Enhancement of Mechanical and Metallurgical Performance of SS Joint using Weld Bonds

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***Abstract*--** **In this invetigation, theoritical and experimental study was performed for the adhesive joining, resistance spot welding and weld bonding (combination of adhesive and resistance spot welding) on Stainless Steel of Grade 304 as a work picece (100 × 25 × 1 mm) and 2-C Plain Epoxy Resin as a adhesive by using PECO Bench Spot welding machine for spot weld. The adhesive joints were cured on Furnace. The Tensile - Shear tests were performed on prepared samples using Universal Testing Machine (UTM). It is observed that ultimate shear tensile load of adhesive joints are greater than the resistance spot weld and shear tensile load of weld-bonds are greater than the spot welding and adhesive bonding alone. It is also observed that surface roughness of 220 emery grade gave maximum adhesive joint strength to 304 grade of stainless steel. After the tensile shear test, the nugget size and hardness of the resistance spot weld and weld bond (which is cured at 120 ^{0}C for 60 minutes) were observed. It was found that the hardness of weld nugget and HAZ lies in the range of (358-414 VHN) and (417-464 VHN) respectively.**

***Index Term*--** **Stainless Steel, Adhesive, Weld Bond, Resistance Spot Welding and Nugget**

1. Introduction

During recent years, industries have been continuously attempted to manufacture a products, having a number of metal combinations at once. This has been carried out to obtain the beneficiary properties of each metal within the same product on required specific parts. Joining of metals are also served in saving of cost of final product. For example, in cutting tools, the tooling part is made up of highly wear resistant and hard metals, while the base is made up of steel in order to reduce cost. Hence, Metals can be joined to each other by various methods, laser welding being of primary importance in joining dissimilar metals. Joints between dissimilar metals are used in a lot of industries mainly automotive, electronics, power generation, etc [1-2].

Lo et al. [3] reviewed the developments of stainless steels were made since 1990s. Some of new applications that involve the use of stainless steel were also introduced by them. A brief introduction of various classes of stainless steels, their precipitate phases and the status quo of their production around the globe gave first. Further, Ghosh et al. [4] investigated weld bond of stainless steel. They fabricated Lap joints of 1.0 mm thick of austenitic stainless steel sheets by adhesive bonding, conventional resistance spot welding and weld bonding processes and studied the size of weld nugget, microstructures of the weld and HAZ and hardness of the nugget and HAZ, resulted from different welding parameters (current and time), in both the resistance spot welds and weld-bonds. The weld-bonds which were prepared at optimum process parameters are found to have superior mechanical properties than those of the conventional resistance spot welds, especially under dynamic loading [5]. Darwish et al. [6] directed towards manufacturing and characteristics of weld-bonded commercial aluminium sheets. They tested dynamic response (natural frequency and damping), nugget size, and tensile shear strength and reported a tremendous improvement in tensile shear strength associated with higher damping capacity for weld-bonded joints. However, they also reported that the natural frequency seems to be independent on shear strength as well as joining technique (spot welding or weld-bonding) [7]. Apart from experiments, researchers are developed the mathematical and computational model such as Ing et al. [8] Investigated nugget development during resistance spot welding. The thickness of nugget was calculated by finite difference analysis and compared with the measured data. Further, Schroeder et al. [9] described the computation of temperature distribution and thermal stress distribution during spot welding, and then after a cooling step, the residual stresses of the spot weld were calculated with allowance for the actual behaviour of material. To analyse spot welding process, disk and electrodes were asymmetrically and quarterly modelled. They reported that weld time has needed to preheat the work-piece and to decrease the effect of surface conditions. The maximum temperature of the work-piece was not raised over the melting point at the first weld time. Accordingly, the welding conditions at this time have little effect on the residual stress. But at the second weld time, the magnitudes of weld current and weld time produce a considerable effect on the residual stress. As the second weld current increases, the residual stress becomes smaller [10].

There are large amount of literature available for resistance spot welding and their application on account of the excellent properties of weld-bonded structures mentioned above, such as high strength, light weight and good acoustical damping performance, the weld-bonding technique has been used in the manufacturing of aeroplanes, automobiles, vehicles and many other structures. The technique can be used in the joining of aluminium alloys, titanium alloys, composites of boron and aluminium, stainless steel and coated steel. The weld-bonding technique has very great potential in the combining of different materials that cannot be joined with other joining methods now in existence [11-13]. There are so many factors in which the properties of weld bond is dependent such as characteristic of an adhesive, thickness of adhesive layer, time and temperature of curing of the adhesive, surface penetration and spot welding parameters. The optimum strength of weld bond is generally achieved by avoiding unnecessary current density and increasing the electrode force. But the property of weld bond increasingly depends upon the viscosity and types of adhesive also. The presence of adhesive varies contact resistance which significant affect the weld thermal cycles, resulting into the requirement of conventional welding process. However, the various technical and scientific aspects of this relatively new joining process as discussed above is not well understood so far.

