Metallurgical and Corrosion Properties of Explosively Welded Ti6Al4V/Low Carbon Steel Clad

Nizamettin Kahraman[1)†] *and Behçet Gülenç*[2)]
1) Karabük Technical Education Faculty, Z.K.U., Karabük, Turkey
2) Technical Education Faculty, Gazi University, Ankara, Turkey

[Manuscript received July 12, 2004, in revised form February 28, 2005]

Titanium alloy (Ti6Al4V) and low carbon steel (LCS) were joined by explosive welding method using different ratios of explosive. Some metallurgical properties of joined samples were investigated. Joined samples were examined by means of optical microscope, scanning electron microscope (SEM) and tensile-shearing tests. Bending, tensile, hardness and corrosion behaviour of the samples were investigated. Separation was not occurred on the joining interface after tensile-shearing and bending tests. It is seen that hardness of both plates were increased with increasing explosive. It is found that increasing explosive ratio leads to an increase in corrosion. It is also found that corrosion rate was high at the beginning of the experiment but the rate of the corrosion decreased subsequently during the experiment.

KEY WORDS: Explosive welding; Joining; Corrosion; Ti6Al4V; Low carbon steel

1. Introduction

In order to join metals preserving their properties and to join metals having different properties, solid-state welding methods are used[1]. Explosive welding is a solid-state process in which controlled explosion forces to join two or more materials together under high pressures[2~5]. It is used to joint directly a wide variety of similar or dissimilar metals that cannot be joined by any other welding or bonding technique[6~8]. The parameters of the system include: (1) the explosive characteristics; (2) the buffer materials; (3) the stand-off distance; (4) the welding set-up; (5) the energy transfer medium; (6) the metals involved; (7) the collision parameters; (8) the surface roughness; (9) the melting temperature; and (10) the dynamic bend angle[9]. The bond is generally wavy with a good tensile strength or shear strength because of the large and wavy contact surface, although a straight interface can be at least equally strong as the one exhibiting a wavy interface[10]. The strength of the clad is always greater than that of the weaker of the mating metals[9]. The cladding of steel with a corrosion resistant overlay has a number of advantages. It is economic, since, except for thin sections, clad are cheaper than solid stainless steel. It minimizes the risk of catastrophic failure, for example, due to stress corrosion cracking or hydrogen embitterment and cracking of the austenitic material, while for high-pressure conditions, such as nuclear vessels, hydro crackers and coal conversion vessels. It provides the optimum combination of mechanical properties with corrosion resistance[2].

Titanium is one of the most important non-ferrous metals and has extensive applications in the aerospace industry, because of its lightweight, excellent corrosion resistance, high strength level, attractive fracture behaviour and high melting point[11]. α-β Ti alloys present good formability and cold strength at temperatures under 300°C. In this group, Ti-6Al-4V has been the main alloy for mechanical components[12]. Ti-6Al-4V with excellent specific tensile and fatigue strengths and corrosion resistance have been mainly used for aircraft structural and engine parts[13]. Titanium clad carbon steel and other clad corrosion resistant materials are beginning to be used in some of the more aggressive environments. The cost of providing a component whose full thickness is completely comprised of titanium or some other expensive metal is strictly cost prohibitive. With the advent of new, efficient methods of cladding using titanium, stainless steel, high nickel and inconel type materials, processes such as roll bonding, explosive welding and weld overlay are gaining rapid acceptance and use[14]. The metallurgical characteristics and mechanical properties of the explosively welded various metals and their alloys have been investigated by several investigators[2]. However, there lack of information about explosively welded Ti-6Al-4V to low carbon steel (LCS) and their corrosion behaviour. The aim of this study is to investigate some metallurgical properties of joining interfaces of explosively welded titanium alloy and LCS plates using various amount of explosive material.

2. Experimental

In this study, titanium plates (Ti6Al4V) and low carbon steel (LCS) plates with the dimension of 100 mm×150 mm×1.5 mm were bonded by explosive welding method. Chemical compositions of the titanium and LCS were given in Tables 1 and 2, respectively.

