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STUDIES ON FATIGUE BEHAVIOUR OF WELD-BONDS OF Al-Mn-Mg ALLOY

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ABSTRACT

In the present paper, fatigue and metallurgical behaviour of weld-bonds and adhesive bonds developed using 2 mm thick aluminium alloys namely 5052 alloy have been reported. Weld-bonds were prepared using structural adhesive (Epoxy resin) and spot welding (20 kA welding current for 6 cycles welding time at welding pressure of 0.5 MPa). Curing after applying Epoxy resin for developing adhesive bonds and weld bonds was performed at a temperature of 100 ^{o}C for 90 min. Fatigue tests were conducted under tension–shear loading pattern with stress ratio of 0.5 and loading frequency of 5 Hz. The maximum tensile shear load for fatigue test was kept at different level i.e. 90%, 80%, 70% and 50% of the ultimate shear tensile strength of weld bond and adhesive bonds. The fatigue lives of both adhesive bond and weld-bond joints decreased with increase in maximum tensile shear load. Fatigue performance of weld bond was higher than adhesive bond especially at high load.

Keywords: 5052 Aluminium alloy, weld bonding, mechanical properties.

1 INTRODUCTION

The engineering systems such as cars and aircrafts have variety of joints including spot welds. These joints are invariably subjected to fatigue loading during the service. Efforts are continuously being made by technologists to enhance the fatigue performance of spot weld joints using different hybridization approaches spot weld-solder/braze joint, spot weld-adhesive joint etc (Long et al. 2008, Goncalves et al. 2006, Chang et al. 1999, Wang et al. 1995). A combination of spot welding and adhesive joining is called *weld-bonding*. Recently some work has been published on fatigue behavior of weld bonds on steel and aluminium alloys. Long et al. (2008) studied fatigue properties and failure mode of spot weld and weld bonds of high strength steels and reported that weld bonds show significantly higher fatigue strength than spot weld especially at low load condition (high cycles fatigue). Goncalves et al. (2006) reported higher ultimate load and displacement for weld bonds than adhesive bonds and spot welds. Chang et al. (1999) reported fatigue behavior and fracture characteristics of three types of joints and showed that the application of adhesives in spot welding greatly improves the fatigue performance of the joint, while the presence of weld spots in adhesive-bonding has a negative effect on the joint fatigue performance. Wang et al. (1995) investigated the failure behavior of the weld-bonded aluminum joint and found that adhesive bonds offer slightly higher fatigue performance than weld-bonded as presence of resistance spot weld decreases the fatigue strength. Further, the fatigue performances of spot welds of aluminium and steel were reported to be much lower than the respective weld bonds. Buddle et al. (1992) reported that the weld bonds show slightly longer fatigue life as compared to adhesive bonds. Further, the limiting range of stress for weld bond was found to be much superior to spot welds. The literature on fatigue studies of weld-bonds of Al-Mn-Mg aluminium alloy (AA 5052) is very scant therefore, in this study, an attempt has been made to investigate the fatigue and metallurgical characteristics of weld bonds of 2 mm thick Al-Mn-Mg aluminium alloy (AA 5052 H32).

2 MATERIALS & METHODS

A weld-bonded joint is composed of spot weld nugget, the heat-affected zone (HAZ), base metal and the adhesive layer, each with different microscopic compositions. The schematic of weld bond joint is shown in Fig. 1. The chemical composition of the 5052 H32 aluminum alloy and properties of resin and hardener used for adhesive bonding are shown in Tables 1 and 2.

Table 1: Chemical composition (wt%) of Al 5052 H32 used in present work

Si	Fe	Cu	Mn	Mg	Cr	Zn	Balance
0.15	0.33	0.03	0.07	2.68	0.1	0.03	Al

Table 2: Properties of adhesive selected

Material	Viscosity (Pa)	Relative density (g/cm^3)	Max. working time min.	Mix ratio (R/H)	Thermal conductivity W/m/^{0}C	Average thermal expansion coeff. K^{-1}
Resin (R)	24-45	1.15-1.25	20 min.after mixing	50:50	0.22	23.6 X 10^{-6}
Hardener (H)	20-30	0.94-0.98				