2. EXPERIMENT METHODS

2.1. Material and Its Preparation:

An austenitic stainless steel sheet of thickness 1 mm was used in this work. The chemical composition of the sheet was analyzed by atomic absorption spectrometer (Perkin Elmer Model No. 2380 & C-S MAT, Stroline Put Ltd. Germany) and found as given in Table 1. The sheet was cut into pieces of dimension 100 x 25 mm for preparation of various lap joints. After cutting the edges of specimens were smoothened on belt grinder. The faying surface of the specimen was then prepared by mechanical polishing using emery paper of grades 220, 320 and 400 mesh to obtain new surface of required roughness. After polishing the faying surface was cleaned by acetone.

Table I
Chemical Composition of the Stainless Steel Chemical Composition (Wt %)

C	Mn	Ni	Ci	Si	P	S
0.08	1.96	9.4	18.5	1.02	0.0033	0.005

2.2. Preparation of Adhesive:

Commercial adhesive Araldite a CIBA GEIGY Ltd product was used as an adhesive for adhesive bonding and weld bonding. Araldite was basically an epoxy base resin, used with hardener. Adhesive was prepared by mixing of epoxy resin and hardener in equal amount by weight. After a proper mechanical mixing, the adhesive was kept in vacuum chamber for degassing, in order to remove entrapped air from the adhesive. Vacuum degassing was done in a vacuum chamber having pressure of the order of 0.01 mbar for 5 minutes

2.3. Adhesive Joining:

The pieces of stainless sheet of grade 304 thickness 1 mm were adhesive bonded by application of epoxy adhesive. Epoxy resin adhesive was referred to the adhesive which was cured chemicals which are contains epoxy group with amines and acid anhydride. Before application of adhesive, the surface of the specimen was cleaned mechanically (by different emery grades) followed by wiping with acetone in order to obtain oxide free different surface roughness and required surface degreasing respectively. After getting sufficient strength of adhesive joint, curing was employed to the specimens at different curing times and temperature of 100°C. (Increasing in curing temperature results in decreasing the curing time)

2.4. Resistance Spot Welding:

Spot welds were fabricated on foot operated PECO Bench Spot welding machine which is shown in Figure 2 (a) and fabricated samples are shown in Figure 2 (b). This machine was equipped with control system for welding current, secondary voltage, weld heat and weld time. The secondary voltage of welding transformer might be adjusted the load on eleven steps from 0.25 to 45 volts where the welding intensity increases with the voltage. Setting of the weld current amplitudes were made by phase shift of the A.C. half cycles by turning the multi potentiometer button. The effective current welding was measured with the help of a PECO weld current monitor (Type SM 12 A, Messer Griesheim), having a range up to 200 kA. The stainless steel thickness of 1 mm was resistance spot welded using the Welding Controller foot operated PECO Bench spot welding machine of capacity 64 kVA. Before welding, the faying surface of the specimens were cleaned mechanically by rubbing with 220 emery grade paper followed by wiping with acetone in order to remove the excess oxides and grease from the surface. Then, bring the specimens together and by keeping them in right position in order to prepare lap joint which was used as the tensile test specimen. Resistance spot welding was carried out by using water cooled conical Cu electrode has been shown in Figure 1. Welding was carried out by varying the welding current and weld time at given voltage and electrode pressure respectively.

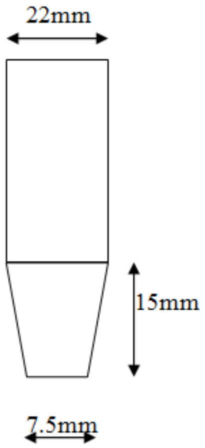


Fig. 1. Electrode design.

Fig. 2 (a). PECO Bench Spot Welding Machine

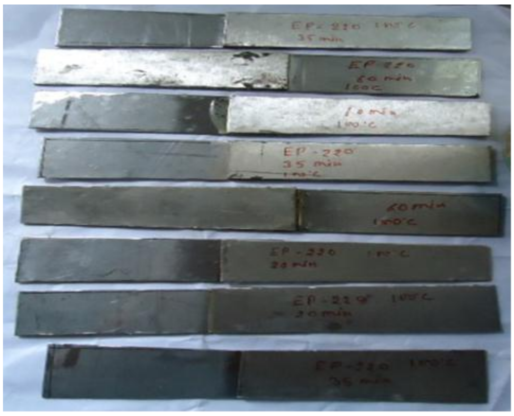


Fig. 2 (a). Fabricated Samples by Spot Welding Machine

Fig. 3. Showing conducting of the tensile shear testing on universal testing machine.