Some other properties of these materials were also given in Table 3. Different explosive ratios and 5° oblique geometry were used to see the effect of explosive ratio and hence the velocity of flyer plate on bonding interface. Microstructures, mechanical properties and corrosion behaviour of the bonded samples were investigated.

Elbar-5 (92% ammonium nitrate+5% diesel fuel+3% TNT) was used as explosive for welding. Detonator was used to start the explosion and gelignite dynamite were

† Assist. Prof., Ph.D., to whom correspondence should be addressed, E-mail: nizamettinkahraman@hotmail.com.

Table 1 Chemical composition of Ti-6Al-4V alloy (wt pct)

C	Al	V	Fe	N	O	H	Ti
0.08	5.5~6.5	3.5~4.5	0.25	Max 0.03	Max 0.13	Max 0.012	Balance

Table 2 Chemical composition of the LCS (wt pct)

C	Mn	Si	Cr	Ni	Cu	Mo	Co	Fe
0.061	0.299	0.028	0.028	0.001	0.070	0.001	0.002	Balance

Table 3 Hardness and tensile strength values of bonded samples

Material	Hardness/$HV_{0,2}$	Tensile strength/MPa
Ti6Al4V	210±3	705±5
Low carbon steel	142±2	530±4

used to make a contact between detonator and powder explosive. Powder explosive was filled into a cardboard box with the dimension of 150 mm×100 mm×50 mm. Detonator and gelignite were attached into the explosive and then the box was sealed to prevent the powder to spread out.

Explosive amount used was in a ratio with the total weight of flyer plate (Ti6Al4V) and buffer plate. LCS plate was used as buffer between explosive and Ti6Al4V flyer plate. Ti6Al4V plate was placed onto LCS with a 5° oblique angle. Welding assembly was placed on a steel anvil and then the explosion was carried out in a sand pool. A rubber layer with the thickness of 6 mm was placed onto anvil to protect it. Detonation was started with a magnetic remote system. Three samples were welded together each time. Explosive amounts used in this study are given in Table 4. This was calculated using the following equation.

$$V_p^2 = 2E\frac{3}{\left[1+5\left(\frac{m}{c}\right)+4\left(\frac{m^2}{c^2}\right)\right]} \quad (1)$$

where V_p is flyer plate velocity; M is flyer plate mass; $2E$ is gurney energy; $2E$ is 2560000 m/s; c is detonator mass.

Metallographic examination was carried out through the standard metallographic preparation method using hot mounting. As the etching agent, 2% nitric acid +98% methanol and 45 ml HCl, 15 ml HF, 15 ml nitric acid, 25 ml distilled water were used to etch the steel and Ti6Al4V, respectively.

A PRIOR optical microscope at the University of Gazi, Department of Materials and a Jeol JSM-5600 type scanning electron microscope (SEM) at the University of Kirikkale, Department of Physics were used for the microstructural examination. Microhardness measurement was also done with a ZWICK 3212002/00 type microhardness machine applying 200 g load. Microhardness measurement was taken from the various distances of the interface and average values were obtained after five different measurements.

Three samples, which were cut parallel to the detonation were obtained from each of 15 explosively welded samples for tensile-shearing tests. Samples were prepared in accordance with ASTM D 3165-95[15] by machining (sample with 25.4 mm in width and 12.7 mm in length with a coating of 1.62 mm in thickness). Samples were prepared and tested in dimensions as indicated in Fig.1, where "a" shows the thickness of flyer plate while "W" shows the width of the tensile-shearing test specimens. Additional tensile-shearing tests were performed on the specimens whose width was equal to the thickness of coating material (L=a±2%) in accordance with the literature [5].

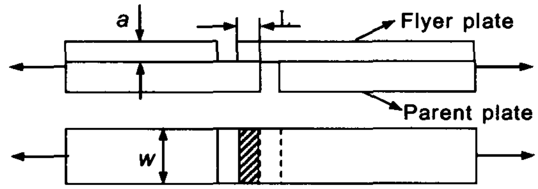

Fig.1 Schematic representation of tensile-shearing test in accordance with ASTM D 3165-95

Explosively welded samples which were prepared according to ASTM D 3165-95 and literature [5] were tested using an INSTRON MFL SYSTEM tensile machine at the tensile speed of 1 mm/s and three measurements were carried out for each identical sample.