Adhesive was composed of resin (bisphenol epoxy) and hardener (mixture of polyaminoamide and aliphatic polyamine). The weld bonds of the aluminium alloy (5052 H32) sheet of size 100 X 25 X 2 mm^3 were developed using following steps (Mittal, 2012) and the same has been exhibited shown in Fig. 2. The test specimens of adhesive bond were prepared with overlap length of 25 mm. Surface of aluminum sheet was roughened with 220 emery grade paper. Spot welding was performed using welding current of 20 kA, welding time of 6 cycles, and welding pressure of 0.5 MPa after applying adhesive samples. Thereafter, curing was done at 100 ^{o}C for 90 minutes. All weld-bonds were tested after 72 h of curing. Standard metallographic procedure was used for prepapration of samples for microstructure study. The polished specimens were etched using a solution of 5% diluted hydro-fluoric acid (5 ml HF, 95 ml water). The micro structural studies of the weld were carried out under an optical microscope. The microhardness testing of the weld-bond specimens was carried out using Vickers micro hardness indentation at a load of 50gms or 490.3mN. The hardness of HAZ was studied at a distance of about 0.1 mm from the fusion boundary in weld-bonded joint. The hardness was measured in two directions a) major axis and b) minor axis of elliptical shape nugget of weld bonds (Fig. 3). The fatigue–shear tests were carried out in hydraulically operated dynamic universal testing machine. The fatigue tests were performed in terms of different percentages of the ultimate shear tensile load at fracture. Values corresponding to 90%, 80%, 70%, and 50% of this load (in accordance to ASTM D3166 specifications) were complemented with additional values at 60%, 40% and 30% for a better characterization of the fatigue response at low levels of loading. The fatigue loading was performed at constant load ratio R (L_{max}/L_{min}) of 0.5 at loading frequency of 5Hz for all the tests. Complete separation of the test piece (for adhesive-bonded and weld-bonded joints) was considered as failure. The fatigue life as the number of cyclic loading to fracture of the specimens was obtained at different maximum shear loads. The results reported in this work are valid at room temperature only because the adhesive layer tends to get damaged when exposed either to high temperature or humid atmosphere.

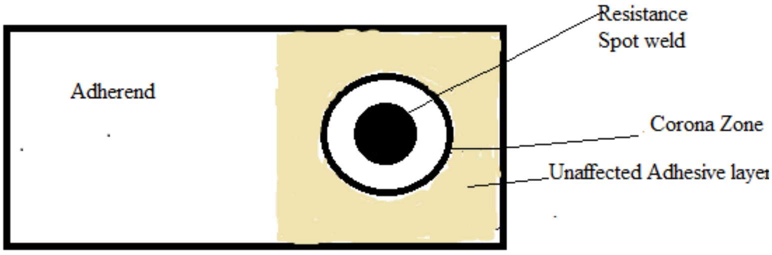


Figure 1: Schematic of weld bond joint.

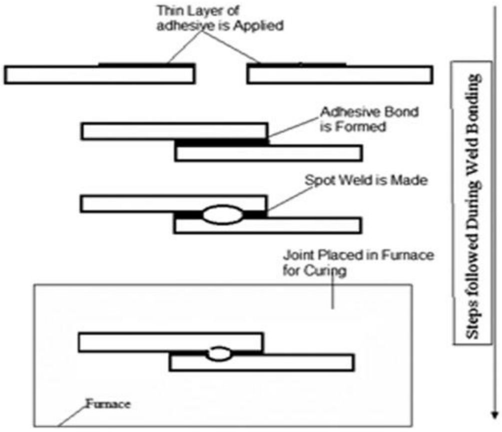


Figure 2: Schematic representation of steps in weld-through technique of weld bonding (Mittal et a. 2012)

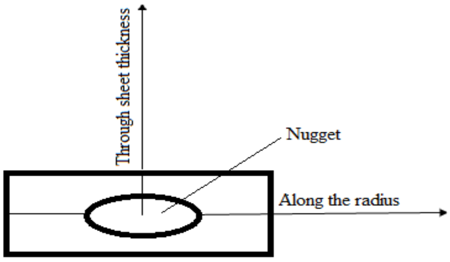


Figure 3: Schematic diagram showing direction of hardness measurement from the centre of the weld nugget of weld bond

