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The influence of some factors on steel/steel bonding quality on there characteristics of explosive welding joints

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Explosive welding is a solid state process in which controlled explosive detonations force two or more metals together at high pressures. The resultant arrangement is joined with a high quality metallurgical bond. The aim of this study was to investigate of strength of explosive welding metals which had same chemical compositions. In this study, it was taken different welding interfaces (straight, wavy and continuous solidified-melted) with changing explosive welding parameters (stand-off distance (s), explosive loading (R) and anvils). Joined metals were investigated in heat treatment and non heat treatment conditions. Microstructures, microhardness, tensile shear strength and bending test results were reported. Effect of anvil on explosive welding process was evaluated in joining/no joining performance. It was shown that bonding interface changed from straight to wavy structure when explosive loading and stand-off distance were increased. On wavy interface, when explosive loading was increased wavy length and amplitude increased. Results of tensile shear and bending tests showed that heat treated specimens have more strength than which of unheat-treated ones. According to tensile shear test results, straight and wavy interfaces had similar strength. Also, bending zone has shown some cracks after the bending test of unheated specimens.

1. Introduction

The explosive welding of two similar or dissimilar kinds of metallic plates is accomplished by the intensive deformation due to high pressure and high temperature generated at the collision point. Extensive researchers on explosive welding have been focused on the microstructural changes at the interface between the different the kind of metals [1–4] and the effects of base plate or flyer plate on the wave morphology in welded interfaces [5]. Explosive welding is one example of a constructive application of explosives in which the energy produced by the detonating explosive is used to accelerate a metal plate (flyer plate) across a predetermined distance (stand-off distance) into contact with another plate (base metal) and achieve a solid state joining. Explosive welding affords the welding of two or more similar or dissimilar metals. This process is called as cold technique, but local high temperature forms on interface due to dynamic of this method [6].

On this bases, some theoretical [7, 8] and experimental [9–14] papers were reported about explosive welding. Several will be highlighted here: In a specific study [10], an AA5083 Al alloy plate and SS41 steel plate were cladded by an explosive welding method using an AA 1050 Al alloy interlayer plate. The effects of interlayer thickness on the interface morphology and the shear deformation behavior of the cladded plates were studied. The interfacial was composed of an intermetallic compound, feAl_3, formed by the AA 1050 interlayer. The intermetallic compound acted as a crack source at the AA 1050/SS 41 interface, and the thickness and morphology of the interfacial zone were depended on the thickness of the AA1050 interlayer. In a shear deformation test, the crack propagation behavior varied according to the morphologies of the interfacial zone, and the shear strength of the cladded plates decreased with the interlayer thickness. In a recent paper [14], investigation of cracks and fracture on interfaces of explosive welded metals were reported using tensile shear and bending test. In this study, different welding interfaces were observed with changing explosive welding parameters. Joined metals were investigated before and

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after heat treatment. Microstructural and mechanical behaviors of joined samples were also reported.

The effect of anvil to welding is not understood. Therefore, in order to have more understanding of this point, two chemical identical steel plate were explosively welded and than microstructure, micro hardness and tensile shear strength were investigated in original and heat treated samples in this study. In this welding, different parameters (explosive rate, anvil, stand-off distance) were used and various interfaces (straight wavy and continuously melted and solidified) were obtained and tensile shear and bending tests of these joints were performed and fracture surfaces were examined as a result of those experiments.

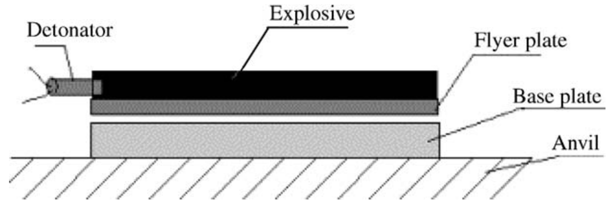

Figure 1 Shematic view of explosive welding.

2. Experimental details

In the present study, steel plates, 1110 degree, were used for welding of dimension 2 × 250 × 250 mm flyer plate and 6 × 250 × 250 mm parent plate. The chemical compositions of welded materials were tabulated in Table I. While hardness of flyer plate 134 Hv, parent plate was 136 Hv. Elbar-5 explosive (produced by MKE Barutsan Company, TR) was used to weld steel-steel plates. The used explosive rate (i.e., explosive loading which is proportion of explosive mass to flyer plate), stand-off distance anvil data were shown in Table II. It was seen Table II that the dimension of anvil (I) was 2000 × 450 × 450 mm and hardness was 320 Hv and its material was cast steel. Anvil (II) was rolled steel and its dimension was 2000 × 1500 × 60 mm and the hardness was 180 Hv. Schematic view of explosive welding applicationused in the present work is shown in Fig. 1. The specimens were cut for metallographic study in the explosion direction. The micro hardness test was carried out in Zwick machine (3212002/00) using 100 g load. For each sample, 5 different measurements were taken and average values were reported. Shear test was done in Instron-1185 machine in compression direction. The shearing speed of that machine was 0.5 mm/min. three samples were tested for each welding and average values were reported in the study. Bending test was also carried out in the same Instron-1185 machine. In the bending test, three samples were tested for each welding. Microstructure, microhardness, shear and bending specimens were investigated for both orrigiginal and heat-treated conditions.

3. Results

3.1. Effect of anvil to joining performance

In the present work, joining was unsuccessful in case of using sand anvil. Also, there was no success in joining of the samples in case of the usage of 500 × 500 × 20 mm and 500 × 500 × 25 mm steel anvil, and 500 × 500 × 100 mm cast steel anvil too. Successful welding was obtained in case of using 2000 × 450 × 450 mm steel anvil (anvil I). In this case, no buffer plate was used in between lower plate and anvil. However, in case of using 2000 × 1500 × 60 mm steel anvil (anvil II), successful joining was only established for higher explosion rate ($R = 2.4$) and wider stand-off distance ($s = 2t$). Incase of using 2000 × 450 × 450 mm anvil, 5 mm rubber buffer was used and joining was unsuccessful for 1.6 and lower explosive rates. Joining and no joining samples in explosive welding were shown in Table I.