2.5. Preparation of Weld Bond:

Weld-Bond was carried out on prepared specimen by application of adhesive followed by resistance spot welding. The spot welding was carried out by using the above mentioned resistance spot welding machine of capacity 64 kVA. The adhesive was prepared according to procedure given in section preparation of adhesive. After applying the adhesive on the faying surfaces, the faying surfaces were kept at right position. Welding was carried out by varying the welding current and weld time at fixed voltage and electrode force of 4 V and 0.6 kN respectively. For weld bonding, the optimize parameter of resistance spot welding were used. Since, in weld bonding some amount of heat was absorbed by adhesive, the weld time was varied on higher side to get optimized Weld-Bond parameter. Weld curing was also employed on the joints for one hour at the temperature of 120 ^{0}C to facilitated adhesive bonding and cross linking.

2.6. Metallographic Studies:

Specimens for metallographic examinations were collected from the transverse section across the centre line of the weld spot in resistance spot weld and weld bond. After that specimens were mounted in Bakelite by embedding in moulding press. The specimens were polished by various grades of emery papers (120, 220, 320, 400, 600, 800 and 1000) from coarse to fine respectively. Then, these specimens were polished by using grade III alumina powder (0.014 µm) on a polishing wheel having silvyt cloth mounted on it. The polished specimens were etched by dipping them into a solution having 10 cc HNO_3, 10cc Acetic Acid, 5cc glycerine and 15cc HCl. After 4 - 5 min, followed by washing with stream of water and then drying with cotton to reveal the micro structure of weldment. The micro structure studies and estimation of nugget diameter of the weld were carried out under an optical microscope at magnification of 100 X.

2.6.1. Hardness Test:

Hardness of weld nugget and heat affected zone (HAZ) of resistance spot weld and weld bond specimens were studied on the transverse section of weld nugget as it was prepared for metallographic studies. The hardness study was carried out by Vickers micro hardness indentation at a load of 100 gm. During the micro hardness study the indentation was made on centre of weld nugget and on the interface. However the hardness of HAZ was studied at a distance of about 0.1 mm from interface.

2.6.2. Determination of Adhesive Layer Thickness:

Adhesive layer thickness of adhesive bonds were determine by polishing the edge of adhesive specimens with various grades of emery paper (220, 320 and 400) from coarse to fine respectively. Then, the specimens were polished by using grade III alumina powder (0.014 µm) on a polishing wheel having silvyt cloth mounted on it. The polished specimens were seen in the optical microscope at the magnification of 25 X. The adhesive layer thickness was measured with the help pf scale mounted on optical microscope. A graph was plotted to compare the adhesive layer thickness with load applied. Optimization of adhesive layer thickness was done by carrying tensile shear tests.

2.6.3. Tensile – Shear Test

The tensile shear test of the adhesive joint and resistance spot weld was carried out by uniaxial gripping of two ends of the lap joints which is shown in Figure 3. Schematic diagrams of the adhesive joint and resistance spot weld are shown in Figure 4 (a), (b) and (c) respectively. The sub size area of overlap was used for the preparation of adhesive joint, is primarily to ensure the failure from the joint so that the effect of various parameters on the joint strength could be studied. The test was carried out at a cross head speed of 1 mm/min on a hydraulically operated dynamic universal testing machine (Mohr & Federhaffag Mannheim-Germany). The ultimate shear tensile load in kN and failure mode characteristics has been recorded.

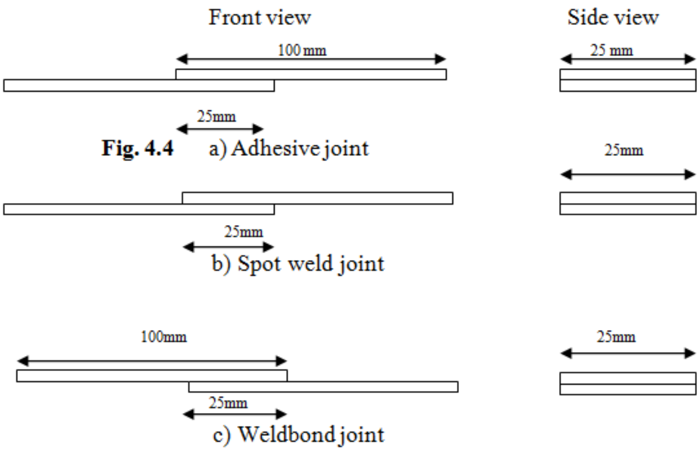


Fig. 4. Schematic of Different Joints

3. Result and Discussion

3.1 Adhesive Joining

3.1.1. Effect of Curing Time on Tensile Shear Strength of Adhesive Joint:

The role of curing time at curing temperature of 120°C, on adhesive joint strength (having identical joint area) of austenitic stainless steel under specific surface roughness is presented in Table 2. The graphical representation of the results is shown in Figure 5. It is observed that at a given surface roughness of austenitic stainless steel the ultimate shear tensile load (USTL) carrying capacity of the adhesive joint enhanced with increase of curing time up to about 60 min followed by a decrement in it with further increase in curing time up to 100 min. The decrease in joint strength with the increase of curing time beyond 60 min is possibly happened due to dreadful conditions of the adhesive under long thermal treatment which unfavorably affects the adhesive strength.

