ANALYSIS OF CHOSEN WELD PROPERTIES OF EXPLOSIVELY BONDED STAINLESS STEEL WITH TITANIUM

MAZANCOVÁ Eva[1], KUČERA Pavel[1], SAKSL Karel[2], ĎURIŠIN Martin[2], BALGA Dušan[2], SZABO Juraj[2]

[1] *Technical University of Ostrava, Faculty of Metallurgy and Materials Engineering, Czech Republic, EU,* eva.mazancova@vsb.cz, dimitrij.o@seznam.cz, pavel.kucera.st@vsb.cz
[2] *Institute of Material Research of SAS, Košice, Slovakia, EU,* ksaksl@imr.saske.sk, mdurisin@imr.saske.sk, dbalga@imr.saske.sk, jszabo@imr.saske.sk

Abstract

The work deals with chosen properties of bimetal weld and its neighbourhood of Ti-clad Cr/Ni steel after one or double heat treatment (at 600 °C / 1.5 h / air) applied after explosive bonding. Notch impact strength values were compared with bimetal weld of C-Mn steel bonded with Ti after the same heat treatments. After double annealing, stainless steel Ti-clad showed the best transition temperature level (-60 °C at 310 J / cm^2) unlike the Ti-clad C-Mn steel (-38 °C at 140 J / cm^2). One annealing applied after explosive bonding resulted in worse parameters (decrease by 33 % and/or 87 % for stainless steel and/or C-Mn steel). Next part of work was target on sulphide stress cracking under tensile test and bent-beam test for Cr/Ni steel joined with Ti only after double heat treatment. Threshold level (for tensile) corresponded to 40 MPa and maximal deflection at 160 MPa to 0.609 mm without any defect. Results have been confronted with by now found facts.

Keywords: Cr / Ni-Ti weld, annealing, Charpy-test, SSC tests, microfractography

1. INTRODUCTION

Former Cowan et al [1] showed that formation of the wavy bonded zone in explosive cladding is analogous to the formation of an oscillating wave and vortex stress in fluid flow passing an obstacle. Weld and its close surroundings of explosively bonded materials logically represent critical area of potential failure. In this area, internal stresses are concentrated, especially after welding and so followed annealing must be applied leading to decrease of those stresses [2]. In case of Ti-clad Cr/Ni Saksl et al [3] reported, that double annealing at 600 °C for 1.5 hour (2HT) after own bonding not only reduced negative stresses but also induced favourable comprehensive strains at the weld region. Moreover, this type of heat treatment maximally contributes to titanium microstructure balancing and its maximal refining as it was also former published [4-6]. After explosive welding of Ti-clad Cr/Ni and/or C-Mn numerous workers [1, 7, 8] demonstrated that at high kinetic energy conditions, dissipated heat causes melting of the mixture, leading to molten zones, where minimally FeTi and Fe_2Ti intermetallic phases were identified by use of conventional SEM and/or X-ray diffraction [9, 10]. In vortexes of bimetal Cr/Ni welded with Ti, Saks et al [3] identified, using hard X-ray micro-diffraction experiment performed at beamline P07 and PETRA III (electron storage ring operating at energy 6GeV with beam current 100 mA), Fe_2Ti only. In recent work [6] fatigue properties, anticorrosion resistance of HIC type were studied both after one heat treatment (1HT) followed welding process and double annealing (both at 600 °C / 1.5 hour/air for above mentioned bimetal), which showed positive impact on studied properties after double heat treatment. Again in those samples of weld, resp. in vortexes only Fe_2Ti was detected and its portion was significantly reduced after double annealing application (by more than 66 % [3]).

The aim of presented paper is a study of bimetal weld and its surroundings (Ti-clad Cr/Ni type, event. C-Mn) after impact loading in bend (Charpy V) and sulphide stress cracking (SSC) both in tensile and in bent-beam, because similar works had not been presented by now or partially only [6]. Results fill in by now found information. It can be supposed, given tests show important properties for technical praxis, since investigated bimetal (Ti-clad Cr/Ni) is commonly used material in energy conversion, including geothermal and also in chemical and petroleum industry.