3 RESULTS & DISCUSSION

3.1 Microstructure

The micrographs of the different location in weld nugget of weld-bond prepared using welding current of 18 kA, weld time of 6 cycles and welding pressure of 0.5 MPa are shown Fig. 4 (a-c). The microstructure of base metal depicted alpha aluminium and second-phase particles in aluminium matrix (Fig. 4 a). The heat affected zone exhibited coarser grain structure than base metal and weld nugget (Fig. 4 b). At the centre of weld nugget, fine dendritic structure was observed while columnar dendritic structure was noticed near the fusion boundary as shown in Fig. 4 (c). These observation are in agreement with Cross et al. (1994) as it was reported that in general the microstructure of spot weld metal of the non-heat-treatable alloys i.e. 5xxx alloy is composed of columnar, epitaxial grains with a cellular or columnar-dendritic substructure with inter-dendritic eutectic constituent i.e. Mg_3Al_2. Apart from the above common micro-constituents observed in weld metal and base metal Al-Mg-Mg alloy, weld nugget of weld-bonds also exhibited inclusions (Fig. 5). These inclusions develop primarily due to entrapment of by-products produced due by thermal decomposition of adhesive during spot welding. The heat affected zone around the weld nugget showed coarsening and recrystallization due to weld thermal cycle experienced by the base metal during spot welding. There changes are expected to cause softening of heat affected zone in weld bonds of Al-Mn-Mg alloy.

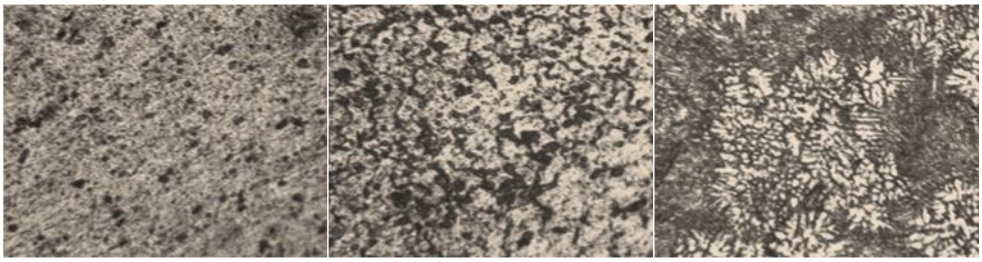


Figure 4: Optical micrographs of the different location of weld-bond a) base metal, b) heat affected zone and c) fusion zone (100X)

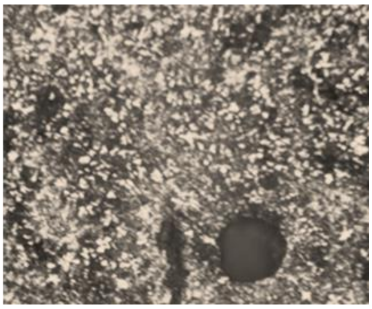
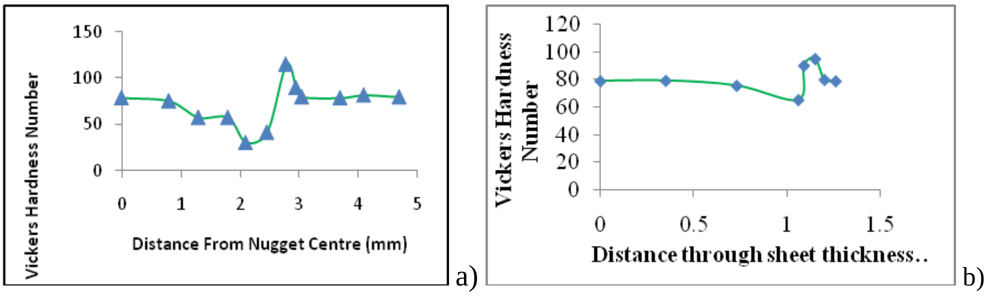


Figure 5: Macrograph of weld nugget of weld-bond inclusion due to present of adhesive (100X)

