HYDROGEN SUSCEPTIBILITY OF EXPLOSIVELY WELDED ANTICORROSION STEEL AND TITANIUM OF COMMERCIAL PURITY

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Abstract

The work deals with hydrogen susceptibility of joint of explosively welded anticorrosion steel of 18Cr/10Ni type with titanium of commercial purity. Studied welds were after twice heat treatment (600°C/1.5 h/air) and those were tested in corrosive solution in accord with NACE Standard TM0177-2003 (sulphide stress cracking under stress), representing dynamic test. Threshold level lay close to 40 MPa, approximately. The sources of failure were intermetallic phases of the Fe_2Ti type detected using EBDS. Results were confronted with former results and accessible literature.

Keywords: 18/10-titanium weld, explosive welding, hydrogen susceptibility, intermetallic phase, EBDS

1. INTRODUCTION

Degradation of steel properties activated by hydrogen sulphide is known for a long time and in this context numerous concepts including influence of different structural-metallurgical parameters were worked out [1-3]. The most of works are interested in hydrogen response of sheets, profiles, seamless pipes and pipe-lines made from welded sheets. A special attention has been paid to welds, potentially sensitive areas to hydrogen.

Beside the conventional joint of two dissimilar materials, explosive welding process has been also applied. This bonding technique is very attractive because of more favourable properties of final component [4-6]. Core-materials of lower quality can be joined with material of a higher grade being un-connectible under conventional conditions. Among such material types belong stainless steel and titanium of commercial purity. Given explosively welded material is among others applied in heavy chemistry and energetic including geothermal one. Weld represents potentially weaker position of connected materials, where typical defects in the vortices due to solidification are shrinkage, cracks and gas porosity. Further, adiabatic bands in the vicinity of joint through extreme temperatures and pressures are formed during explosive bonding. These bands, own bonding wave line in nature and extreme fine grains, being result of the welding type, internal pressures, higher dislocation density and especially intermetallic formation in nearby of bonding line, respectively in mixed zones of heat effective zone, can be the main factors responsible for hydrogen embrittlement level [7-9]. Mudali [10] presented acceptable corrosive resistance of dissimilar Ti and 304 stainless steel bimetal in nitric acid. Lubliňska et al [11] reported that hydrogen after cathodic charging causes shear strength decrease of 410S and C-Mn steel bimetal. Mazancová [12] published promising hydrogen induced cracking (HIC) results of the 304 SS clad with titanium and shoved favourable results of hydrogen charging of fatigue samples in 0.1 M solution of sulphuric acid after 8 hours and current density of 15 $mA.cm^{-2}$ which were in heat treated state. No study was realized in frame of sulphide stress crack (SSC) corrosion, representing the most real conditions. Bimetal of 304 SS clad with titanium is supposed to be used in geothermal conditions and therefore the SSC tests, necessarily carried out in case of the highest grades of oil country tubular goods (OCTG) guaranteeing their lifetime, could be suitable for bimetal welds evaluation. The thing is that, none standards for bimetals are in existence.

The aim of work is to find threshold level of lifetime for above mentioned bimetal after double heat treatment which showed favourable impact on already presented properties [12], especially on intermetallic phase Fe_2Ti portion decrease detected by use of synchrotron [12] and being preferentially responsible for hydrogen embrittlement [12, 13]. In this paper the EBSD technique for presented phase analyses was applied.

Table 1 Chemical compositions of explosively welded materials [wt. %]

Element	C	Si	Mn	Cr	Ni	P	S
Stainless steel	0.04	0.45	1.96	18.42	9.74	0.006	0.011
Element	C	Fe	O	N	H	-	-
Titanium	0.01	0.05	0.05	0.005	0.006	-	-

