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ORIGINAL ARTICLE

Weld-bonding of 6061 aluminium alloy

Md Faseeulla Khan · Gaurav Sharma · D. K. Dwivedi

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Abstract This paper presents a comprehensive study on effect of surface roughness, curing time, welding current, weld time and electrode pressure on ultimate shear tensile load (USTL) on weld-bonds of a 2-mm-thick 6061T651 aluminium alloy sheet. Weld-bonding is a combination of adhesive bonding and resistance welding process in which adhesive is pre-placed in the joint and a spot weld is made through the adhesive. The tensile shear resistance of the adhesive joint and resistance spot welds were evaluated using uni-axial load on two ends of the lap joints and applying shear tensile load. A comparative study of ultimate shear tensile load of weld-bonds, resistance spot welds and adhesive bonds was carried out.

Keywords Weld-bonding · Tensile shear strength · Resistance spot welding · Adhesive bonding · Al 6061 alloy sheet

1 Introduction

Joining of metals by spot welding in combination with adhesive bonding has drawn considerable attention of numerous scientists and industrialists and is being used in the sophisticated areas like the air craft industry, automobile and missile technology [1]. In typical spot weld joint, high stress concentration exists which leads to their poor static and fatigue load performance. Additionally, in corrosion atmosphere, corrosion of the inner surface of spot-welded lap joints takes place in joints used in the aviation and space-flight industries. These shortcomings of spot-weld joints can be effectively overcome by weld-bonding which was developed way back in the 1950s. Experimental studies on weld-bonded structures have shown improvement in the static and fatigue strength as compared to spot-welded structures besides increased durability and tearing strength of weld-bonds than the adhesive bonds alone [2–4]. There are two approaches used for developing weld-bonds, namely flow in and flow through. 'Flow-in' method as shown in Fig. 1a basically involves first spot welding of sheets then an adhesive is flowed in to the joint. A low viscosity adhesive is used which penetrates the overlap joint by capillary action; thereafter, curing is done. The 'Weld-Through' method which is shown in Fig. 1b follows the sequence of spot welding, adhesive application followed by curing [5–8]. The properties of weld-bond largely depend on surface characteristics of the substrate and the type of adhesive used besides factors affecting weld nugget of spot welding such as welding current, pressure and weld cycle time. For an optimum joint strength, the welding parameters for the preparation of weld-bond differ from those used in the case of spot welding alone [9]. Use of aluminium in automotive industries is encouraging researchers for weld-bonding of an aluminium alloy sheet mainly to reduce weight of the vehicle [6, 7]. Literature survey revealed that almost no work has been done on weld-bonding of a 2-mm-thick sheet of aluminium alloys. Therefore, in the view of the promising future of weld-bonds of aluminium alloys, an effort has been made in this investigation to study the effect of relevant parameters on weld-bond characteristics of a 6061T651 aluminium alloy sheet.

2 Experimental procedure

The experimental study has been carried out to investigate the effects of process parameters, i.e. surface roughness, curing time, welding current, weld time and electrode pressure, on ultimate shear tensile load (USTL) in weld-bonding process.

M. F. Khan · G. Sharma · D. K. Dwivedi (✉)
Department of Mechanical and Industrial Engineering, Indian Institute of Technology, Roorkee, Uttarakhand 247667, India
e-mail: dkd04fme@iitr.ernet.in

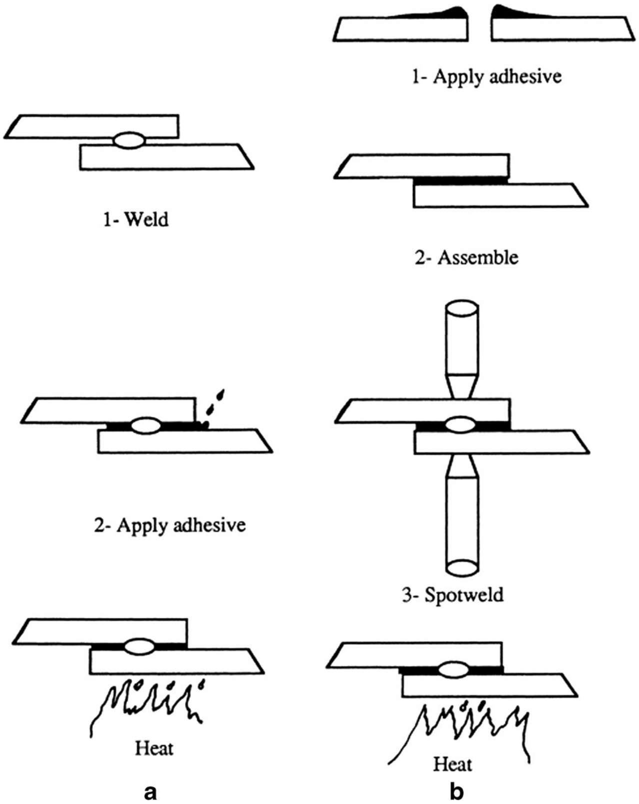


Fig. 1 Weld-bonding techniques. **a** Flow-in and **b** Weld-Through [5]

In the present study, the process parameters of weld-bonding and ranges were identified by conducting pilot experiments for the adhesive joining and resistance spot welding and then the optimized parameters of spot welding and adhesive joining were used to study the characteristics of weld-bonds. The procedures used for adhesive bonding, spot welding and weld-bonding are described below.

2.1 Adhesive bonding

The aluminium sheet 6061T651 of thickness 2 mm was adhesive bonded using epoxy adhesive (consisting of equal amount of resin and hardener by weight) to study the effect of surface preparation and curing time. The surface of the specimen was cleaned by mechanical rubbing using emery grades. Rubbing is done in the direction perpendicular to the load applied during tensile testing, followed by wiping with acetone for roughening and degreasing surface before applying adhesive. Table 1 shows the different emery grit sizes and range of surface roughness (μm) as per ISO standard. Thereafter, curing was done at 120 °C for different curing schedules (curing times up to 100 min). Scheme of the variables and parameters selected to produce aluminium adhesive joint as shown in Table 2.

