http://dx.doi.org/10.21172/ijiet.93.03

Mechanisms of friction and their correlation to bond strength of friction welded Ti-6Al-4V similar welds, Low Carbon steel-Stainless steel and Aluminium-Copper dissimilar welds.

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Abstract- There have been various mechanisms used to explain the phenomenon known as friction. This paper studies these mechanisms and identifies the correct mechanism/combination of mechanisms for the case of friction welding of Low Carbon steel-Stainless steel combination, Aluminium to Copper and similar Ti-6Al4V welds. It tries to correlate bonding based on tensile strength obtained based on the mechanisms which are predominant in each of these friction welded combinations.
Keywords- Mechanisms of friction, recrystallization, Upset pressure, Bond unsaturation

I. INTRODUCTION

Friction is probably due to various mechanisms that may appear in different proportions under different circumstances. The word friction is generally used to describe the gradual loss of kinetic energy in many situations where bodies move relative to one another. "internal friction' dampens vibrations of solids. This type of friction is due to the interactions that happen at the atomic or molecular level. Viscous friction slows the internal motion of liquids. Skin friction acts between a moving aeroplane and the surrounding air." Solid friction is the friction between two solid bodies that move relative to each other. The need to control friction is the driving force behind this study. In many cases, low friction is desired(bearings, gears, materials processing operations) and sometimes high friction is the goal(brakes, clutches, screw threads, road surfaces, friction welding, friction stir welding and friction surfacing).

II. THEORIES OF FRICTION

A. Early theories

Amontons saw the cause of friction as collision of surface irregularities. He determined the two main laws of friction, often called Amontons' laws which are:

- The friction force is proportional to the applied load.
- The friction force is independent of the apparent area of contact.

The same relationships had been observed by Leonardo da Vinci 200 years earlier.

Euler (1707) a Swiss physicist said that friction was due to hypothetical surface ratchets as shown in Figure 1.In friction welding, ratchets or unevenness of the surface is may have a very negligible contribution to the bond strength because the frictional force and the upset force are high and the unevenness evens out very soon.