3.2. Metallographic study

The optical micrographs of the welding samples are shown in Figs 1–19. The grains are elongated in explosion direction for un-heat treated samples. After the heat treatment, elongated grains are recrystallised and transformed into the original form. In Fig. 2, interface is shown for a specific explosion loading (1.4)

TABLE I The chemical compositions of welded materials

Elements	C	Si	Mn	P	S	Cr	Ni	Al
Materials								
2 mm steel sheet (flyer plate)	0.06	0.01	0.34	0.011	0.011	0.10	0.01	0.02
4 mm Steel sheet (base plate)	0.07	0.02	0.35	0.010	0.012	0.16	0.01	0.08

TABLE II Joined and un joined samples for various anvil, stand-off distance and explosive loading conditions

Anvil	Explosive loading							Stand-off distance	
Sand	1.0 (−)	1.2 (−)	1.4 (−)	1.6 (−)	1.8 (−)	2.0 (−)	2.4 (−)	1/2 t	t
2000 × 450 × 450 mm (anvil I)	1.0 (−)	1.2 (−)	1.4 (−)	1.6 (−)	1.8 (+)	2.0 (+)	2.4 (+)	1/2 t	t
2000 × 1500 × 60 mm (anvil II)	1.0 (−)	1.2 (−)	1.4 (+)	1.6 (+)	1.8 (+)	2.0 (+)	2.4 (+)	1/2 t	t
500 × 500 × 20 mm	1.0 (−)	1.2 (−)	1.4 (−)	1.6 (−)	1.8 (−)	2.0 (−)	2.4 (−)	1/2 t	t
500 × 500 × 25 mm	1.0 (−)	1.2 (−)	1.4 (−)	1.6 (−)	1.8 (−)	2.0 (−)	2.4 (−)	1/2 t	t
500 × 500 × 100 mm	1.0 (−)	1.2 (−)	1.4 (−)	1.6 (−)	1.8 (−)	2.0 (−)	2.4 (−)	1/2 t	t

(−) Unjoined samples; (+) Joined samples.

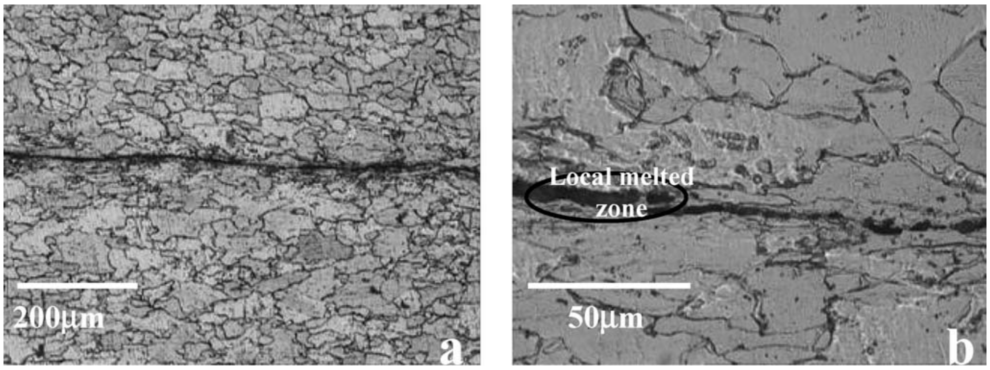

Figure 2 The microstructure of joint A (explosion loading: 1.4; stand-off distance: t; anvil: $2000 \times 1500 \times 60$ mm steel (anvil II)): (a) $\times 100$ and (b) $\times 500$.

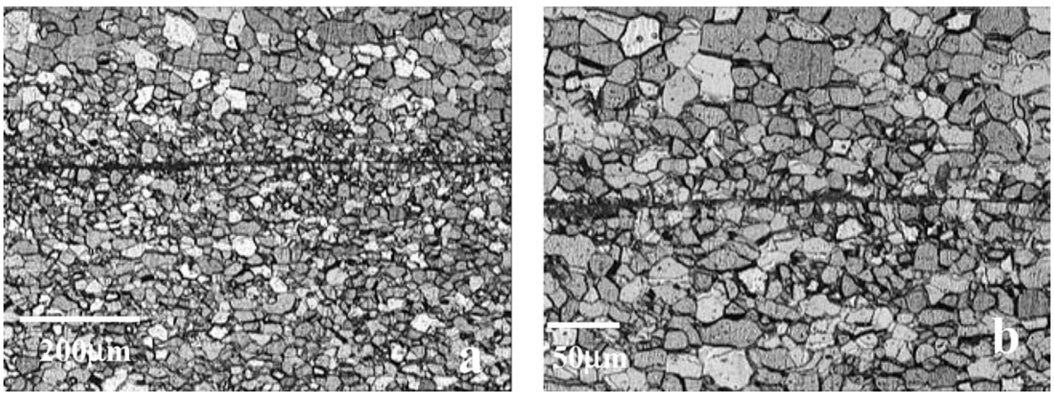

Figure 3 The microstructure of heat treated (30 min at 675°C) sample for joint A (explosion loading: 1.4; stand-off distance: t; anvil: $2000 \times 1500 \times 60$ mm steel (anvil II)): (a) $\times 100$ and (b) $\times 200$.

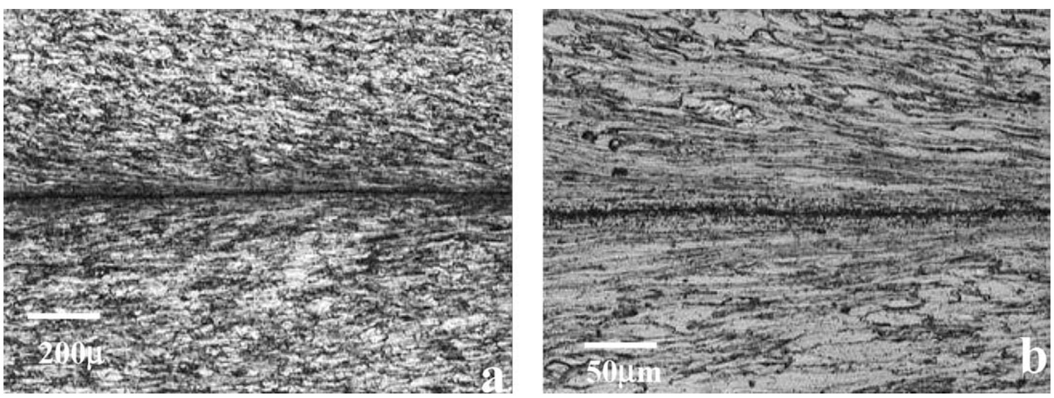

Figure 4 The microstructure of joint B (explosion loading: 1.6; stand-off distance: 0.5 t; anvil: $2000 \times 1500 \times 60$ mm steel (anvil II)): (a) $\times 50$ and (b) $\times 200$.

