WELDBONDING OF MILD STEEL

by
P.K. GHOSH and CHINAPPA RAO
Welding Research Laboratory, Department of Mechanical & Industrial Engineering,
University of Roorkee, Roorkee - 247 667, India

ABSTRACT

Weldbonding of mild steel sheets was carried out by adhesive joining followed by resistance spot welding of two pieces. Finally the joint was cured at different temperatures and times. The spot welding was carried out at different welding currents and weld times. Conventional resistance spot weld and normal adhesive joints of the mild steel were also prepared. The normal adhesive joints were used to optimise the curing schedule. The microstructure, hardness, ultimate shear tensile load carrying capacity and fatigue life of the weldbond and resistance spot weld were studied and compared. The weldbonding was found to improve the strength and fatigue life of the joint considerably in comparison to those observed in the case of conventional resistance spot weld.

INTRODUCTION

Weldbonding is a relatively new joining process, which combines spot welding with adhesive bonding of metal sheets. It is found as an effective process for significant improvement in strength, dynamic properties and corrosion resistance of the joint, over those observed in the case of conventional resistance spot weld (1-4). In view of these advantages, a wide-ranging laboratory/service trial of weldbonding has already been made for various applications in military aircraft, space vehicles and automobile industries (5). The weldbonding is especially considered where the spot welding is largely employed for fabrication of components enjoying dynamic loading under corrosive environment. However, the properties of weldbond of any material are largely dependent upon many factors such as the characteristics of an adhesive, surface preparation prior to application of the adhesive, thickness of the adhesive layer, time and temperature of curing of the adhesive and resistance spot welding parameters. Various types of adhesives like epoxy resin, PVC (polyvinyl chloride), plastisol etc. are so far used to produce weldbonding of steel as well as aluminium (2). Prior to application of adhesive a mechanical surface treatment of a substrate, by grinding or rubbing with emery paper has been found to improve the joint strength of weldbonded steel sheets (6). It is well known that an increase in bond line thickness of adhesive reduces the bond strength, as in this case the cohesive force of adhesive determines the bond strength instead of the interfacial adhesive force between the substrate and adhesive. The strength of adhesive bonding is largely governed by curing cycle. For optimum bond strength the time-temperature relationship of the curing cycle depends upon characteristics of an adhesive. Under-curing gives lower bond strength, whereas an over-curing results in a brittle adhesive layer. However, ultimately the properties of a weldbond are to a great extent dictated by the resistance spot welding parameters, which are primarily identified as welding current, welding time and electrode force. Expulsion during weldbonding considerably affects the joint properties and it is primarily determined by the electrode force, thickness of oxide at the surface, current density and current up-slope time (8). Optimum strength of weldbond is generally achieved by avoiding excessive current density and increasing the electrode force and up-slope time (4). But the welding schedule for optimum properties of the weldbond significantly depends upon viscosity and type of adhesive (7). The viscosity of an adhesive varies as welding progresses due to heat dissipation through the sheet. The presence of adhesive also enhances contact resistance and thus affects significantly the weld thermal cycle, resulting in requirements of unconventional welding schedule (7). However, the various technical and scientific aspects of this relatively new joining process, as discussed above, are not well-understood so far.

In this investigation, an effort has been made to study the effects of welding parameters and curing after welding on the characteristics of the weldbond of a structural mild steel sheet, such as its microstructure, hardness, shear tensile properties and fatigue life. The characteristics of the weldbond were also compared to those of the conventional spot weld and normal adhesive joints of the same steel sheet.

EXPERIMENTATION

Weldbonding Procedure

Mild steel sheets of thickness 1.2mm, having chemical composition as given in **Table I**, were weldbonded by application of adhesive followed by resistance spot welding. The welding was carried out using a resistance spot welding machine of capacity 64KVA. Prior to welding the surface of the specimens, especially the faying surfaces, was cleaned mechanically by rubbing with 220 Grd. emery paper followed by wiping with acetone in order to remove the rust and grease from the surface. Then the adhesive (Araldite AW 106 + Hardener HV 953U), consisting of thoroughly mixed resin and hardner in equal amount by weight, was applied on the faying surfaces. By holding the faying surfaces together in correct position (lap joint), the resistance spot welding was carried out by using water cooled conical Cu-Cr alloy electrodes of 5.5mm in diameter. Welding was carried out by varying the welding current (effective) and time at a given voltage and electrode force of 4.0V and 0.6kN respectively as shown in **Table II**. The effective current of welding was measured with the help of a PECO weld current monitor (Type SM 12A, Messer Griesheim) having a range up to 200kA. The voltage during welding was measured across the electric circuit. The electrode force and weld time (1 cycle = 0.02 sec) were controlled by setting of the welding machine. The weld joints were prepared as per specifications to produce tensile shear test specimens, as discussed later. After welding, curing was also employed to the joints at temperatures of 120 and 180°C for 15 and 45 minutes to facilitate wetting and cross linking. For a comparative study conventional resistance spot welds were also prepared at the same welding parameters as mentioned in **Table II**. Some adhesive joints of the base material, having surface finish similar to that used during preparation of the weldbond, were also prepared for a comparative study and optimisation of the curing schedule.

TABLE I – Chemical Composition of the Mild Steel

Chemical composition (Wt.%)				
C	**Mn**	**Si**	**P**	**S**
0.22	0.95	0.4	0.023	0.024

TABLE II – Scheme of the Welding Parameters

Electrode Force (kN)	Voltage (V)	Welding Current (kA)	Welding Time (cycle)
0.6	4.0	6.2	8.0
0.6	4.0	8.2	10.0
0.6	4.0	9.8	15.0

Metallography

The transverse section across the centre line of the spot weld and weldbond as well as a similar section of the base plate were prepared by standard metallographic procedure and etched in 2% alcoholic nitric acid solution. The microstructural studies and the estimation of nugget diameter of the weld were carried out under an optical microscope.