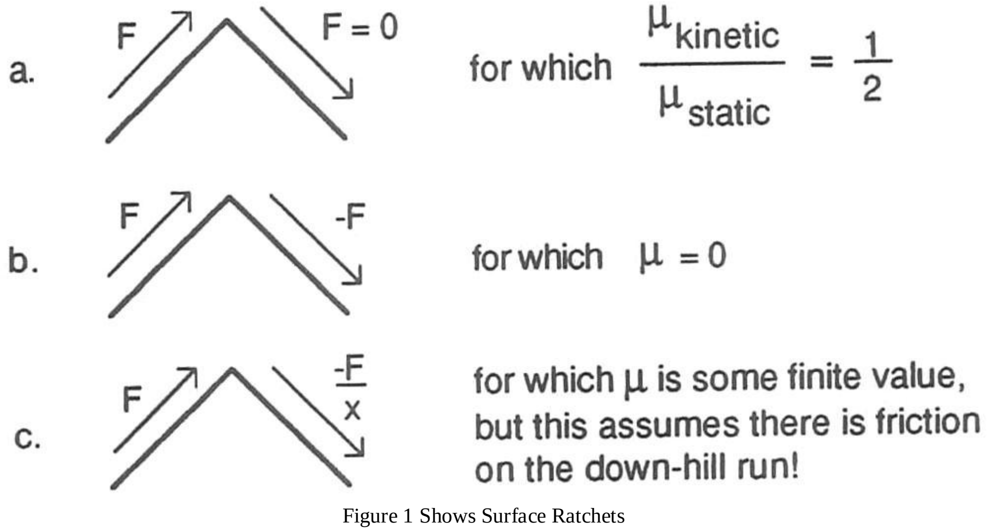

Figure 1 Shows Surface Ratchets

Euler developed the first clearly analytical approach to friction. He was also the first to use μ for coefficient of friction and to draw a clear distinction between static and dynamic coefficients μ_k and μ_s. According to Budinski (2001), Coulomb said friction was due to the interlocking of asperities. He was well aware of attractive forces between surface because of the discussions of that time on gravitation and electrostatics. However, he discounted adhesion as a source of friction because friction is usually found to be independent of area of contact. In recent times, dry friction is almost universally known as "Coulomb" friction in mechanics and physics.
Samuel Vince, an Englishman said that $\mu_s = \mu_k$ + adhesion. Leslie argued that adhesion can have no effect on a section parallel to the surface since adhesion is a force perpendicular to the surface. Rather, friction must be due to the sinking of asperities. Sir.W.B. Hardy stated that friction is due to molecular attraction across an interface. He found that co- efficient of friction of clean glass was about 0.6, but on glass covered with a single layer of fatty acid, it was 0.06. Hardy was also aware that molecular attraction operates over short distances and hence, he differentiates between real area of contact and apparent area of contact. Tomlinson also elaborated on this molecular adhesion approach.

B. Current theories
Research in friction reached a firm foundation with the work of Bowden and Tabor (1950) [1]and Dowson (1979) [2]in the mid 20th Century. The adhesion theory of friction is often attributed to Bowden and Tabor. Figure 2 shows a typical adhesive junction pull off and wear generated by friction in the weaker material.

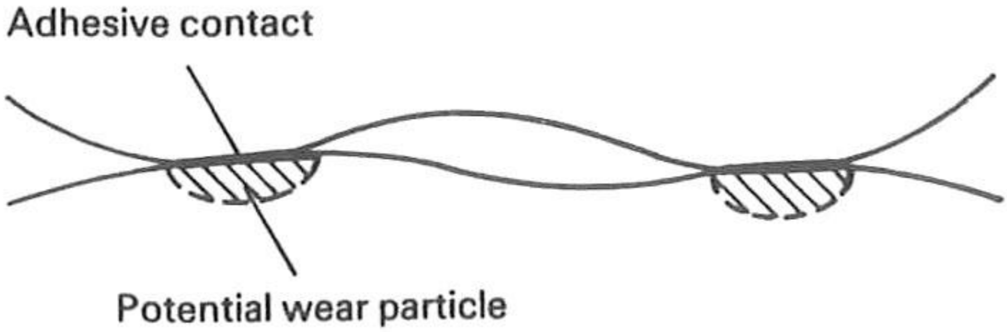

Figure 2 -Adhesive junction pull off

The interfacial forces caused by adhesion dominate friction when the surfaces are very clean. The contacting surface asperities cold weld together and form intimate atomic bonds across the interface. Recent work using Atomic force microscopy has shown that when two surfaces are brought closer together at a distance of a few atomic diameters, they will attract each other to form interatomic bonds according to Guo (1989).[3] This type of attraction seems to be the case in the case of welding of Ti-6Al-4V as will be explained in this paper.
From an engineering viewpoint, strong adhesion between sliding surfaces becomes important only for very clean surfaces in a very high vacuum. The amount of adhesion is affected by possible surface alterations like segregation of solute or impurity atoms on the surface, formation of compounds etc. In this work, especially for Aluminium-Copper welding, surface preparation is very important and clean surfaces give better Tensile Strength of weld after friction welding.. All the welding was done with both surfaces being smooth.
Buckley (1981)[4] has demonstrated that the adhesion between two surfaces depends on the degree of matching between the crystal planes. The highest adhesion and friction forces are observed for matched planes of the same material.
Adhesive friction may also be related to other fundamental properties. One such property is the degree of d-valence bond character of the transition metals. Titanium, which has a very high degree of bond unsaturation, shows a strong tendency to bond with almost anything, such as a matching Titanium surface or a non-metal. In this case also when preliminary experiments were conducted on Ti-6Al-4V as shown in Table 1.bonds were very good and good Tensile Strength of weld was obtained.

C. Microscopic mechanisms
Some of the mechanisms on a microscopic scale as reported by Larsen et al (1992) [5] are shown in Figure 3.

