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Structure and properties of explosively formed laminar composite

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Paper presents results of investigations with three-layer explosively formed composite called trimetal consisting of steel, titanium and aluminium. Structure and properties after explosive welding have been analysed as well as influence of annealing on conversions in and properties of bonding zones and bonded materials. It has been proved that elaborated parameters of explosive system ensure complete welding both in steel-titanium and titanium-aluminium regions. The weld is characterized by corrugated joint with insignificant number of penetrations, and good mechanical properties. Heat treatment (stress relief annealing) has been executed in temperature being higher than working temperature provided for trimetal as structural component. Stress relieving removes strain hardening caused by explosion and, simultaneously, activates decomposition of unbalanced phases created in steel at steel-penetration phase boundary (bainite, martensite) in the course of explosive bonding, and causes diffusion of carbon from supersaturated solid solutions into penetrations being rich with titanium. This process leads to precipitation of TiC precipitates. However, inconsiderable amount of penetrations guarantees that precipitation processes do not impair workability of bonding zone.

1. INTRODUCTION

Application of explosive welding enables bonding of different, mutually unweldable metals [1]. Obtained joint represents high mechanical properties and good workability. Production of so called welding connectors is one of possible areas of explosive welding application. Generally, the welding connectors are metal composites having e.g. steel layer from one side and aluminium or aluminium alloy layer from the other. Three-layer composites in which carbon steel layer is separated from aluminium alloy layer by intermediate layer of pure aluminium are also very common. Another example of three-layer connectors are composites with intermediate layer made out of pure titanium. Such connectors are used in anode systems applied in electrolysis of aluminium as well as in shipbuilding industry for welding aluminium alloy structures to steel decks.

Application of titanium as intermediate layer enables connector to work in higher temperatures (up to 500°C). In that case, holding in a temperature of 500°C removes both strain hardening and hardening caused by phase transitions occurring in such specific bonding conditions [2,3]. It is especially essential for electrolysis of aluminium since the process can be performed at higher current intensities without misgivings about damage of anode system at bonding zone between aluminium rod and steel part of the anode. Moreover, using such type of connector the process of welding aluminium elements with steel ones can be done at higher welding parameters. Systems composed of aluminium and steel layers only and those with intermediate layer made out of pure aluminium have limited application since temperature of aluminium-steel joint should not exceed 350°C.

Paper presents results of tests performed on laminar composite steel-titanium-aluminium manufactured by ZTW "Explomet".

1. MATERIAL FOR TESTS AND THEIR COURSE

Trimatel plate having dimensions 480 x 500 x 55.5 mm was made up of ASME SA-516 Gr. 70 low-carbon steel plate, 40 mm thick and containing 0.12 ÷ 0.20 % C, ASME SB-265 Gr.1 (>99.5% Ti) titanium plate 1.5 mm thick, and EN-573-3 EN AW Al99.7 aluminium plate 14 mm thick.

Explosive welding of all three materials was done simultaneously in the course of one shot after foregoing selection, calculation and testing of welding parameters such as type and amount of explosive, detonation velocity and structure of the system. Investigations presented in the paper refer to the trimetal of repeatedly good parameters ensured by appropriate welding parameters[*)].

nvestigations covered analysis of the wave, determination of quantitative portion of penetrations, analysis of macro- and microstructure, as well as change of hardening caused by explosive welding and subsequent heat treatment. Heat treatment consisted in heating up to 500°C, holding in such temperature for 24 hours and cooling down in surrounding air.

2. RESULTS OF TESTS AND THEIR ANALYSIS

Macroscopic tests performed on sections parallel to direction of explosion propagation showed that contact surface of obtained joint was corrugated (Fig. 1) regardless of the place of sampling, i.e. regardless of distance from the point where explosion was initiated. The joint is characterised by parameters of the wave, amount of present penetrations and voids. The wave created at steel-titanium phase boundary has average length of about 2760 μm and height about 530 μm, whereas at titanium-aluminium phase boundary these values are accordingly 1570 μm and 310 μm. Thus, the average wave length and height on steel-titanium side are about √3 bigger than those on steel-aluminium side.