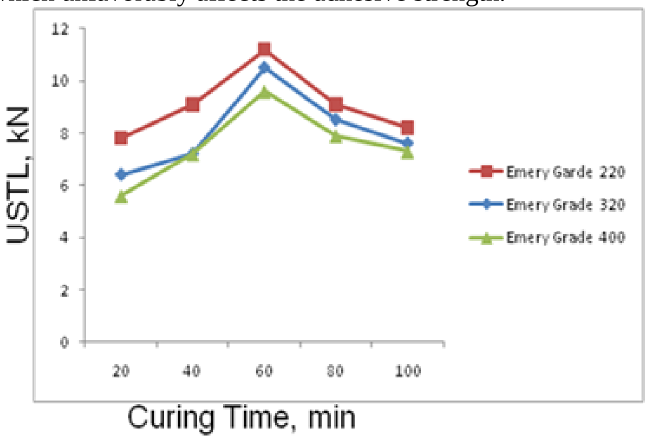


Fig. 5. Effect of curing time on tensile shear strength of the adhesive bonded joint at different surface roughness.

3.1.2. Role of Surface Roughness on Tensile Shear Strength of Adhesive Joining of Austenitic Stainless Steel

The effect of surface roughness on USTL carrying capacity of the adhesive joint (having identical joint area) is also been presented in Table 2. The strength of the joint was observed at different curing times at curing temperature of 120°C. At a given curing time and temperature of 60 min and 120°C respectively, the effect of surface roughness of different emery grades on ultimate shear tensile load (USTL) carrying capacity of the joints are shown in Figure 6.

The Figure 6 shows that the decrease in surface roughness from the emery grade of 220 to 400, which increased the joint strength followed by increases emery grade up to 220. Afterwards, decrement in surface roughness (increases in emery grade number) up to emery grade of 400 which reduced joint strength. The increase in joint strength with the increase in surface roughness up to 220 grade of emery paper might be primarily caused by the enhancement in mechanical locking whereas the decrease in joint strength with further increase in surface roughness might be primarily caused by the reduction in surface area of adhesive bonding. This is promises because the surface roughness affects the joint strength in two ways (one by surface area of adhesive bonding which is increased with fineness of surface roughness resulting from using higher grade of emery paper and two by providing mechanical locking primarily depends upon geometry of surface roughness which is varied with the change in grade of emery paper).

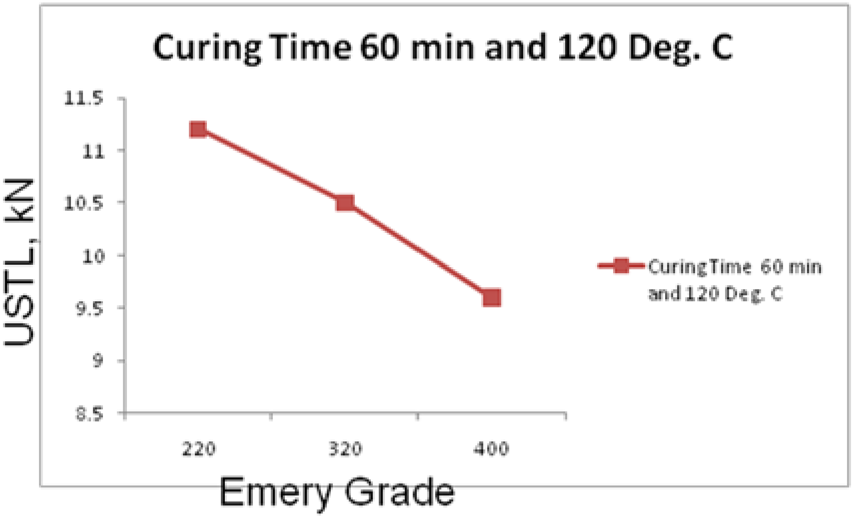


Fig. 6. Role of surface roughness on tensile shear strength of the adhesive bonded joint of austenitic stainless steel sheet.

3.2 Effect of Load on Adhesive Layer Thickness:

The effect of load on adhesive bonded specimens is shown in Figure 7 and Figure 8. From the Figures, it is observed that at a given curing temperature and time of 120^0C and 60 min and at a given surface roughness, the increases in load from 1 to 7 N decreases the adhesive layer thickness from 0.4 mm to 0.08 mm. the graph tells that with the increase of load up to 3 kg, the adhesive layer thickness decreases at a constant rate followed by a decrease with a faster rate with a further increase in load 3 to 5 N.