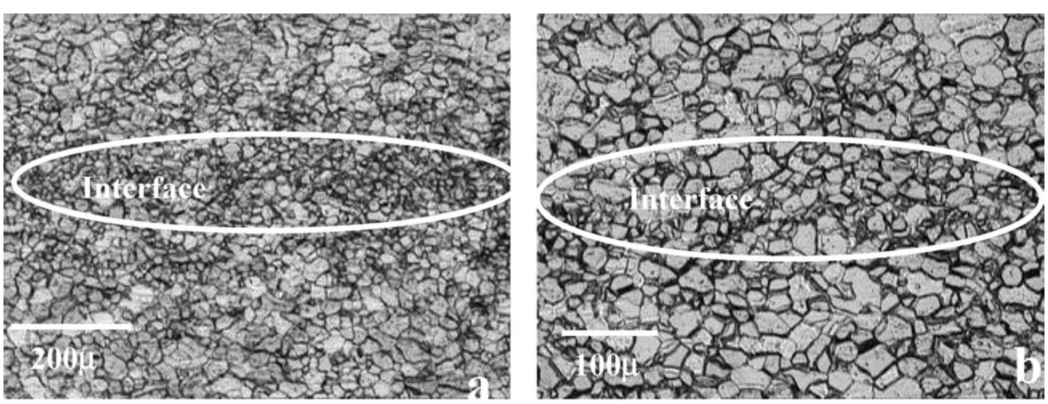

Figure 5 The microstructure of heat treated (30 min at 675°C) sample for joint B (explosion loading: 1.6; stand-off distance: $0.5t$; anvil: $2000 \times 1500 \times 60$ mm steel (anvil II)): (a) $\times 100$ and (b) $\times 200$.

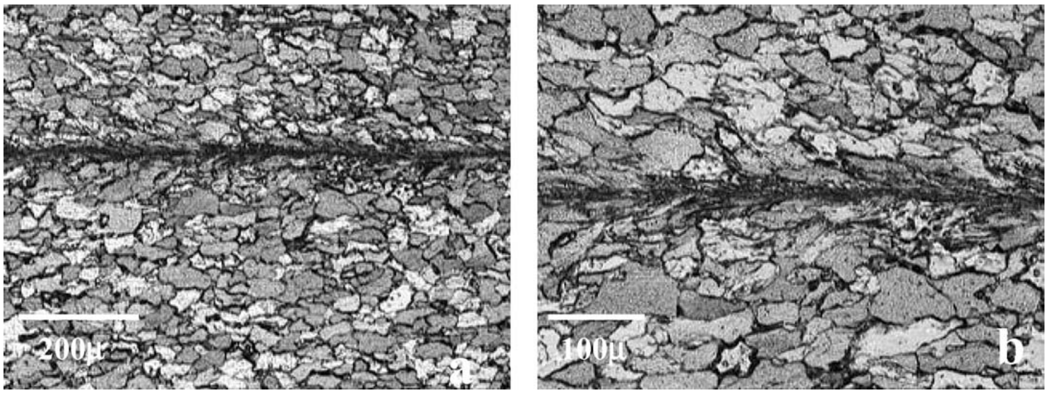

Figure 6 The microstructure of joint C (explosion loading: 1.6; stand-off distance: t; anvil: $2000 \times 1500 \times 60$ mm steel (anvil II)): (a) $\times 100$ and (b) $\times 200$.

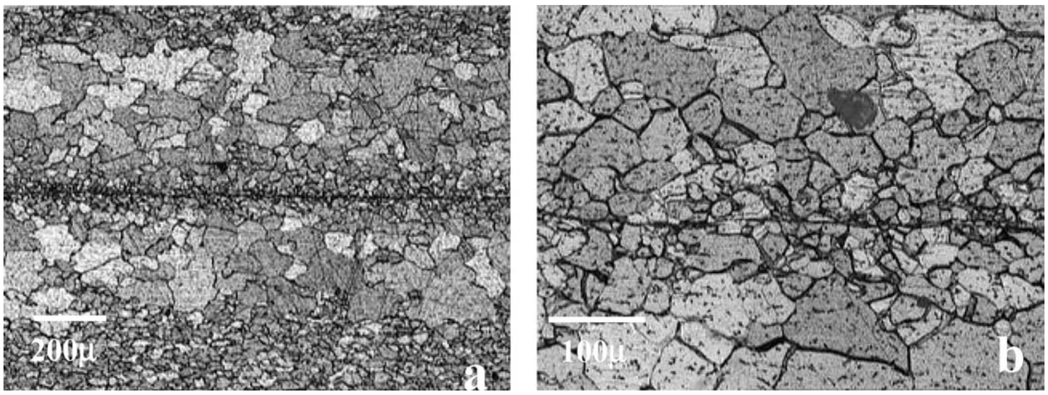

Figure 7 The microstructure of heat treated (30 min at 675°C) sample for joint C (explosion loading: 1.6; stand-off distance: t; anvil: $2000 \times 1500 \times 60$ mm steel (anvil II)): (a) $\times 50$ and (b) $\times 100$.

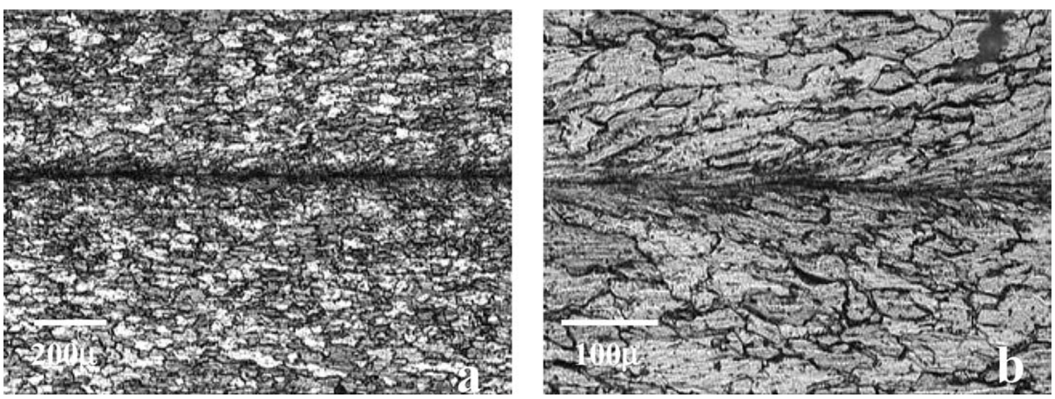

Figure 8 The microstructure of joint D (explosion loading: 1.8; stand-off distance: 0.5t; anvil: $2000 \times 1500 \times 60$ mm steel (anvil II)): (a) $\times 50$, (b) $\times 200$.

