INFLUENCE OF FRICTION WELDING PARAMETERS ON THE TENSILE STRENGTH OF BIMETALLIC WELD JOINTS

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Abstract: *In the present investigation, the influence of friction welding parameters on the ultimate tensile strength has been reported. The joining of RPV steel-Stainless steel was carried out using conventional arc welding processes. The paper also discusses the microstructural characterization of bimetallic weld joints fabricated using friction welding approach. An attempt has been made to relate the micro-structural and microscopic behaviour of the friction welded bimetallic weld joints with the variation in friction welding process parameters. A full factorial technique was utilized to analyze the effect of parameters. The results exhibited that burn-off-length has the greatest influence in determining the mechanical behaviour.*

Keywords *- RPV Steel, Friction Welding and Bimetallic Welding.*

I. INTRODUCTION

The principle of friction welding is that one of the components being joined is rotated while the other is kept stationary. The two components are then brought together by an axially applied load. The two contact surfaces rub each other and produce sufficient heat so that local plastic zones are formed and axially applied load causes the plasticized metal along with the lighter impurities to be extruded from the joint. Thus two automatically clean surfaces are brought together under pressure and an inter metallic bond is formed. The heat generated is confined to the interface, heat input is low and the hot work applied to the weld area results in a grain refinement. This rapidly, easily controlled and easily mechanized process has been used extensively in the automotive industry for items such as differential casings, half shafts and bi-metallic valves. An important characteristic of conventional friction welding is its ability to weld ferrous and non ferrous metals that cannot be welded by existing fusion welding methods (Ananthapadmanaban et.al (2009)). It is possible to make dissimilar metal joints, joining steel, copper and aluminium to themselves and to each other without hot cracking. The primary reason for this is that no melting takes place and thus no brittle intermetallic phases are formed. Friction welding provides a "full strength" bond with no additional weight. Bi-metallic welding is commonly used in Nuclear Industry, where carbon steel and stainless steel joints are generally used in the nuclear reactor systems (Chhibber R et.al (2006)). The elimination of tube machining, gas and consumable costs, combined with the higher production rates of friction welding, easily offset the high hourly cost of this process. Some of the disadvantages of conventional arc welding methods like high heat input and usage of non-matching filler wire can be avoided by using friction welding. Friction welding parameters such as friction force, RPM, upset force and burn off length have to be selected based on the parent metals to be welded and prior experience. The parameters should be selected properly in the experiments since these directly affect the welding quality (Sahin Mumin et.al. (2007)). In this study, friction welding of bimetallic weld joint, i.e. ferritic steel to austenitic stainless steel has been reported.

This combination is useful in applications like nuclear power generation in joining pressure vessel steel and primary heat transport piping material made up usually of austenitic stainless steel. Various researchers carried out different studies on friction welding. The friction welding method was investigated in 1960s by Vill (1962) and Tylecote (1968). Later, Jenning (1971) and Lucas (1971) investigated the properties of the dissimilar materials welded by friction welding and the process parameters on friction welding method in 1970s. And, Ellis (1977) examined the relationship between "friction time-work piece diameter", "shortening–upsetting pressure" and "carbon equivalent-hardness variation".

II. EXPERIMENTATION

2.1 Materials & Methods

The materials used in this experimental study were cylindrical rods of Austenitic stainless steel – 304 and RPV steel having length 70 mm and diameter 12 mm each. The chemical composition for both types of steels is given below in Table 1.

Table 1: Composition of Base Materials

Elements / Materials	C	Si	Mn	Ni	Cr	Cu	Fe	Mo
RPV Steel	0.165	0.216	1.5	0.65	0.0536	--------	--------	0.5
Stainless Steel-304	0.0541	0.855	1.89	8.31	19.6	0.495	68.2	--------

Modified vertical milling machine was used for friction welding, dial indicator was used to control the burn off length, and forge & friction forces were precisely controlled by a piezoelectric dynamometer. All relevant data for every weld was recorded. Sixteen different combinations were welded by varying four parameters viz. Friction force, Forge force, RPM and Burn off Length up to two levels as shown below in Table 2. For each experiment four specimens were made.