Table II
Tensile Shear Strength of Adhesive Bonded Joints

Emery grade	Curing time at 120°C (min)	Ultimate Shear Tensile Load (kN)
220	20	7.8
220	40	9.1
220	60	11.2
220	80	9.1
220	100	8.2
320	20	6.4
320	40	7.2
320	60	10.5
320	80	8.5
320	100	7.6
400	20	5.6
400	40	7.2
400	60	9.6
400	80	7.9
400	100	7.3

On increase in load beyond 5 N it decreases with a comparatively slow rate. The possibility of this behavior could be explained with the flow behavior of adhesive, when a load was applied on the thick adhesive layer, the adhesive flows out up to that limit where adhesive layer could be sustained the load. At thick adhesive layer the flow of adhesive primarily was governed by the deformation characteristic of the adhesive. That's why initially the adhesive layer thickness decreases at constant rate and adhesive layer thickness goes up to 0.08 mm. At this thickness of adhesive layer, its flow was not primarily governed by the deformation behavior of adhesive. Therefore, at higher load when adhesive layer thickness becomes very thin the adhesive flows at a slow rate and thus adhesive layer thickness decreases slowly.

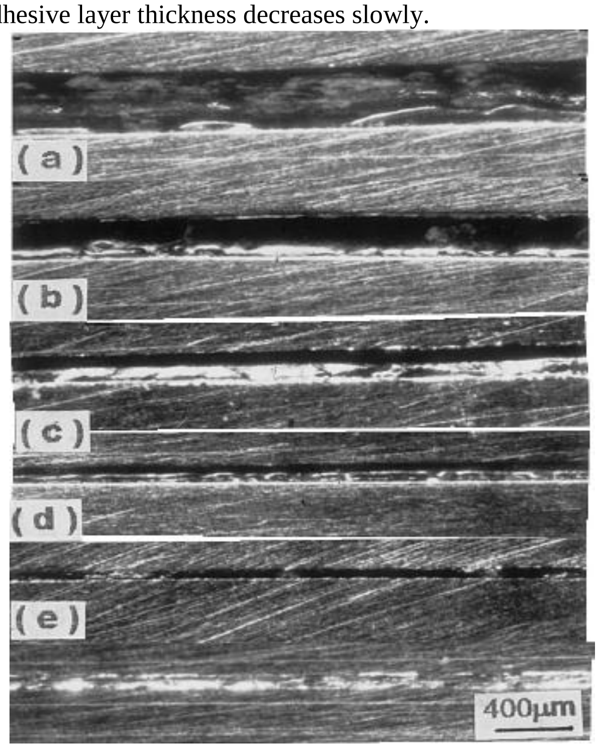


Fig. 7. Photographs showing the variation in thickness of adhesive layer at different load of rolling of (a) 1 N, (b) 3 N, (c) 4 N, (d) 5 N, (e) 6 N and (f) 7 N.

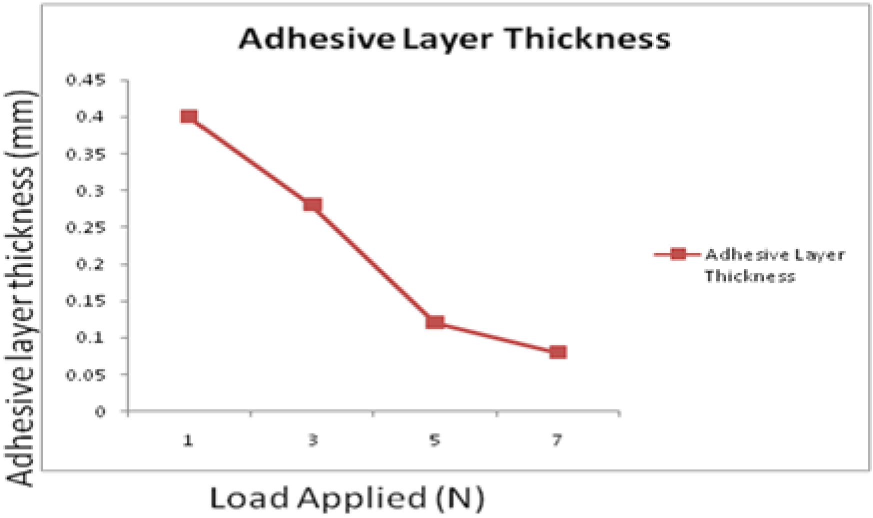


Fig. 8. Effect of load on adhesive layer thickness

3.2.1 Optimization of Adhesive Layer Thickness with Respect to Joint Strength of Adhesive Bond:

A graph between adhesive layer thickness and USTL carrying capacity is plotted as shown in Figure 9 and the experimental observations are shown in Table 3. From the observation, as the adhesive layer thickness increases from 0.4 mm to 0.28 mm, the load carrying capacity of the joint increases rapidly. This is due to the formation of continuous layer of adhesive and thus increases the surface area as well as loads carrying capacity of adhesive bond but further increase in adhesive layer thickness from 0.1 mm to 0.4 mm, decreases the load bearing capacity of adhesive joint. The probable reason of this might be, at very thin adhesive layer breaks the continuity and adhesive separates at different points of bonded area. This decreases the total bonded area and thus decreases the load carrying capacity of adhesive joint.