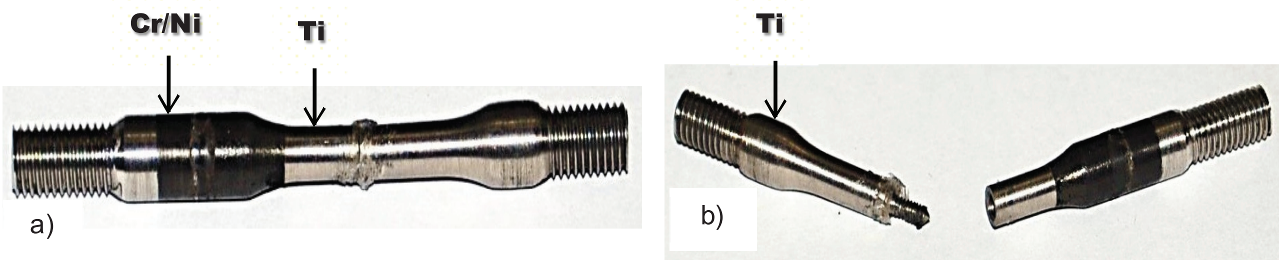

Fig. 1 Shape of used SSC bars after more than 720 hours exposition which was not fractured; a) the dark part represents anticorrosion steel, the light one Ti and central part is screwed and stabilized by silicon adhesive material, b) two unscrewed parts

2. EXPERIMENTAL APROACH

For study explosively welded bimetal of stainless steel 18Cr/10Ni (110 mm sheet in thickness) with titanium (6 mm sheet in thickness) of commercial purity was used. Chemical compositions of both explosively welded materials are summarized in **Table 1**. Explosive welding was carried out in Explomet-Opole, Poland. After ultrasonic testing bimetal was twice heat treated so that the internal stresses were maximally reduced and also the portion of intermetallic phase Fe_2Ti was decreased as it results from works [12, 13]. 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 tests were manufactured with thread, which was glued up with quick-setting silicon adhesive as it **Fig. 1** demonstrates. The SSC samples were exposition in accord with the above mentioned standard in 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 150, 110, 80, 60 and repeatedly at 35 MPa, under the yield stress similar as it was already presented in previous works [6, 12]. Subsequently, after removing of exposed samples from corrosive solution those were looked over. Chemical analysis through weld of both joined materials after double chemical composition using SEM Jeol JSM-6490 was also part of solution. By use of electron microscope Jeol JSM 7000F equipped with EBSD for phase diffraction analysis the samples welds both after one heat treatment (600 °C/1.5h/air) and after next one (again 600 °C/1.5/air) were tested. The aim of this step was to find, respectively to confirm presence of intermetallic phase Fe_2Ti and its dissolution after the second heat treatment, how it was detected in the same material using synchrotron and presented recently [12, 13]. The SSC bar dimensions represent the greatest problem for testing. Weld should be centrally located (according the NACE Standard TM0177-2005), however the clad titanium corresponds to 6 mm and the measured SSC bar should be 25.4 mm in length. Solution for this test was sample screwed from two parts as it **Fig. 1** demonstrates. One half includes stainless steel explosively clad with titanium, hence the weld area (see the **Fig. 1a**), the other **Fig. 1b** shows one half of stainless steel clad with titanium and with internal thread in titanium part (see right part of **Fig. 1b**) and the second half made from 8 mm titanium plate in thickness with external thread of the same chemical composition like the clad one (see light part of **Fig. 1b**). It must be note partial handicap represents minimal set of samples according above mentioned standard (other tests are running now) and given results represent preliminary tests.

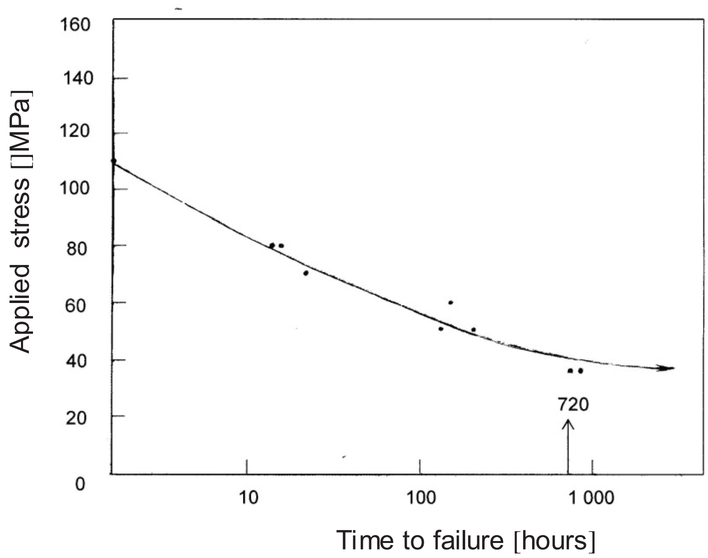

Fig. 2 Threshold level of explosive weld of anticorrosion steel clad with Ti after double heat treatment (twice 600 °C/1.5 h/air)

