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Corrosion and mechanical-microstructural aspects of dissimilar joints of Ti–6Al–4V and Al plates

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Abstract

In this study, Ti–6Al–4V and Al plates were joined by explosive welding at various explosive loads. Tensile-shear, bending, hardness, microstructure and corrosion behaviours of the explosively joined samples were investigated. At the end of the tensile-shear tests carried out according to ASTM D 3165-95 standard, no seperation was observed in the interfaces of the joined samples. The results of the bending tests also showed no sign of any distinctive seperation, crack and tear in the interfaces. The highest hardness values were measured in regions next to interfaces. The optical microscope and SEM examinations revealed that an increment in wavelength and amplitude was observed with increasing explosive load. It is seen from the corrosion test results that materials loss was high at the beginning of the corossion tests but the rate of material loss decreased later on. Furthermore, increasing deformation with increasing explosive load increased the materials loss in corrosion tests.

Keywords: Titanium; Aluminium; Explosive welding; Microstructure; Corrosion

1. Introduction

Titanium and its alloys have been considered as one of the best engineering metals for use in industrial applications [1]. Ti–6Al–4V alloys exhibit excellent corrosion resistance and high strength to weight loads which make them ideal candidates for use in primarily two areas of application: corrosion resistant service and specific strength efficient structures [2]. Welding of titanium and alloys is difficult because titanium is extremely chemically reactive at high temperatures. During welding, titanium alloys pick up oxygen and nitrogen from the atmosphere easily [3]. Therefore, titanium and its alloys should generally be welded using solid-state welding methods.

Explosive welding or cladding is an unconventional technique of joining two metals by the use of explosives [4]. It is used to join a wide variety of similar or dissimilar metals that cannot be joined by any other welding or

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bonding technique [5–6]. Explosive welding is a solid-state process in which controlled explosion forces two or more materials to join together under high pressures [7–9]. The resulting bond is generally in a wavy pattern [10] with a good tensile strength (Fig. 1). In all shear strength tests, large and wavy contact surfaces [11,12] were obtained. The bond is metallurgical in nature and usually as strong or stronger than the weaker parent metal [13]. The advantage of this technique is that the bonding strength of the welded interface is very high and reliable, in comparison with joints made by some other techniques, such as diffusion bonding, etc. [14]. Although the explosive detonation generates heat, there is no time for heat transfer to the metal surfaces [15].

Basic parameters of the explosive welding are flyer plate velocity, collision point velocity and collision angle. The process variables that affect these parameters are explosive detonation rate, explosive mass, standoff distance, and/or present angle. Two basic geometric configurations of the explosive welding process are commonly used: angle bonding and parallel plate bonding [16]. It is known that the quality and morphology of the interface depend on the collision angle, the impact velocity, the properties of the materials, and the geometry of the welded plates [17]. The main disadvantages of the explosive welding process, from a planetary protection point of view, are the small thickness of the stripped layer and the propensity of the bond to form interface waves that may prevent eject from completely leaving the bonded area and trap some surface particles within these waves [18]. The purpose of the cladding will generally be for protection of the substrate material from corrosion [19]. Literature on the joint preparation and corrosion performance in sea water for the dissimilar joints of titanium to aluminium is very scarce.

The aim of this study was to produce a composite plate via cladding of titanium plate to aluminium plate with explosive welding. Titanium has better corrosion resistance than aluminium in sea water. Its mechanical properties are also much better than aluminium. The reason for using composite plate instead of single material is to lower cost while effecting better corrosion resistance, acceptable strength, improved electrical properties or better wear and corrosion resistance. For this purpose, titanium plates were cladded on aluminium plates via explosive welding. Tests were carried out on the joined samples to determine mechanical and microstructural properties and corrosion resistance in sea water.

2. Experimental procedure

Ti–6Al–4V alloy and aluminium plates used in this study were in $100 \times 150 \times 1.5$ mm and $100 \times 150 \times 2$ mm in dimensions and their chemical compositions are given in Tables 1 and 2, respectively. The aluminium used in this study had an UTS of 235 MPa.