Welded samples were subjected to the bending test. Bending test was done by placing both Ti6Al4V and LCS plates up and down. Bonding test was also carried out with the INSTRON MFL SYSTEM tensile machine at a bending rate of 0.5 mm/s.

Corrosion test was carried out in accordance with TS 8589 by holding the 15 mm×15 mm sample in % 3, 5 NaCl-water solution for 672, 1344 and 2016 h. Mass variation of the samples was checked with scale, which has 1/10000 precision.

3. Results and Discussion

The ratio of R=1 of the explosive did not result in a successful welding. The reason for the unsuccessful attempt of explosive welding is insufficient power to make a bonding between plates. Insufficient explosive could not accelerate enough to weld plates.

3.1 Metallographic results

Optical micrographs of explosively welded samples

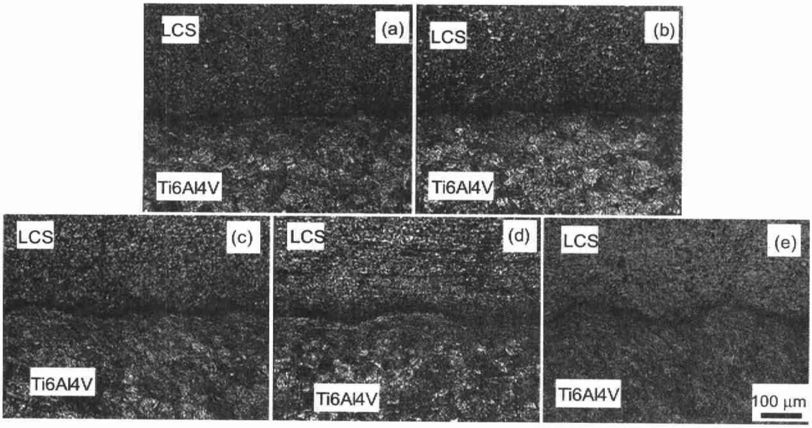

Fig.2 Optical pictures of interface welded with different explosive ratio: (a) R=1.2, (b) R=1.5, (c) R=2, (d) R=2.5, (e) R=3

are given in Fig.2. Explosive ratio is increasing from minimum to a maximum through R=1.2 to R=3 in Fig.2. Increasing explosive ratio caused some changes in microstructure of LCS while causing limited changes in Ti6Al4V. In the Ti6Al4V plate welded with high ratio of explosive, grains near to the interface are elongated parallel to the detonation direction. Grains far from the interface are not affected from the detonation. Such a result is consistent with literature [1].

As can be seen in Fig.2 that wavelength and amplitude of the interface increases with increasing explosive ratio. In Fig.2(a), for samjples welded with the minimum ratio of explosive (R=1.2), the surface of the interface is almost planar. Amplitude of the interface was pronounced with increasing explosive ratio and amplitude and wavelength of the wave reached a value of 10~15 μm and 100~120 μm, respectively.

The interface of welded LCS and Ti6Al4V, which were welded using an explosive ratio of R=2 (Fig.2(c)), exhibits an interface with a wavelength of 180~200 μm and amplitude of 15~20 μm. Wavelength and amplitude of the interface continued to increase with increasing explosive ratio.

Explosive ratio of R=2.5 resulted in a wavelength of 220~235 μm and amplitude of 25~30 μm. The ratio of 3, the maximum one, gave wavelength of 280~300 μm and amplitude of 40~50 μm (Fig.2(e)).

Welding interface of LCS and Ti6Al4V is transforming to a waviness form from the linear form with increasing explosive ratio. It is known that as the explosive ratio increases, collision speed of welding increases due to high explosion energy. Thus high collision pressure leads to deformation and then interface of the bonding plates became waviness. Cowan *et al.*[16] investigated the form of waving of the explosively welded interfaces. Their work showed that explosively welded interface has a waviness form; however welding with low collision speed does not give rise to a waviness interface. But using high explosive ratio and increasing collision angle resulted in a waviness interface. Livne and Munitz[17] explosively welded copper and steel plates and investigated welding interface by scanning electron microscopy and X-ray diffraction (XRD). Investigations showed that bonding interface exhibits a wavy form and the wavelength is strictly dependent on explosive ratio and the distance between plates.