3. REACHED RESULTS AND ANALYSIS

Results of the SSC test are summarised in **Fig. 2**. Samples loaded at the highest applied stress were raptured immediately, after loading in region of screw join. Hence the failure was not realized in weld. Without reference to position of failure, the samples loaded at 150 MPa and 100 MPa corresponded to loading of 58 % and 39 % of the bimetal yield stress in weld which was found out before fatigue tests formerly [12]. The strength corresponded to 328 MPa in average. At lower applied stresses (80 MPa, 60 MPa and 35 MPa) testing bars showed more favourable hydrogen response corresponding to 13.4 % of the yield stress in the latest case, when the samples were not destroyed and this level can be also taken for the threshold level of hydrogen response. Similar results were reached in case of fatigue evaluation after welds charging in 0.1 M solution of sulphuric acid for 8 hours (current density was of 15 $mA \cdot cm^{-2}$) and cycling at 20 Hz, when the threshold value was lying at the level of 38 MPa [12]. Both compared tests are a bit different, however bimetal welds were under dynamic loaded in both cases. Minimal number of samples of the SSC tests is the main handicap and other tests have been carried out at present time, so that by now reached data could be confirmed and/or completed.

After exposition, in corrosive solution chemical composition through weld was found out including melted zones. The studied interphase region was approximately 150 μm thick. These results after double heat treatment are summarized in **Fig. 3** and are in accord with findings of the works [6, 8, 12]. In previous papers chemical composition by use of SEM and EDX was not quite exact and was not able to reveal intermatillic phases reliably [12]. Using synchrotron radiation at beam-line P07 at Petra III ((positron storage ring) [13] presence of only intermetallic phase of Fe_2Ti type was detected, beside Ti-hcp, Fe-fcc and Fe-bcc, even when numerous authors detected more other intermetallic phases like FeTi, Fe_2Ti_4O, Cr_2Ti, TiO [8], while Manikandan et al. [14] also FeTi using EDS analysis and Yadegari et al. [15] revealed after heat treatment at

700 °C only FeTi, Cr_2Ti and NiTi with $NiTi_2$. By use of EBSD technique original conclusions from synchrotron radiation [13] were also confirmed, how it **Figs. 4** and **5** demonstrate.