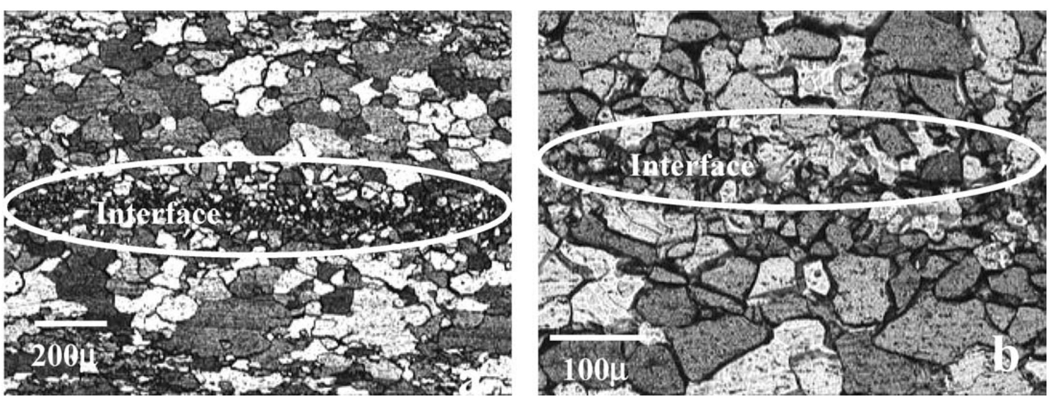

Figure 9 The microstructure of heat treated (30 min at 675°C) sample for joint D (explosion loading: 1.8; stand-off distance: 0.5t; anvil: $2000 \times 1500 \times 60$ mm steel (anvil II)): (a) $\times 50$ (b) $\times 200$.

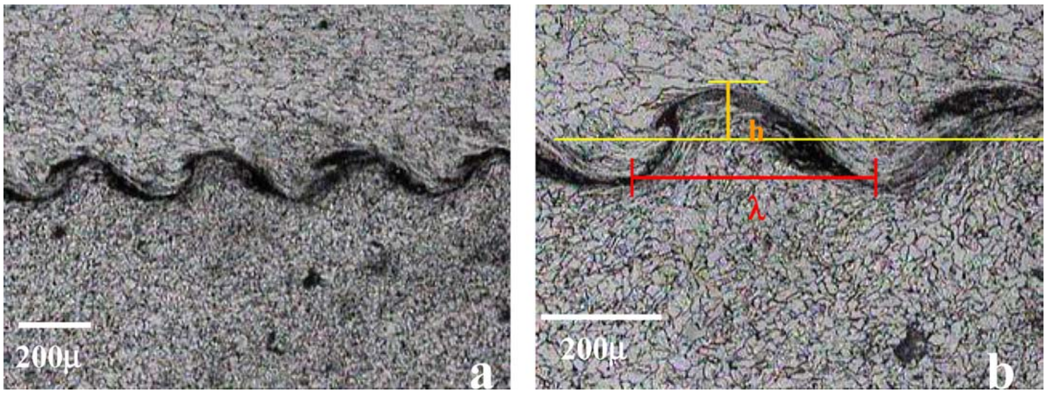

Figure 10 The microstructure of joint G (explosion loading: 1.8; stand-off distance: t; anvil: $2000 \times 1500 \times 60$ mm steel (anvil II)): (a) ×50 and (b) ×100.

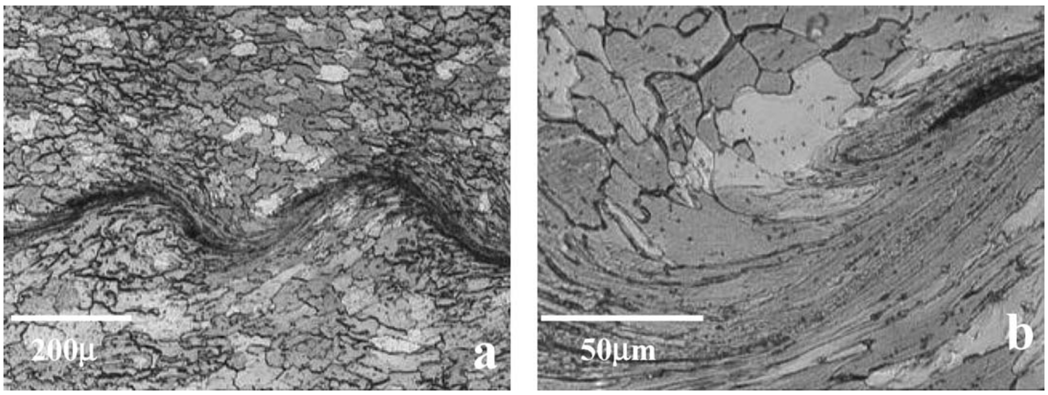

Figure 11 The microstructure of heat treated (30 min at 675°C) sample for joint G (explosion loading: 1.8; stand-off distance: t; anvil: $2000 \times 1500 \times 60$ mm steel (anvil II)): (a) ×50 and (b) ×100.