Microhardness Measurement

The Vicker's microhardness measurement of the weld, heat affected zone (HAZ) and base

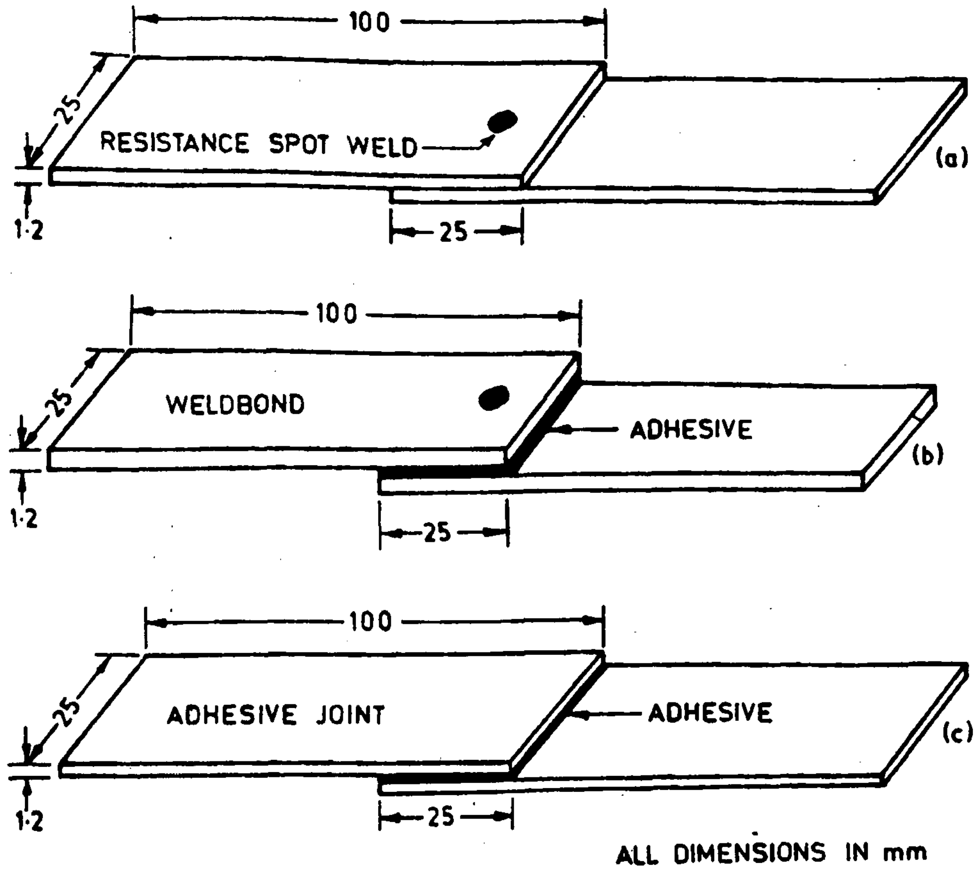


Fig. 1 : Schematic diagram of the shear-tensile test specimen; (a) Conventional resistance spot weld, (b) Weldbond and (c) Adhesive joint.

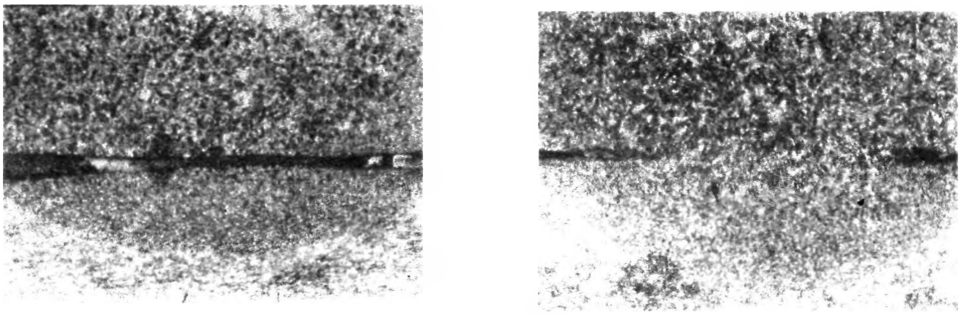
metal was also carried out on the metallographic specimens at a load of 100g. During the microhardness study the indentation was randomly made on the matrix. However, the hardness measurement of HAZ was carried out with specific attention for identation at a distance of about 0.1mm from the fusion line.

Shear-Tensile Test

The shear tensile test of the conventional resistance spot weld and weldbond specimens, prepared according to the specification AWS C1.1-50 as shown in **Fig.1 (a & b)** respectively, was carried out on a microprocessor-controlled servohydraulic universal testing machine. The shear tensile test of the adhesive joints, **Fig. 1(c)**, was also carried out on the specimens of same specification. The tests were carried out at a cross-head speed of 1mm/min.

Fatigue Test

The fatigue properties of the conventional resistance spot weld and weldbond specimens **(Fig. 1 a & b)** respectively), prepared at the welding current and weld time of 9.8kA and 8 cycles respectively, were determined at dynamic loading on the universal testing machine and compared. The weldbond specimens were cured at the temperature and time of 120°C and 15 minutes



(a) (b)

Fig. 2 : At a given welding current of 6.2kA the influence of weld time on the nugget formation at weldbond in presence of a thick adhesive layer at the interface; (a) 8 cycles and (b) 15 cycles.

respectively. The tests were carried out in load control mode at sinusoidal dynamic loading of tensile shear nature, where the stress ratio t_{min}/t_{max}) was kept constant at 0.5. The fatigue life as the number of cyclic loading to fracture of the specimens was measured at different levels of maximum stress where the mean stress was varied as usual. The *shear stress (strength)* was estimated as :

$$\text{Shear strength (t)} = \frac{2F}{\pi \, d2} \quad \text{(i)}$$

where.

F = Force (Load)

d = Diameter of the weld nugget.

RESULTS AND DISCUSSIONS

Weld nugget

In the presence of a thick adhesive layer at the interface of the two sheets, the characteristics of nugget formation during weldbonding between the sheets have been shown in **Fig. 2(a & b)**, where the energy input of welding is varied by increasing the weld time from 8 to 15 cycles at a given welding current of 6.2kA. The micrographs presented in **Fig. 2** show that keeping a low weld time of 8 cycles resists the formation of weld nugget between the sheets due to absorption of a significant amount of energy by the thick layer of adhesive. However, the increase in energy input by enhancement of weld time up to 15 cycles **(Fig. 2b)** *has been found* to give rise to the formation of nugget. Thus, finally during preparation of the weldbond the excess adhesive was manually pressed out from the interface between the sheets up to maximum extent, which improved the condition of welding. However, the required thickness of adhesive layer for the preparation of good weldbond has to be optimized by carrying out further studies in this area.

At different welding currents of 6.2 and 9.8 kA the influence of weld time on the diameter of weld nugget of the spot weld and weldbond specimens has been shown in **Fig. 3.** The figure shows that at a given welding current, the increase in weld time from 8 to 15 cycles as well as at a given weld time, the increase in welding current from 6.2 to 9.8kA enhances the nugget diameter significantly. This happened due to increase in energy input with the increase in welding current or weld time. However, it is interesting to note that at a given welding *current and weld time, the nugget* diameter of the weldbond specimen was significantly lower than the nugget diameter of the conventional resistance spot weld. This may be primarily attributed to the absorption of certain amount of energy by the adhesive present in the region of nugget formation between the sheets, as stated earlier.