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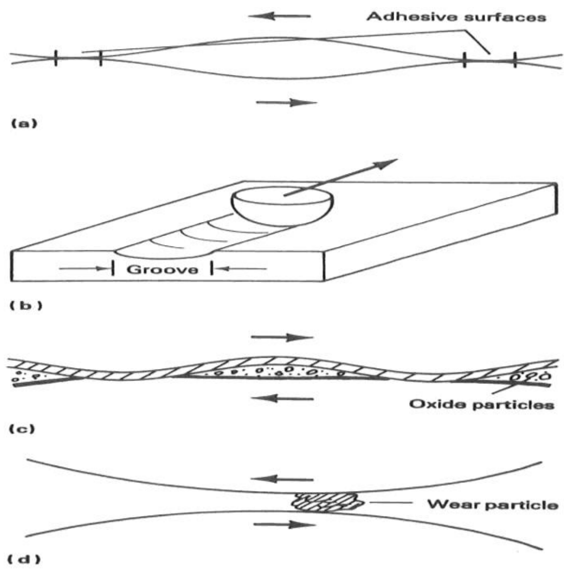

Figure 3- (a) Adhesion (b) Plowing (c) Deformation and fracture of oxide (d) Trapped wear particles

The microscopic mechanism that are involved, to varying degrees in generating friction are (1) Adhesion (2) Mechanical interactions of surface asperities (3) Plowing of one surface by asperities on the other (4) deformation and/or fracture of surface layers such as oxides and (5) interference and local plastic deformation by third bodies, primarily agglomerated wear particles, trapped between the moving surfaces.

III. EXPERIMENTAL WORK

A. Tensile testing

Tensile testing was done using ASME Section IX-2004 standards.The equipment used was a UTM Machine model UTN-40 with a maximum capacity of 400kN..The welded specimen was prepared according to the procedures given in ASME Section ix-2004 and typical dimensions of the specimen are shown below in Figure 3.

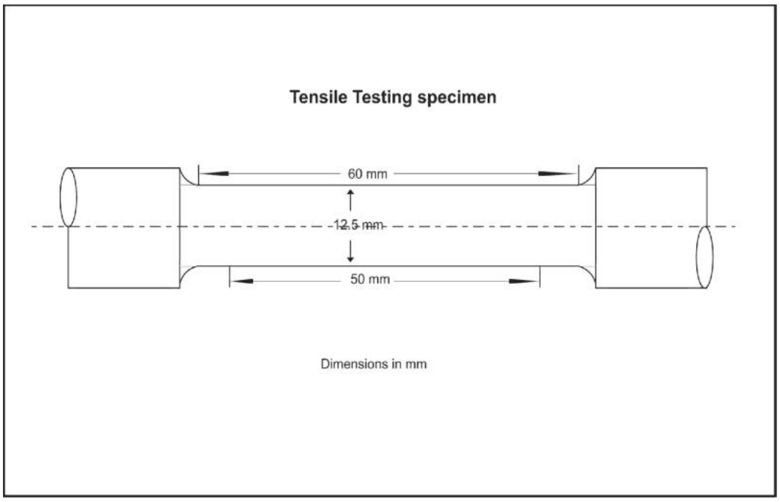

Figure 3- Tensile Testing specimen

Friction welding of low Carbon Steel –Stainless Steel was performed. Many trial runs were conducted out of which 3 important friction welding parameters which are relevant to this work are reported.

Table 1-Friction welding parameters for Low Carbon Steel-Stainless Steel combination

S No	Friction Pressure (MPa)	Upset Pressure (MPa)	Burn-off length (mm)
1	80	160	1
2	160	280	1
3	160	280	2

Table 2- Friction welding parameters for Ti-6Al-4V

S.No.	Friction force (MPa)	Upset force (MPa)	Burn off length (mm)
1	118	236	1.5
2	118	236	3
3	118	472	1.5
4	118	472	3
5	236	236	1.5
6	236	236	3
7	236	472	1.5
8	236	472	3

IV RESULTS AND DISCUSSION

Results are shown below

Table 1-Tensile strength of Ti-6Al-4V

Sample No	Yield strength (MPa)	UTS (MPa)	% elongation	Fracture location
1	777.03	1006.05	9.94	Base Metal
2	734.05	979.9	7.8	Base Metal
3	887.08	976.45	12.0	Base Metal
4	883.36	977.42	6.8	Base Metal
5	892.71	1035.38	10.2	Base Metal
6	880.71	1007.70	9.6	Base Metal
7	869.57	991.47	9.6	Base Metal
8	883.19	1001.22	8.0	Base Metal

Since all the specimens failed in the base metal, it can be concluded that welds are stronger than the base metal.