3.2 Microhardness

The hardness in the weld et zone of weld bond was measured in two directions one along the radius of the nugget (major axis) and the other along the sheet thickness (minor axis) and results of the same are shown in Fig. 6(a, b). The hardness at the centre of the weld nugget was found to be approximately same as that of the base metal. On approaching from weld nugget centre towards the fusion boundary reduction in the hardness of weld nugget was observed. This variation in hardness is attributed to difference in grain structure of the weld near fusion boundary and at the centre of the weld nugget. Finer grain structure at centre of weld nugget results in higher hardness than that near fusion boundary. The dissolution of magnesium and manganese in alpha aluminium matrix is expected to increase the hardness of HAZ by solid solution strengthening. However, coarsening of the aluminum grain would be having opposite effect on the hardness of HAZ.

Study of the variation in hardness of weld bond developed using different combination of spot welding parameters also showed similar trend of variation in hardness of weld nugget zone, HAZ, and the base metal. However, weld bonds were found to differ in respect of spot weld nugget diameter, depth of fusion and width of HAZ. It has been reported that the width of HAZ becomes greater for spot weld than weld-bond of Al 6061 (ASM handbook 1994). This is attributed to that fact that the presence of adhesive layer in weld-bonds reduces heat conducted from weld to base metal because thermal conductivity of aluminium (180 W/m °C) is much higher epoxy adhesive (0.22 W/m°C).



a) b)

Figure 6: Variation in hardness of weld bond from center of weld nugget in direction of a) major axis and b) minor axis

3.3 Fatigue Testing

The fatigue performance of the adhesive bond and weld bond is shown in Fig. 7 (a-b) and Table 3.

Table 3: Fatigue tests experimental results for adhesive bonding and weld bonding

Joint type	Number	Stress Ratio	Maximum Load (%of USTL), (KN)	Minimum Load (KN)	Alternating Load (KN)	Mean Load (KN)	No. of Cycles N
Adhesive Bonded Joint	**1**	**0.5**	**4.7 (80)**	2.3	1.2	3.5	**1534**
	2	**0.5**	**4.1 (70)**	2.0	1.05	3.05	**6037**
	3	**0.5**	**3.5 (60)**	1.7	0.9	2.6	**12198**
	4	**0.5**	**2.9 (50)**	1.4	0.75	2.15	**19645**
	5	**0.5**	**2.3 (40)**	1.1	0.6	1.7	**24553**
Weld	**1**	**0.5**	**10 (80)**	5	2.5	7.5	**1314**

Bonded Joint	**2**	**0.5**	**8.8 (70)**	4.4	2.2	6.6	**4456**
	3	**0.5**	**7.5 (60)**	3.7	1.8	5.6	**8789**
	4	**0.5**	**6.3 (50)**	3.1	1.5	4.7	**14367**
	5	**0.5**	**5.0 (40)**	2.5	1.2	3.7	**19000**
	6	**0.5**	**3.7 (30)**	1.8	.95	2.7	**22367**

In general, the fatigue lives of both weld-bond and adhesive bond increase with reduction in maximum tensile-shear load applied during fatigue test. Weld bonds offer longer fatigue life than adhesive-bond under identical loading condition. Fatigue strength of weld bonds was found almost two times greater than of adhesive bonds in range of load studied in this work. This improvement is primarily due to the fact that application of adhesive in weld bond reduces stress concentration which in turn increases the ultimate shear tensile load carrying capacity. The adhesive provides an extra strength to the joint and protects the spot-weld nugget from minor eccentricities during fatigue testing. Observation of fracture surface of the weld-bond sample and comparison with adhesive-bonded joints, showed that an unbonded area exists around the weld nugget, which is formed primarily due to two reasons: a) the damage of the adhesive layer by heat generated during spot welding, and b) the evolution of gases generated by the thermal decomposition of the adhesive around the nugget. Both these factors in turn reduce the bonded area of the joints (Dwivedi et al., 2010). Chang et al. (2001) also concluded that under applied loads, the stresses in weld-bonded joints are low and uniform, so that weld-bonded joints have better mechanical properties and fatigue performance than spot weld. The spot weld in the weld-bonds can provide higher tear strength than adhesive-bonded joint.

