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MECHANICAL PROPERTIES OF FRICTION WELDED 6063 ALUMINIUM ALLOY AND MARTENSITIC STAINLESS STEEL

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ABSTRACT

The mechanical and metallurgical properties of 6063 aluminium alloy / 410 martensitic stainless steel friction welds were studied. Friction welds produced from low friction pressures and high forging pressures exhibited high tensile strength and failed within the aluminium alloy substrate. Welded samples failed at the 6063-aluminium alloy and stainless steel interface, showing poor ductility. An increase in the forge pressure increased tensile strength of dissimilar welds. Tensile strength and impact strength are maximum at the condition of low friction pressure, high forge pressure and low burn-off length. The losses of axial shortening are a good correlation with friction pressure and forge pressure. The axial shortening is maximum at the condition of low friction pressure and high upset pressure. Maximum axial shortening gave maximum tensile strength. Detailed microstructure and micro hardness analysis were performed to study the interface of the dissimilar welding.

Keywords: *6063 Aluminum Alloy, 410 Martensitic Stainless Steel, Friction Welding, Axial Shortening.*

1. Introduction

Friction welding is a technique that is used to join bulk components essentially having rotational symmetry. In this welding method, the components are brought into contact, and with one of them remaining stationary, the other is rotated while pressure is applied. When the temperature of the interface has reached an appropriate value, the rotation is halted, while the pressure remains unchanged or increased [1–5]. This method, while consuming little time, leads to intensive plastic deformation at the welding temperature. The welding of aluminum to steel is of particular interest, since the resulting products join the very different but favorable properties of each component, namely, the high thermal conductivity and low density of Al, and the low thermal conductivity and the high tensile strength of steels [6]. The demand for aluminum/steel and especially aluminum/stainless steel joints has therefore increased in many areas including cryogenic applications, spacecraft, high vacuum chambers and cooking utensils owing to their superior properties. In these structures aluminum has been partially replaced by stainless steel. In this case, it is necessary to join stainless steel to aluminum alloys [7,8]. The earlier application of aluminum/steel friction welding, which has resulted in considerable cost saving, is the production of down hanger assemblies. These consist of a mild steel billet joined to aluminum alloy bar, for use in aluminum smelters [9]. The properties of the interface of Al/steel components depend on the choice of the material to be welded. The most commonly used are pure Al or Al-Mn-Si as the aluminum component, and ferritic carbon steels or austenitic stainless steels as the steel component [10]. The problems concerning friction welding of different metals is not only associated with their individual properties such as hardness, melting point, etc., but also with the reactions taking place at the interface. These reactions can lead to the occurrence of brittle inter-metallic phases or other undesired components. In Al/steel friction welding, plastic deformation of the carbon steel or stainless steel component has also been observed. The deformation causes a reduction in the grain size at the outer sections of the weld leading to an increase in the micro hardness. The quality of a weld is determined by the properly set welding parameters. The choice of the welding parameters influences the microstructure.

2. Experimental Work

2.1. Parent metals

The parent metals employed in this study are AISI 410 Martensitic stainless steel and 6063 aluminium alloys. The composition of the parent metals is given in Table1.

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Table 1: Composition of Parent Materials

Al	Cu	Mg	Si	Fe	Mn	Zn	Ti	Cr
Bal	0.1	0.4-0.9	0.3-0.7	0.6	0.3	0.2	0.2	0.1

Composition of AISI 410 Martensitic Stainless Steel

C	Si	Mn	Cr	S	P	Ni	Fe
0.12-0.17	1	1	13	0.03	0.01	-	Bal

Martensitic stainless steel rod of 75mm and 6063 aluminium alloy rod of 100mm lengths are used in this experimental work with 16mm diameter rod.

2.2 Friction welding

Welding is performed on a continuous drive friction-welding machine at a speed of 1500 rpm in a continuous and step less variable speed machine of 10 KW capacity. In the continuous drive friction welding process a stationary member is pressed against a rotating member with an axial pressure. The relative motion generates frictional heat, which causes the material to soften and plastically deform. After a preset displacement has occurred, the machine is rapidly braked, and the pressure is increased to generate a high quality solid-state weld. During welding, the primary parameters (friction pressure, forge pressure, burn-off length and rotational speed) are continuously monitored and recorded. Few more trials are carried out with different parameters in order to get defect- free welds. The main parameters employed are friction pressure, forge pressure and burn-off length (length loss during friction/forge stage). Trial welds were made by varying one parameter keeping other parameters constant to find the limits.