The quality and integrity of welds were examined by carrying out tensile tests and Micro hardness tests of the welded specimen. Optical microscopy of the welded joints was done to observe changes in microstructure in different zones of weld.

Table 2: Showing sixteen different combinations for two levels & four factors

No. of Experiments (specimen no.'s)	**Parameters**			
	Friction Force (F) in Newton (N)	Forge Force (f) in Newton (N)	Burn off Length (L) in mm	RPM (R)
1 (1,2,3,4)	5650 (-)	11300 (-)	1.5 (-)	1400 (-)
2 (5,6,7,8)	7910 (+)	11300 (-)	1.5 (-)	1400 (-)
3 (9,10,11,12)	5650 (-)	11300 (-)	2.5 (+)	1400 (-)
4 (13,14,15,16)	5650 (-)	11300 (-)	1.5 (-)	1800 (+)
5 (17,18,19,20)	7910 (+)	11300 (-)	2.5 (+)	1400 (-)
6 (21,23,23,24)	5650 (-)	11300 (-)	2.5 (+)	1800 (+)
7 (25,26,27,28)	7910 (+)	11300 (-)	1.5 (-)	1800 (+)
8 (29,30,31,32)	7910 (+)	11300 (-)	2.5 (+)	1800 (+)
9 (33,34,35,36)	7910 (+)	13560 (+)	2.5 (+)	1800 (+)
10 (37,38,39,40)	5650 (-)	13560 (+)	2.5 (+)	1800 (+)
11 (41,42,43,44)	7910 (+)	13560 (+)	1.5 (-)	1800 (+)
12 (45,46,47,48)	7910 (+)	13560 (+)	2.5 (+)	1400 (-)
13 (49,50,51,52)	5650 (-)	13560 (+)	1.5 (-)	1800 (+)
14 (53,54,55,56)	7910 (+)	13560 (+)	1.5 (-)	1400 (-)
15 (57,58,59,60)	5650 (-)	13560 (+)	2.5 (+)	1400 (-)
16 (61,62,63,64)	5650 (-)	13560 (+)	1.5 (-)	1400 (-)

III. RESULTS & DISCUSSIONS

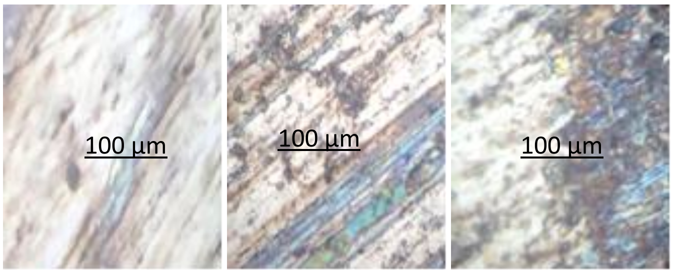
3.1 Macroscopic Examination

Visual examination of the welded specimens showed uniform and good welded joints. The flash obtained was also symmetric and even which indicates plastic deformation on both RPV steel and Stainless steel side.

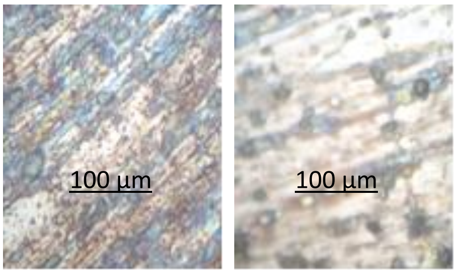
Figure 1: Micrograph of friction welded specimen

3.2 Optical Microscopy

Optical micrographs were taken with an optical microscope. The etchant used was 2% Nital and all the microstructures were observed at a magnification of 100X. Optical microscopy of the interface of the longitudinal section of the welded specimen did not reveal any cracks. Five distinct zones can be seen across the welded specimens, namely the RPV steel base metal, the HAZ on the RPV side near interface, plastically deformed interface and the HAZ on the stainless steel side near Interface and Stainless steel base metal as shown in Figure. 3. Fine grained structure in the plasticized zone has been observed. This is due to the severe deformation commonly observed during friction welding, the refined grain structure is observed at the weld interface zone which results in improvement in properties at interface and near interface on stainless steel and RPV steel side.