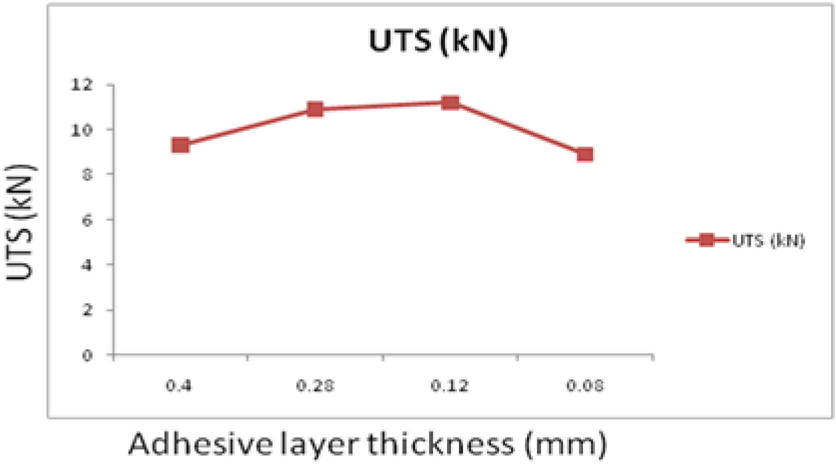


Fig. 9. Adhesive layer thickness with respect to joint strength of adhesive bond

Table III
Variation of UST w. r. t. Adhesive layer thickness

Load applied (kg)	Thickness (mm)	UST (kN)
1	0.4	10.4
3	0.28	10.9
5	0.12	11.20
7	0.08	8.9

3.3 Ultimate Shear Tensile Strength:

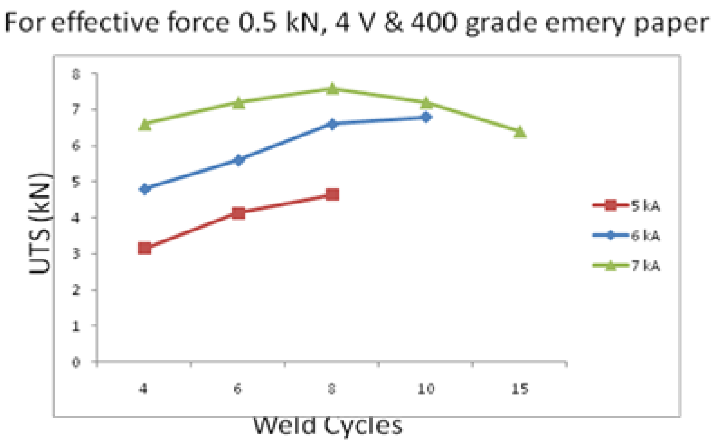
3.3.1. Resistance Spot Weld:

At different welding currents of 5, 6 and 7 kA and the effect of weld time (cycles) on UST load carrying capacity of RSW are shown in Table 4 for varying effective force. The graph has been plotted at different weld cycles the effect of weld current on UST load carrying capacity of the RSW are shown in Figure 10 (A) and (B). The graph depicted that at constant welding current the increment in weld time up to 8 cycles, enhances the UST load carrying capacity followed by almost constant value at 10 cycles and then decrement after further increment in weld time up to 15 cycles. The increase in UST load carrying capacity of the spot weld with increase of weld time up to 8 cycles might be primarily due to increase in diameter of weld nugget but the decrease in UST load carrying capacity of weld prepared at the weld time beyond 10 cycles was caused by a significant expulsion during welding. It is also observed that at a given weld time of 4, 6 and 8 cycles, the increment in welding current enhances the UST load carrying capacity of spot weld significantly primarily, due to enhancement in nugget size. However, it might be noted that during welding, at all the parameters an expulsion was observed. At lower current and lower weld time expulsion was miner but at higher weld current and weld time the expulsion was severe. Also at higher value of weld time the electrodes sticks to the work piece.