Microstructural Studies

Effect of welding current and weld time on microstructure of weld nugget of the conventional resistance spot weld has been shown in **Fig. 4**. The figure shows that microstructure of the weld nugget consists of a mixture of columnar dendrite and recrys-

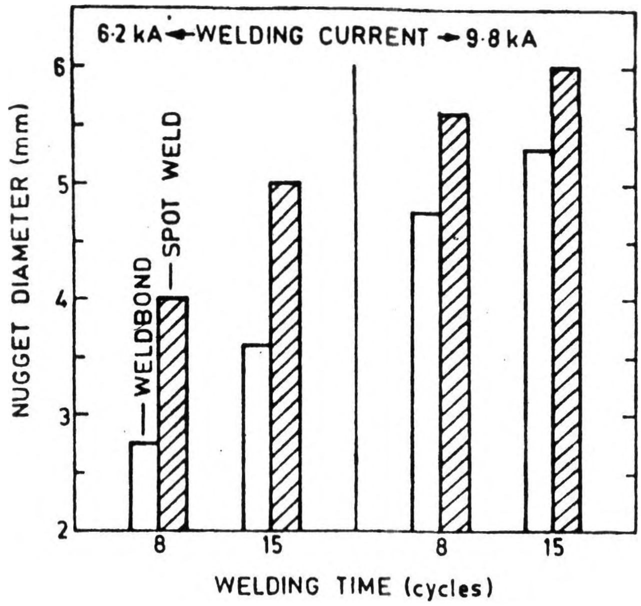


Fig. 3 : At a given welding current the influence of weld time of the nugget diameter of resistance spot weld and weldbond.

tallized grains. In general, it is observed that the increase in energy input up to the welding current and weld time of 9.8kA and 15 cycles respectively, coarsens the microstructure of the weld nugget.

At a given welding current of 6.2kA, the effects of weld time as well as curing temperature and time on microstructure of the weldbond nugget have been shown in **Fig. 5**. Similarly at a higher welding current of 9.8 kA the effects of weld time as well as curing temperature and time on microstructure of the weldbond nugget have been

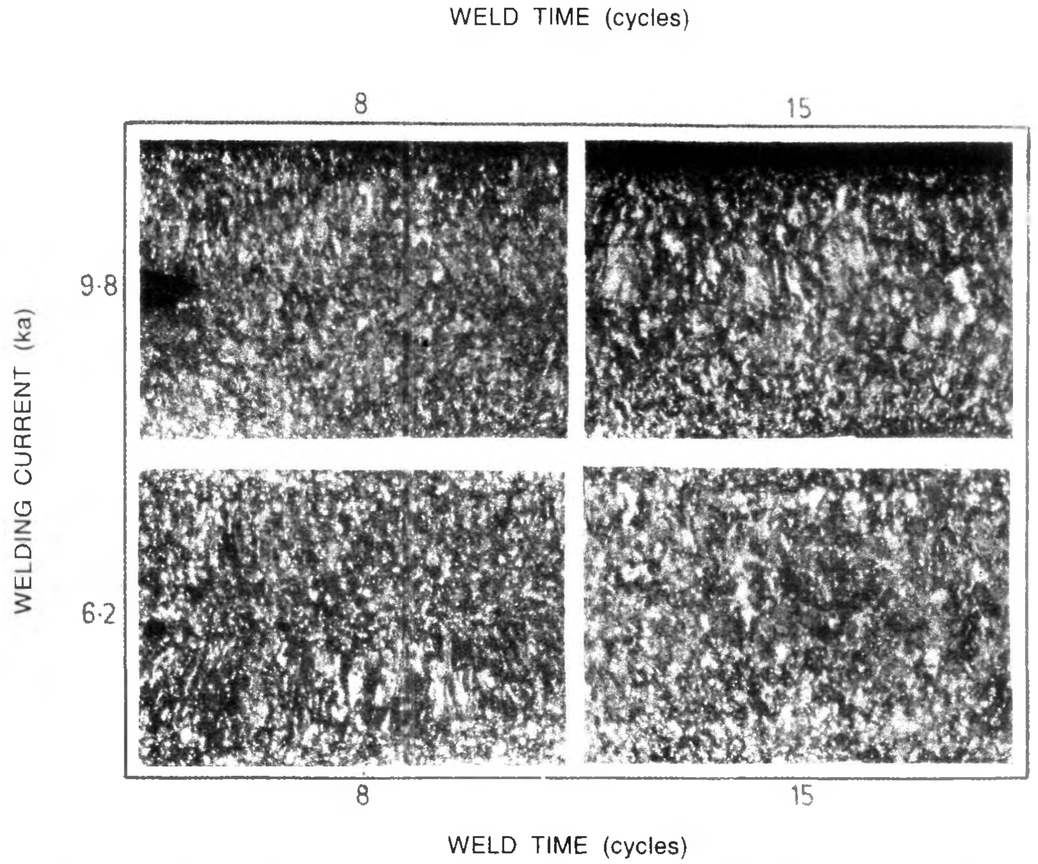


Fig. 4 : Effects of welding current and weld time on the microstructure of weld nugget of resistance spot weld.