Table 1 Different emery grit sizes and range of surface roughness (μm) as per ISO standard

Emery grit size	As per ISO range of surface roughness (μm)
120	100–102
220	53–75
400	33.5–36.5
600	24.8–26.8
800	20.8–22.8

Table 2 Scheme of the variables and parameters selected for adhesive joining

Sample material	6061T651 aluminium sheet of 2-mm thickness
Sample size	100×25×2 mm
Overlap length	25 mm
Emery grades	120, 220, 400 and 600
Curing times at 120 °C	20, 40, 60, 80 and 100 min
Type of adhesive	2-C plain epoxy resin

Muffle furnace is used for curing adhesive joint

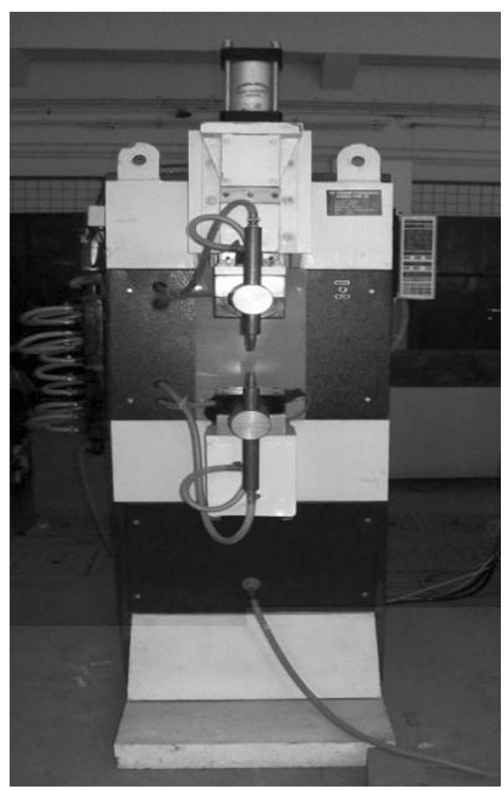


Fig. 2 Welding controller AK-54 spot welding machine

Table 3 Scheme of the variables and parameters for resistance spot welding

Sample material	6061T651 aluminium sheet of 2-mm thickness
Sample size	100×25×2 mm
Overlap length	25 mm (width equal to overlap)
Range of welding current	14–20 kA
Range of welding time	4–10 cycles
Range of welding pressure	4–6 kg/cm^2
Electrode material	Copper electrode

2.2 Resistance spot welding

The 6061T651 aluminium alloy sheet of 2-mm thickness was resistance spot welded by using the microprocessor-controlled spot welding machine (Fig. 2) of 150 kVA rating. The faying surfaces of the specimen were cleaned mechanically by rubbing against 400 emery grade paper followed by wiping with acetone before welding. Resistance spot welding was carried out by varying the welding current, weld cycle time and electrode pressure from 4 to 6 kg/cm^2. Scheme of the variables and parameters selected to produce spot weld joint of aluminium alloy is shown in Table 3.

2.3 Weld-bonding

The 6061T651 aluminium sheet of thickness 2 mm was weld-bonded by application of adhesive bonding followed by resistance spot welding. The surface of the specimen was cleaned mechanically with 220 grade emery paper followed by wiping with acetone before adhesive joining. Then resistance spot welding was carried out by

Table 4 Scheme of the variables and parameters for weld-bonding

Sample material	6061T651 aluminium sheet of 2-mm thickness
Sample size	100×25×2 mm
Overlap length	25 mm (width equal to overlap)
Emery grades	220
Curing time at 120 °C	60 min
Type of adhesive	2-C plain epoxy resin
Range of welding currents	12–10 kA
Range of welding times	2–8 cycles
Range of welding pressure	4–6 kg/cm^2
Electrode material	Copper electrode

Muffle furnace is used for curing adhesive joint

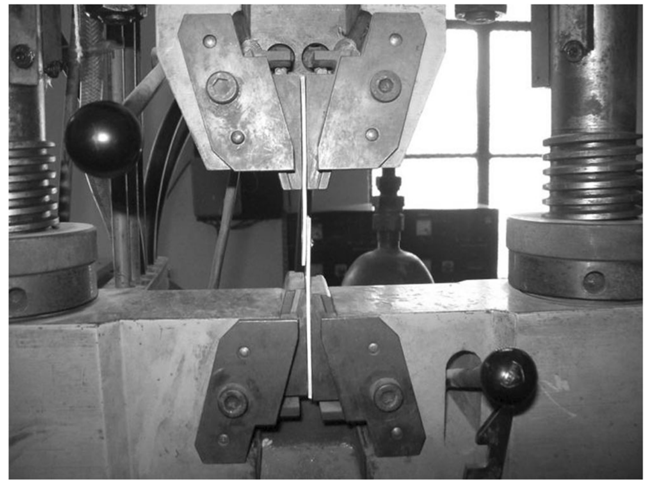


Fig. 3 Experimenting tensile test on the universal testing machine

using controlled welding parameters. After spot welding, curing of joint was employed at optimal conditions of 120 °C for 60 min to facilitate adhesive bonding and cross-linking. The weld-bonds so prepared were used to get tensile shear test specimens. Scheme of the variables and parameters selected to produce aluminium weld-bond joint is shown in Table 4.

2.4 Metallographic studies

Specimens for metallographic examination were collected from the transverse section across the centre line of the weld spot in the resistance spot weld and weld-bond. The specimens were mechanically polished with various grades of

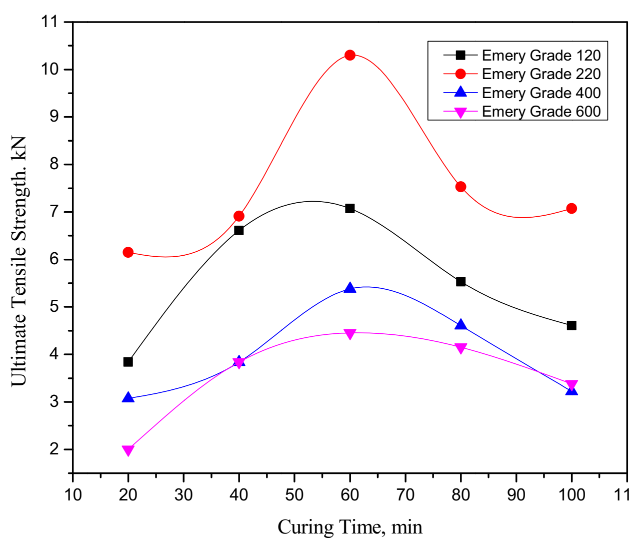


Fig. 4 Effect of curing time on tensile shear strength of the adhesive-bonded joint at different surface roughness

Fig. 5 Adhesive bond joint after tensile testing (cured at 120 °C for 60 min)

emery papers from coarse to fine respectively. Then the specimens were polished by using grade III alumina powder (0.014 μm) on a polishing wheel having velvet cloth mounted on it. The polished specimens were etched in a solution of hydrofluoric acid (5 ml HF, 95 ml water) by dipping them into the etchant 60–80 s followed by washing with stream of water and then drying with cotton to reveal the microstructure of weld metal. The microstructural studies and the estimation of nugget diameter of the weld were carried out under an optical microscope.