Table IV
Observation of UST at 4 V and 400 grade emery

Weld current (kA)	Weld cycle	Effective Force 0.5 kN	Effective Force 0.6 kN
		UST (kN)	UST (kN)
5	4	3.14	3.6
5	6	4.13	3.9
5	8	4.64	4.3
6	4	4.8	4.4
6	6	5.6	5.5
6	8	6.6	6.22
6	10	6.8	6.5
7	4	6.6	6.1
7	6	7.2	7.4
7	8	7.6	8.3
7	10	7.2	7.64
7	15	6.4	7.28

(A)



(B)

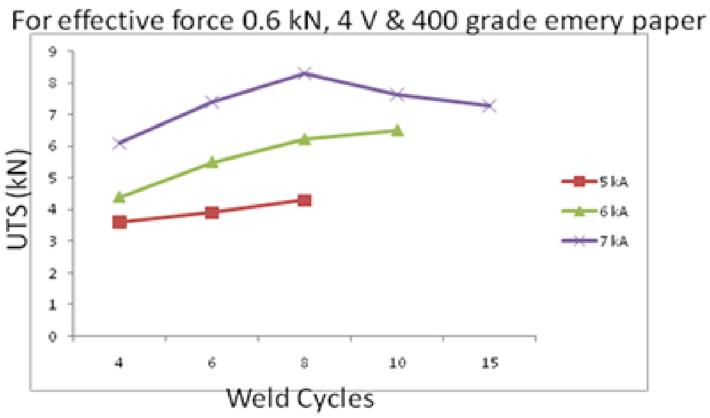


Fig. 10. The effect of weld time (cycles) on UST load carrying capacity

3.3.2. WELD BOND:

At a constant welding current of 7 kA, the effect of weld time on UST load carrying capacity of weld bond is shown in Figure 11. The specimen was cured at the temperature of 120 ^{0}C for 60 minutes. The Figure 11 shows that the increase in weld time from 8 to 15 cycles enhances the UST load carrying capacity of weld bond. It is primarily due to increase in nugget size, resulting from enhancement in energy input. Further, increase of weld time up to 20 cycles, decrement of UST load carrying capacity was observed because of severe expulsion which causes defects in weld nugget. It is also observed that the optimize welding parameters of weld bond are welding current 7 kA and weld time of 15 cycles which is shown in Table 5. It is different from the optimize parameter of resistance spot welding (7 kA and 8 Cycles). This is because of presence of adhesive in weld bond which absorbs significant heat during welding.

Table V
The effect of weld cycles on UST load carrying capacity at constant 4 V, 400 grade emery, Curing temp 120^{0}C & Curing Time 60 min

Weld current (kA)	Weld cycle	Effective Force 0.6 kN	Effective Force 0.5 kN
		UST (kN)	UST (kN)
7	8	14.6	13.6
7	10	15.1	14.1
7	15	16.6	15.6
7	20	16.1	15.1

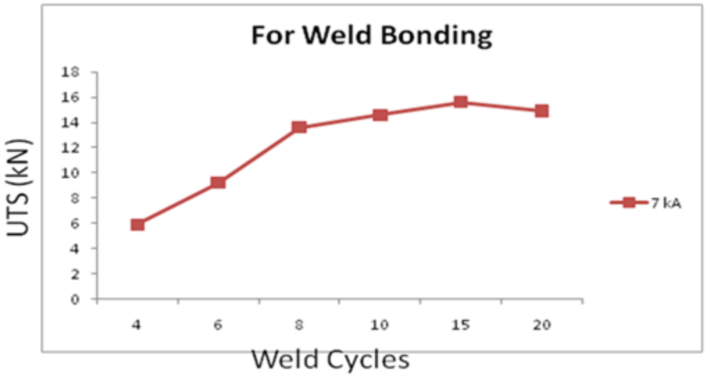


Fig. 11. The effect of weld time (cycles) on UST load carrying capacity

3.4 Nugget Size

3.4.1. Resistance Spot Weld

At a constant welding current of 7 kA, the effect of weld time on the nugget size of resistance spot weld is shown in Table 6. At a constant weld time of 8 cycles, the effect of welding current on nugget size of resistance spot weld is observed that size of weld nugget enhances more significantly with the increase of welding current at a given weld time. The increase in size of weld nugget with increase in weld time or weld current primarily happens due to increase in energy input.

3.4.2. WELD BOND

At a constant welding current of 7 kA, the effect of weld time on the nugget size of weld bond was observed. From the observation which is shown in Table 7 could be concluded that increase in weld time from 8 to 15 cycles, enhances the nugget size of weld bond and also it is interested to note that at a given welding current and weld time, the nugget size of weld bond specimen are lower than the nugget size of spot weld. This might be primarily attributed to absorption of significant amount of energy by the adhesive present in between the two sheets at weld region.