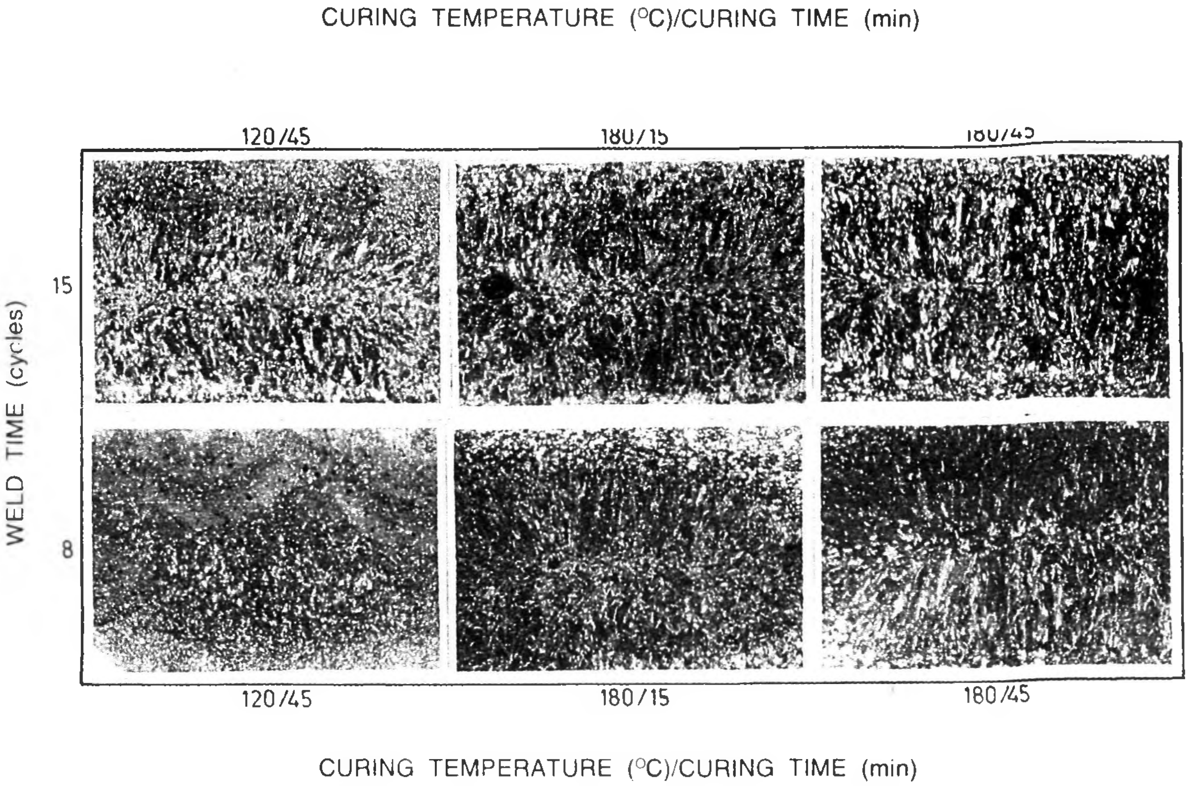


Fig. 5 : At a given welding current of 6.2kA the influences of weld time and curing schedule on the microstructure of nugget in weldbond.

shown in **Fig.6**. The micrographs presented in **Figs. 5** and **6** show that the increase in energy input with the increase of welding current or weld time enhances the coarsening and recrystalliza-tion of microstructure of the weld nugget. It is also observed that the increase in curing temperature and time does not have any significant influence on the microstructure of the weld nugget.

Hardness of Weld and HAZ

Effects of welding current and weld time on hardness of weld nugget and HAZ of the conventional resistance spot weld are shown in **Fig. 7**. The figure shows that at a given welding current of 6.2 kA the increase in weld time from 8 to 15 cycles enhances hardness of the weld nugget. The hardness of the weld nugget has been found to enhance further with an increase in welding current to 9.8 kA at a weld time of 8 cycles, followed by a reduction in it with a further increase in welding time to 15 cycles at the same welding current. The hardness of HAZ has been found to enhance with the increase in weld time from 8 to 15 cycles at a given welding current of 6.2 kA. But the variation in weld time from 8 to 15 cycles at the higher welding current at 9.8 kA has not been found to influence the hardness of HAZ significantly over that observed at the welding current and weld time of 6.2 kA and 15 cycles respectively. The hardness of HAZ is primarily a function of heat input and cooling rate, where the heat input affects the transformation of austenite and cooling rate affects the transformation of the austenite to bainite and martensite. Because of low heat input at the welding current and time of 6.2 kA and 8 cycles respectively, possibly the amount of austenite transformation was not enough to form a significant amount of hard phase in HAZ, resulting in its low

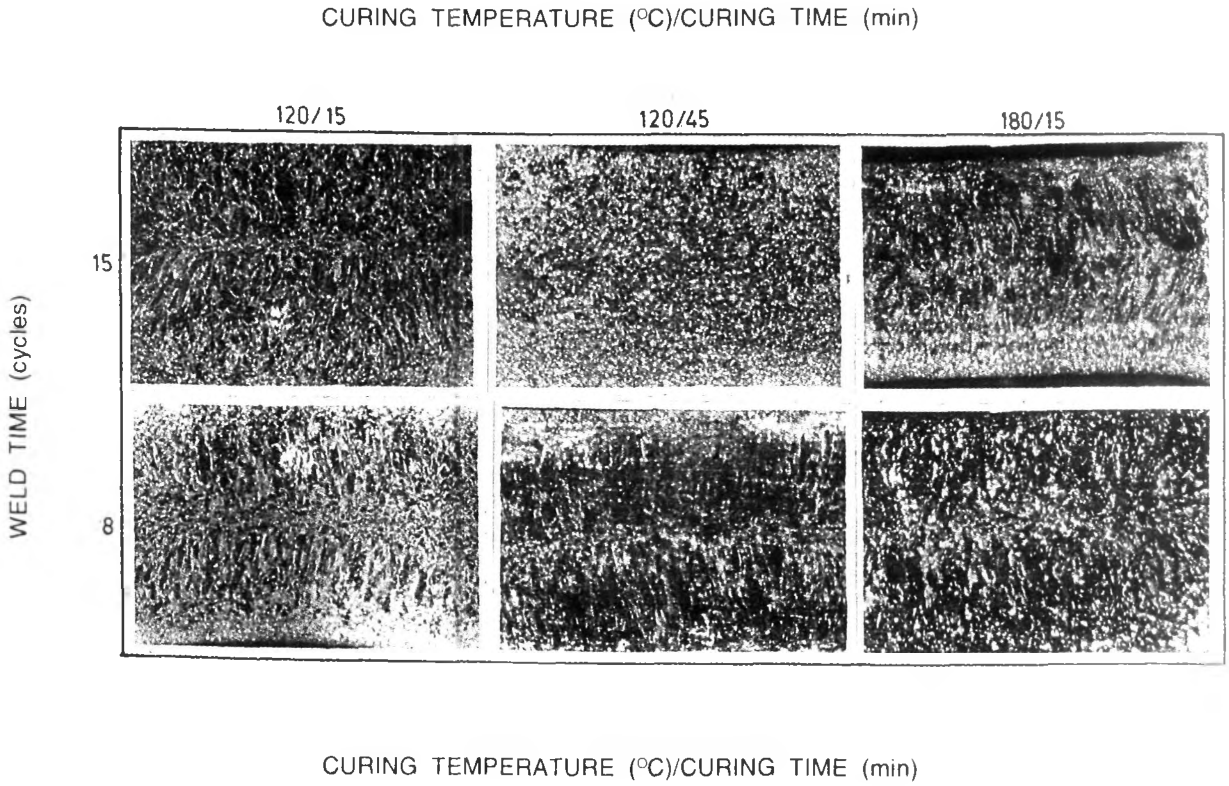


Fig. 6 : At a given welding current of 9.8 kA the influences of weld time and curing schedule on the microstructure of nugget in weldbond.