2.5 Tensile shear test

The tensile shear tests of the adhesive joint, resistance spot weld and weld-bonds were carried out using uniaxial loading on two ends of the lap joints. The test was carried out at a cross head speed of 1 mm/min on a hydraulically operated dynamic universal testing machine

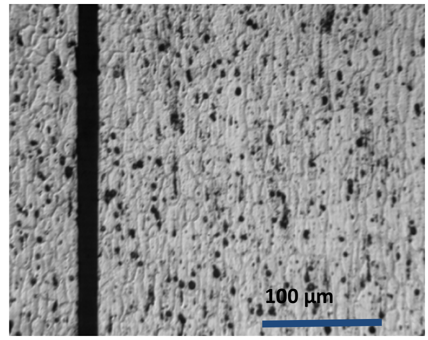


Fig. 7 Microstructure of adhesive joint (layer thickness 15 μm)

(Fig. 3). The ultimate shear load (kN) and failure mode characteristics were studied.

3 Results and discussion

3.1 Shear strength of adhesive joint

3.1.1 Effect of curing time on tensile shear strength of the adhesive joint

The role of curing time at constant curing temperature of 120 °C on adhesive joint strength (having equal joint area) of 6061T651 aluminium alloy at varying surface roughness is shown in Fig. 4. It is observed that the USTL-carrying capacity of the adhesive joint increases with the increase of curing time up to 60 min followed by a decrease in USTL with further increase in curing time up to 100 min. The decrease in joint strength with the increase of curing time beyond 60 min possibly happened due to degradation (bond breaking) of the adhesive which adversely affects the adhesive strength

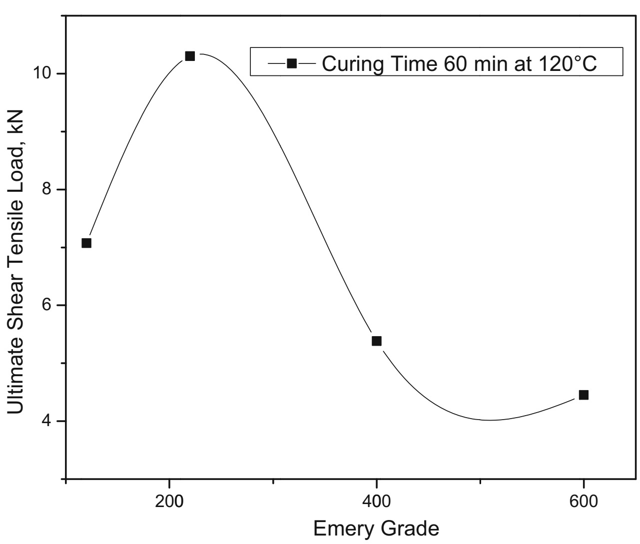


Fig. 6 Role of surface roughness on tensile shear strength of the adhesive-bonded joint of aluminium sheet

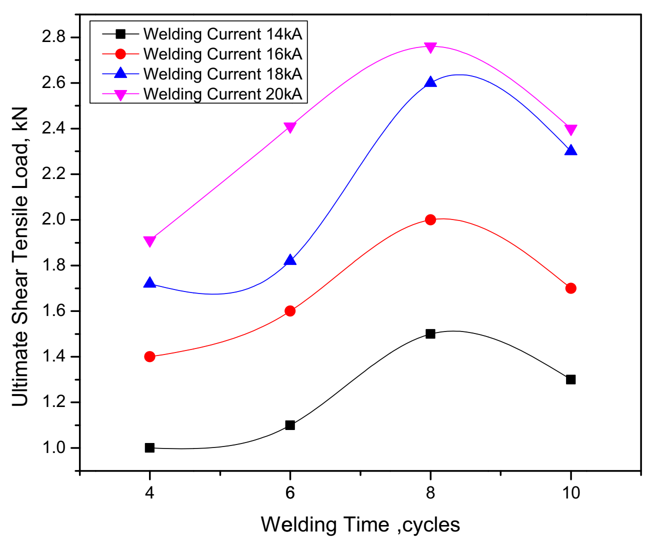


Fig. 8 Effect of welding time on tensile shear strength of the spot welding of aluminium sheet of 2-mm thickness at welding pressure of 5 kg/cm^2 with different welding current levels

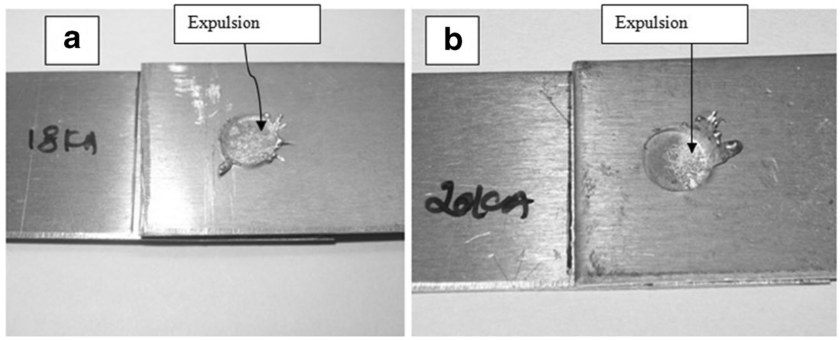


Fig. 9 Expulsion in spot welding at welding currents 18 and 20 kA (**a** and **b**, respectively), welding time 10 cycles and welding pressure 5 kg/cm^2

[10]. Figure 5 shows the adhesive-bonded joint cured at 100 °C for 60 min after conducting tensile test.