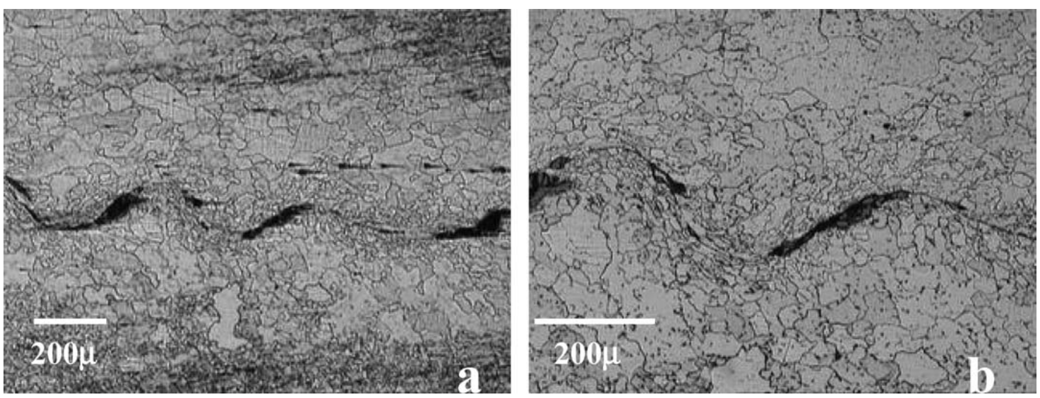

Figure 12 The microstructure of joint H (explosion loading: 2.0; stand-off distance: 0.5 t; anvil: $2000 \times 450 \times 450$ mm steel (anvil I)): (a) ×100 and (b) ×500.

and stand-off distance (t) of $2000 \times 1500 \times 60$ mm steel plate (anvil II). It is clear from this figure that interface has got some local melting. In Fig. 3, the heat treated (30 min in 675°C) sample for the same explosion loading, stand-off distance and anvil with Fig. 2. It is noted that elongated grains transformed into original grains via recrystallisation. Similar microstructure is illustrated in Figs 4–9 for higher explosion loading and various stand-off distances.

The wavy interface is also illustrated in Fig. 10 for a particular explosion loading (1.8) and stand-off distance (t) of $2000 \times 1500 \times 60$ mm steel plate (anvil II). In Fig. 11 the heat treated (30 min. in 675°C) specimen for identical explosion loading, stand-off distance and anvil with Fig. 10. Similar microstructure is also shown in Figs 12–19 for higher explosion loading and various stand-off distances.

3.3. Micro hardness results

Micro hardness results of explosively welded samples were illustrated in Table III. The measurements are taken from both interface and various distances from the interface, such as 100, 200 and 2000 μm. It is seen from Table III there is a great difference between heat-treated and unheat treated samples. It is also clear from this table that hardness decreases in the far area from the welding interface. This point will be discussed in the next chapter.

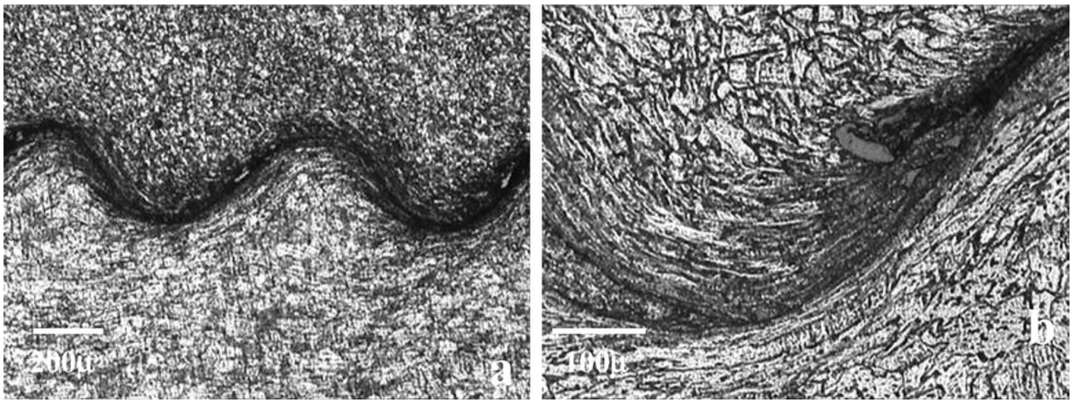

Figure 13 The microstructure of joint I (explosion loading: 2.0; stand-off distance: 0.5t; anvil: 2000 × 1500 × 60 mm steel (anvil II)): (a) ×50 and (b) ×200.

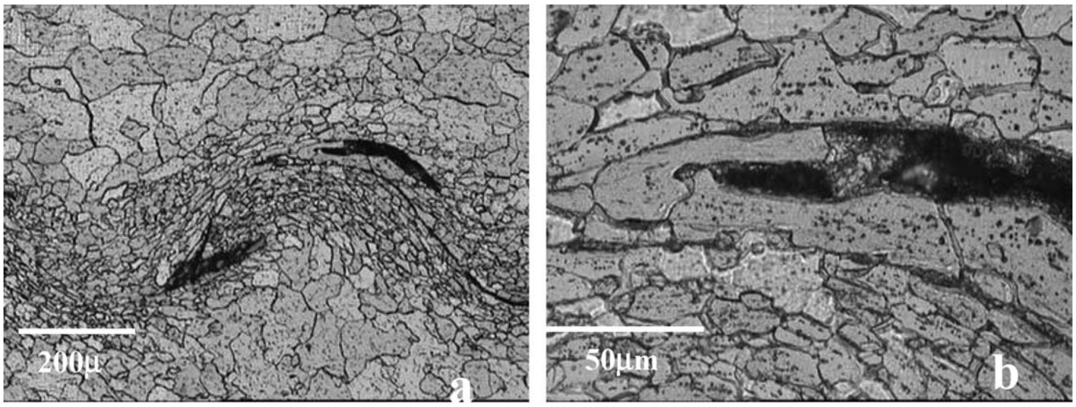

Figure 14 The microstructure of heat treated (30 min at 675°C) sample for joint I (explosion loading: 2.0; stand-off distance: 0.5t; anvil: 2000 × 1500 × 60 mm steel (anvil II)): (a) ×50 and (b) ×100.

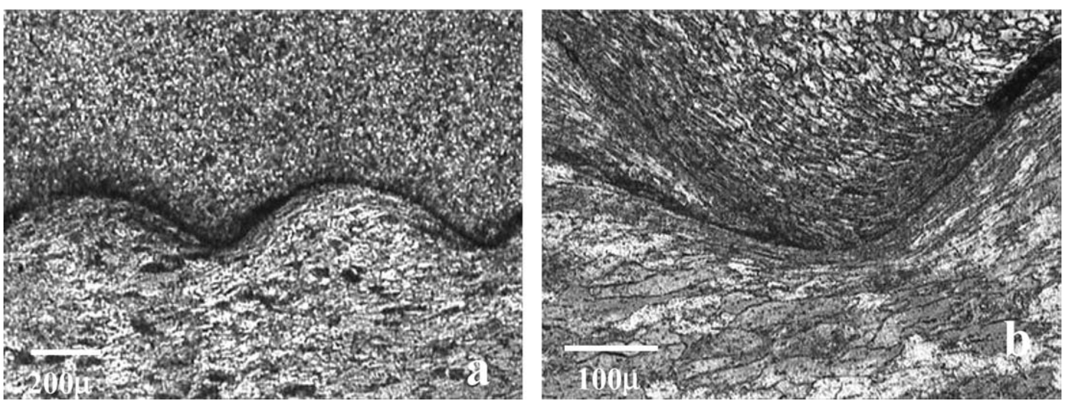

Figure 15 The microstructure of joint J (explosion loading: 2.0; stand-off distance: t; anvil: 2000 × 450 × 450 mm steel (anvil I)): (a) ×50 and (b) ×200.