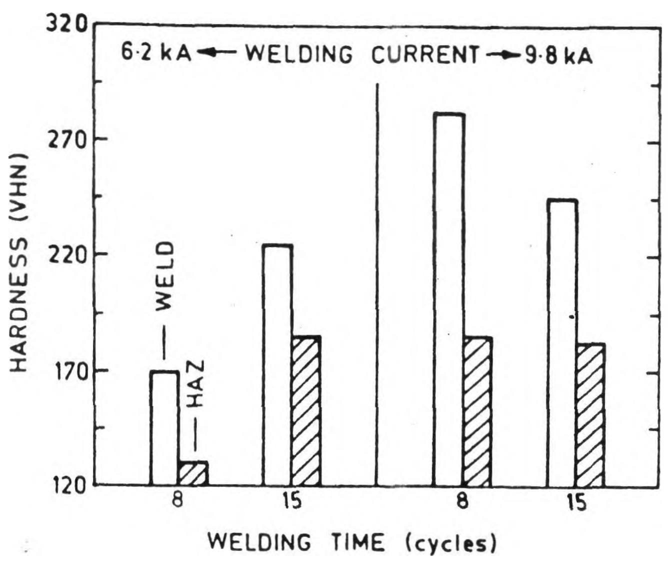


Fig. 7 : Effects of welding current and weld time on the hardness of weld nugget and HAZ in resistance spot weld.

hardness. The enhancement in hardness of HAZ with the increase in heat input by the increase of weld time to 15 cycles at the welding current of 6.2 kA or by the increase of welding current to 9.8 kA at the welding time of 8 cycles also corroborates this phenomenon. A further increase in heat input (9.8 kA, 15 cycle) possibly did not cause any more change in the amount of austenite or cooling rate of HAZ leaving its hardness practically unchanged. In case of high heat input at the welding current and time of 9.8 kA and 15 cycles respectively, the lowering of hardness of weld nugget is primarily

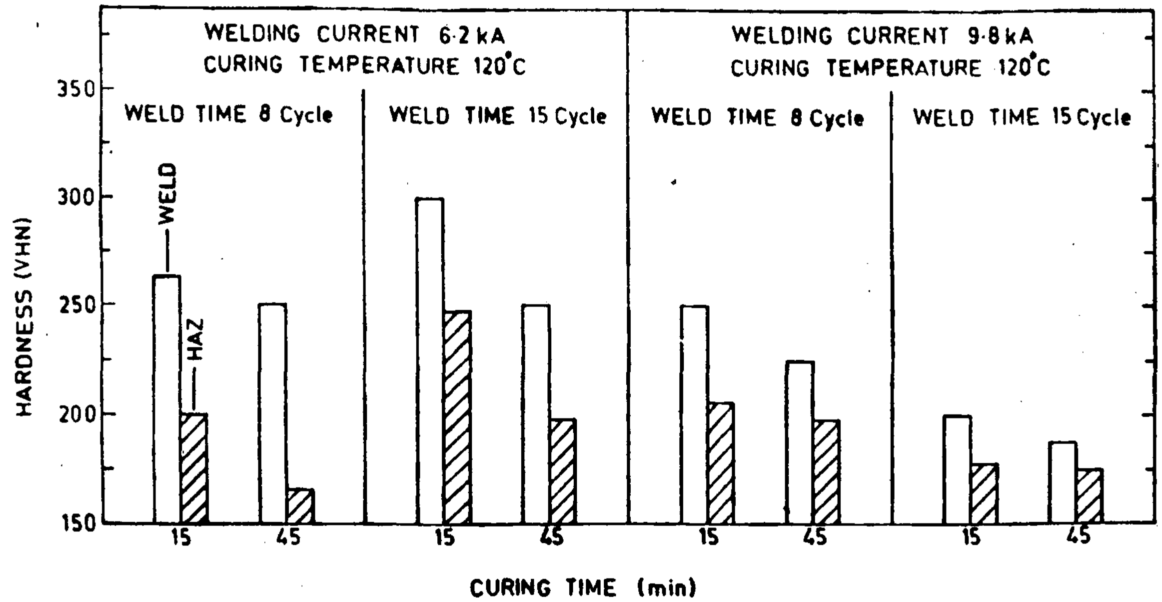


Fig. 8 : At different welding currents and times the influence of curing time on the hardness of weld and HAZ of weldbond cured at temperature of 120°C.

caused by the coarsening of its microstructure (**Fig. 4**).

At a given curing temperature of 120 and 180°C, the effects of curing time on hardness of weld and HAZ of the weldbond prepared at different welding currents and weld times are shown in **Figs. 8 & 9,** respectively. The figures depict that the increase in curing temperature and time comparatively reduces the hardness of both the weld and HAZ, possibly due to relieving of residual stress. In the histograms presented in **Figs. 8 & 9**, it is also interesting to note that at a given condition of curing the increase in energy input with the increase of welding current and time also comparatively reduces the hardness of weld and HAZ. This may have happened due to the influence of heat input on the adhesive, where the adhesive may have undergone a certain physico-chemical transformation during welding, affecting the weld thermal cycle. Further work should be carried out in this area to understand this phenomenon.

Shear-Tensile Strength

At different welding currents of 6.2, 8.2, 9.8 kA the effect of weld time on ultimate shear tensile (UST)) load carrying capacity of the conventional resistance spot weld has been shown in **Fig. 10.** The figure shows that at a given welding current the increase in weld time as well as at a given weld time the increase in welding current enhances the UST load carrying capacity of the weld. The influence of weld time on the strength of the weld has been found to be more significant at the welding current of 9.2 kA. However, during welding at all the parameters an expulsion from the interface was observed. The increase in strength of the weld with the increase of welding current or weld time happened primarily due to increase in nugget size, as typically shown in **Fig. 3.**

At different welding currents of 6.2, 8.2 and 9.8 kA the effect of weld time on the UST load carrying capacity of the weldbond specimens cured at room temperature has been shown in **Fig. 11.** The figure shows that at any welding current the increase in weld time from 8 to 10 cycles enchances the joint strength, followed by relative decrease in it with a further increase in weld time to 15 cycles. However, like

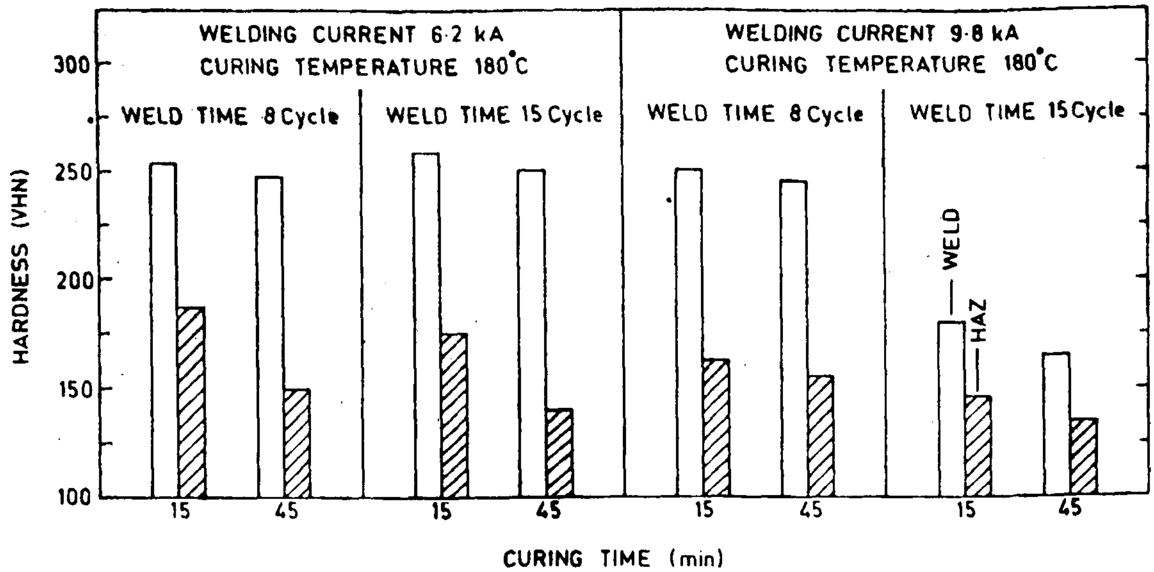


Fig. 9 : At different welding currents and times the influence of curing time on the hardness of weld and HAZ of weldbond cured at temperature of 180°C.