Created wave deformed titanium intermediate layer in such a way that initial thickness of titanium plate changed locally from 1.5 mm to about 1 mm (between wave tops) and 2 mm (between wave hollows). No voids or penetration were observed by macroscopic manner in obtained trimetal. Generally, in that kind of bonds such imperfections are disposed at the wave combs.

[*)] Detailed data is the property of ZTW "Explomet"

Changes of microhardness in bonding zone were determined on cross-section at wave top and hollow ($HV_{0.2}$), and at micro-areas containing penetrations or other substantial phase transitions ($HV_{0.1}$). Hardness of steel near the phase boundary with titanium in non-heat treated joint is the biggest and amounts to about 310 $HV_{0.2}$. The hardness decreases to about 225$HV_{0.2}$ as distance from contact line increases. Hardness of intermediate titanium layer varies in the range from about 215 to 230 $HV_{0.2}$, whereas that of outside aluminium layer varies from about 40 to 50 $HV_{0.2}$. Applied heat treatment reduced hardness of steel, titanium and aluminium to about 200 $HV_{0.2}$, 140 $HV_{0.2}$ and 30 $HV_{0.2}$, respectively. Annealing ensured removal of strain hardening in all three metals, which significantly had occurred in titanium and aluminium.

Microscopic tests at not large magnifications show significant similarity of structures regardless of heat treatment condition. However, detailed observation reveals number of essential differences. Steel structure at bonding line consists of ferrite, pearlite and bainite-martensite regions (Fig. 2). In the course of heat treatment, in bainite-martensite regions located closest to bonding line the phase transitions take place, which consist in cementite precipitation and diffusion of carbon towards steel-titanium boundary. As a result of these transitions the above mentioned regions become fine-grained ferrite. The transitions are particularly active at wave combs where penetration layers and micro-voids occur (Fig. 3). As results from microhardness tests (Fig. 4), the biggest hardness belongs to penetrations, bainite-martensite regions represent high value of hardness and the lowest hardness is that of titanium, nevertheless it is much higher than that of initial state before explosive welding (about 130 $HV_{0.2}$). After heat treatment due to mentioned diffusive transitions the hardness of steel decreases while that of penetrations remains at very high level (Fig. 3 and 4). Heat treatment activates diffusion of carbon from steel towards penetrations. This results in creation of thin, nearly continuous layer of precipitated titanium carbide TiC.

There are no such diffusive processes at titanium-aluminium welding boundary and still remain substantial differences between hardness of bonded materials and hardness of penetrations amounting to 700 - 800 $HV_{0.1}$. Number of penetrations in analysed joint is small.

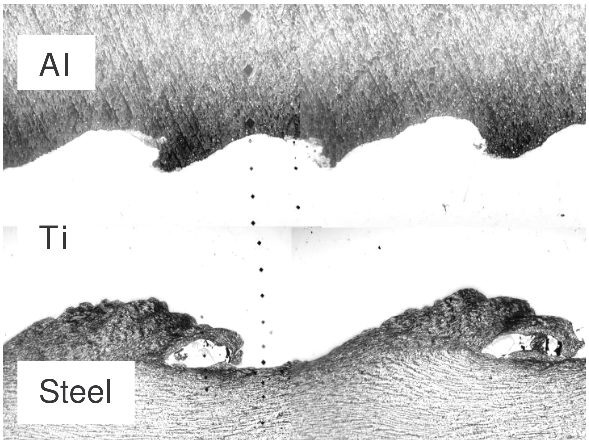

Fig. 1. Macrostructure of explosive welded joint steel-titanium-aluminium; visible points of microhardness measurements.