A. Comparison of available theories and current work

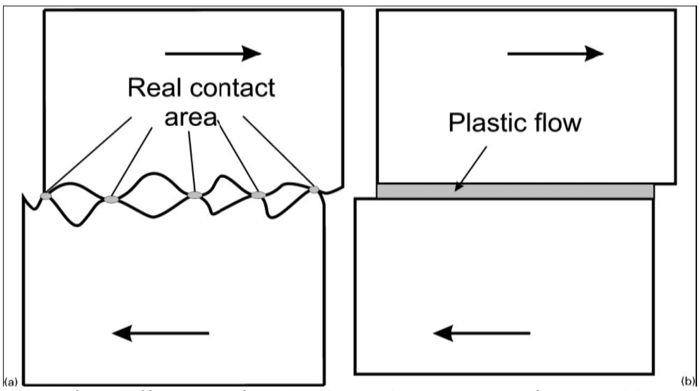

Figure 4- Schematic of two different interfacial conditions that may arise in friction welding-Maalekian (2007)

In the case of Aluminium-Copper joints, it is proposed that at lower Upset Pressures, the first mechanism is predominant. So, the heat generated due to asperity contact holds the dissimilar metal surfaces together. As the Upset pressure increases, chances are that plastic flow readily occurs and also chances are that the whole area is in contact and the 2^{nd} mechanism starts dominating at higher Upset pressures

Sahin et al (2005) [6] have shown that in dissimilar metal joints diffusion can either improve or deteriorate the weld properties. For instance when welding a high carbon alloy steel to a medium plain carbon steel, the decarburisation across the weld may increase the ductility of the joint. In this research work, ductility of the joint is not bad and there is a possibility of some decarburization in the Low Carbon-Stainless Steel joints. On the other hand, formation of hard interlayers, such as intermetallic phases when joining iron and Aluminium, copper and titanium, etc., may cause the joint to become brittle. This seems to be the case for the Aluminium-Copper joints. It is seen that ductility is very poor of the order of 0.5-1.0% and hence there is a possibility of brittle intermetallic formation.

B. Aluminium-copper welds
Vill et al [7] showed that co-efficient of friction increases as speed of rotation decreases. The graph shown below gives variation of co-efficient of friction with speed of rotation

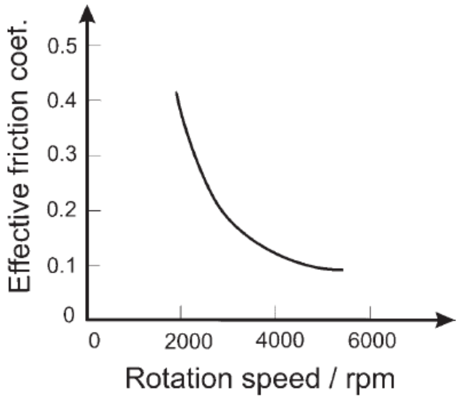

Figure 5- Variation of friction Co-efficient with speed

The curve can be extrapolated to lower values of rpm, for example 500rpm where co-efficient of friction is expected to be even higher. When co-efficient of friction is higher, higher frictional heat is generated which could lead to better bonding and higher tensile strength. The heat generation equation will be a function of friction co-efficient $q_{FW} = \mu p_N \alpha\omega \cos(\omega t)$ according to Vairis et al (2000).[8]

It was also recognised by Bowden et al (1950) that two mechanisms comprising shearing of asperity junctions and ploughing of hard asperities through a softer surface contribute to friction. Hollander et al.(1963)[9] also found that the effective coefficient of friction decreases as rotational speed increases. Further, Gel'man et al (1959)[10]

also discovered that the friction coefficient decreases with an increase in pressure and velocity, and with a rise of temperature it increases rapidly at the beginning and then decreases. The reason was attributed to deep ploughing in the initial stage which accounts for the high coefficient of friction. The increase in the temperature brings about deep ploughing to alter into polishing and the friction coefficient is dramatically reduced.