conventional resistance spot weld (**Fig. 10**), here also it is observed that at a given welding time the increase of welding current comparatively enhances the strength of the joint.

At different curing times of 15 and 45 minutes, the effect of curing temperature on UST load carrying capacity of the normal adhesive joints of the sheet has been shown in **Fig. 12**. It is observed that at a given curing time the increase in curing temperature from 120 to 180° reduces the joint strength, whereas at a given curing temperature the increase in curing time enhances the strength of the joint. The maximum strength of the joint was achieved at the curing temperature and time of 120°C and 45 minutes respectively. It is inferred that the increase of curing temperature from 120 to 180°C possibly degrades the adhesive, due to its decomposition or burning.

At different welding currents of 6.2, 8.2, 9.8 kA the effect of weld time on the UST load carrying capacity of the weldbond specimens has been shown in **Fig. 13**, where the specimens were cured at 120°C for different curing times of 15 and 45 minutes. Similarly at different welding currents of 6.2, 8.2 and 9.8 kA the effect of weld time on UST load carrying capacity of the weldbond specimens has been shown in **Fig. 14**, where the specimens were cured at 180°C for different curing times of 15 and 45 minutes. **Fig. 13** shows that during welding at a low current of 6.2 kA the increase in weld time enhances the strength of the joints considerably, whereas at a higher welding current of 8.2 kA the increase in weld time from 8 to 10 cycles enhances the joint strength followed by a decrease in it with a further increase in weld time to 15 cycles. During welding at a further high welding current of 9.8 kA, the increase in weld time from 8 to 15 cycles has been found to reduce the joint strength considerably. The figure also depicts that at the given curing temperature of 120°C, the increase in curing time from 15 to 45 minutes reduces the strength of weldbond. But the **Fig. 14** shows that during curing at 180°C the effect of weld time on the strength of the weldbonds prepared at different welding currents is different from that

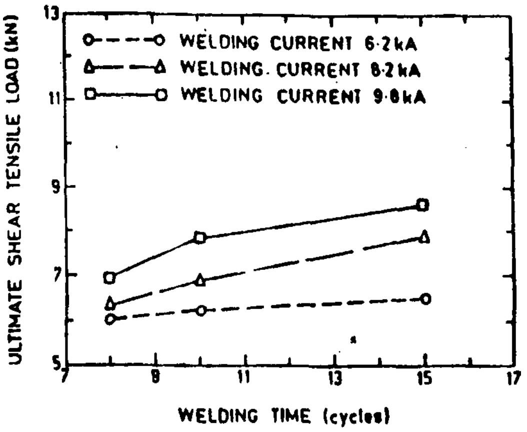


Fig. 10 : At different welding currents the effect of weld time on the UST load carrying capacity of resistance spot weld.

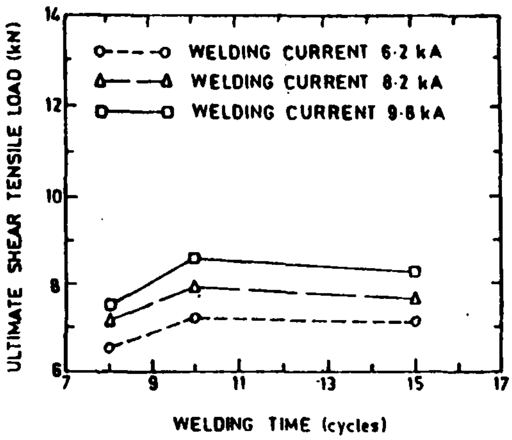


Fig. 11 : At different welding currents the effect of weld time on the UST load carrying capacity of weldbond cured at room temperature.

observed in case of the weldbond prepared at a low curing temperature of 120°C (**Fig. 13**). The **Fig. 14** shows that at the low welding current of 6.2 kA the increase in weld time for 8 to 15 cycles relatively increases the joint strength, but at the higher welding current of 8.2 and 9.8 kA the increase in weld time does not influence the joint strength significantly. As it was observed in the case of the curing temperature of 120°C (**Fig. 13**), here also it is observed that at a given curing temperature of 180°C the increase in curing time from 15 to 45 minutes reduces the strength of the weldbond. However, the strength of the weldbond cured at 180°C was always found to be comparatively lower than that of the weldbond cured at 120°C. Considering the results presented in **Figs. 13** and **14**, it is clearly understood that the strength of the weldbond is largely governed by the characteristic of adhesive bonding which is affected by the thermal cycles of welding and curing. Bond strength of the adhesive possibly deteriorated during welding at high heat input and during curing at the high temperature of 180°C. It is interesting to note indeed that the weldbond prepared at the welding current, weld time, curing temperature and curing time of 6.2 kA, 15 cycles, 120°C and 45 minutes respectively, is having significantly higher strength of about 14.2 kN, in comparison to the strength of the conventional resistance spot weld (6.5 kN) prepared at the similar welding current and weld time. It is also marked that the weldbond gives higher strength than the conventional resistance spot weld inspite of its lower nugget size (**Fig. 13**), which shows a considerable role of adhesive in governing the joint strength of weldbond.

During shear-tensile test of both the conventional resistance spot weld and weldbond specimens, the fracture was always found to take place from HAZ, except in case of the weld carried out at a low current and time of 6.2 kA and 8 cycles respectively, where the fracture took place from the nugget. The failure from nugget occurred in case of both the weldbond and spot weld, primarily due to small nugget diameter.

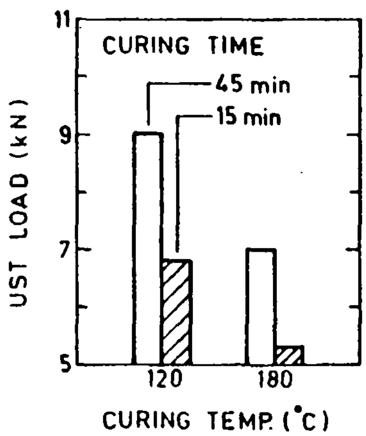


Fig. 12 : At a given curing time the effect of curing temperature on the UST load carrying capacity of adhesive joint.