Welding with low explosive ratios (R values) caused minor changes in the shape of the grains close to the interface while welding with high ratios changed a lot. It is seen from the microstructure that grains were elongated parallel to the detonation propagation, however grains far from the welding interface remained unaffected. In a similar work, Yang *et al.*[18] explosively welded LCS to Ti6Al4V and investigated welding interface. They found that, in the joining area, grains were elongated in the direction of detonation by a sudden cold deformation.

SEM images of the samples joined with explosive welding using maximum and minimum explosive ratios (R=1.2 and R=3) are given in Fig.3, respectively. There is no evidence for any intermetallic or any bonding failure in the interface area. Elemental point analyses taken from both sides did not indicate any diffusion on both sides.

3.2 Tensile-shearing results

Tensile-shearing test results are tabulated in Table 5 for explosively welded samples. Tensile-shearing tests were done in accordance with ASTM D 31665-95. Any of explosively welded samples did not show a failure after tensile-shearing test. All explosively welded samples fractured from the LCS side. Tensile strength of the LCS was lower than that of Ti6Al4V (Table 3). Furthermore, the tensile-shearing strength of welded samples increased with increasing explosive ratio. All the test results suggest that bonding strengths of all explosively claded composites are higher than that of the softer of two metallic components. This result is consistent with the literat-

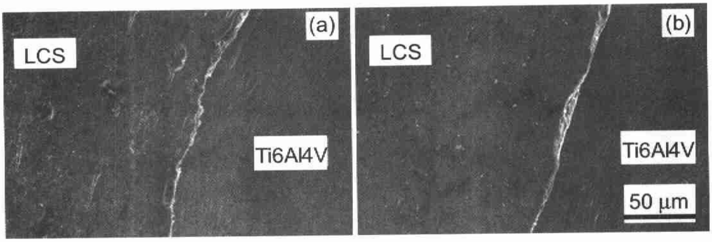

Fig.3 SEM micrographs of explosively welded samples with R=1.2 (a) and R=3 (b)

Table 4 Explosive ratios of the experiment

Mass of buffer and flyer plates /g		Total weight /m	Explosive ratio R	Explosive amount $m{\cdot}R$/g	Velocity of flayer plate /(m/s)
Titanium	Buffer plate (Fe)				
100	115	215	1	215	876
100	115	215	1.2	270	1010
100	115	215	1.5	322	1120
100	115	215	2	430	1306
100	115	215	2.5	537	1452
100	115	215	3	645	1571

Table 5 Tensile shearing test results for the explosively welded samples welded with different explosive ratios

Explosive ratio	Tensile-shearing strength/MPa
R=1	—
R=1.2	540±4
R=1.5	546±4
R=2	550±4
R=2.5	552±4
R=3	554±4

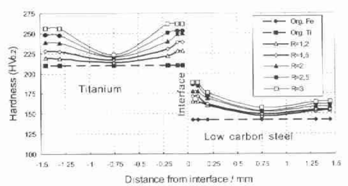

Fig.4 Hardness values of original and claded plates

ure [6]. Another work of explosively welded iron and copper plates reveals that the bonding strength of interface is at least as high as the strength of copper. Claded copper and iron composite fractured from the copper did not from the interface[17].

3.3 Bending test results

Bending test was applied to the all claded LCS/Ti6Al4V composites in both sides. After bending to 180°, no separation or cracking was seen for any sample by visual examination. Bending tests also showed that all explosively welded plates have perfect bonding properties. Bending test results are also consistent with the literature [19].

3.4 Hardness results

Hardness values of original plates and explosively welded composites are given in Fig.4. The hardness curve of 1 and 5 in Fig.4 represents the samples welded using explosive ratios of R=1.2 and R=3, respectively. As can be seen from Fig.4 that, all hardness values taken from the different areas of all claded samples are higher than that of these original plates. In the LCS side, while the hardness value of unwelded steel is 142 HV, hardness values in the areas of 50, 100, 200, 750, 1300, 1450 μm away from the interface of the crossection are 165.4, 165.3, 160.6, 147.3, 153.3 and 154.1 HV, respectively, for the sample welded with R=1.2 explosive ratio. These values of hardness show that interface area gave the highest hardness value and the center of the crossection gave the minimum value of hardness. In addition, while the R=1.2 explosive ratio resulted in a hardness value of 165.4 HV, R=3 explosive ratio resulted in a hardness value of 188.3 HV. That means, hardness value of the welded sample increases with increasing explosive ratio.