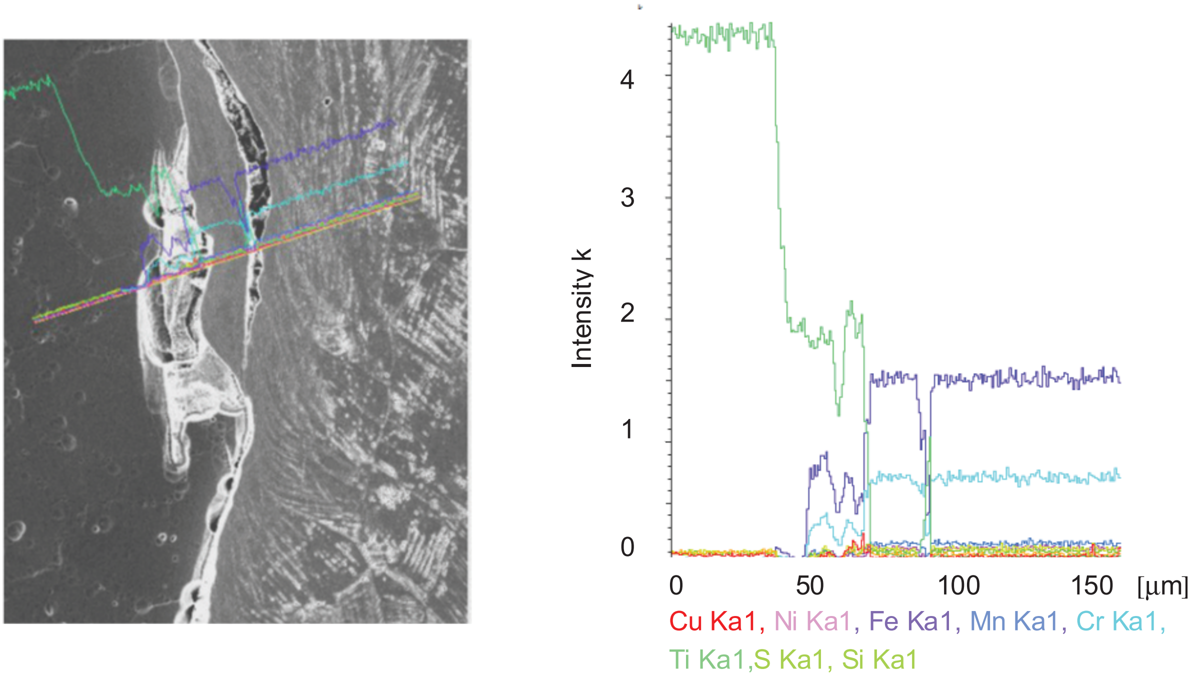

Fig. 3 Example of wavy interface of stainless steel and titanium weld with melted zone and chemical analysis through the weld after double heat treatment.

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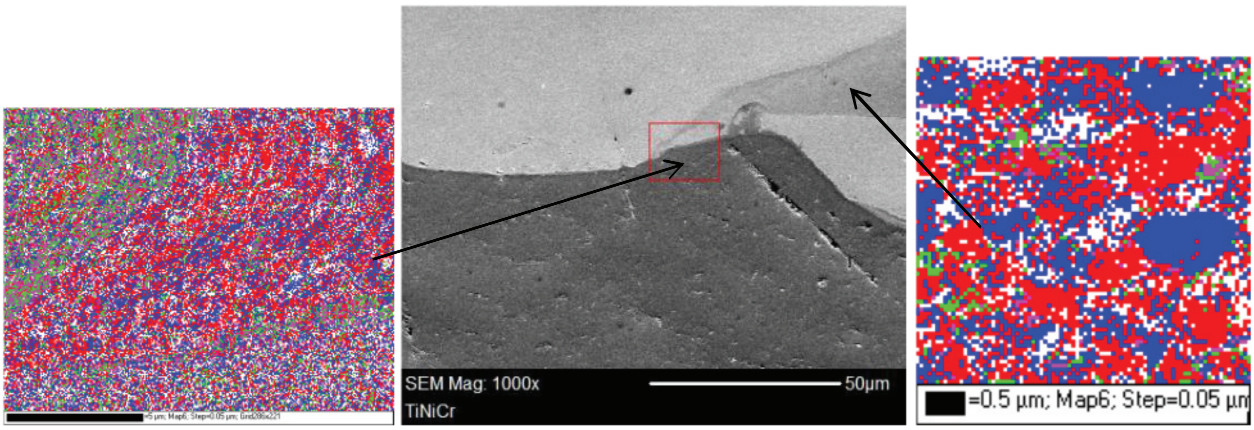

Fig. 4 The EBSD analysis of the join of anticorrosion steel clad with titanium in as-received state. Blue colour represents Ti, green one Fe-fcc, violet colour Fe-bcc and red represents intermetallic phase Fe_2Ti

Using the EBSD technique an occurrence of the Fe_2Ti intermetallic phase was revealed at interface of the weld. At higher magnifications it was also found out, that after the second heat treatment the undesirable intermetallic phase of Fe_2Ti type (in EBSD maps marked by red colour - see **Figs. 4, 5**) was dissolved under the detection boundary. This confirms the results from synchrotron presented by Ostroushko et al in work [12]. After one heat treatment he detected 17.5 vol. % of Fe_2Ti, while after the second one just 5.25 vol. %. These results confirm conclusions from [12, 13] and also a fact, that none other intermetallic phases were not presented at stainless-titanium bimetal weld and its vicinity. Intermetallic phases represent hard and brittle particles being potential hydrogen traps. On one hand it is a paradox, that lower portion of Fe_2Ti is responsible for more favourable hydrogen response, because generally, the more hydrogen traps are in matrix the more homogeneous hydrogen atoms distributions can be realized and consequently in trap regions lower stress can be concentrated and on the contrary. Elucidation of our situation and higher hydrogen resistance of bimetal after double heat treatment can be maximal decreasing of other residual internal stresses being heritage of explosive bonding leading to total lower stresses being not able, in superposition with hydrogen, to reach a critical stress level leading to faster failure.