To see the effect of explosive load on bonding interface, different explosive loads and 5° oblique geometry were used [5]. For joining of the materials, Elbar-5 (90% Ammonium Nitrate, 4.5% diesel fuel, and 3% TNT) was used as explosive in powder form produced in MKE Barutsan A.S., TR. During the explosion, aluminium was used as flyer plate and 1 mm thick steel was put on flyer plate as buffer. The used explosive amount was determined as the proportional amount of total mass of buffer plate and aluminium used in explosive welding.

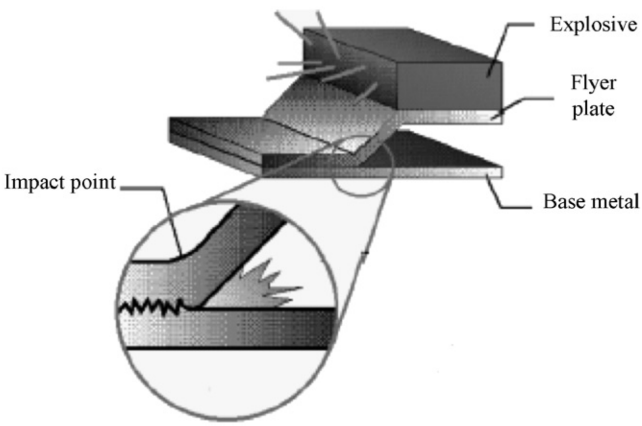

Fig. 1. Schematic illustration of explosive welding.

Table 1
Chemical composition of titanium alloy used in experiments (wt %)

	C	Al	V	Fe	N	O	H	Ti
Titanium	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 aluminium used in experiments (wt %)

	Mn	Si	Mg	Zn	Cu	Ti	Fe	Al
Aluminium	0.0111	0.163	0.0365	0.0241	0.146	0.0237	0.516	Balance

Table 3
Explosive loads of the experiment

Mass of buffer and flyer plates (g)		Total weight (m)	Explosive load (R)	Explosive amount ($m \times R$) (g)	Velocity of flayer plate (m/s)
Aluminium	Buffer plate (steel)				
80	115	195	1	195	876
80	115	195	1.2	235	1010
80	115	195	1.5	292	1120
80	115	195	2	390	1306
80	115	195	2.5	487	1452

Explosive amounts used in this study are given is Table 3. This was calculated using the following equation:

$$V_{\mathrm{p}}^2 = 2E\frac{3}{\left[1+5\left(\frac{m}{c}\right)+4\left(\frac{m^2}{c^2}\right)\right]}, \tag{1}$$

where V_{p} is the flyer plate velocity, m the flyer plate mass, $2E$ the Gurney energy, $2E = 2\,560\,000$ m/s, c the detonator mass.

In the experiment, a steel anvil plate in the dimension of $1500 \times 2000 \times 150$ mm was used. This steel plate was placed into a sand pool. Also, a 6 mm thick rubber plate was installed in between the anvil and titanium in order to protect the titanium from damaging during the explosion. The explosive materials was prepared cardboard box and covered its front surface. Explosions were carried out by a remote control. Exploding processes were performed as 3 times for each explosive load and after explosion, materials were left for cooling in open air. Then tensile-shear, bending, micro hardness and corrosion tests were carried out and also welded specimens were examined using optical microscope and SEM.

From the explosively joined specimens, 3 samples from each group, and a total of 15 samples were cut in parallel direction to explosive process. The cut samples were prepared in milling machine according to the conditions (Fig. 2). These conditions are required by ASTM D 3165-95 standard [20]. ASTM D 3165-95 requires the sample with 25.4 mm width and 12.7 mm length for a 1.62 mm thickness of coating.