The increasing hardness value in the welded sample can be attributed to the cold deformation because of high collision rate. Mamalis *et al.*[6] showed that the interface area exhibits the maximum hardness value and both plates exhibited higher hardness values than their initial values. They indicate that the increasing hardness was resulted from localized shock hardening. An investigation[20] carried out for the steel/steel cladding showed that hardness value decreases as the measurement area running away from the interface. That investigation also says that hardness value of welded sample increases due to the plastic deformation during the collision. Trut-

Table 6 Weight variation of the explosively welded samples subjected to the corrosion test

	Mass variation/(±0.00006 g/cm^2)						
Time/h	Original titanium	Original low carbon steel	R=1.2	R=1.5	R=2	R=2.5	R=3
672	0.01617	−2.08377	−2.68175	−2.75841	−2.90155	−3.11216	−3.17156
1344	0.02716	−3.05569	−3.82062	−4.01351	−4.15124	−4.20772	−4.42293
2016	0.0327	−3.52685	−4.62793	−4.86464	−4.98659	−5.03606	−5.12276

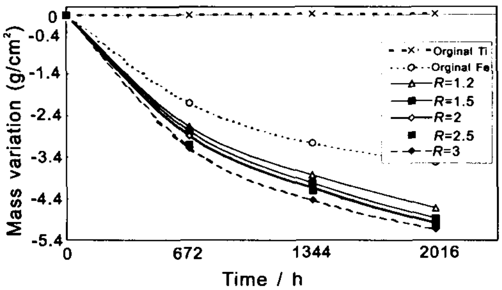

Fig.5 Weight variation of the explosively welded and original materials due to corrosion

nev *et al.*[21] has investigated the welding of Al/Ti and Ni/steel by means of microhardness. They revealed that the hardness of the interface area of Ti, steel and Ni are higher than that of other areas because of work hardening during the collision.

3.5 Corrosion test results

As clad materials are usually used in sea environment, all explosively welded LCS-Ti6Al4V samples were subjected to the corrosion test in seawater. Table 6 tabulates the changes in weight for original materials.

Figure 5 also shows the weight variation in the explosively welded samples. Figure 5 indicates that the mass of unwelded LCS and all claded samples decreases while mass of original Ti6Al4V increases. The reason for increasing mass of Ti6Al4V is its oxidation while the reason for decreasing mass of unwelded LCS and explosively welded components is the formation of a brittle metal oxide layer on the surface of those metals. In addition, increasing explosive ratio led to high degree of deformation consequently high activation energy. The more the activation the more the corrosion tendency. This tendency increases nucleation intensity on the deformed surfaces. In a similar work Turker[22] investigated high temperature oxidation behaviour of MA 956 and ODM 751 superalloys and found that nucleation density increased on the plastically deformed surfaces as a result of cold deformation. In addition, he also stated that increasing nucleation decreased the grain size of the oxide layer. In another study on oxidation behaviour of ODS alloys, Turker and Hughes[23] found that after a certain thickness oxide layer breaks away and it also removes a fragment of the surface. This, in turn, causes mass loss.

It can also be seen in Fig.5 that corrosion rate was higher at the beginning of the test. Mass losses for explosively welded sample were 3 and 5 g after a test period of 672 h and 2016 h, respectively. Here, the corrosion test time was increased 3 times, but weight loss increased less than two times. In the corrosion test, initially an oxidation layer was formed on the surface of the metals and this layer prevents the metals from oxidation. These findings are in agreement with the published studies[24,25]. Prevention ability of this oxide film is affected by solubility of corrosion product, adhesion properties of products, diffusivity of film, electrical resistance of film and the mechanical strength of film. Soluble film is easily removed from the surface, for this reason it cannot protect the metal surface.

4. Conclusions

(1) None of the explosively welded samples was separated after tensile-shearing test.