Table 1 Chemical compositions of explosively welded materials (wt. %)

Element	**C**	**Si**	**Mn**	**Cr**	**Ni**	**P**	**S**
Cr/Ni steel	0.04	0.45	1.96	18.42	9.74	0.006	0.011
C-Mn steel	0.19	0.35	1.46	0.06	0.02	0.010	0.003
Element	C	Fe	O	N	H	-	-
Titanium	0.004	0.022	0.047	0.005	0.003	-	-

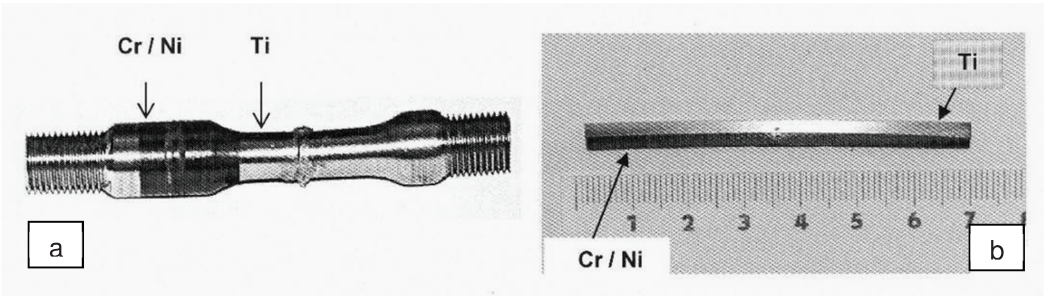


Figure 1 Shape of used SSC bars after 720 hour exposition (dark part represents Cr/Ni steel, the light one Ti) a) sample after tensile test - dimensions are part of text, b) sample after bent-beam test

2. EXPERIMENTAL APROACH

For study explosively welded bimetal of stainless steel Cr/Ni (110 mm plate in thickness) with Ti of commercial purity was used. **Table 1** summarizes chemical composition of mentioned bimetal and also chemical composition of Ti-clad C-Mn steel chosen for comparison of notch impact toughness of both bimetal types. Titanium thickness corresponded to 6 mm sheet in thickness always. Explosive welding was carried out in Explomet-Opole, Poland. After ultrasonic test bimetals were annealed at 600 °C / 1.5 h / air. For Charpy tests (according ČSN EN ISO 148-1) were manufactured conventional samples (10 x 10 x 55 mm) with V-notch finishing in Ti, 2 mm above weld both after the first mentioned heat treatment and also after the second one corresponding to repeated annealing (double one) at 600 °C / 1.5 h / air so that the internal stresses were maximally reduced [6] and also the portion of intermetallic phase Fe_2Ti was decreased as it results from former reported works [3, 6]. Charpy tests were carried out in temperature in range from -120 °C (Cr/Ni - Ti bimetal), resp. -75 °C (C-Mn - Ti bimetal) to +20 °C. In second step the SSC, resp. tensile test and bent-beam test in case of Ti-clad Cr/Ni after double heat treatment (600 °C /1.5 h / air) were carried out. With respect to thicknesses of both welded materials and to the SSC testing bar dimensions according the NACE Standard TM0177-2005, samples for the SSC tensile test were manufactured with thread, which was glued up with quick-setting silicon adhesive so that bimetal weld would be in exposition chamber with corrosive medium centrally as it **Figure 1a** demonstrates. Exposition of tensile samples was in accord with the above mentioned standard (corrosive solution A at 25 ± 3 °C). Starting pH corresponded to 3.5 and the final one to 3.8. Bars were tested at applied stresses in range from 150 MPa to 35 MPa, under the yield stress similar as it was partially presented in previous work [6]. Subsequently, after removing of exposed samples from corrosive solution those were looked over. Samples were 64 mm in length and exposed body was 3 mm in diameter. Six mm of Ti surfacing on Cr/Ni was lengthened by Ti of the same grade so that regular testing bar according NACE Standard TM0177-2005 could be manufactured. Samples (14 pieces totally-see **Figure 1b)** were subjected to three-point bending under loading in interval from 35 MPa to 160 MPa and after exposition possible failures were investigated using stereoscope and deflections (all in accord with above mentioned standard) were calculated. Exposition was carried out in corrosive solution A at 25 ± 3 °C and pH solution corresponded to 2.7 in the test beginning and to 2.9 in the end. From applied stress, beam length, thickness and elastic modulus deflection was calculated (assuming elastic conditions and ignoring the stress concentration effect of the holes and the test specimen plasticity at high stress levels) in accord with NACE Standard TM0177-2005. Microstructure and microfractography study were realized by light microscope Olympus IX 70, SEM JEOL JSM-6490 with EDA and JEOL JSM-7000.