The shearing tests were carried out using specimens prepared according to ASTM D 3165-95 standard. Additional shear tests were also carried out at the same conditions after a small change was made on the prepared shear specimens according to Ref. [7]. It is stated in Ref. [7] that shearing width (L) can be equal to the thickness of metal cladding (a). The joined titanium–aluminium was subjected to bending test according to pr EN 910 standard [21]. The width of welded samples was prepared as 25 mm and bending diameter was selected as 15 mm. The bending tests were performed in both conditions when the titanium cladding plate was inside and outside of the bending direction. Tensile-shear and bending tests were performed in tensile machine of Instron MFL System in forward speed of 0.5 mm/min.

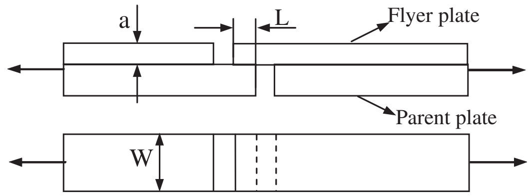

Fig. 2. Schematic representation of tensile-shearing test in accordance with the ASTM D 3165-95.

Hardness specimens were mounted in bakelite ground the surface and also polished. Micro hardness were measured in Zwick machine as 3212002/00 type and 200 g load was applied. Eighteen measurements from six points (three measurements from each point) were taken 200 μm away from the bonded specimens' outer surfaces and bonding interface and the centreline of the each plate bonded. The results were averaged.

Nine specimens for each group were obtained for the samples welded in the condition of $R = 1$, 1.2, 1.5, 2, 2.5 explosively loads. After, 45 specimens in the dimension of 15×15 mm were prepared for each group for determination of corrosion behaviours of explosively joined samples according to EN ISO 7384 (TS 8589) standard [22]. Furthermore, 9 samples from as-received titanium and aluminium were also prepared at the same dimensions for comparison. Surface area for all samples was calculated one by one due to differences in thickness of the samples resulted in various welding process. Specimen calculated surface area were weighed on an electronic weighting machine in the sensitivity of 1/10.000 g and values were reported.

The prepared samples for corrosion test were placed into a glass of solution consisted of 3.5% sea water as indicated in the EN ISO 7384 standard. This standard indicated that total experiment time depends on materials type, environmental conditions, applied experimental method and experimental evaluating criteria. Also according to standard, one of the experimental time of 24, 48, 96, 240, 480, 720 and 2016 h should be chosen. In the present study, experimental time was selected as 2016 h so that experimental error could be minimum. This duration time was divided into three equal parts of 672, 1344 and 2016 h. After corrosion test, samples (3 samples for each measurement) were pulled out from the corrosive environment and they were cleaned as defined in the standard. Test samples were weighed by an electronic scale and then mass variation was reported. Variations in weight of welded specimens after corrosion measurements were calculated for 1 cm^2 surface area and average results for three measurements were evaluated for each test.

3. Experimental results and discussion

3.1. Metallographic results

Optical microscope images are given in Fig. 3 for the Al–Ti composites joined by explosive welding at various explosive loads. It is seen from Fig. 3 that when the explosive load $R = 1$ a flat interface was obtained. However, a wavy interface is seen in Fig. 3b at a explosive load of $R = 1.2$. In this case, the wavelength was measured as 190–200 μm and the amplitude as 20–25 μm. In the case of a higher explosive load ($R = 1.5$), the wavelength and amplitude are increased further as 260–280 μm and 40–50 μm, respectively. Similarly, for $R = 2$ explosive rate, the wavelength was found to be as 400–420 μm and the amplitude as 80–90 μm (Fig. 3d) and for $R = 2.5$ explosive rate, the wavelength and the amplitude increased with the increasing explosive load. Balasubramanian and co-workers [13] reported that explosive load affects the wavelength and amplitude of explosively welded parts, however stand-off distance affected only wavelength in explosively welded zone.