(a) on SS (b) near interface on SS (c) on interface



(d) near interface on RPV (e) on RPV

Figure 2: Micrographs on different zones of the welded specimen

Microstructures from the weld interface appear as combination of very fine and dense ferrite + pearlite , tempered martensite in HAZ near RPV steel and stainless steel parent metal, ferrite + pearlite in RPV steel and austenite grains in stainless steel. This microstructure indicates formation of different phases along the longitudinal section of the weld due to exposure to different thermal regimes. There is also evidence of formation of decarburised zone in RPV steel near interface and Stainless Steel near interface due to the migration of carbon from RPV steel towards Stainless steel.

3.3 Tensile Test Results

Tensile testing was done on Universal Testing machine. Tensile strengths varied from 480.77 to 682.37 MPa depending upon the friction welding conditions used. Tensile properties of the welds are shown in Table 3.

Table 3: Showing UTS, percentage elongation and fracture location for different welded specimens

No. of Experiments (specimen no.)	**Parameters**				**UTM Results**		
	Friction Force (F) in N	Forge Force (f) in N	Burn off Length (L) mm	RPM (R)	UTS (N/mm^2)	Percentage Elongation (%)	Fracture Location

1 (3)	5650	11300	1.5	1400	494.27	1.4	Weld
2 (7)	7910	11300	1.5	1400	488.49	2.1	Weld
3 (11)	5650	11300	2.5	1400	682.37	1.5	Weld
4 (15)	5650	11300	1.5	1800	502.91	1.6	Weld
5 (19)	7910	11300	2.5	1400	547.59	2.7	Weld
6 (23)	5650	11300	2.5	1800	536.12	5.4	Weld
7 (27)	7910	11300	1.5	1800	511.56	2.1	Weld
8 (31)	7910	11300	2.5	1800	667.38	5.5	Weld
9 (35)	7910	13560	2.5	1800	486.24	2.4	Weld
10 (39)	5650	13560	2.5	1800	488.54	2.8	Weld
11 (43)	7910	13560	1.5	1800	580.75	1.7	Weld
12 (47)	7910	13560	2.5	1400	493.93	2.9	Weld
13 (51)	5650	13560	1.5	1800	537.24	2.5	Weld
14 (55)	7910	13560	1.5	1400	532.24	1.8	Weld
15 (59)	5650	13560	2.5	1400	494.34	2.0	Weld
16 (63)	5650	13560	1.5	1400	480.77	1.3	Weld

The tensile property data shows that for all the friction welding parameter combinations, strength of the weld is good. All the specimens broke in the weld region and percentage elongation was measured across the weld region. The use of 2 level 4 factor full factorial design approach was used to estimate the effect of parameters on the weldment. Experimental design pattern in Table 4 and equations were made to study this effect.

Table 4: Two level 4 factor full factorial experiment design pattern

RUN	Combinations	**Factors**			
		A (friction force)	**B (forge force)**	**C (burn off length)**	**D (RPM)**
1	(1)	-	-	-	-
2	A	+	-	-	-
3	B	-	+	-	-
4	Ab	+	+	-	-
5	C	-	-	+	-
6	Ac	+	-	+	-
7	Bc	-	+	+	-
8	Abc	+	+	+	-
9	D	-	-	-	+
10	Ad	+	-	-	+
11	Bd	-	+	-	+
12	Abd	+	+	-	+

13	Cd	-	-	+	+
14	Acd	+	-	+	+
15	Bcd	-	+	+	+
16	Abcd	+	+	+	+

In the above Table 4, + and - signs are indicating higher value and lower value for 4 factors respectively. The following are the main interaction effects of four factors on tensile strength as shown in Table 5.