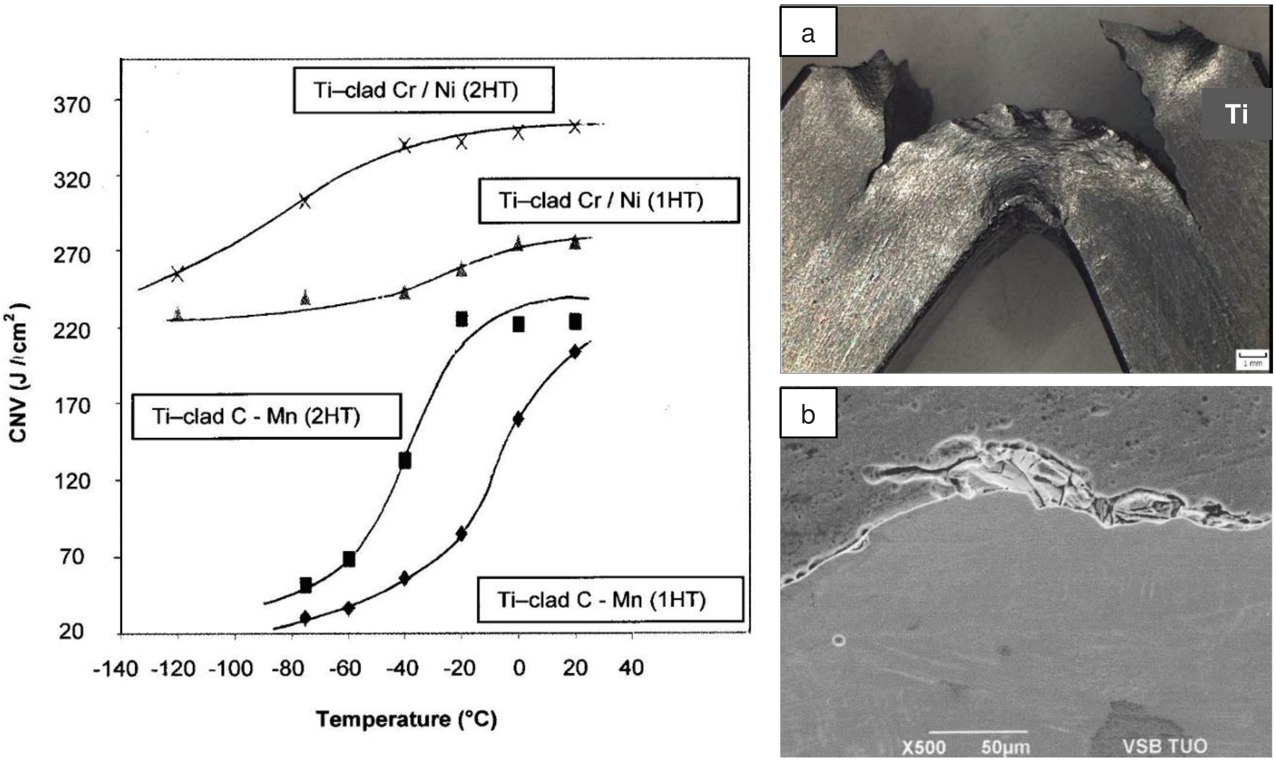


Figure 2 Charpy V values vs temperature for Ti-clad Cr/Ni and/or C-Mn steel after 1HT and 2HT applied after explosive welding, a) Charpy V sample after 2HT tested at -40 °C (Ti-clad Cr/Ni), b) character of crack propagation in join and/or mixed zone of Charpy V sample (detail of **Figure 2a** after grinding and polishing)