Livne and Munitz [23] joined copper and steel plates via explosive welding and they examined the joined interface by means of SEM and X-ray diffraction. In this research, they reported that wavy interface obtained in case of higher explosive load and wave formation were dependant upon explosive ratio and stand-off distance. In another study, Acarer and co-workers [24–26] found that welded interface metallurgy is also dependant upon the properties of parent materials, a suitable arrangement of welding parameters. Therefore, a small stand-off distance will result in a slower impact velocity and produce very small amplitude and wavelength. They [24–26] also reported that a wavy interface will be obtained with increasing stand-off

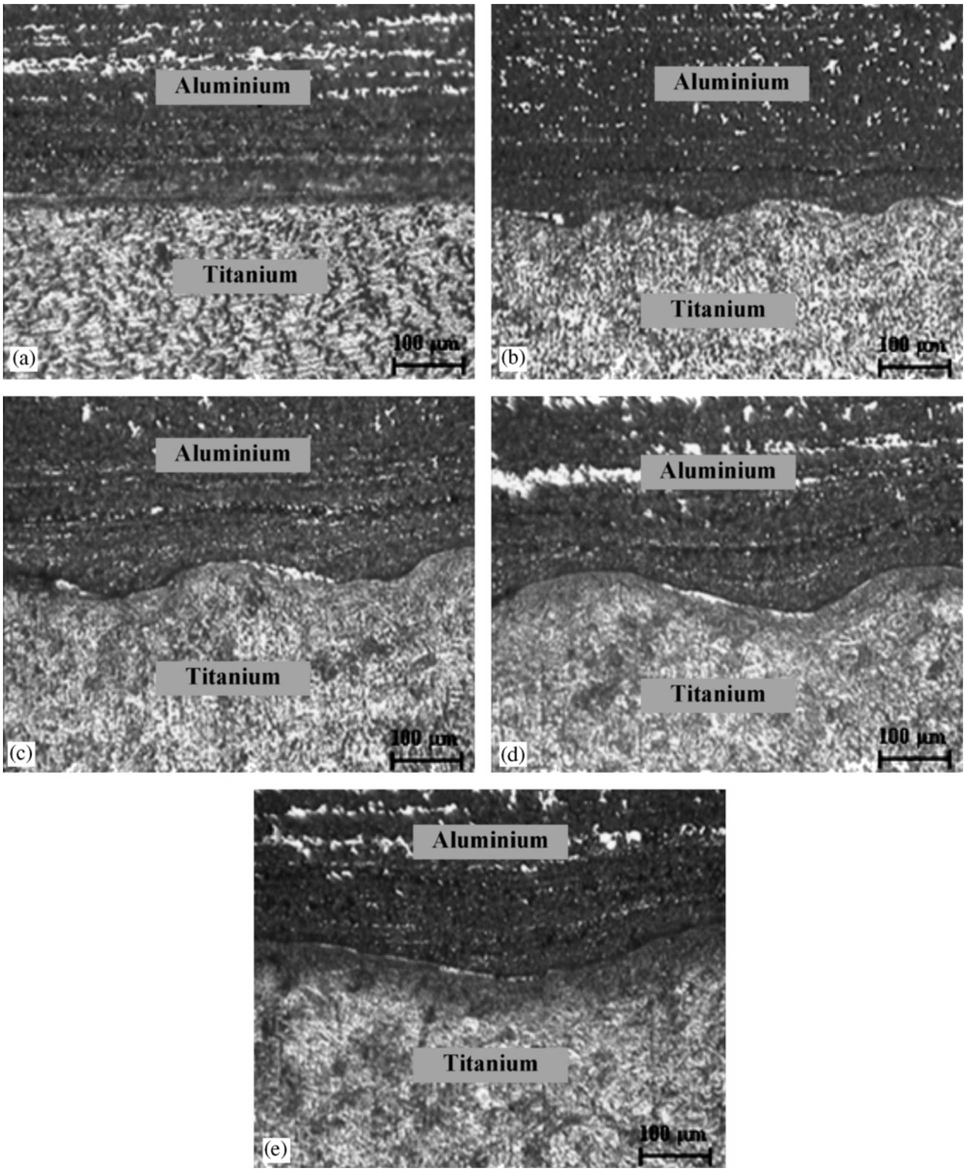

Fig. 3. The optical microscope views of the interface in explosively welded parts for various explosive loads as; (a) $R = 1$ (b) $R = 1.2$ (c) $R = 1.5$ (d) $R = 2$ and (e) $R = 2.5$.