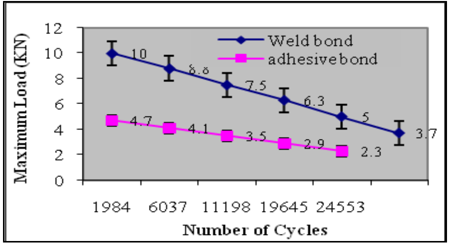


Figure 7: Fatigue test results of adhesive bond and weld-bond

3.4 Fatigue Fracture Surfaces

The photographs of fatigue fracture surface of adhesive bond and weld bond are shown in Fig. 8 (a, b). The fatigue fracture surfaces of adhesive bond shows failure of both a) adhesive layer and b) metal surface-adhesive interface. However, area on fracture surface corresponding to adhesive failure is more than that of metal surface-adhesive interface (Fig. 8a). The fatigue fracture surfaces of weld-bond show failure from three distinct ways: a) failure of adhesive layer, b) failure of metal surface-adhesive interface and c) failure weld nugget zone. Area on fracture surface corresponding to adhesive failure is significantly greater than that of spot weld zone and metal surface-adhesive interface (Fig. 8a). The shining fracture surface in weld nugget zone of the weld bond suggests the metallic failure due to overloading as shown in Fig. 8 (b). Higher fatigue strength of weld bond than adhesive bonds can be attributed to the metallic failure of the weld bonds from weld nugget zone. Closer look of fatigue fracture surfaces of weld bond using scanning electron microscopy showed fine shallow elongated dimples (like parabolas) indicating failure under tensile shear loading (Fig. 9 a, b). The fracture surface also exhibited long deep secondary cracks at the centre besides few shallow fine cracks near the edges as shown in Fig. 9 (c, d).

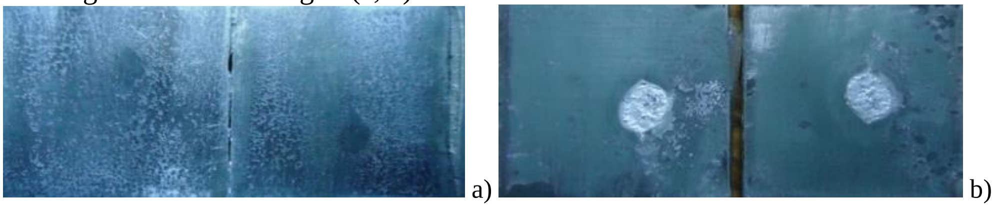

a) b)

Figure 8: Photographs of fatigue fracture surface of (a) adhesive bond and (b) weld bond

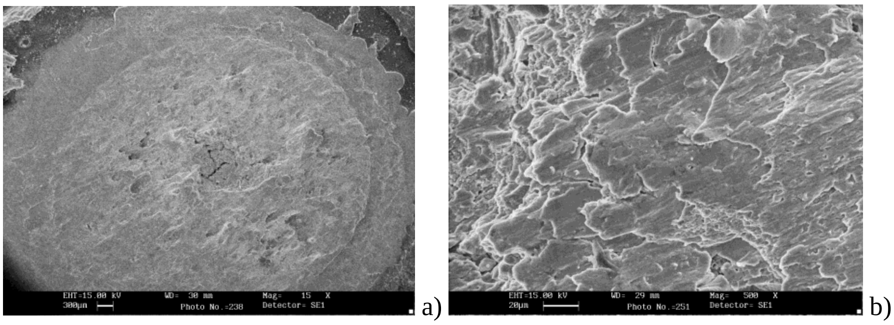


Figure 9: SEM Fractographs of weld bonded Al 5052 H32 under conditions of tensile shear load a) macrograph of entire fracture surface of weld bond and b) micrograph of fracture surface showing elongated dimples

4 CONCLUSION

Based on above results and discussion, it is concluded that-

- Weld nugget of weld bond consists of finer dendritic structure at the centre and columnar dendritic structure near the fusion boundary in the weld nugget. Weld bonds showed tendency of inclusion formation due to presence of adhesive.
- Hardness at weld nugget centre is greater than that near weld fusion boundary. The peak hardness in weld bond is developed in the HAZ.
- Fatigue strength of weld-bond is almost two times greater than adhesive bond joints. The fatigue performance of weld bond is better than adhesive bond especially at high maximum tensile shear load.

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