Fatigue Life

The fatigue life, defined as the number of cycles (N) to fracture of the conventional resistance spot weld and weldbond specimens at different test conditions, has been shown in **Table-III**. The table depicts that at a given condition of maximum load, the maximum shear stress (t_{max}) at the nugget of the weldbond was always higher than that observed at the nugget of the resistance spot weld, due to the former's smaller nugget size than that of the latter. But it is interesting to note that inspite of the higher t_{max} the weldbond specimens have shown a longer fatigue life than the resistance spot welds, under a given condition of loading. These behaviours are more appropriately revealed in the t_{max} (S) vrs. fatigue life (N) plots of the weldbond and resistance spot weld presented in **Fig. 15**. The S-N curves of the two types of joints shown in **Fig. 15** clearly depict that at a given t_{max} the fatigue life of the weldbond is considerably higher than that of the resistance spot weld. The figure also depicts that the weldbond may work satisfactorily at a higher fatigue stress level than which can be used in case of a resistance spot weld. The improvement in fatigue life or fatigue strength of the weldbond is primarily caused by the reduction in notch effect at the boundary of the nugget due to presence of adhesive at this region, and modification in shear strains as well as force distribution at the joint (1,9).

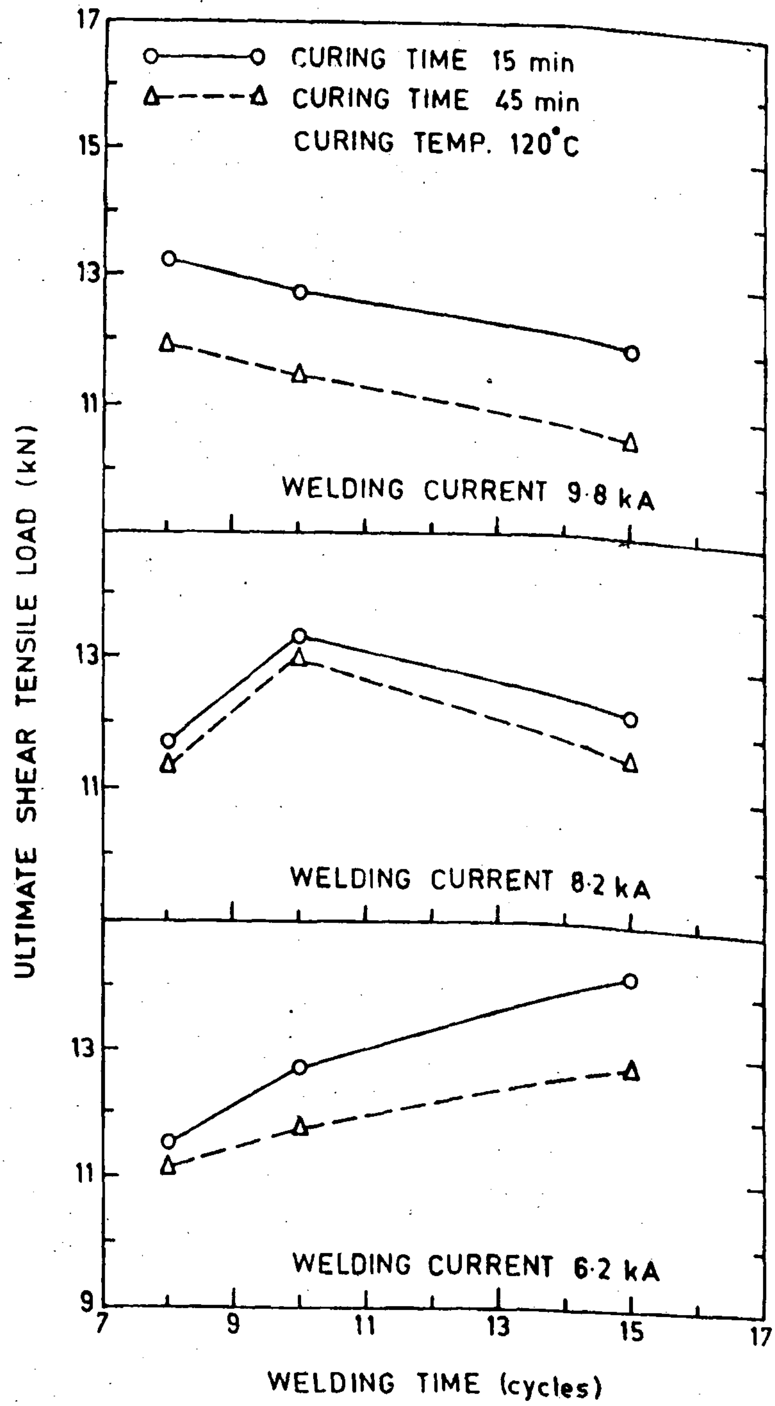


Fig. 13 : At different welding currents the effect of weld time on the UTS load carrying capacity of weldbond cured for different periods at temperature of 120°C.

CONCLUSIONS

The observations of the present investigation can be concluded as follows.

1. At a given welding current and weld time the nugget size of weldbond becomes lower than that of the conventional resistance spot weld.
2. At a given welding current and weld time the microstructure of weld nugget of the conventional resistance spot weld shows more recrystallization of dendrites in comparison to that observed in case of weldbond.
3. At a given welding current and weld time the hardnes of weld and HAZ of the weldbond is generally found to be higher than that of the conventional resistance spot weld.
4. A significant higher strength of the weldbond can be achieved when it is prepared