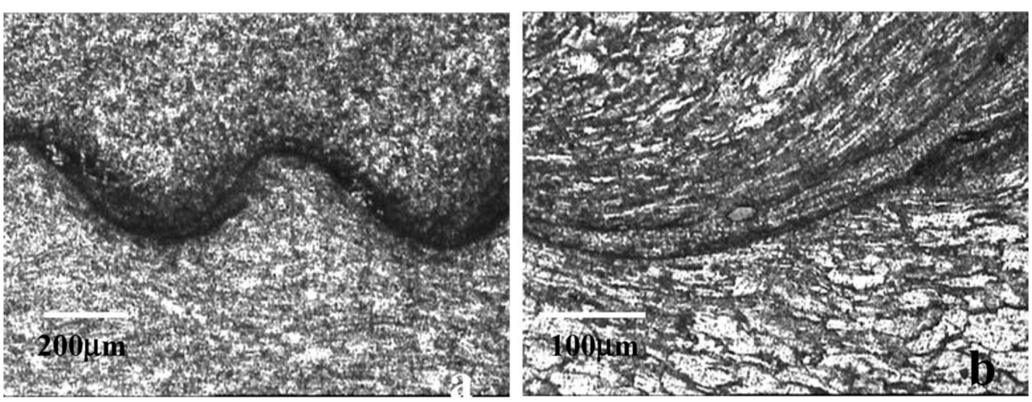

Figure 16 The microstructure of joint K (explosion loading: 2.0; stand-off distance: t; anvil: 2000 × 1500 × 60 mm steel (anvil II)): (a) ×50 and (b) ×200.

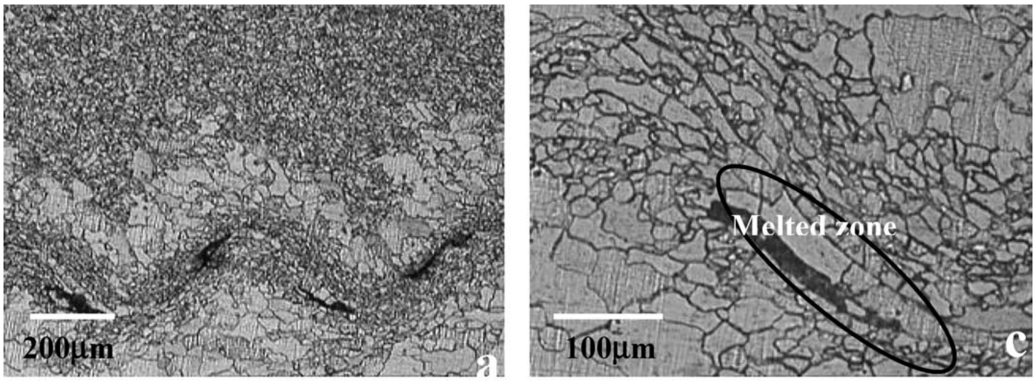

Figure 17 The microstructure of heat treated (30 min at 675°C) sample for joint K (explosion loading: 2.0; stand-off distance: t; anvil: $2000 \times 1500 \times 60$ mm steel (anvil II)): (a) ×50 and (b) ×200.

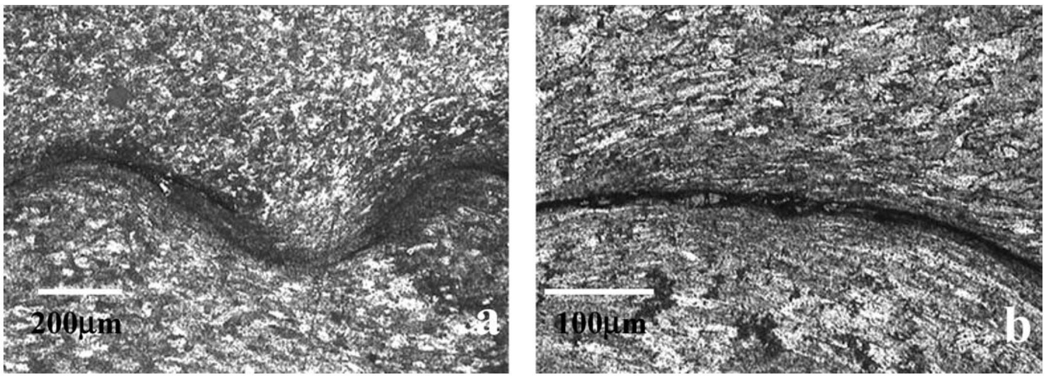

Figure 18 The microstructure of joint L (explosion loading: 2.4; stand-off distance:0.5t; anvil: $2000 \times 450 \times 450$ mm steel (anvil I)): (a) ×50 and (b) ×200.

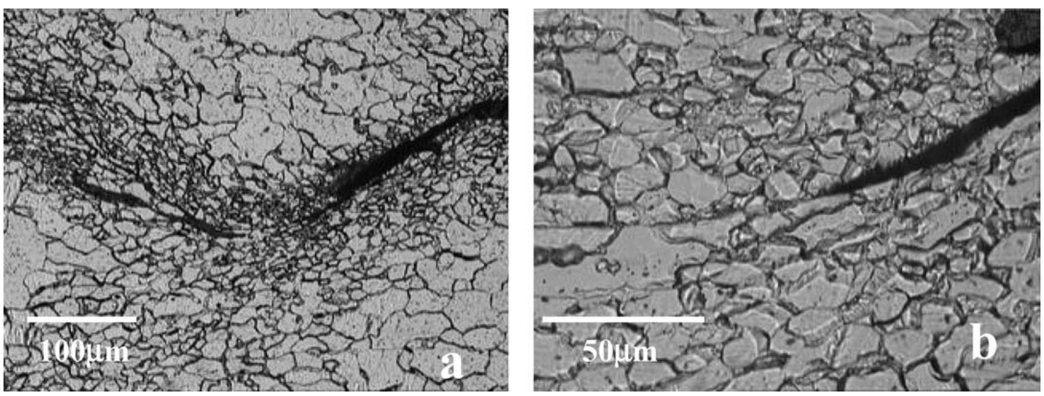

Figure 19 The microstructure of heat treated (30 min at 675°C) sample for joint L (explosion loading: 2.4; stand-off distance: 0.5t; anvil: $2000 \times 450 \times 450$ mm steel (anvil I)): (a) ×50 and (b) ×200.