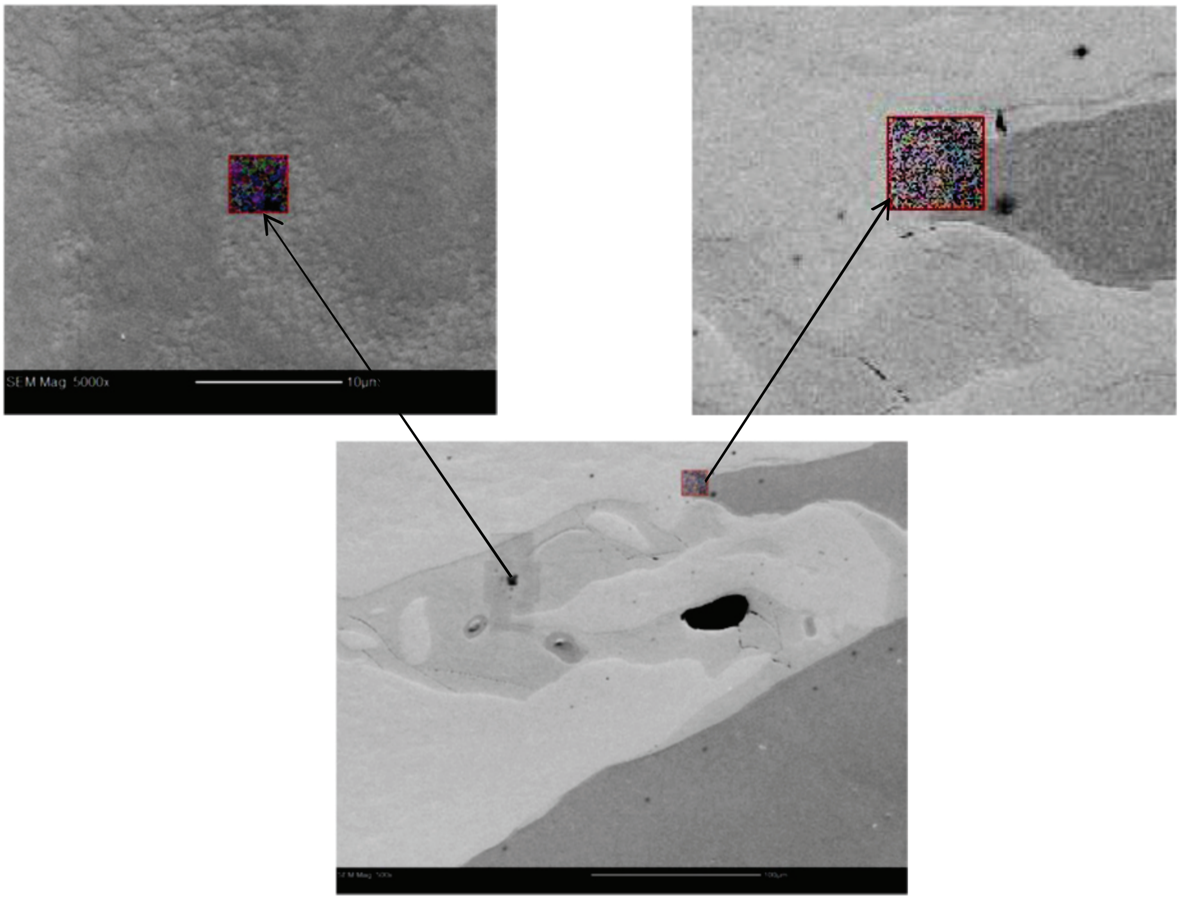

Fig. 5 The EBSD analysis of the join of anticorrosion steel clad with titanium after double heat treatment. Blue colour represents Ti, green one Fe-fcc, violet colour Fe-bcc and red represents intermetallic phase Fe_2Ti

3. CONCLUSIONS

Under dynamic conditions hydrogen susceptibility of welds of explosively joined 18Cr/10Ni anticorrosion steel type with titanium of commercial purity after bimetal welding and double annealing was studied.