2.3 The mechanical tests

The specimens are turned to required size and cleaned with acetone after machining. The aluminium alloy sample is fixed in a rotating member while stainless steel sample is fixed in a stationary member. The welding parameters are selected in a computer as per requirement. In this experiment, the friction pressure, forge pressure and burn-off length are varied while rotational speed and duration of welding are fixed. After welding the sample is taken out from the machine and tensile sample is prepared according to ASTM-E8 standard. The joint efficiency is measured in terms of the tensile strength of welded metal divided by tensile strength of weaker metal of dissimilar metal {(Tensile strength of weld joint / Tensile strength of softer metal) x100 (%)} [11]. The mechanical properties like tensile strength and joint efficiency of welded sample are recorded with increase in friction pressure (Table 2) and with increase in forge pressure (Table 3).

Table 2: Tensile Strength for Different Friction Pressure

Forge pressure = 146.34 MPa, Burn-off length = 1mm

Friction pressure, MPa	Tensile strength, MPa	Joint efficiency
24.40	168.835	78.528
73.20	108.427	50.432
97.58	96.809	45.027

Table 3: Tensile Strength for Different Forge Pressure

Friction pressure = 24.4 MPa, Burn-off length = 1mm

Forge pressure, MPa	Tensile strength, MPa	Joint efficiency
97.58	142.503	66.281
146.34	168.835	78.528

The welded V-notch impact specimen is prepared according to Charpy test dimensions using milling machine. The dimensions of charpy test are 55mm x 10mm x 10mm and V-notch is prepared at interface of the welded sample of 2mm depth and 45^0 angle as shown in Figure 1**.** The toughness property of welded dissimilar metal is recorded after experimentation with increase in friction pressure (Table 4) and with increase in forge pressure (Table 5).

Fig. 1 Charpy Impact Test Sample of Dissimilar Metal

Table 4: Toughness for Different Friction Pressure

Forge pressure = 146.34 MPa, Burn-off length = 1mm

Friction pressure, MPa	Toughness, Joules
24.40	37.68
73.20	28.64
97.58	22.00

Table 5: Toughness for Different Forge Pressure

Friction pressure = 24.4 MPa, Burn-off length = 1mm

Forge pressure, MPa	Toughness, Joules
97.58	29.84
146.34	37.68

2.4 Axial shortening

The axial length of the sample is measured using digital vernier caliper before welding and after welding. The difference is called as axial shortening. In observation the shortening of axial length is observed in 6063 aluminium alloy side only and there is no axial shortening in martensitic stainless steel side. The axial shortening decreases with the increase in friction pressure (Table 6) while it increases with forge pressure (Table 7).

Table 6: Axial Shortening for Different Friction Pressure

Friction pressure, MPa	Axial Shortening, mm
24.40	20.88
73.20	5.21
97.58	4.65

Table 7: Axial Shortening for Different Forge Pressure

Forge pressure, MPa	Axial Shortening, mm
97.58	11.76
146.34	20.88

2.5 Micro hardness

The micro hardness of samples is measured using MMT-3 micro hardness tester with a load of 100gf. The readings are taken on the aluminium alloy and martensitic stainless steel sides from interface as shown in Fig. 2. The values are shown in Table 8 with increase in forge pressure.

Table 8: Hardness Variation for Different Forge Pressure

Forge pressure, MPa	Micro hardness at interface, Hv
97.58	93.2
146.34	138.3

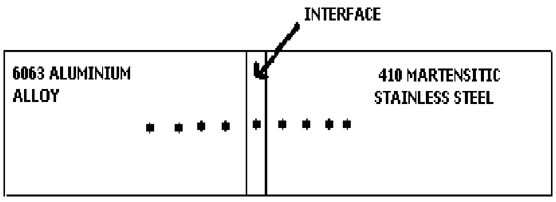

Fig. 2 Micro Hardness in Dissimilar Metals

2.6 Metallography

Low magnification stereomicroscope of Leitz make was employed for observing the welded joint. Micro structural features and grain deformation were observed under Scanning Electron Microscope.

3. Results

3.1 Metallography and visual examination

Views of friction weld joints shown in Fig. 3 exhibits higher flash with increase in forge pressure and lower flash with increase in friction pressure. The flash was observed to be from aluminium alloy and martensitic stainless steel did not participate in the flash formation suggesting deformation is mainly limited to aluminium alloy side. Typical cross-sectional view of the weld (24.4-146.34-1) and microstructure details at the center and periphery are presented in Fig. 4 shows that the deformation is mainly confined to aluminum alloy.