Table VI
Effect of spot weld on nugget size at constant 4 V, 400 grade emery

Weld current (kA)	Weld cycle	Nugget Size (EF 0.5 kN)		Nugget Size (EF 0.6 kN)	
		Weld Length (mm)	Weld Width (mm)	Weld Length (mm)	Weld Width (mm)
7	8	3.97	1.56	5.8	1.2
7	10	4.76	1.33	5.5	1.4
7	15	5.8	1.24	5.8	1.24

Table VII

Effect of weld bond on nugget size at constant 4 V, 400 grade emery, Curing temp 120^{0}C & Curing Time 60 min

Weld current (kA)	Weld cycle	Nugget Size (EF 0.5 kN)		Nugget Size (EF 0.6 kN)	
		Weld Length (mm)	Weld Width (mm)	Weld Length (mm)	Weld Width (mm)
7	8	5.1	1.19	4.81	0..19
7	10	4.91	1.76	4.35	0.67
7	15	4.76	1.34	4.64	0.89

3.5 Hardness of Weld Nugget and Heat Affected Zone (HAZ):

3.5.1. Resistance Spot Weld

The hardness of the weld nugget and HAZ of the resistance spot weld and weld-bond are shown in Table 8. The table shows that the hardness of HAZ is greater than the weld centre. That's why the fracture of spot welded joint occurs at HAZ. At a given welding current, increase in weld time increases the hardness of weld and HAZ. The increase in hardness of weld is possibly attributed to increase in heat input. The hardness of the weld nugget and HAZ was found to lie in the range of (442 – 488 VHN) and (388 – 572 VHN) respectively from the Table VIII.

Table VIII

Effect of spot weld on hardness at constant effective force 0.6 kN, 4 V, 400 grade emery

Weld current (kA)	Weld cycle	Hardness (VHN)			
		Weld center	Fusion line	HAZ	Base metal
7	8	414	378	458	461
7	10	358	351	417	430
7	15	392	388	464	350

3.5.2. Weld Bond:

The harness of weld centre and HAZ of weld bond has been shown in Table IX. The table shows that the hardness of weld nugget first decreases with increase in weld time 8 to 10 cycles and then further increases with increase in weld time from 10 to 15 cycles. The decrease in harness is possibly due to increase in heat input up to weld time of 10 cycles but increase in hardness with further increase in weld time from 10 to 15 cycles which is shown in Figure 12. In case of weld-bond a slight different behaviour was observed with the presence of adhesive layer between the interface when the hardness of weld nugget and HAZ was found to lie in the range of (358-414 VHN) and (417-464 VHN) respectively from the Table IX.

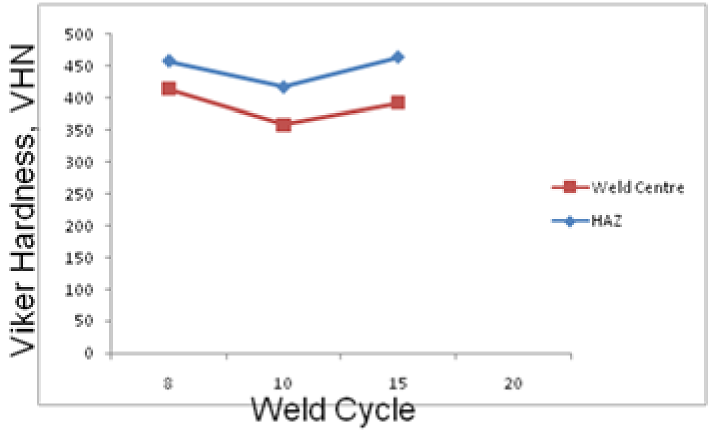


Fig. 12. The Effect of Weld Cycles on Viker Hardness of Weld Bonding at 7kA, Effective Force 0.6 kN and 4 V

Table IX

Effect of weld bond on hardness at constant effective force 0.6 kN, 4 V, 400 grade emery, Curing temp 120^{0}C & Curing Time 60 min

Weld current (kA)	Weld cycle	Hardness (VHN)			
		Weld center	Fusion line	HAZ	Base metal
7	8	414	378	458	461
7	10	358	351	417	430
7	15	392	388	464	350

4. Conclusion

The following major conclusion were drawn from present investigation:

1. The adhesive layer thickness decrease with increases in load after using surface roughness of 400 emery grade and commercial adhesive Araldite. An adhesive layer thickness of 0.12 mm gives maximum adhesive joint strength of bonded joint which was cured at the temperature 120 ^{0}C for 60 minutes.
2. The welding current 7 kA and weld time 8 cycles gives the maximum ultimate tensile shear load carrying capacity of resistance spot welding.
3. Nugget size of both resistance spot weld and weld bond were found very influencive with the increase in energy input. At lower current and weld time, expulsion was miner but at higher weld current and weld time the expulsion was severe. Also at higher value of weld time the electrodes sticks to the work piece.
4. The increase in hardness of weld was possibly attributed to increase in heat input. The hardness of the weld nugget and HAZ was found to lie in the range of (442 – 488 VHN) and (388 – 572 VHN) respectively. In case of weld-bond a slight different behaviour was observed because of presence of adhesive layer at counterface when the hardness of weld nugget and HAZ was found to lie in the range of (358-414 VHN) and (417-464 VHN) respectively.

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