3.1.2 Effect of surface roughness on tensile shear strength of the adhesive joint

The effect of surface roughness of an aluminium alloy sheet (obtained by rubbing different grades of emery paper) on USTL-carrying capacity of the joint (for a given curing time of 60 min and curing temperature of 120 °C) is shown in Fig. 6. It is found that the decrease in surface roughness increases the joint strength up to surface roughness obtained by 220 grade of emery. Further decrease in surface roughness (i.e. increase in emery grade number) lowers the joint strength. The increase in joint strength with the decrease in surface roughness is primarily caused by the enhancement in mechanical locking whereas the decrease in joint strength with a further decrease in surface roughness may be due to the reduction in surface area of adhesive bonding. Surface roughness affects the joint strength in two ways: (a) surface area of adhesive bond increases with fineness of surface roughness obtained after rubbing with high grade of emery paper and (b) mechanical locking occurring between various peaks and valleys present on surfaces especially when rough surface is produced using low-grade emery paper. Lower shear load-carrying capacity of joint produced with surface roughness obtained from 120 grade emery paper than that obtained from 220 grade emery paper is due to the fact that a too high peak and valleys on the surface lead to insufficient adhesive filling in the deep valleys which in turn results in porous adhesive joints which reduces shear strength capability of the adhesive joint [10]. Figure 7 shows the microstructure of the adhesive bond joint having layer thickness 0.015 mm.

3.2 Shear strength of resistance spot weld

3.2.1 Effect of welding time on tensile shear strength of the spot weld joint

Effect of weld time on shear strength of weld joints is shown in Fig. 8. It can be observed that an increase in weld time up to 8 cycles at the welding current of 14 and 16 kA increases the

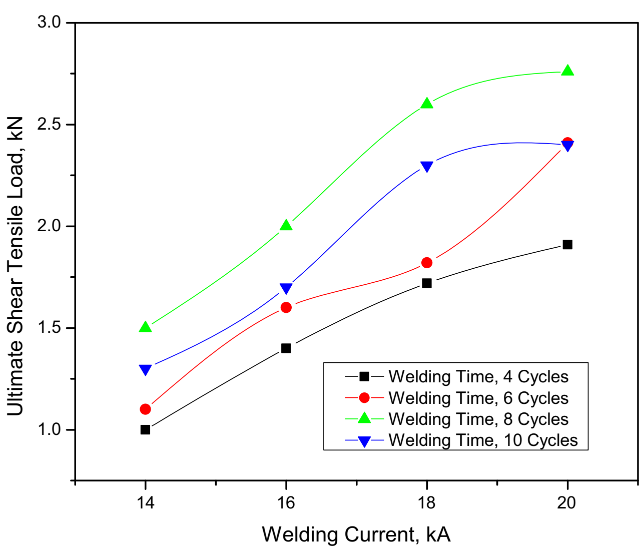


Fig. 10 Effect of welding current on tensile shear strength of the spot welding of aluminium sheet of 2-mm thickness at welding pressure 5 kg/cm^2 with different welding times

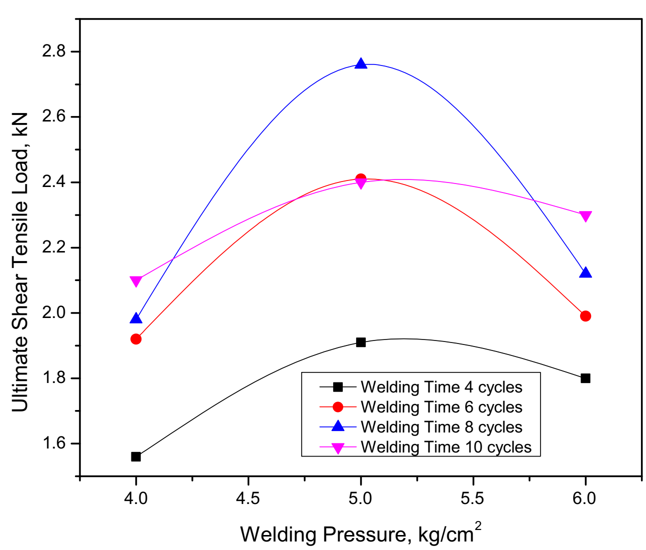


Fig. 11 Effect of welding pressure on tensile shear strength of the spot welding of aluminium sheet of 2-mm thickness at welding current 20 kA with different welding time cycles

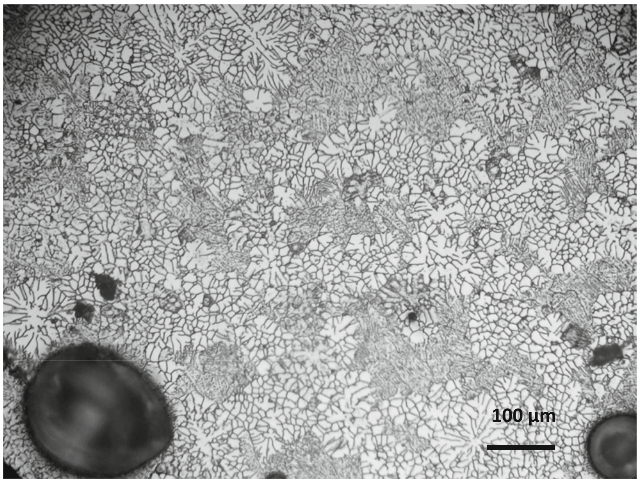


Fig. 12 Microstructure of spot weld joint

USTL-bearing capacity of weld followed by a decrease in USTL with a further increase in weld time up to 10 cycles. The increase in USTL-bearing capacity of the weld with the increase of weld time up to 8 cycles is primarily caused by the increase in diameter of weld nugget. Decrease in USTL-bearing capacity of weld prepared at the weld time of 10 cycles was due to significant expulsion during spot welding [2, 3]. At welding current of 18 and 20 kA, the increase in weld time from 4 to 8 cycles also showed significant increase in the USTL-bearing capacity of the weld. Moreover, at both these welding currents (18 and 20 kA), the preparation of the weld joint beyond 10 cycles weld time would not be realized due to excessive expulsion and melting except at 6-kg/cm^2 welding pressure (Fig. 9).

3.2.2 Effect of welding current on tensile shear strength of the spot weld joint

It is observed from Fig. 10 that an increase in welding current (at a given weld time of 4, 6, 8 and 10 cycles) in general enhances the USTL-bearing capacity of weld significantly primarily due to increase in nugget size especially when there was no expulsion [2, 3].