The central region consists of fine grains while peripheral region consists of coarse grains. Typical microstructural features in various regions of the weld across the interface are shown in Fig. 5. The central region consists of equiaxed grains and is confined to aluminium alloy. Adjacent to this region bent and elongated grains are observed on the 6063 aluminium alloy side. The martensitic stainless steel side consists of parallel-banded features adjacent to the central equiaxed grain structure at the interface.

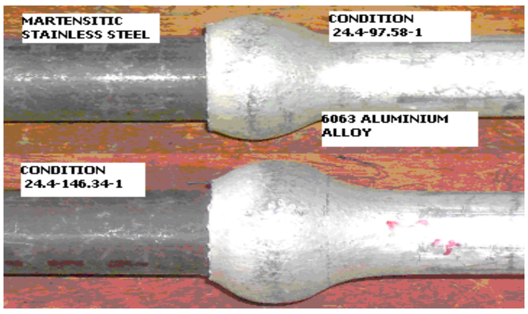

Fig. 3(a) Higher Flash with Increasing Forges Pressure

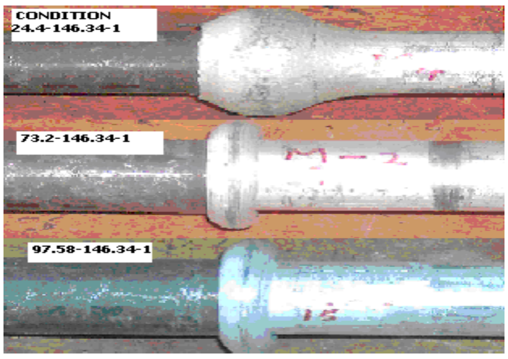

Fig. 3(b) Lower Flash with Increasing Friction Pressure

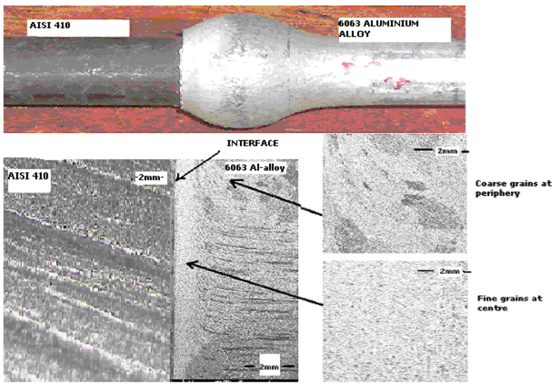

Fig. 4 Typical Friction Weld and its Cross-Sectional View (24.4-146.34-1)

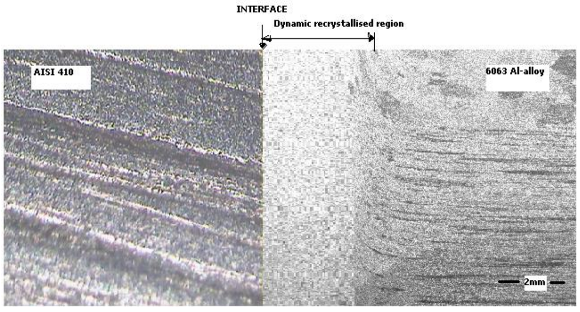

Fig. 5 Micrographs of Friction Weld at Center (24.4-146.34-1).

3.2 Mechanical properties

The tensile strength decreases with increase in friction pressure (Fig.6) due to high heat generation that leads to coarse grain structure. The fine micro structural features at high forge pressures can be attributed to the higher strain energy while the coarse microstructures are due to prolonged retention time at high temperature that resulted grain coarsening. The tensile strength is higher at low friction pressure and high upset pressures gave more plastic deformation and higher flash at interface. The flash developed at interface due to forge pressure and it increases with increase in forge pressure and take place in aluminium alloy side only. The tensile strength is lower at high friction pressure and low forge pressures that resulted poor deformation and lower flash at interface. The poor thermal conductivity of martensitic stainless steel result is the coarse in aluminium alloy side only. The deformation rate depends on heat developed at the interface during friction welding, which depends on friction pressure and burn-off length. The impact strength/toughness also decreases with increase in friction pressure (Fig.7) due to grain coarsening. Toughness observed is higher at higher forge pressure as shown in Fig.8. This is resulting due to equiaxed fine grain formation with higher degree of working at the interface.