3. REACHED RESULTS AND ANALYSIS

Summarized results of Charpy V tests (CNV) of Ti-clad Cr/Ni bimetal after one and double annealing after explosive welding in comparison with the same treated bimetal of C-Mn bonded with Ti shows **Figure 2**, which gives evidence in favourable effect of used heat treatment [3, 4, 6] as well as bonding of stainless steel and Ti. For double heat treatment transition temperature lays at level of -60 °C (at 310 J / cm^2) and difference of notch toughness values between low and upper shelf (range from -120 °C to +20 °C) corresponds to 96.4 J / cm^2. After 1HT, transition temperature was shifted approximately by 20 °C at the level of -40 °C (at 241 J / cm^2). In this case both shelfs shows difference of 46 J / cm^2. Bimetal with basic C-Mn steel demonstrates shifting of transition temperature to the more positive values to -38 °C (at 140 J / cm^2) and to -5 °C (at 129 J / cm^2) after 2HT and/or after 1HT. The curves are more typically erect with differences of both shelfs (between -80 °C and +20 °C) corresponding to 200 J / cm^2. Those findings are supported by fracture surfaces predominantly showing trans-crystalline ductile failure with shallow dimples and at the lowest temperatures trans-crystalline cleavage failure dominates, with numerous finer ductile ridges responsible for generally high toughness levels. **Figure 3** demonstrates fracture surfaces features at +20 °C and at -40 °C. After 2HT, finer facets can be observed in **Figure 3a** than in **Figure 3c** (both at -40 °C) as well as finer and longer ductile ridges in **Figure 3b** in comparison with **Figure 3d** (both at +20 °C). In fractured Charpy V samples, there was a guest to find dependence of crack length on temperature testing, however the results were too chaotic and any dependence was not able to define. Cracks were propagated both in bonding line and along that one. Cracks were also often observed in area of vortexes, where recently intermetallic phase Fe_2Ti was detected - see **Figure 2b** [67].

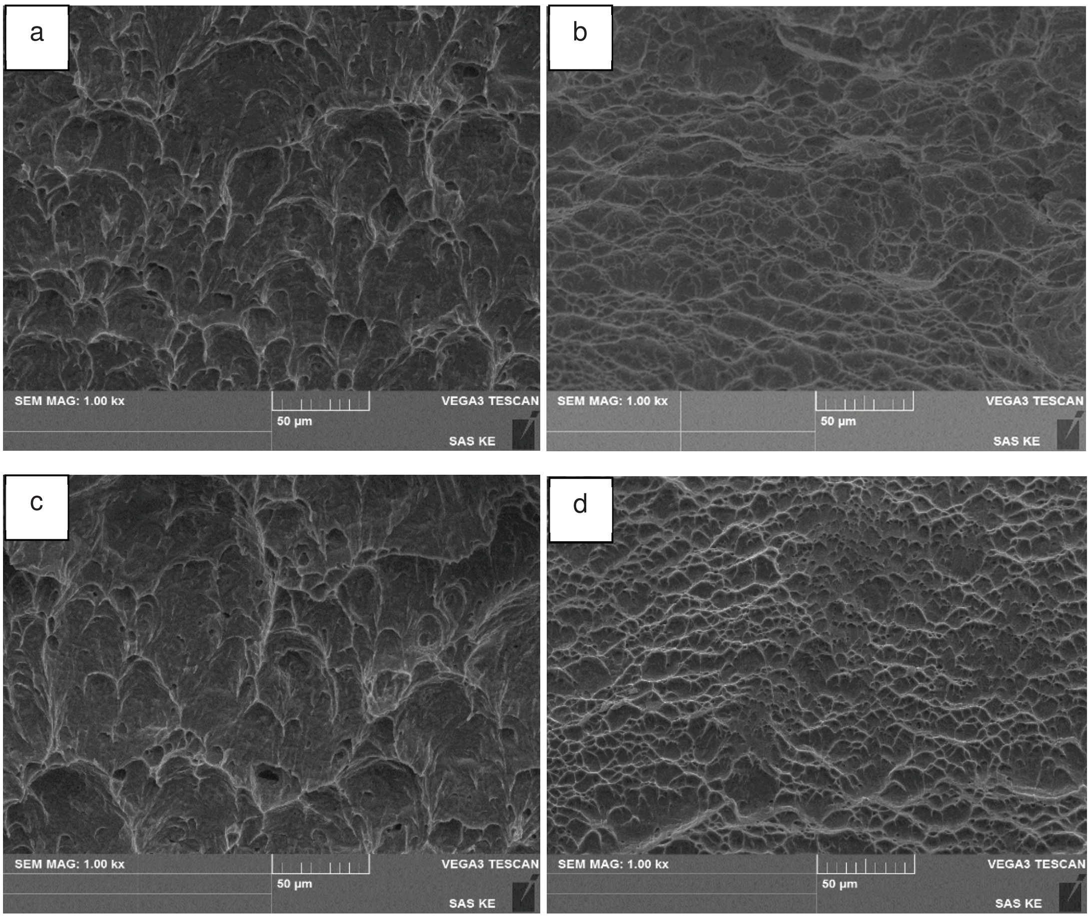
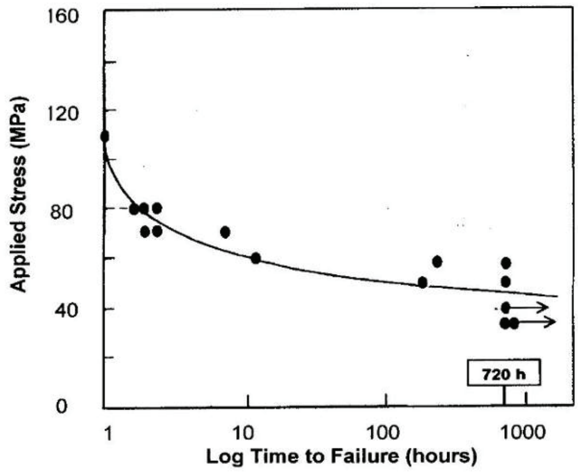