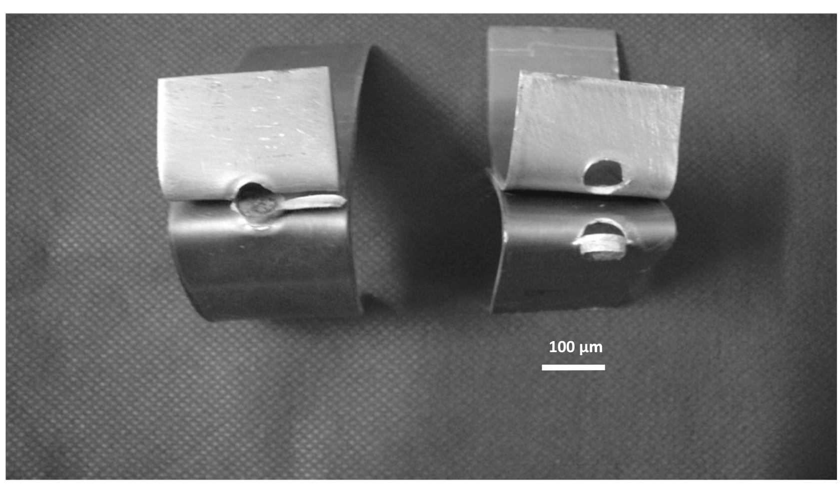
3.2.3 Effect of welding pressure on tensile shear strength of the spot weld joint

The effect of welding pressure on strength on spot welding of an aluminium sheet (at welding current of 20 kA with different welding time cycles) is shown in Fig. 11. It is observed that an increase in welding pressure (at welding current of 20 kA) reduces the strength of the spot welding joint. This is due to the fact that as the pressure is increased, the contact resistance and so the heat generation at the interface are reduced. Therefore, to increase the heat to the weldable conditions, welding current or weld time must be increased to compensate the effect of low heat generation caused by reduction in contact resistance [2, 3]. Figure 12 shows the microstructure of the spot weld joint. Tear test was conducted on the spot weld joint to confirm the nugget formation. Figure 13 shows the tear testing of spot weld joint.

3.3 Shear strength of weld-bonding

Weld-bonding of the 2-mm-thick 6061T651 aluminium alloy sheet was realized only for narrow window of two sets of parameters: (a) low current at high weld time (12 kA and 6 cycles) and (b) high current at low welding time cycles (20 kA and 3 cycles) with low welding pressure (4 kg/cm^2). The heat build-up occurring at contact interface during the first 4 to 6 cycles of weld current flow is greater in the case of weld-bonding. Thus, an initial joint strength developed during four to six weld current cycles as a result of solid phase welding across the interface with localized melting during weld-bonding.

Fig. 13 Tear testing of a spot weld joint



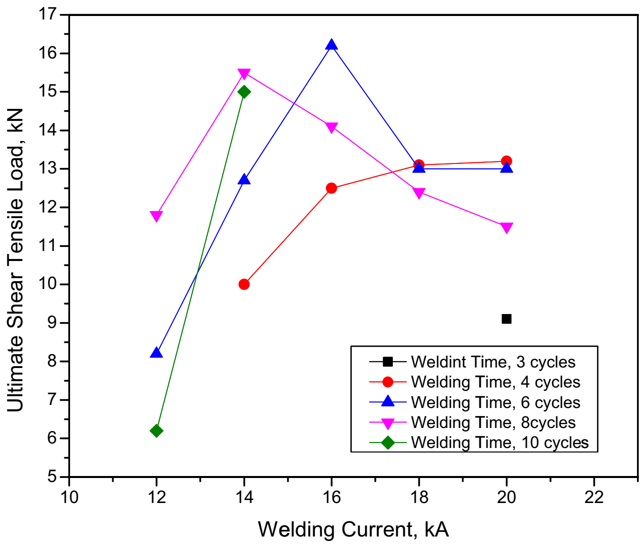


Fig. 14 Effect of welding current on tensile shear strength of the weld-bond of aluminium sheet of 2-mm thickness at welding pressure 4 kg/cm2 with different welding time cycles

3.3.1 *Effect of welding current on tensile shear strength of the weld-bond joint*

The effect of welding current on shear strength of the weld-bond of aluminium sheet (of 2-mm thickness at welding pressure 4 kg/cm^2 at varying welding time cycles) is shown in Fig. 14. Increase in welding current from 12 to 16 kA increased the strength of the weld-bond joint during the initial welding time of 6 cycles. However, further increase in welding time from 6 to 8 cycles decreases the strength of the weld-bond joint because heat produced during few initial weld current cycles formed the weld nugget. The presence of an insulating epoxy adhesive layer increases the contact resistance and current density during the welding and thus enhances the heat input. At high welding current such as 18 and 20 kA, using long weld cycle of 8 and 10 cycles causes a drift in strength of the weld-bond primarily due to occurrence of moderate and heavy expulsion as observed in the case of welding current of 18 and 20 kA. The ejection of molten metal from the liquid nugget during welding can frequently be observed during the welding stage when welding is performed using high current which in turn results in loss of liquid metal from the nugget during welding and so produces weld defects in the nugget, such as voids and porosity [11, 12]. Presence of weld defect in nugget can reduce weld strength. Expulsion also destroys the adhesive layer of weld-bonding (Fig. 15).

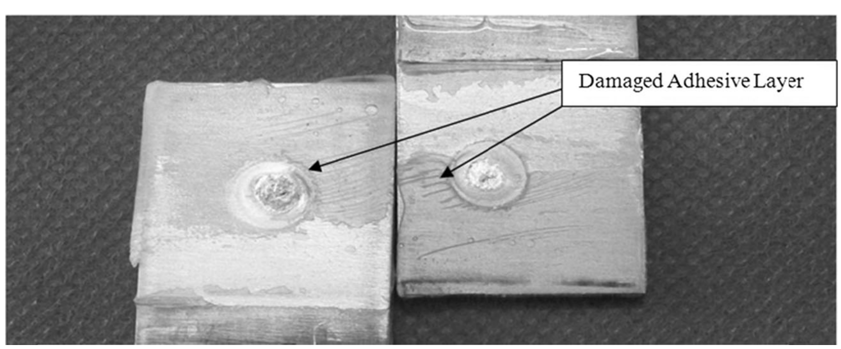
3.3.2 *Effect of welding time on tensile shear strength of the weld-bond*

The effect of welding time on strength of the weld-bond of aluminium sheet produced using welding pressure of 4 kg/cm^2 and different levels of welding current is shown in Fig. 16. A combination of longer weld time (of 8 and 10 cycles) and higher welding current (18 and 20 kA) did not result any weld-bond due to severe expulsion. Increase in weld time at high currents causes severe electrode indentation on the sheet besides expulsion, and presence of adhesive between the faying surfaces acts as an insulator and produces more heat at contact interface hence increases melting which in turn results in larger nugget size. Welding current of 16 kA for welding cycle time of 6 cycles shows the maximum strength because a sufficient weld nugget diameter was observed compared to that produced using low welding current of 14 kA for welding time of 4 and 6 cycles. Similarly in the case of welding current of 20 kA, a moderate expulsion was observed which lowers the strength of the weld-bond joint. Careful observation of these results indicates that a welding current of 14 kA for weld time of 6 cycles and welding current of 20 kA for weld time of 4 cycles result in the same weld-bond strength of 13 kN. It means that low welding current at high welding time and high welding current at low welding time give the approximate equal results in shear strength of the aluminium weld-bonded joint [11, 12].