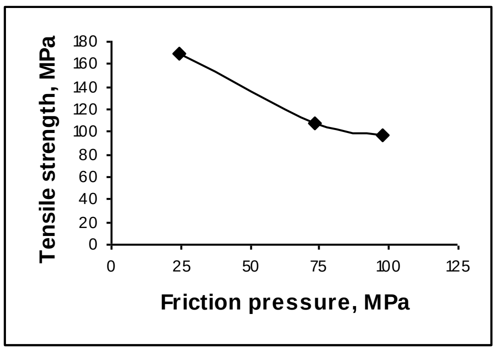

Fig. 6 Tensile Strength vs Friction Pressure

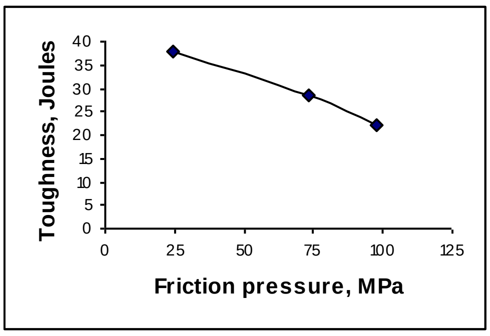

Fig.7 Toughness vs Friction Pressure

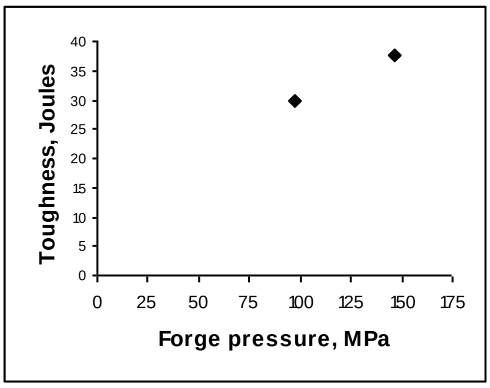

Fig. 8 Toughness vs Forge Pressure

The failure of the welded component is occurred in the interface of the weld (Fig 9). This supports the fact that joint has good interface forming with good toughness. The tensile strength of welded joint is less than the tensile strength of weaker material (Aluminium alloy) as shown in Table 9. However the failure in the interface is due to intermetallic compound.

3.2 Shortening of axial length

Low friction pressure allows sufficient time for the adjacent material to heat up and stabilizes the weld with respect to heat distribution resulting high axial shortening. The shortening of axial length increases

Fig. 9 Tensile Failure of the Friction Welded Component at Interface

Table 9: Comparison of Tensile Strength for Parent Metal and Welded Metal

Material	Tensile strength, MPa
Martensitic Stainless Steel	450
6063 Aluminium alloy	215
Friction welded Martensitic Stainless Steel & 6063 Al-alloy	168.835

with increase in forge pressure while it decreases with increase in friction pressure. The tensile strength increases with increase in shortening of axial length (Fig. 10) due to high degree of working resulting in higher flash. Friction pressure and sufficient burn-off results in softer region at interface during rotation and application of high forge pressure axially, resulting plastic deformation in the form of flash and length loss shortening of axial of welded sample.

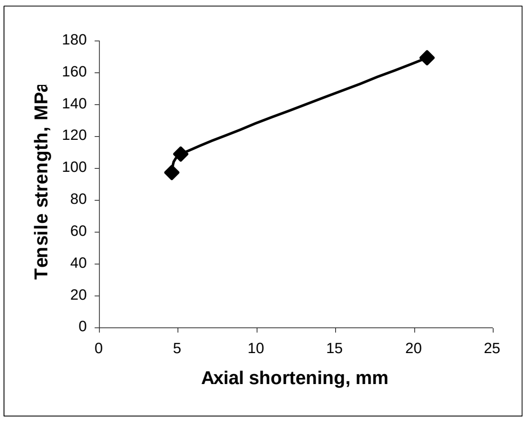

Fig. 10 Tensile Strength Vs Axial Shortening

3.3 Micro hardness

The micro hardness at interface also varies with welding parameters. The micro hardness is higher at higher forge pressure (Fig. 11) at the interface of dissimilar welding of aluminium alloy and martensitic stainless steel. The micro hardness trend suggests that low friction pressures and high forge pressures leads to high hardness. This can be due to lesser heat input available at the center resulting in high degree of working. This situation leads to conditions similar to cold working where the hardness increases commensurate with the degree of cold working. This high hardness due to heavy cold working is a result of high-density dislocations during plastic deformation. Weld combination 24.4 – 146.34 – 1, shows higher hardness in the group of welds as shown in Fig. 12. The micro hardness increases with increasing axial shortening.