(2) Microstructural examination of the interface of the explosively welded samples showed that low explosive ratio resulted in a planar interface while the interface was transformed from planar to wavy form with increasing explosive ratio.

(3) Explosively welded samples were subjected to a bending test on both sides and any kind of failure was not observed.

(4) The hardness of the cladded samples was found to be higher than those of original plates.

(5) Corrosion tests revealed that corrosion rate of the samples was relatively high at the beginning of the test and then it got slower gradually.

(6) Increasing explosive ratio increases the deformation. This increasing deformation made a more active material for the corrosion.

Acknowledgements

We thank M.K.E Barutsan Company, Turkey for their kindly supplying the materials, equipment and staff. This work was financially supported under Gazi University Project (07/2002-07).

REFERENCES

[1] M.Acarer., B.Gülenç and F.Findik: *Mater. Design*, 2003, **24**(8), 659.

[2] R.Kaçar and M.Acarer: *Mater. Sci. Eng. A*, 2003, **363**(1-2), 290.

[3] Y.Li, H.Hashimoto, E.Sukedia and Y.Zhang, Z.Zhang: *J. Electron Microscopy*, 2000, **49**(1), 5.

[4] D.G.Brasher and D.J.Butler: *Adv. Mater. Process.*, 1995, (3), 37.

[5] Explosion Welding, Fundamentals of *Process, Welding* Handbook, 1992, **3**, 264.

[6] A.G.Mamalis, A.Szalay, N.M.Vaxevanidis and D.I.Pantelis: *Mater. Sci. Eng. A*, 1994, **188**, 267.

[7] A.Abe: *JSME Inter. J.*, 1997, **40(3)**, 395.

[8] V.Balasubramanian, M.Rathinasabapathi and K.Raghukandan: *J. Mater. Process. Tech.*, 1997, **63**, 83.

[9] K.Aghukandan: *J. Mater. Process. Tech.*, 2003, **139**(1-3), 573.

[10] M.Gerland, H.N.Presles, J.P.Guin, D.Bertheau: *Mater. Sci. Eng. A*, 2000, **280**, 311.

[11] Z.Li, S.L.Gobbi, I.Norris, S.Zolotovsky and K.H.Richter: *J. Mater. Process. Tech.*, 1997, **65**, 1997, 203.

[12] E.N.Codaro, R.Z.Nakazato, A.L.Horovistiz, L.M.F.Ribeiro, R.B.Ribeiro and L.R.O.Hein: *Mater. Sci. Eng. A*, 2003, **341**(1-2), 202.

[13] J.Oh, N.J.Kim, S.Lee and E.W.Lee: *Mater. Sci. Eng. A*, 2003, **340**(1-2), 232.

[14] S.Kleven: *Mater. Eval.*, May 1996, 557.

[15] ASTM Designation D 3165-95, *ASTM Standard*, November 1995, 199.

[16] G.R.Covan, O.R.Bergman and A.H.Holtzman: *Metall. Trans.*, 1971, **2**, 3145.

[17] Z.Livne and A.Munitz: *J. Mater. Sci.*, 1987, **22**, 1495.

[18] Y.Yang, Z.Xinming, L.Zhenghua and L.Qingyun: *Acta Mater.*, 1996, **44**(2), 561.

[19] B.Crossland and J.D.Williams: *Metall. Rev. Review*, 1970, **144**, 79.

[20] M.Acarer, B.Gülenç and F.Findik: *5th Inter. Fracture Conference*, Firat University, Elaziğ-Turkey, 2001, 301.

[21] V.V.Trutnev and Svar. Proiz: *Welding Production*, 1973, **7**, 33.

[22] M.Türker: Ph.D. Thesis, School of Materials, University of Leeds, Leeds, UK., 1993, 112.

[23] M.Türker and A.T.Hughes: *Oxid. Met.*, 1995, **44**(5-6), 505.

[24] Yalçin and T. Koç: *Corrosion for Engineers*, UCTEA, Publishing of Chamber of Chemical Engineers, Ankara, 1997, 1.

[25] N.Kahraman: Ph.D. Thesis, Gazi University, Ankara, Turkey, 2003.