3.4. Shear test results

Shear test results were shown in Table IV for explosively joined samples. It was seen from Table IV that minimum shear strength was obtained G2 and G3 samples (280–290 MPa), while maximum shear strength was observed in E3 and E4 specimens (495–620 MPa). In shear test samples, fracture is not obtained at the explosively joined area. The shear results are obtained at the upper and lower plate during the first failure is observed. Shear strength of the heat treated samples are generally bigger than unheat-treated samples.

3.5. Bending test results

After completion of the bending test, separation of the joint area is shown in Table V. It is seen from this table that M and N coded joints were completely separated before 90°C bending of the sample. 40 and 25% separation were observed in the joints of A and C, and B and D, respectively. The rest joints almost kept their original form and no distinguished separation was observed.

4. Discussion

4.1. Type and thickness of anvil

Sand anvil was used in explosively welded joints by the previous workers [15, 16]. However, welding was not successful in case of using sand (A) and steel anvils (D, E, F) in the present work shown in Table I. The reason is that probably due to the smaller dimension of the samples comparing to the industrial usage. Therefore, small samples were buried into sand anvil during

TABLE III The various interface after explosive welding

Specimen code	R: Explosive loading and s: Stand-off distance	Wave length (λ), μm	Wave amplitude (h), μm
A	R:1.4 s: t	FLAT	
B	R:1.6 s: 1/2 t	FLAT	
C	R:1.6 s: t	FLAT	
D	R:1.8 s: 1/2 t	FLAT	
E	R:1.8 s: 1/2 t	FLAT	
F	R: 1.8 s: t	FLAT	
G	R:1.8 s: t	350–400	40–50
H	R:2.0 s: 1/2 t	350–420	45–60
I	R:2.0 s: 1/2 t	570–650	75–90
J	R:2.0 s: t	600–670	80–100
K	R:2.0 s: t	650–700	90–120
L	R:2.4 s: 1/2 t	800–1000	120–200
M	R:2.4 s: 1/2 t	FLAT (melted)	
N	R:2.4 s: t	FLAT (melted)	

the explosion welding. The thickness of the samples in explosive welding was used in between 60 mm up to 450 mm employing enough loading ($R \geq 1.8$). However, edge of the samples was not completely joined in explosive welding. This result is consistent with the previous work [17, 18].

4.2. Microstructural inquiry

It is seen from the Figs 2–19 that the grains are elongated in explosion direction due to higher deformation in the welding zone. Explodes with an explosion rate and draw the upper plate near to the lower one. This is also reported by the earlier workers [5, 13–16]. After the finishing of explosion welding, flat (Fig. 2) and wavy (Fig. 10) interfaces were obtained. It is also seen from Table II that wavy interface is obtained with the increasing of stand-off distance and explosion loading. This is consistent with the earlier works [19–21]. In the present work, explosion loading was chosen as 1.0 and over, however unsuccessful results were obtained in between 1.0 and 1.4 explosion loading. Crossland [22] reported successful welding in the lower explosion loading. This is not consistent with the present study. The reason of the contradiction is probably due to the using smaller specimens in the current work comparing with the earlier study [22].

4.3. Hardness alteration

It is seen from Table IV that micro hardness gradually decreases in the far area from the welding interface. The reason is that possibly due to the higher plastic deformation in the welding zone comparing with the far area. This result is consistent with the previous work [5, 6, 11, 15, 23–25]. In addition, hardness increases with the increasing of stand-off distance and explosion load due to the higher plastic deformation (Table IV). Similar results are also reported by earlier workers [6, 19, 26].

4.4. Shear query

The current shear tests were done according to ASTM A 264 standard [27] and the shear results were obtained

TABLE IV Microhardness results of the explosively welded samples

Sample		Mikrohardness (Hv) Distance from interface (μm) 0	10	100	200	2000
A	Unheat treated	175 ± 7	165 ± 5	141 ± 8	149 ± 4	162 ± 4
	Heat treated	110 ± 5	132 ± 3	109 ± 5	107 ± 6	108 ± 6
B	Unheat treated	178 ± 4	168 ± 4	152 ± 6	151 ± 5	165 ± 6
	Heat treated	107 ± 6	135 ± 6	110 ± 7	107 ± 6	110 ± 8
C	Unheat treated	170 ± 6	165 ± 7	151 ± 4	147 ± 7	166 ± 7
	Heat treated	95 ± 8	95 ± 5	92 ± 8	90 ± 9	90 ± 5
D	Unheat treated	171 ± 5	167.5 ± 7	152 ± 3	149 ± 2	168 ± 4
	Heat treated	95 ± 7	94.5 ± 3	92 ± 8	86.3 ± 8	80 ± 6
E	Unheat treated	168 ± 4	167 ± 5	154 ± 6	153 ± 5	165 ± 10
	Heat treated	95 ± 6	95 ± 8	93 ± 8	90 ± 7	92 ± 3
F	Unheat treated	160 ± 5	171 ± 5	150 ± 5	153 ± 6	165 ± 4
	Heat treated	95 ± 6	98 ± 7	95 ± 5	96 ± 7	95 ± 8
G	Unheat treated	160 ± 7	160 ± 4	156 ± 6	157 ± 8	168 ± 3
	Heat treated	110 ± 4	115 ± 6	121 ± 8	119 ± 8	122 ± 5
H	Unheat treated	165 ± 7	160 ± 5	141 ± 2	140 ± 4	180 ± 7
	Heat treated	110 ± 6	122 ± 6	117 ± 3	95 ± 8	115 ± 6
I	Unheat treated	164 ± 7	184 ± 7	141 ± 7	139 ± 5	180 ± 4
	Heat treated	95 ± 5	100 ± 7	95 ± 9	92 ± 6	117 ± 2
J	Unheat treated	160 ± 3	155 ± 6	139 ± 5	138 ± 6	178 ± 3
	Heat treated	112 ± 4	132 ± 7	125 ± 4	97 ± 8	115 ± 5
K	Unheat treated	160 ± 6	168 ± 5	141 ± 7	138 ± 2	178 ± 4
	Heat treated	117 ± 5	130 ± 5	100 ± 5	95 ± 3	110 ± 6
L	Unheat treated	178 ± 7	217 ± 3	197 ± 2	176 ± 9	183 ± 2
	Heat treated	115 ± 3	133 ± 4	94.5 ± 6	89 ± 6	132 ± 8
M	Unheat treated	165 ± 5	175 ± 5	135 ± 4	136 ± 7	137 ± 5
	Heat treated	110 ± 8	123 ± 3	127 ± 7	115 ± 8	113 ± 4
N	Unheat treated	168 ± 4	174 ± 5	136 ± 5	136 ± 5	138.7 ± 3
	Heat treated	95 ± 2	101 ± 3	94.5 ± 6	94 ± 5	102.5 ± 5