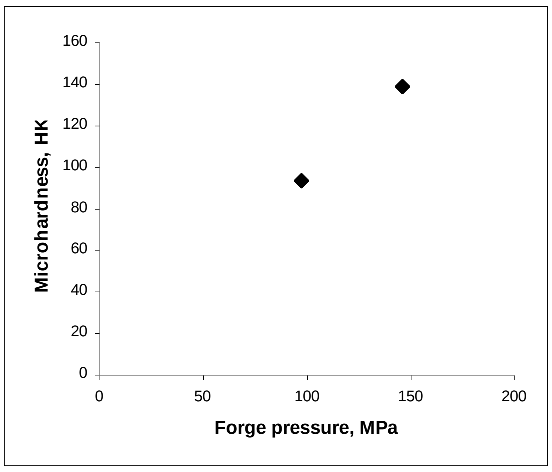

Fig. 11 Micro Hardness Increases at Interface with Increasing Forge Pressure

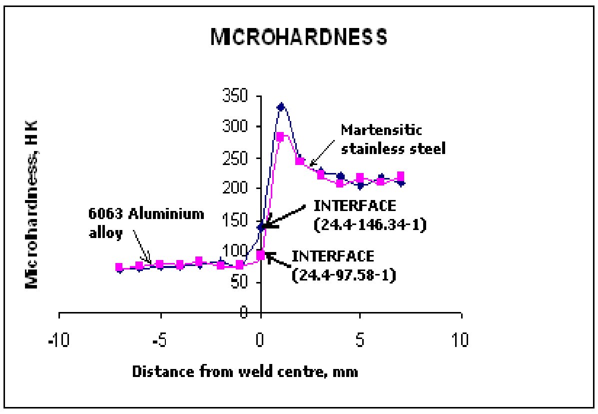

Fig. 12 Micro Hardness Varying with Weld Combinations

4. Discussions

The different thermal and physical properties of the materials to be welded in dissimilar metal welding (heat capacity, thermal conductivity, relation between hardness and temperature) generally results in asymmetrical deformation. Martensitic stainless steel has lower thermal conductivity and greater hardness at higher temperatures when compared to aluminium alloy. For this reason martensitic stainless steel does not undergo extensive deformation while aluminium alloy specimen undergoes extensive deformation. The same phenomenon has been reported during friction welding of aluminium to steel, etc. [12]. The formation of upset collar (flash) on the aluminium alloy side only is due to low strength of the aluminium alloy. A narrow zone of deformation (Fig. 4) on the martensitic stainless steel suggests that this region undergoes deformation although it does not take part in the upset collar suggesting that the deformation is not extensive.

The shortening of the aluminum alloy rod substantiates the view that only aluminum alloy takes part in upset collar formation only. The coarser grain structure observed in low forge pressure combination can be attributed to lower degree of working of the material than at high forge pressure that result in higher degree of working. The central region consists of fine grains, while the peripheral region consists of coarse grains (Fig. 4) [13]. The fine grain size at the central region is due to dynamic recrystallization. The temperature of the peripheral region would be higher [14] and therefore exhibits coarse grain size.

The mechanical and thermo-physical properties of dissimilar substrates will have a major influence on the properties of the dissimilar joints because the temperature attained by each substrate markedly depends on the thermo-physical properties of the two substrates and on the joining parameters selected. Consequently, the flow stress–temperature relations for each substrate will have an important influence on the joint properties produced during friction welding. In general high forge pressures resulted in high toughness and tensile strength. Fine grain structure exhibited high strength and low toughness while coarse grain microstructure exhibited a reverse trend.

5. Conclusions

The tensile strength increases with increase in forge pressure. The axial shortening increases with increasing forge pressure. The tensile strength is maximum at maximum axial shortening. The toughness is also maximum at maximum axial shortening. Microstructure shows fine grains at the center and coarse grains at periphery. Micro hardness at interface increases with increasing forge pressure. At the condition of low friction pressure and high forge pressure yielded better mechanical properties.

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