Therefore, while Coulombic friction controls the interface forces at low loads according to Amontons'law, as the load increases to the point where the real area of contact is equal to the apparent area of contact, friction becomes independent of pressure and takes on the value ty, which is the shear yield stress of the workpiece material.

In Aluminium-Copper welds, Higher strengths were obtained at lower speeds. The higher strengths at low speeds can be attributed to better contact and hence better bonding at lower rpms. Generally, at lower speeds of rotation, frictional heat generated is high and it is expected that bonding also will be better. So, at lower speeds of rotation, higher frictional heat produced could be one of the factors responsible for better bonding and hence, higher tensile strength But, in the case of friction welding of Aluminium-Copper, the stick slip mechanism of bonding is prevalent. This mechanism does not depend much on the heat generated. It mainly depends upon the upset pressure. Hence, it is suggested based on the results of friction welding of Aluminium-Copper at low speeds of revolution, both higher frictional heat generated and higher upset pressure contribute to better strength.

C. Low carbon steel-stainless steel welds
Wanjara et al (2005),[11] Duffin et al (1973)[12] and Hazlett et al (1966)[13] have done metallographic examination of weld and HAZ areas for different materials. During friction welding, the metal within the HAZ experiences a temperature change and a gradient of strain and strain rate and undergoes a number of microstructural changes. Generally, the HAZ can be divided into different zones according to Hazlett et al (1966)[13] : (i) contact zone (severe plastic deformation zone).This is the zone where rubbing occurs and fragments of metal transfer from one rubbing surface to the other. The strain rate is controlled by the rotational velocity. The material in this zone is subject to severe plastic deformation. This zone has a very fine grain structure due to severe straining and full recrystalisation (ii) fully plasticised zone (dynamic recrystalisation zone). The material is subject to a considerable amount of plastic deformation but it does not participate in the rubbing and material transfer process. Within this region, the dislocation density is increased extremely and, due to the a real contact area is asperities with small fraction of apparent contact area and deformation occurs only in asperities (i.e. sliding condition); full plasticity at interface arises when real and apparent areas of contact are equal (i.e. sticking conditions). At sufficiently high temperature, the material undergoes dynamic recrystallisation. The grains in this zone are fine and equiaxed (iii) partly deformed zone. The strain rate, temperature and amount of plastic deformation are lower than those appeared in zone (ii). The microstructure

becomes coarser because of the associated reduction in strain and strain rate (iv) undeformed zone. In this region, depending on the peak temperature, the material (e.g. steel) may undergo phase transformation, but plastic deformation does not occur. Grain growth may take place in this zone. In this research work, it is found that fine, equiaxed grains are found in the weld region as shown in Figures 6 and 7.Recrystallization has been shown to occur. However, only 3 zones could be seen –Parent metals and the recrystallized weld zone.These are shown in Figures below