Magnification: 16x

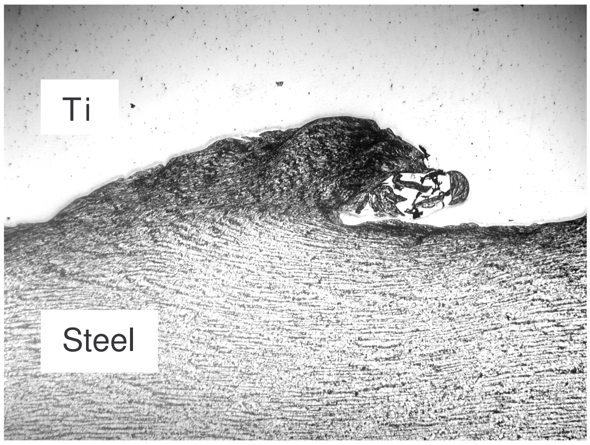

Fig. 2. Part of microstructure of steel-titanium bonding area - non-heat treated condition.

Magnification: 50x

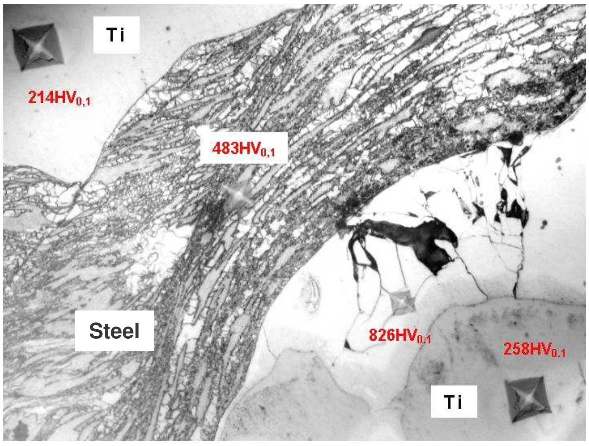

Fig. 1. Macrostructure of explosive welded joint steel-titanium-aluminium; visible points of microhardness measurements.

Magnification: 750x

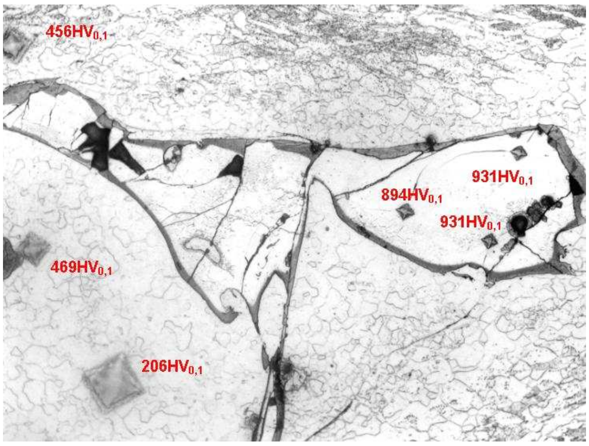

Fig. 2. Part of microstructure of steel-titanium bonding area - non-heat treated condition.

Magnification: 750x

It was determined by so called equivalent penetration layer thickness, i.e. the ratio of area occupied by penetrations to the overall length of contact line. Thickness of this layer amounted to 17.5 μm at steel-titanium boundary and about 25 μm at titanium-aluminium boundary.

4. CONCLUSIONS

Basing on performed investigations the following conclusions can be drawn up:

- contact surfaces between steel and titanium as well as between titanium and aluminium are corrugated; there is small amount of penetrations and voids at bonding zone;
- aluminium and titanium sustain hardening throughout entire section while steel mainly at bonding vicinity;
- hardening of aluminium and titanium results from dynamic plastic strain occurring in the course of explosive welding; hardening of steel comes from strain hardening and martensitic phase transitions;
- heat treatment (annealing at 500°C for 24 hours) removes hardening owing to recrystallization and decomposition of martensitic phases.

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