3.3.3 *Effect of welding pressure on tensile shear strength of the weld-bond*

The effect of welding pressure on the strength of the weld-bond produced using welding current of 16 kA for varying welding time cycles is presented in Fig. 17. It can be observed

Fig. 15 Adhesive layer damage in weld-bond at high welding current 18 kA and welding time 6 cycles



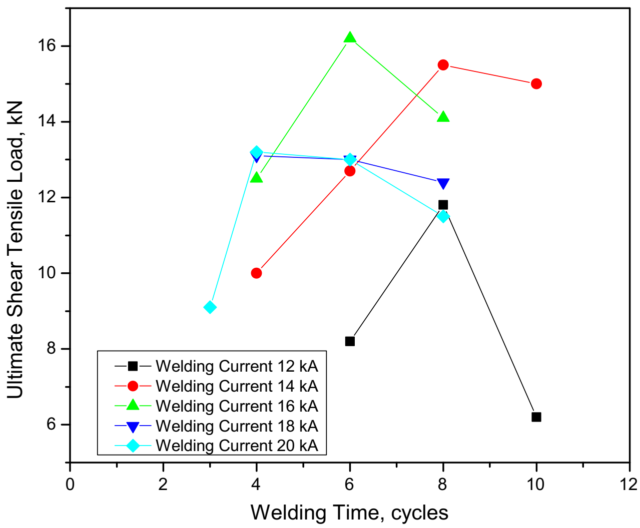


Fig. 16 Effect of welding time on tensile shear strength of the weld-bond of aluminium sheet of 2-mm thickness at welding pressure 4 kg/cm^2 with different welding current levels

that with the increase in welding pressure, the strength of weld-bond decreases because welding at high pressure, the adhesive present between the sheets is expelled (or thinned) out from the interface which lowers contact resistance and so decreases heat generation compared to low welding pressure [11, 12]. Tear test was conducted on the weld-bond joint to confirm the nugget formation. Figure 18 shows the tear testing of weld-bond joint. Figure 19 shows the microstructure of weld-bond joint.

3.3.4 Comparative studies of spot weld and weld-bond joints

The effect of welding current on the USTL of weld-bond and spot weld joints produced using varying parameters of weld-

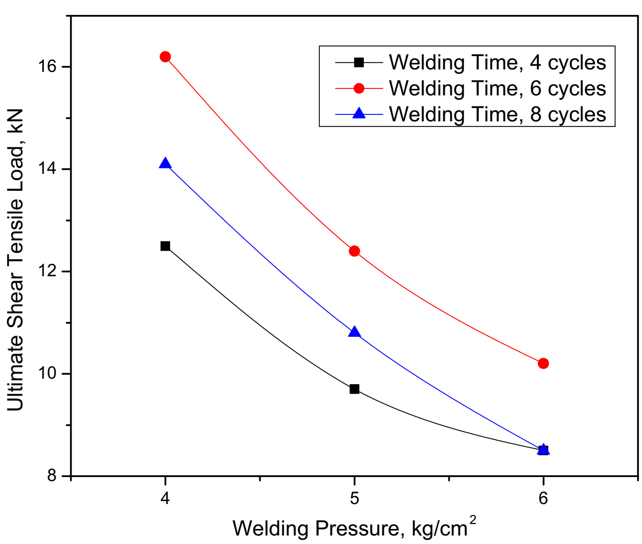


Fig. 17 Effect of welding pressure on tensile shear strength of the weld-bond of aluminium sheet of 2-mm thickness at welding current 16 kA with different welding time cycles

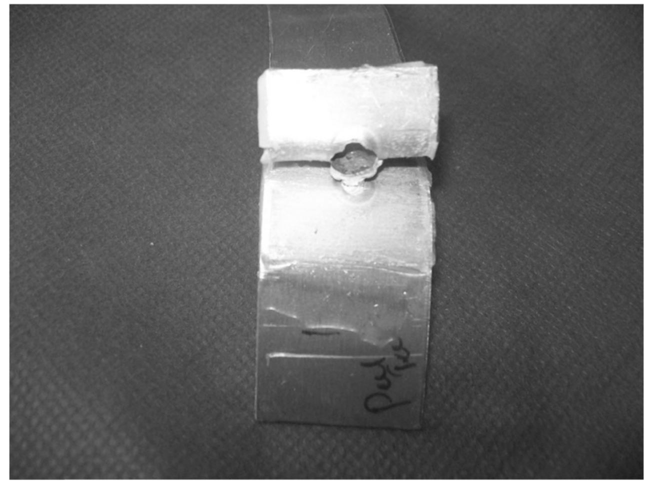


Fig. 18 Tear test of a weld-bond specimen

bonding is shown in Fig. 20. The USTL of weld-bonded specimens increases with increase in the welding current. However, severe expulsion occurs when the welding current exceeds 8 kA at which maximum USTL is obtained. Weld-bonds can achieve a much higher USTL than spot-welded specimens with increase in the welding current from 4 to 6 kA, as shown in Fig. 20. The slope of the USTL vs. welding current plot for spot-welded specimens is larger than that in weld-bonded specimens. Increase in welding current beyond 6 kA shows reverse effects. In absolute terms, the highest USTL value for the spot weld was obtained at 20 kA. Owing to the existence of an insulating adhesive layer at the faying surface, the contact resistance between work pieces in the case of weld-bonding is higher during the initial welding stage and consequently more heat is generated, according to Joule's law, which in turn results in larger nugget size in weld-bonding as compared with spot-welded specimens [1]. Hence, weld-bonded specimens have a higher USTL than spot-welded specimens. Increase in welding current up to an