Table 5: Interactions effects on tensile strength

Factors		**Equations**		**Outcomes**
A	**=**	1/8n [-(1)+a-b+ab-c+ac-bc+abc-d+ad-bd+abd-cd+acd-bcd+abcd]	=	**11.45**
B	**=**	1/8n [-(1)-a+b+ab-c-ac+bc+abc-d-ad+bd+abd-cd-acd+bcd+abcd]	=	**-42.08**
AB	**=**	1/8n [(1)-a-b+ab+c-ac-bc+abc+d-ad-bd+abd+cd-acd-bcd+abcd]	=	**11.61**
C	=	1/8n [-(1)-a-b-ab+c+ac+bc+abc-d-ad-bd-abd+cd+acd+bcd+abcd]	=	**33.53**
AC	=	1/8n [(1)-a+b-ab-c+ac-bc+abc+d-ad+bd-abd-cd+acd-bcd+abcd]	=	**-13.01**
BC	=	1/8n [(1)+a-b-ab-c-ac+bc+abc+d+ad-bd-abd-cd-acd+bcd+abcd]	=	**-75.52**
ABC	=	1/8n [-(1) +a+b-ab+c-ac-bc+abc-d+ad+bd-abd+cd-acd-bcd+abcd]	=	**-11.41**
D	=	1/8n [-(1)-a-b-ab-c-ac-bc-abc+d+ad+bd+abd+cd+acd+bcd+abcd]	=	**12.09**
AD	=	1/8n [(1)-a+b-ab+c-ac+bc-abc-d+ad-bd+abd-cd+acd-bcd+abcd]	=	**33.82**
BD	=	1/8n [(1)+a-b-ab+c+ac-bc-abc-d-ad+bd+abd-cd-acd+bcd+abcd]	=	**10.78**
ABD	=	1/8n [-(1)+a+b-ab-c+ac+bc-abc+d-ad-bd+abd+cd-acd-bcd+abcd]	=	**-36.29**
CD	=	1/8n [(1)+a+b+ab-c-ac-bc-abc-d-ad-bd-abd+cd+acd+bcd+abcd]	=	**-22.08**
ACD	=	1/8n [-(1)+a-b+ab+c-ac+bc-abc+d-ad+bd-abd-cd+acd-bcd+abcd]	=	**32.21**
BCD	=	1/8n [-(1)-a+b+ab+c+ac-bc-abc+d+ad-bd-abd-cd-acd+bcd+abcd]	=	**-7.53**
ABCD	=	1/8n [(1)-a-b+ab-c+ac+bc-abc-d+ad+bd-abd+cd-acd-bcd+abcd]	=	**-30.69**

Based on these calculations the effect of burn off length (C = 33.53) has the greatest influence on the tensile strength although the main effects of friction force (A = 11.45) and RPM (D = 12.09) are also significant. The interaction between friction force and RPM (AD = 33.82) produces a great positive effect on the tensile strength and also the interaction of friction force, burn off length and RPM (ACD = 32.21) produces a similar positive effect on the tensile strength as is the effect of interaction of forge force and RPM (BD = 10.78) and friction force and forge force (AB = 11.61) on tensile strength. The rest of the factorial interactions affect the tensile strength in the negative direction.

3.4 XRD Test Results

XRD analysis was performed in order to investigate the phases formed during friction welding and to confirm the occurrence of crystallization during friction welding. XRD traces are shown below in Figure 3.