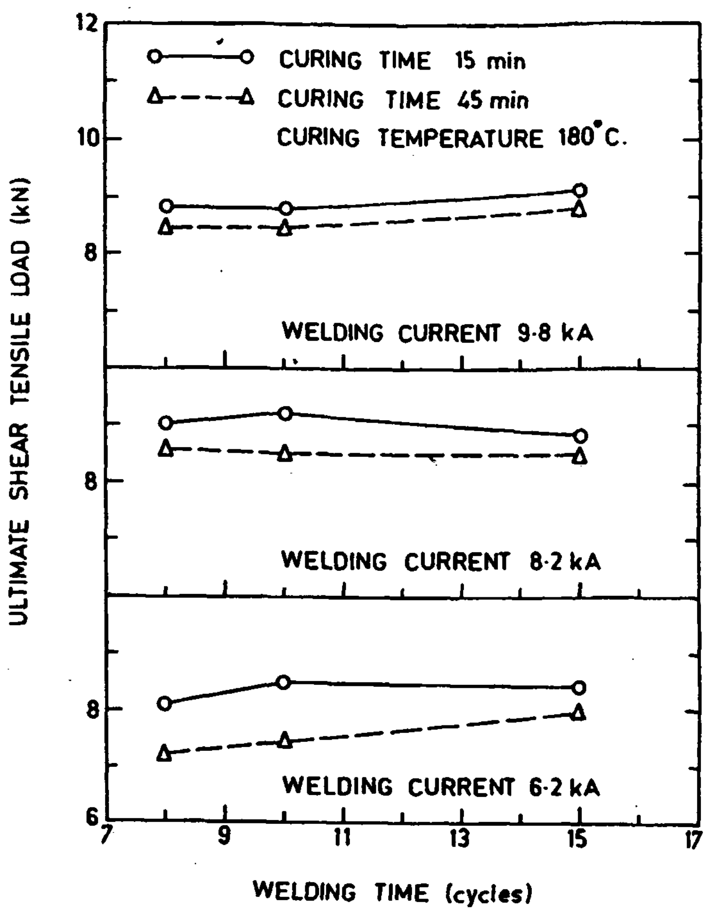


Fig. 14 : At different currents the effect of weld time on the UST load carrying capacity of weldbond cured for different periods at temperature of 180°C.

TABLE III – Fatigue Characteristics of the Two types of Joints at Different Test Conditions

Type of joint	Nugget dia. (mm)	Max. load (kN)	Min. load (kN)	Max. stress (N/mm^2)	Fatigue life (cycles)
Weldbond	4.75	4.0	2.0	112.82	32,300
	4.75	5.0	2.5	141.02	19,050
	4.75	5.5	2.75	155.12	11,100
	4.75	6.0	3.0	169.23	4,800
	4.75	6.5	3.25	183.33	100
Resistance	5.6	4.0	2.0	81.17	25,000
Spot Weld	5.6	5.0	2.5	101.46	4,750
	5.6	5.5	2.75	111.61	-
	5.6	6.0	3.0	121.75	1,500
	5.6	6.5	3.25	131.90	2,500

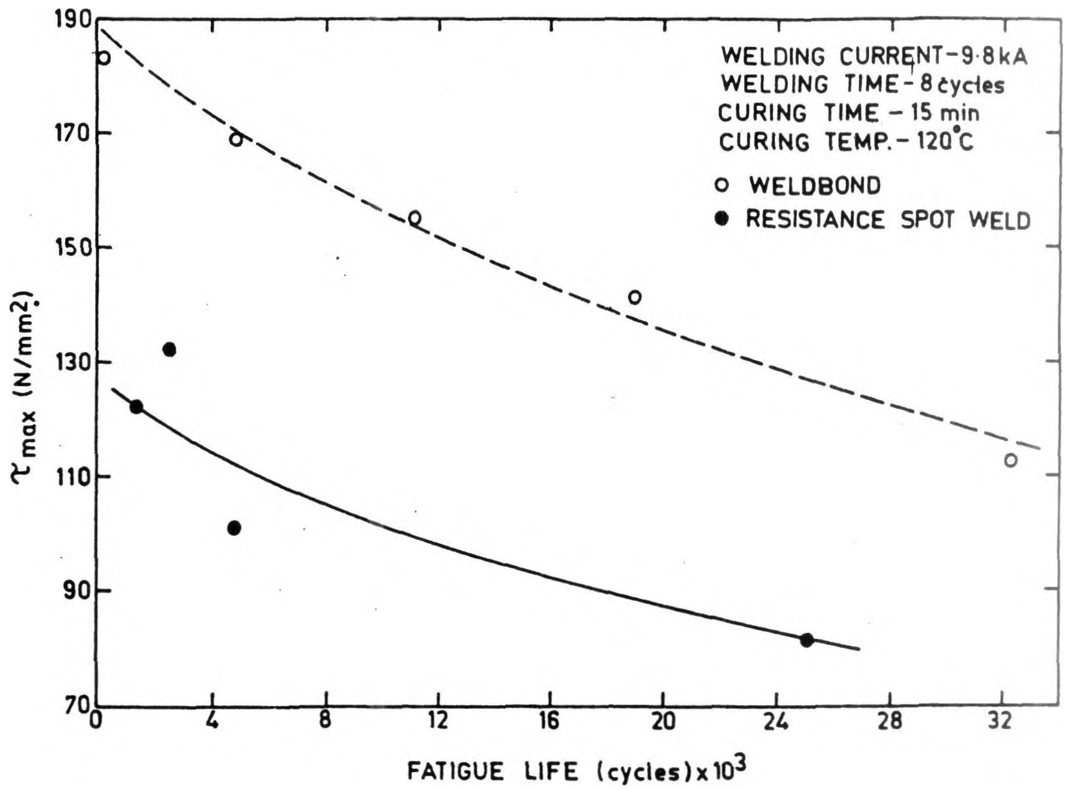


Fig. 15 : Comparison of fatigue life of the resistance spot weld and weldbond prepared at a given welding current and weld time.

at a welding current, weld time, curing temperature and curing time of 6.3 kA, 15 cycles, 120°C and 15 minutes respectively.

5. The weldbond shows a considerably higher fatigue life and fatigue strength than those observed in the case of conventional resistance spot weld.

REFERENCES

1. P.C. Wang, S.K. Chisholm, G. Banas and F.V. Lawrence, Jr., Weld. J., 74, 2, (1995) 41-47S.
2. Friedrich Eichhorm and Bernd H. Schmitz, Schweissen und Schneiden, 36, 3, (1984) E38-39.
3. F. Eichhorn, O. Hahn, G. Otto and H. Stepanski, Untersuchungen zum Festigkeits und Alterungsverhalten von Punktschweissklebverbindungen. Abschlussbericht zum AIF-Vorhaven 3226, Aachen, (1977).
4. O. Hahn and H. Stepanski, Kombiniertes Punktschweissen und Kleben. DVS-Bericht, 51, (1978) S38-45.
5. J.D. Minford, F.R. Hoch and E.M. Vader, Weldbond and its Performance in Aluminium Automotive Body Sheer, SAE-Nr. 750462. USA, (1975).
6. Lutz Dorn and Georgios Moniatis, Adhesive Bonding and Spot Weldbonding of High Strength Steel Plates - Strength Characteristics of the Joints After Ageing, Schweissen und Schneiden, 40, 1, (1988) E17-18.
7. K. C. Wu, Resistance Spot Welding of High Contact-Resistance Surfaces for Weldbonding, Weld. J., 54, 12, (1975) 436-39S.
8. K.C.Wu, The Mechanism of Expulsion in Weldbonding of Anodized Aluminium, Weld. J., 56, 8, (1977)238-44S.
9. Roger D. Beemer, High fatigue life results from titanium spot welding innovations, Weld. J., 49, 3, (1970)89-92S.