Firstly shape of testing bar was designed so that it corresponded to NACE Standard TM0177-2005 demands for the sulphide stress cracking (SSC) and simultaneously it took the 6 mm titanium clad into consideration.

The firs results showed that applied stress of about 35-40 MPa could be hold for the threshold level of lifetime of studied bimetal welds in sour corrosive environment with hydrogen sulphide. These results corresponded to ones of fatigue tests in 8 % solution of H_2SO_4 presented recently [12]. Verification of findings in this work will be realised in other period of testing. Presence of intermetallic phase Fe_2Ti in mixed zones of bimetal welds as a sole one detected by use of EBSD could be referred to as main responsible reason observed hydrogen susceptibility. Low detected portion of Fe-bcc should not be so dangers from point of hydrogen response. These presented results confirm the conclusions from synchrotron which were presented recently [13].

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REFERENCES

[1] CONTRERAS, A., Albiter, A., Salazar, M., Pérez R. The SSC resistance of steels X52 and X70 under low deformation rate. Mater. Sci. Eng., Vol. A407, 2005, pp. 45-51.

[2] MAZANCOVÁ, E., Havel, S., Mazanec, K. Influence of sour environment on hydrogen embrittlement of steel for oil country tubular goods (OCTG). Int. J. Pres. Ves. & Piping, Vol. 52, 1992, pp. 427-438.

[3] MAZANCOVÁ, E. Structurally metallurgical characteristics by hydrogen induced brittleness (in Czech). Metallurgical J., Vol. 54, Nr. 11-12, 2001, pp. 97-101.

[4] COWAN, G.R., BERGMANN, O.R., Holzmann, A.H. Mechanism of bond zone wave formation in explosion-clad metals. Mater. Trans., Vol. 2, 1971, pp. 3145-3155.

[5] RAO, N.V., SARMA, D.S., NAGARJUNA, G., MADHUSUHAN, G. Influence of hot rolling and heat treatment on structure and properties of HSLA steel explosively clad with austenitic stainless steel. Mater. Eng., Vol. 25, 2009, pp. 1389-1395.

[6] OSTROUSHKO, D., MAZANCOVÁ, E. Chosen properties of sandwich materialTi-304 stainless steel after explosive welding. Mater. Eng., Vol. 18, 2011, pp. 8-10.

[7] FINDIK, F. Recent developments in explosive welding. Mat. Des., Vol. 32., 2011, pp. 1081-1093.

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

[9] RAJANI, H.R.Z., MOUSAVI, S.A.A.A., SANI, F.F. Comparison of corrosion behaviour between fusion cladded and explosive cladded Inconel 626/plain carbon steel bimetal plates. Mat. Des., Vol. 43, 2013, pp. 467-474.

[10] MUDALO, U.K., RAO, B.M.A., SHANMUGAN, K., NATARAJAN, R., RAJ, B. *J. Nucl. Mater.,* Vol. 321, 2003, pp. 40-48.

[11] LUBLINSKA, K., SZUMER, A., GLOC, M., SZPILA, K., KURZYDLOWSKI, K.L. Efect of hydrogen on degradation of explosion welded clad steels. Acta Met. Slovaca, Vol. 13, 2007, pp. 508-511.

[12] MAZANCOVÁ, E., OSTROUSHKO, D., SAKSL, K., NIESŁONY, A. Join hydrogen susceptibility of 304 SS welded with titanium. Arch. Metall. Mater., Vol. 59, 2014, pp. 1605-1610.

[13] OSTROUSHKO, D., MAZANCOVÁ, E., SAKSL, K., MILKOVIČ, O. Phase analysis of explosively welded Ti-Cr/Ni steel in as-received state and after heat treatment using synchrotron. Arch. Metall. Mater., Vol. 59, 2014, pp. 1611- 1614.

[14] MANIKANDAN, P., HOKAMOTO, K., DERIBAS,A.A., RAGHUKANDAN, K., TOMOSHIGE, R. Explosive welding of titanium/stainless steel by controlling energetic conditions. Mater. Trans., Vol. 47, 2006, pp. 2049-2053.

[15] 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., Vol. 29, No. 1, 2013, pp. 69-75.