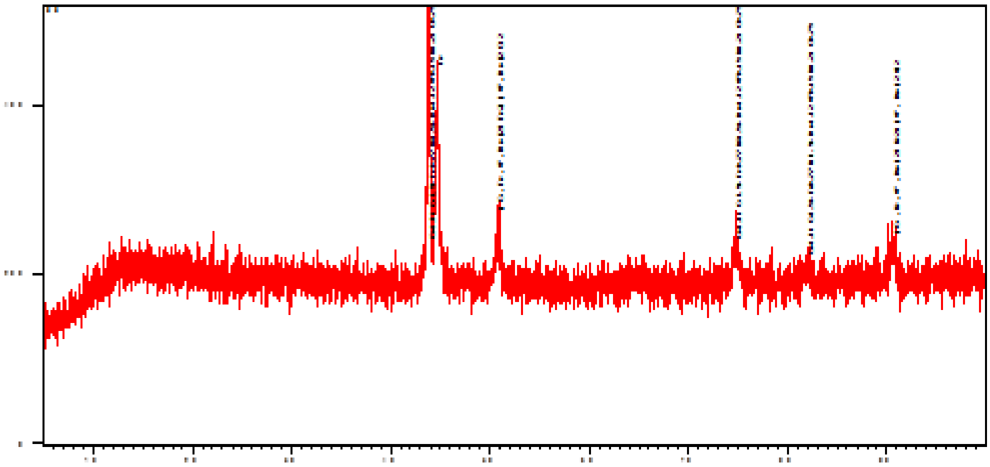


Figure 3: XRD trace

Table 6 given below shows the percentage, compounds, phases formed on friction welded specimens. Oxides, sulfides and carbides are formed due to inclusions. Iron is present in most of the specimens. Iron carbide and sulfide is formed for specimen no. 1, 2, 4, 6, 8 and 9. Vanadium oxide and sulfide, chromium oxide is also presents in some of the specimens. This change is due to the different welding parameters (Friction force, Forge force, Burn off length and RPM).

Table 6: Showing phases formed during welding

No. of Experiments (specimen no.)	Compound name	Chemical Formula
1 (3)	Iron Carbide, Iron Carbide	Fe_3 C, Fe C
2 (7)	Iron Carbide, Manganese Silicide	Fe_3 C, Mn_3 Si
3 (11)	Iron Manganese Nickel, Iron	Fe(0.5) Mn(0.2) Ni(0.3), Fe
4 (15)	Iron Sulfide, Iron-Chromium	Fe S, Fe-Cr

5 (19)	Iron Nickel	Fe(0.7) Ni(0.3)
6 (23)	Iron Carbide, Chromium Oxide	Fe_3 C, Cr O(0.87)
7 (27)	Chromium Iron	Cr(0.7) Fe(0.3)
8 (31)	Iron Sulfide, Iron	Fe S, Fe
9 (35)	Iron Sulfide, Iron Tungsten	Fe S, Fe(0.984) W(0.012)
10 (39)	Silicon Carbide, Iron Tungsten	Si_5 C_3, Fe(0.984) W(0.016)
11 (43)	Vanadium Oxide Iron Oxide-Chromium Oxide	VO FeO-Cr_2O_3
12 (47)	Vanadium Oxide, Aluminum Cobalt	VO, Al(4.85) Co(5.15)
13 (51)	Silicon carbide	Si C
14 (55)	Cobalt Chromium Iron Nickel Molybdenum Tungsten Nitride Carbide (Chromium Iron Tungsten Molybdenum)	Co(1.51) Cr(3.96) Fe(0.77) Ni(1.96) Mo(1.52) W(0.19) N(1.21) C(0.79) (Cr, Fe, W, Mo)23 Fe21(W, Mo,)2 C12
15 (59)	Vanadium Oxide, Chromium Iron	VO, Cr(0.053) Fe(0.947)
16 (63)	Vanadium Oxide, Iron	VO, Fe

IV. CONCLUSION

Friction welding has been successfully employed to weld bimetallic weld joints. Strength of the joints obtained was good. Using factorial design method it was found that the effect of burn off length has the greatest influence on the tensile strength. Interaction of factors such as friction force and RPM also has significant positive effect on the tensile strength. The highest micro hardness values were obtained at weld interface and SS HAZ region. Area fraction measurement to study the evolution of precipitates at the interface has revealed that forge force has the greatest influence. Interaction of friction welding parameters such as friction force, forge force and burn off length has significant effect on evolution of precipitates at the interface during friction welding of bimetallic welds.

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