distance. Cowan et al. [27] investigated wave form in interface of materials cladded with explosive welding. They reported that wavy interface was only obtained when the explosive ratio and impact distance were high; however, in the case of lower impact velocity, a flat interface was obtained.

In Fig. 4, the SEM micrographs are seen for explosively welded Al–Ti composites produced at the lowest ($R = 1$) and the highest ($R = 2.5$) explosive loads. It is clear from the SEM micrographs showed that there are no joining defects in interface. The deformation bands next to the interface area were mainly formed in aluminium. This might be due to its low hardness. However, these bands might also be the result of cold deformation during the Al plate production. In addition, no intermetallic compounds and melting cavities (pores) are seen in the interface. This result confirms that interface is in good condition from metallurgical point of view.

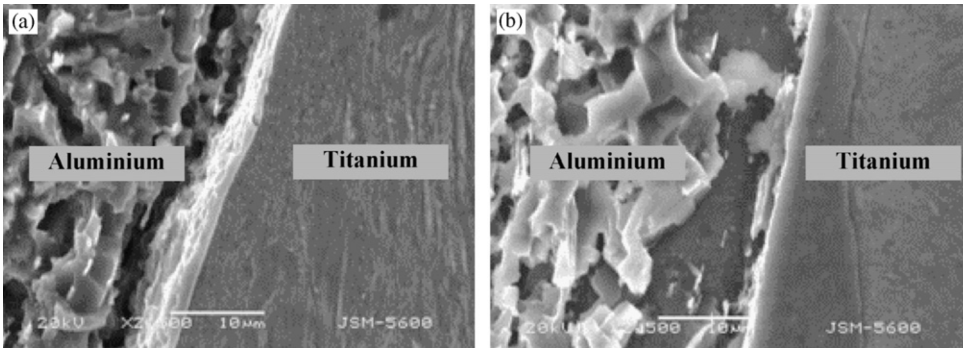

Fig. 4. SEM micrographs of explosively welded parts for (a) $R = 1$ and (b) $R = 2.5$ explosive loads.

Table 4
The tensile-shear test results of Al–Ti composite against explosive load

Tensile-shear strength (MPa)					Ruptured material
$R = 1$	$R = 1.2$	$R = 1.5$	$R = 2$	$R = 2.5$	
237 ± 3	240 ± 3	242 ± 3	245 ± 3	246 ± 3	Aluminium

3.2. Tensile-shear test results

As a result of the tensile-shear tests, following the conditions in ASTM D 3165-95 standard, no separation was formed in interface of Al–Ti composite and Al material was ruptured due to its lower tensile strength than Ti. The measured tensile-shear strength values of the joined materials are shown in Table 4.

It is seen from Table 4 that the tensile-shear strength of explosively welded materials are higher than that of original Al-materials. Furthermore, the tensile-shear strength increases with increasing explosive load in all the joined materials. Increasing tensile-shear strength can be attributed to the increased deformation with increasing explosive load. This result is consistent with the findings of Kahraman et al. [28]. They bonded titanium to stainless steel by explosive welding and reported that the strength and hardness of the titanium increased slightly. They explained this increase by deformation during the collision of the couple.