Figure 3 Fracture surfaces of Ti-clad Cr/Ni steel a) after double annealing (600 °C / 1.5 h / air) at -40 °C and b) at +20 °C, c) after one annealing (600 °C/1.5 h / air) at -40 °C, d) at +20 °C

Results of SSC tensile test are summarized in **Figure 4**. One sample loaded at 150 MPa and one at 50 MPa were raptured immediately after loading in area of screw join and are not part of plotting. Mentioned loadings corresponded to 46 % and 15 % of bimetal yield stress (326 MPa on average) in weld which was formerly found out before fatigue tests [6]. As it from **Figure 4** follows, at loading of 40 MPa none failure was revealed and at 35 MPa tensile bars had been tested up to 820 hours without any defect, too. It could be stated, loading of bimetal weld of Ti-clad Cr/Ni steel equals 11 - 12 % of yield stress. Under presented conditions, this value represents reliable threshold level of hydrogen susceptibility. In case of the same bimetal weld after 2HT, however under fatigue test (alternating load tension-pressure, at 20 Hz and charging in 0.5M H_2SO_4 for 8 hours) [6], loading of 40 MPa corresponded to lifetime threshold, as well. Failure was predominantly situated in mixed zones (**Figure 4**, areas 1, 2) like it was observed in [5], where Fe_2Ti was detected [3]. **Figure 5** demonstrates results of SSC bent-test. Deflection was in range from 0.133 mm (under loading of 35 MPa) to 0.609 mm (under loading of 160 MPa). None failures or defects were observed in microstructure of exposed samples at 720 hours exposition and deflections showed linear increase with higher loading. Any banding by hand was unsuccessful.



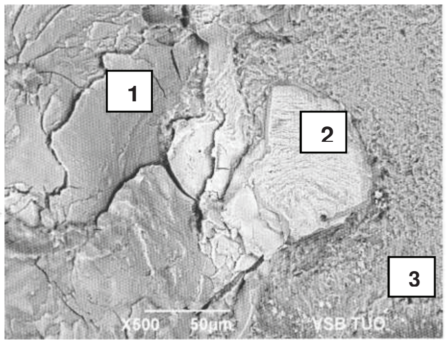


Figure 4 SSC tensile test results of double heat treated (at 600 °C / 1.5 h / air) weld of Ti-clad Cr/Ni after explosive bonding with appearance of fracture surface (exposition under loading of 80 MPa), where **1** represents. approx. 45 Ti, 20 Ti corresponds to **2** and 65 - 95 Ti to **3** (in at. %)