TABLE V Shear test results of explosively welded samples

Specimen code	Anvil	R: explosive loading s: stand-off distance		Interface	Shear strength (MPa)
A	II	R: 1.4	Unheat treated	FLAT	440 ± 10
		s: t	Heat treated		470 ± 12
B	II	R: 1.6	Unheat treated	FLAT	438 ± 9
		s: 1/2 t	Heat treated		533 ± 9
C	II	R: 1.6	Unheat treated	FLAT	415 ± 12
		s: t	Heat treated		496 ± 15
D	I	R: R: 1.8	Unheat treated	FLAT	450 ± 14
		s: 1/2 t	Heat treated		530 ± 15
E	II	R: 1.8	Unheat treated	FLAT	425 ± 10
		s: 1/2 t	Heat treated		460 ± 13
F	I	R: 1.8	Unheat treated	FLAT	465 ± 12
		s:t	Heat treated		555 ± 9
G	II	R: 1.8	Unheat treated	Wavy	450 ± 11
		s: t	Heat treated		575 ± 6
H	I	R: 2.0	Unheat treated	Wavy	385 ± 8
		s: 1/2 t	Heat treated		478 ± 12
I	II	R: 2.0	Unheat treated	Wavy	366 ± 11
		s: 1/2 t	Heat treated		445 ± 15
J	I	R: 2.0	Unheat treated	Wavy	425 ± 14
		s: t	Heat treated		480 ± 9
K	II	R: 2.0	Unheat treated	Wavy	365 ± 14
		s: t	Heat treated		405 ± 12
L	I	R: 2.4	Unheat treated	Wavy	315 ± 6
		s: 1/2 t	Heat treated		345 ± 14
M	II	R: 2.4	Unheat treated	FLAT	280 ± 9
		s: 1/2 t	Heat treated	Melted	285 ± 14
N	I	R: 2.4	Unheat treated	FLAT	292 ± 8
		s: t	Heat treated	Melted	280 ± 10

TABLE VI Seperation of the joints after the bending test

Specimen	A	B	C	D	E	F	G	H	I	J	K	L	M	N
Seperation after bending	%40	%25	%40	%25	–	–	–	–	–	–	–	–	Completely seperated	

higher than minimum level (140 MPa) of that standard. Even the minimum shear strength (G_2 and G_3 samples) results satisfied the certain standard [27] level giving the 280 and 290 MPa strength, respectively. G2 and G3 specimens gave the minimum strength due to the formation of intermetallic compound in the interface. As it is well known that intermetallic compound lowers the ductility and start the brittleness. Decreasing of the strength (joining and bending) could be due to the formation of intermetallic compounds. Crossland [6] reported that the high kinetic energy in the jet will be dissipated as heat causing melting at the interface. Also, both cooling rate, about 10^5–10^7°C/s, during explosive welding and oxide layers on to be welded metals could be cause such a intermetalic or solidified melted layer at the interface. However, owing to the lack of data (no EDX analysis in interface), no evidence is observed. But, in literature intermetallic compounds on the interface were observed and similar lower strength was obtained in the interface during the explosive welding. This is consistent with the earlier papers [11, 28].

Due to the higher plastic deformation in explosively welded (and unheat-treated) samples, higher hardness values were obtained comparing with heat treated samples. Hence, lower shear strength were obtained at welded and unheat-treated samples comparing with the treated ones. This is also consistent with previous studies [6, 21]. Flat and wavy interfaces supplied about the same shear strength and these results are in agreement with the other studies [5, 19, 28].

4.5. Bending analysis
The earlier workers [29] reported that welded joints could be bent up to 180° in the bending test. However, in the present study, M and N joints were separated during the test before 90° bending (Table V) due to the formation of intermetallic compound in the interface. No tearing was observed in heat treated samples during the bending test. However, some distinctive tearing was detected in several specimens (E, F, and H) of unheat-treated ones. The reason is that possibly due to high deformation hardening in explosively welded area. Furthermore, recrystallisation occurred during the heat treatment of welded joints, and then bad effects of prior deformation hardening were eliminated. In the present study, all joints were complied with certain standard [27] conditions, except M and N samples.

5. Conclusions
(a) Joining was unsuccessful in case of using sand anvil due to high pressure during explosion welding.

(b) In case of using $2000 \times 450 \times 450$ mm anvil, 5 mm rubber buffer was used and joining was also unsuccessful for 1.6 and lower explosive rates.

(c) Coarse granular structure is seen in interface after explosive welding. However, microstructure is recrystallised in heat treated specimens.

(d) There is a direct proportionality in between explosion load and wavy structure of interface in welding. With the increasing of explosion load, flat interface transformed into wavy structure.

(e) Microhardness decreased in the far area from he welding interface due to grain growth in explosion area.

(f) Shear strengths of heat treated specimens are higher than unheat treated ones due to better toughness.

(g) Flat and wavy interfaces provided about the same shear strength.

(h) Bending test results satisfied the certain standard and bending strength of heat treated samples were generally bigger than unheat-treated ones.

(i) In bending and shear test, the quality of welding worsens in case of high explosion rate due to formation of intermetallic compound in the interface.

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