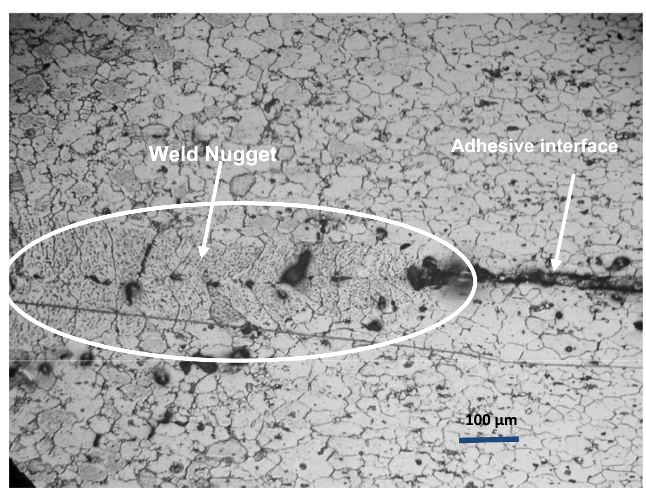


Fig. 19 Microstructure of weld-bonded joint

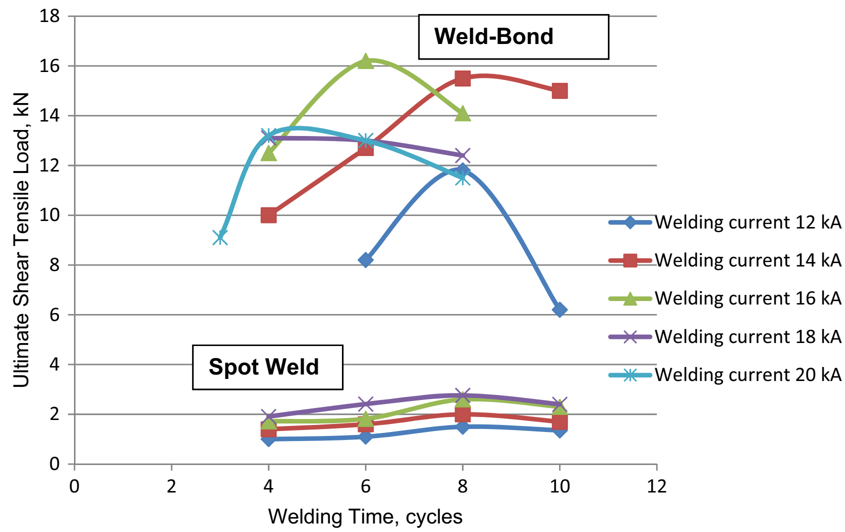


Fig. 20 Comparison of spot weld and weld-bond on tensile shear strength with respect to welding time

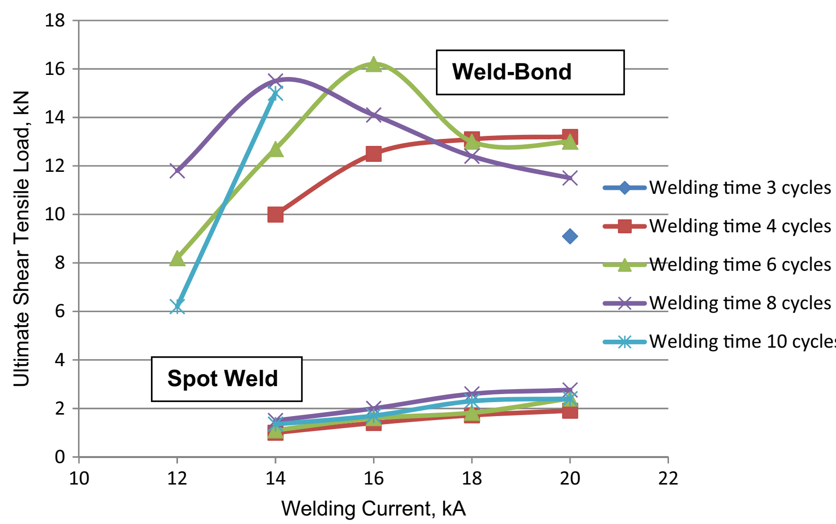


Fig. 21 Comparison of spot weld and weld-bond on tensile shear strength with respect to welding current

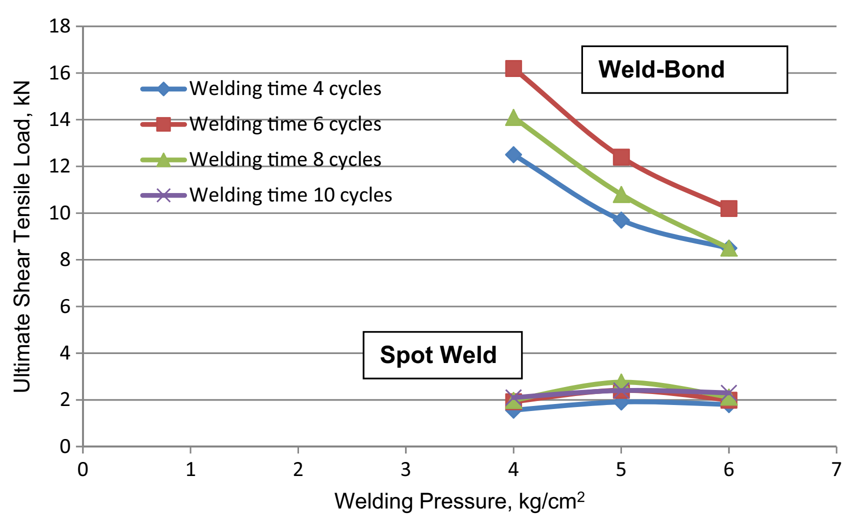
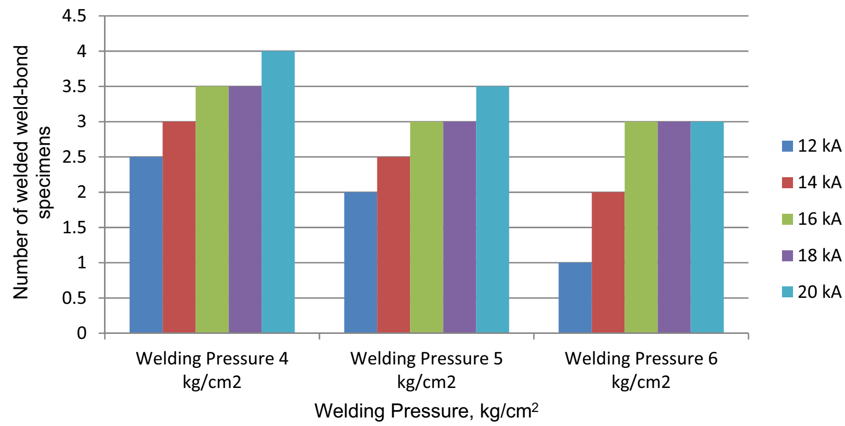


Fig. 22 Comparison of spot weld and weld-bond on tensile shear strength with respect to welding pressure

Fig. 23 Number of welded weld-bond specimens during weld-bonding with respect to welding pressure



optimum value only helps to increase nugget size without expulsion.