In addition to standard tensile-shear tests, following the earlier data [11], as a result of tests, preparing shearing area (L) is equal to tensile area (a), no shearing of the interface was observed and aluminium material was broken due to lower tensile strength. This result indicates that the strength of Al–Ti composite interface is higher than that of Al plates. It is known that surface area of wavy interface is longer than the flat interface obtained at lower explosive loads. However, no separation was observed in the flat interfaces. This implies that a flat interface is also as strong as a wavy one. This is consistent with the earlier work [11].

Mamalis et al. [29] carried out work on explosively joined Ni–Ti materials and they reported that the strength of materials in interface was better than the original materials in case of using suitable welding parameters and higher explosive loads. In another research, Livne and Munitz [23] joined Fe and Cu plates and they reported that the tensile strength of bonding interface was as high as that of Cu plate. They observed that tearing was occurred on Cu plate rather than the interface.

3.3. Bending test results

Bidirectional bending tests were applied to the explosively welded Ti–Al composites and the view of bent samples is shown in Fig. 5 for the lowest explosive load.

Having bent the samples 180° in two directional, no distinctive separation or crack on interface of joined samples was observed. This result showed a reliable and robust bonding of the interface.

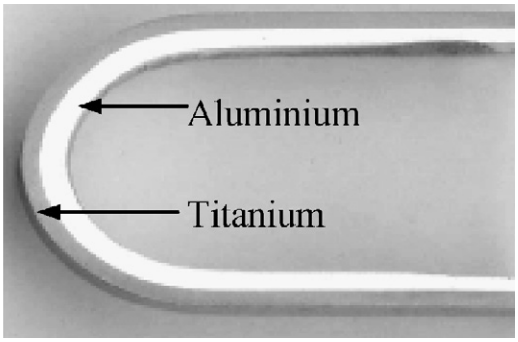

Fig. 5. The view of bent Ti–Al sample.

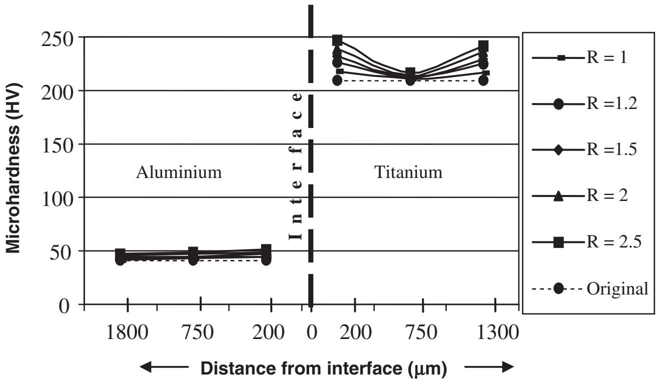

Fig. 6. Micro hardness values of the Al–Ti joints.

Table 5
Micro hardness values of the Al–Ti joints

Material	Distance from interface (μm)	Microhardness (HV)				
		$R = 1$	$R = 1,2$	$R = 1,5$	$R = 2$	$R = 2,5$
Aluminium 42 HV	1800	42.2	43.1	43.9	45.3	47.2
	1000	43.4	44	44.6	47.1	49.1
	200	44.6	45.1	47	49	50.7
Titanium 210 HV	200	217.7	226.8	232.2	239.3	246.6
	750	211.1	211.9	212.4	214.4	216.3
	1300	216.6	224.4	229.3	236.7	241

Crossland and Williams [30] reported that explosively welded materials could be bent up to 180°. It can be said that there was no defect in interface of the bent specimen in the present work and they can be easily used for bent form in service conditions.

3.4. Hardness results

The measured micro hardness values of Ti–Al composites joined by explosive welding at various explosive loads are shown in Fig. 6.

