diffusion, and dissolution of the solid surroundings, and to solidification at high cooling rate which all disable chemical homogenisation of the melt, and they are reason for the inequilibrial microstructure.

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