Expulsion occurs when the force from the liquid nugget expansion exceeds the electrode force applied by the spot welding machine. Moreover, the current required to produce expulsion in weld-bonding is lower than that in RSW. Expulsion destroys nugget integrity and thus decreases USTL. It is concluded that weld-bonded specimens have a higher USTL at a lower welding current (without expulsion) and a slightly lower USTL at a higher welding current (with heavy expulsion) compared with spot-welded specimens.

A comparative study of spot weld and weld-bond on shear strength with respect to welding time is shown in Fig. 20. Maximum strength of only spot weld joint was found for welding time of 8 cycles while that in the case of weld-bonds occurred for welding time of 6 cycles only. Comparative study of spot weld and weld-bond on shear strength with respect to welding current is shown Fig. 21. For a given welding current, the weld-bonding joint offers maximum shear tensile load as compared to spot weld joint because spot welding combined with adhesive bonding in weld-bonding increases the area of the weld-bond joint and thus the strength of the weld-bonded joint increased. Therefore, the aluminium weld-bonded joint offers more than five times higher USTL than the spot-welded joint because in the case of spot welding, weld nugget offers high stress concentration at interface of the joint owing its geometry which lowers the strength of the spot weld joint. In spot welding, maximum shear strength was observed at welding current of 20 kA and that in the case of weld-bonding was observed at welding current of 16 kA.

A comparative study of spot weld and weld-bond shear strength with respect to welding pressure is shown in Fig. 22. It can be observed that at low welding pressure, weld-bonding results in maximum tensile shear strength as compared to spot welding. In weld-bonding, low welding pressure produces more heat due to the presence of adhesive layer between the interfaces which increases the contact resistance, thus generating heat required for forming weld nugget. In spot welding, maximum strength was observed at welding pressure of 5 kg/cm^2, and in weld-bonding, maximum strength was observed at welding pressure of 4 kg/cm^2. Thus, for maximum strength, weld-bonding is obtained at welding pressures.

3.3.5 Effect of various spot welding parameters on weld-bond to produce sound weld-bond joint

The effect of various spot welding parameters required to produce successful solid-state weld-bond is shown in

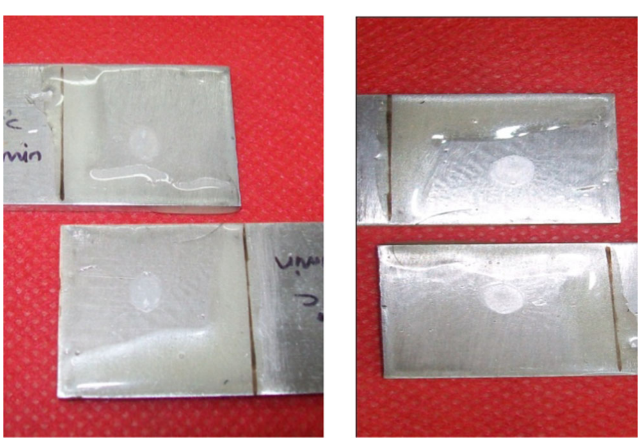


Fig. 24 Un-welded weld-bonded specimen

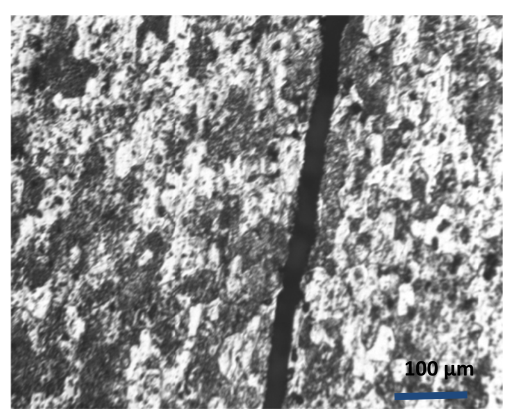


Fig. 25 Microstructure of un-welded weld-bond joint at interface

Fig. 23. It is observed that with increase in welding pressure from 4 to 5 kg/cm^2, the number of successful weld-bonds decreases because with increase in pressure, the adhesive expels out from the interface and so the contact resistance gets decreased which in turn results in low energy heat input compared to that at welding pressure of 4 kg/cm^2. Further, the adhesive present between the sheets (interface) is expelled out completely during increase in welding pressure from 5 to 6 kg/cm^2 and increases directly metal to metal contact which in turn decreases the contact resistance. Decrease in contact resistance lowers the heat generation and hence soundness of the weld-bonds is adversely affected. Figure 24 shows the un-welded weld-bond joints. Figure 25 shows the microstructure of the un-welded weld-bond (nugget not formed) at interface.

4 Conclusions

In the present experimental study, influence of process parameters of adhesive joining, spot welding and weld-bonding of the 2-mm-thick 6061T651 aluminium alloy on ultimate shear tensile load-carrying capacity was investigated. From this study, the following conclusions can be derived:

1. An increase in curing time of adhesive bonds first increases ultimate shear tensile load-carrying capacity and achieves maxima for 120-min curing time; thereafter, further increase in curing time decreases ultimate shear tensile load-carrying capacity irrespective of surface roughness of plates.
2. An increase in surface roughness of plates first increases ultimate shear tensile load-carrying capacity of adhesive bond up to a certain value; thereafter, it decreases. A maximum ultimate shear tensile load-carrying capacity of adhesive bond was found when aluminium sheets were roughened using 220 grade abrasive paper.
3. An increase in weld cycle time and welding pressure during spot welding first increases ultimate shear tensile load-carrying capacity of spot weld joint then it decreases irrespective of welding current.
4. An increase in welding current in general increases the ultimate shear tensile load-carrying capacity of the spot for the welding time (4–10 cycles) used in this study. A maximum ultimate shear tensile load-carrying capacity of spot weld was obtained in the case of joint prepared using 20-kA welding current for eight weld cycle time.
5. An increase in welding time and current first increases the USTL of weld-bonds until a peak value is attained. Further, increase in these two parameters independently decreases the strength of the weld-bond. Increase in welding pressure from 4 to 6 kN decreases load-carrying capacity of weld-bond irrespective of the weld time.
6. Under identical welding conditions, the ultimate shear tensile load of weld-bonds was significantly higher than that of the resistance spot weld and adhesive bond.

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