It is seen from Table 5 and Fig. 6 that hardness is increased in the explosively joined parts comparing to original titanium and this amount is increased with the increment of explosive loads due to cold deformation

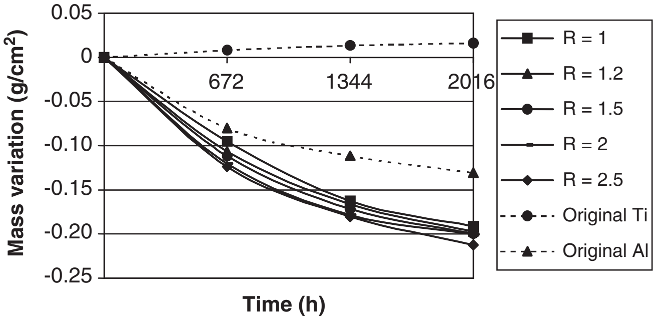

Fig. 7. Mass variations for Al–Ti composites and original materials in corrosion test.

in impact pressure. However, hardness increment in the centring of Ti plate was so low that in case of using lower explosive loads. In all explosive loads, the highest hardness value was measured in interface, and then followed outer surface of plate and finally thickness centre of the plate showed the minimum value.

Examining of Al side of joining it is seen that hardness values after explosion are higher than the original materials. The highest hardness increment was measured in near interface for all explosive loads, the hardness values decreased progressively from interface to outerface. In spite of joining lots of materials (Ti, Ni, steel) with Al, there is no comment on hardness variation in Al material. Trutnev et al. [31] joined Al with Ti, Ni and steel and studied the micro hardness variation in welded samples. They reported that hardness values of Ti, Ni and steel in joining interface showed higher hardness than the other area due to work hardening during the impact of parent materials. Gerland et al. [11] cladded of Al plates with Ni using four different explosives and they reported that hardness was higher in interface and it was increased with the increment of explosive loads. Mamalis et al. [29] bonded the titanium and nickel plates through explosive welding process and found that the zones near the collision interface exhibited the highest hardness values. They also found that the hardness values of the both metal were higher than those of the starting materials and this was attributed to the localised shock hardening at the interface.

3.5. Corrosion test results

Corrosion test results are shown in Fig. 7 for Al–Ti composites joined by explosive welding using various explosive loads.

It is seen from Fig. 7 that mass loss of the all test samples (occurred in corrosion test except from original titanium which showed an increase in mass due to affinity of Ti to oxygen) decrease. This mass loss was fast at the beginning of the test and then it gradually decreased. The mass loss was weighed as 0.1 g/cm^2 after 672 h and as 0.17 g/cm^2 after 1344 h time in the samples joined with explosive welding. This loss of increment slightly continued after 2016 h time and this amount was weighed approximately as 0.2 g/cm^2. The reason is that the first corrosion formed in the clean surface and that is why it was fast and then the surfaces were coated by oxide layer and the corrosion got slower. It is also shown in Fig. 7 that the maximum mass loss was observed in $R = 2.5$, 2, 1.5, 1.2 and 1 explosive loads, respectively. It is understood from these values that mass loss increased with the increment of explosive loads. Here, it is also observed that cold deformation increased with increasing explosive loads. It is observed that corrosion resistance decreases by an increase in deformation due to internal stress. It is known that a metal under corrosion environment exposes to a stress, corrosion speed increases. The results obtained from the studies carried out by Turker [32] and Kahraman [33] showed similar kind of results.

4. Conclusion

i) There was no peeling in interface of explosively welded materials after tensile-shear test according to ASTM D 3165-95.

ii) As a result of tensile-shear test, joining has a flat interface has got tensile stress near to wavy joining interface of materials.
iii) A flat interface was obtained in lower explosive loads in optical microscope; however a wavy interface was obtained in using higher explosive loads due to more pressure.
iv) There were no defects such as separation or torn, etc. In welding interface after bending test with double direction as an angle of 180°.
v) The SEM studies revealed that there was no joining defects (such as oxide remains, melting cavity, etc.) observed on welded samples.
vi) The measured hardness values in welded samples were higher than the original materials and the maximum hardness value was observed on the near interface area of joined materials.
vii) The mass loss in welded samples was fast at the beginning of the corrosion test, and then it continued in a slow rate and corrosion amount was increased with the increment of explosive load.

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