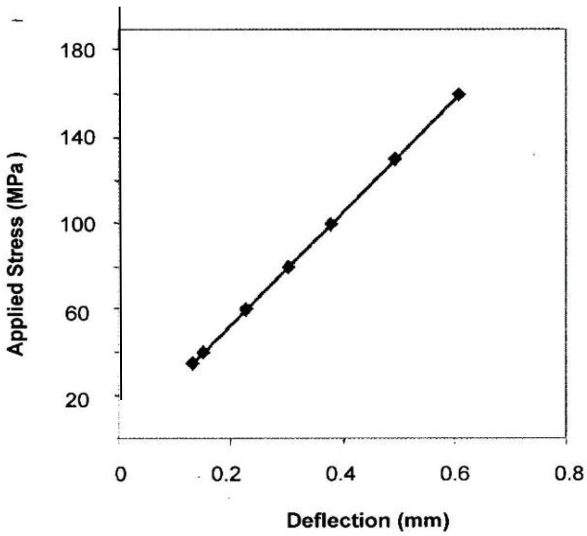


Figure 5 Plotting of applied loading vs counted deflection

4. CONCLUSIONS

Weld of Ti-clad Cr/Ni bimetal was investigated in conditions of notch bending test (after one and/or double heat treatment after welding, always at 600 °C / 1.5 h / air) and only after double annealing (2HT) sulphide stress cracking (SSC) tensile test and three-point bending one in accord with NACE Standard TM0177-2005 were studied. Results showed favourable effect of 2HT on Charpy V values of bimetal interface, because 2HT resulted in higher level of transition temperature. Difference between both HT was 20 °C (-60 °C and -40 °C at 310 J / cm^2 and 241 J / cm^2). Investigation of weld of Ti-clad Cr/Ni in comparison with weld of Ti-clad C-Mn steel revealed deterioration of transition temperature of the second bimetal type by 22 °C after 2HT and by 35 °C after 1HT.

Favourable effect of 2HT can be ascribed to balancing and refining of Ti grain size, to residual stresses decrease, portion decrease in Fe_2Ti intermetallic phase detected in vortexes of welds as it was part of papers [3, 4]. Failure was predominantly revealed in mixed zones.

Results of SSC tensile tests showed lifetime threshold at 40 MPa which was also reached during fatigue tests (amplitude of 20 Hz with sample charging in 0.5M H_2S0_4) presented recently [6]. Results of SSC in three-point bending proved excellent explosive bonding of investigated bimetal, because after 720 hours of exposition in sour corrosive solution any cracks were detected neither in bimetal interface nor out of weld. Counted deflection corresponded to range from 0.133 mm (35 MPa of loading) to 0.609 mm (160 MPa of loading). Presented results complete existing investigation of bimetal weld of Ti-clad Cr/Ni steel.

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REFERENCES

[1] COWAN, G. R., BERGMANN, O. R., Holzmann, A. H. Mechanism of bond zone wave formation in explosion-clad metals. Mater. Trans., 1971, vol. 2, no. 11, pp. 3145-3155.

[2] YADEGARI, M., EBRAHIMI, A. R., KARAMI, A. Effect of heat treatment on interface microstructure and bond strength in explosively welded Ti / 304L stainless steel clad. Mater. Sci. Technol., 2013, vol. 29, no. 1, pp. 69-75.

[3] SAKSL, K., OSTROUSHKO, D., MAZANCOVÁ, E., SZULC, Z., MILKOVIČ, O., ĎURIŠIN, M., BALGA, D., ĎURIŠIN, J., RŰTT, U., GUTTOWSKI, O. Local structure of explosive welded titanium-stainless bimetal, Int. J. Mater. Research, 2015, vol. 106, no. 6, pp. 621-627.

[4] MIRONOV, S. Ju., SALISHEZEV, G. A. Influence of grain size and micro-structure homogeneity on deformation uniformity of commercially pure titanium (in Russian). Fizika Metallov i Metallovedenie, 2001, vol. 92, pp. 81-88.

[5] ALBRECHT, J., LUTJERING, G. Microstructure and mechanical properties of titanium alloys. Sci. Technol., 2000, vol. 1, pp. 363-374.

[6] MAZANCOVÁ, E., OSTROUSHKO, D., SAKSL, K., NIESLONY, A. Join hydrogen susceptibility of 304 SS welded with titanium. Arch. Metallurgy. Mater., 2014, vol. 59, no. 4, pp. 1605-1610.

[7] MANIKANDAN, P., HOKAMOTO, K., DERIBAS, A. A., RGHUKANDAN, K., TOMOSHIGE, R. Explosive welding of titanium/stainless steel by controlling energetic conditions. Mater. Trans., 2006, vol. 47, no. 8, pp. 2049-2055.

[8] SONG, J., KOSTKA, A., VEEHMAYER, M., RAABE, D. Hiearchical microstructure of explosive joins: Example of titanium to steel cladding. Mat. Sci. Eng., 2011, vol. 528A, pp. 2641-2647.

[9] WANG, B., Chen, W., Li, J., Zhu, Z. Microstructure and formation of melting zone in the interface of Ti/NiCr explosive cladding bar. Mater. Des., 2013, vol. 47, pp. 74-79.

[10] MOUSAVI, S. A. A. A., SARTANGI, P. F. Experimental investigation of explosive welding of cp-titanium/AISI 304 stainless steel. Mat. Des., 2009, vol. 30, pp. 459-468.