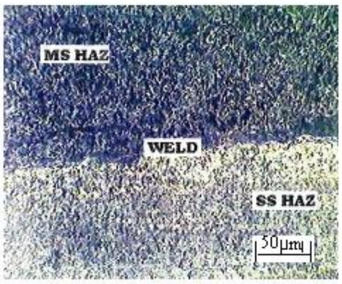

Figure 6 F.P-80MPa,U.P-160MPa,BOL-1mm

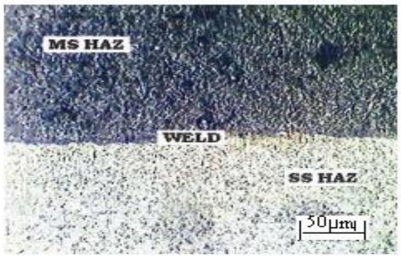

Figure 7 F.P-160 MPa,U.P-280MPa,BOL-1mm

SEM-EDS for friction welded steels are shown below

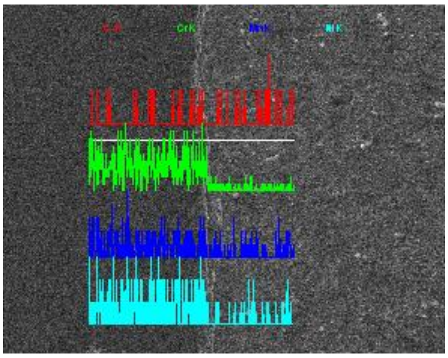

Figure 8- F.P=80,U.P=160B.O.L=1mm

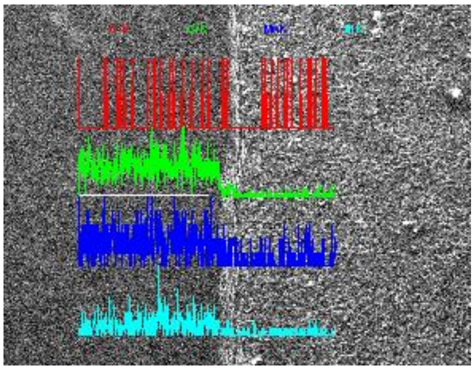

Figure 9-F.P=160U.P-280B.O.L=1mm

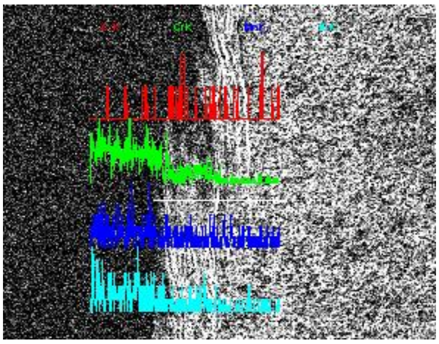

Figure 10-F.P=80,U.P=280,B.O.L=2mm

In Figure 8, the SEM-EDAX photograph shows a sudden drop in the Chromium percentage from the Stainless steel side to the low carbon steel side. Figure 9 shows a slightly gradual drop and Figure 10 shows a more gradual drop in Chromium across the interface.

The upset pressure and burn-off length are more in the case of the friction welding parameters used in Figure 9.Hence, the weld region is also wider and Chromium diffusion also seems to have occurred to a small extent into the weld region, thereby explaining the gradual drop in Chromium content. Presence of Chromium in the welded region could enhance corrosion and could also lead to a stronger joint. The tensile strength for the specimen shown in Figure 8 was 475 MPa, Figure 9 was 505MPa and Figure 10 was 522 MPa. One of the factors for the enhanced tensile strength could be the presence of Chromium at the weld interface.

D. Comparative friction welding mechanisms

The Table 6 shows Comparative Mechanisms which are predominant in different Friction welding combinations.

Table 6- Mechanisms of friction welding

S.No.	Material Combination	Predominant Mechanism
1	Similar Steels	Recrystallization and Diffusion
2	Aluminium to Copper Aluminium to Copper(low speeds of rotation)	Cold deformation due to High Upset Pressure Higher frictional heat and High upset pressure
3	Ti-6Al-4V	Bond Unsaturation

V. CONCLUSIONS

The predominant mechanism affecting tensile strength for friction welding of low carbon steel to stainless steel was thought to be recrystallization at the weld and diffusion of Chromium at the weld region.

The mechanism affecting friction welding of Aluminium to Copper and bond strength of the welds could be cold deformation due to high upset pressure without any recrystallization at moderate and high speeds of rotation, but a combination of high frictional heat generated at low speeds and high upset pressure, at low speeds.

The mechanism having a major impact on the friction welding and bond strength of Ti-6Al-4V could predominantly be bond unsaturation.

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