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Comparison of Friction Welding Technologies

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Abstract

Linear friction welding is a solid state joining process in which a joint between two metals can be formed through the contact of a plasticised layer at the interface of the adjoining specimens. This plasticised layer is created through a combination of frictional heating, which occurs as a result of pushing a stationary work piece against one that is moving, in a linear reciprocating manner, and applied force. The process is currently employed as a niche technology for the fabrication of titanium alloy bladed disk (blisk) assemblies in aero-engines,. However, interest is growing in utilising the process in a wider range of applications that also employ non aero-engine metallic materials.

Introduction

Friction welding is a new method of joining two materials in solid state. This method entails thorough understanding of how coalescence between joining faces occur so that sound components are produced. The basic principles that one needs to be fully aware of are the following:

The concept of static and sliding friction and how the frictional forces and consequential heat are generated and The presence of contaminated and oxide layers in a material surface and how it prevents coalescence to occur and Unevenness of the surfaces at microscopic scale and how this can be dealt with so as to prevent asperities and How plastic deformation can be effected so that unwanted contaminated and oxide layers can be ejected out and the Diffusion of atoms at the interface which may result in undesirable formation of inter-metallic compounds.

Once the principles as stated above are understood, then engineering aspects such as what are the friction welding parameters that govern effective coalescence have to be arrived at. These require elaborate computations of the parameter ranges that have to be set in the machine. One also should understand the consequences of welding outside the range in each parameter.

After going through the science and engineering aspects, it is imperative to have a thorough knowledge of different types of friction welding technologies and where these can be applied. Each type of technology is unique and require an in-depth study of the benefits and limitations of each so that best results can be obtained. The technological intricacies also call for understanding the servo-mechanical systems that are needed to apply the forces, rotational, orbital and linear motion devices that are required to effect dynamic motions, monitoring systems that have to be developed to control all the welding parameters and NDT techniques that have to be employed to assess the soundness of the joints etc.

The purpose of this article is to highlight the basics of the above stated points so that holistic pictures of the friction welding technologies are garnered.

Concept of static and sliding friction

Friction is the force resisting the relative motion of solid surfaces, fluid layers, and material elements sliding against each other. When surfaces in contact move relative to each other, the friction between the two surfaces converts kinetic energy into thermal energy. Dry friction resists relative lateral motion of two solid surfaces in contact. The two regimes of dry friction are 'static friction' between non-moving surfaces, and *kinetic friction* (sometimes called sliding friction or dynamic friction) between moving surfaces. Figure 1 explains the concept of static and sliding friction.

From Figure 1, it can be seen that frictional force reduces during sliding friction and hampers temperature increase. The coefficient of static and sliding friction for different are different material combinations are indicated in the table below:

TABLE

Material combination	Static coeff.of friction	Kinematic coeff.of friction
Al to steel	0.61	0.47
Brass to steel	0.35	0.45
Cast Iron to Copper	1.05	0.75
Copper to steel	0.53	0.35
Teflon to Teflon	0.04	0.04

Only specific material combinations which have high coefficient of friction of friction can be friction welded.

Heating effects during Friction welding

The transient heating and cooling temperature distribution for steel rods are shown in below. From the temperature distribution, it is seen that the calculated peak Temperature in heating for stainless steel at 90sec and 40sec is about 613^{O} C and 378^{O}C and for eutectoid steel is 578^{O}C and 270^{O}C at 200sec and 70sec, peak temperatures in heating for steel rods are obtained at a distance of 7mm from the interface at 490 and 790rpm with constant heat generated. Cooling starts of as the entire process, where the last heating temperature profile has been utilized. Similarly transient heating and cooling temperatures are obtained for similar parameters at 14, 21 and 28mm from the interface. The temperature increases rapidly at the interface, and gradually towards the end of the steel rods. The transient heating and cooling temperature distribution in eutectoid steel is faster. This is due to the higher thermal conductivity in eutectoid steel compared to that in stainless steel. Due to the lower thermal conductivity stainless steel is taking less time for welding when compared to eutectoid steel. As the speed (rpm) is increasing temperature as well as time is decreasing in both the steel rods, but the variation is nearly similar. This can be attributed to accommodating heat losses at interface in the analytical model. A typical plot of temperature v.s time is given in Figure 2.

The thermal heating profile likely exhibits the interaction between the frictional heating power and the frictional characteristics on the surface. However, in a real situation, the pressure distribution is not uniform with time as the two work pieces move in sinusoidal fashion. While the axial force remains constant, the area of contact between the two work pieces changes with movement and leads to the oscillation of the axial pressure at the interface. The increase in the temperature softens the ductile material and brings about deep ploughing on the contact surfaces. Then, the contact seems to have been altered into a polishing-like action and the friction coefficient is dramatically reduced.

Dislodging of contaminated & oxide layers in Friction welding

Any material surface will inherently contain contaminated and oxide layers. Some of them are loose and others very adherent (Figure 3). While loose contaminated layers will disappear on heating, adherent layers must be dislodged and ejected by ploughing or squeezing action through plastic deformation.

In solid state welding, joining has to take place without fusion at the interface. No liquid films must be present at the interface. Also, the two surfaces must be clean without any residues or contaminants. For joining to occur,

Further, the undulations of the mating surfaces at the microscopic level must be evened out and an intimate contact of the virgin surfaces must be ensured so that atomic bonding takes place. This is achieved by plasticizing the mating layers and squeezing the atomic layers. During friction welding there are chances that the dislodged and broken contaminated layers getting embedded at the interface. This will reduce the strength of the joint. To avoid this, friction welding parameters must be carefully optimized. Also, suitable NDT method such as the one based electrical conductivity must be evolved.

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Plastic deformation at high temperatures

Plastic deformation in the broadest sense means permanent deformation in the absence of external constraints (forces, displacements). Though plasticity by slip (Figure 4) is the most important mechanism of plastic deformation, there are other mechanisms as well. Many of these mechanisms may act in conjunction to give rise to the observed plastic deformation (Figure 5).

At high temperatures, where strain rate is the important parameter instead of strain, a power law equation can be written as below between stress and strain rate. The effect of strain rate is compared by performing tests to a constant strain

$$\sigma = \left[A\dot{\varepsilon}^{m} \right]_{\varepsilon,T}$$

A constant M index of strain rate sensitivity If m = 0 stress is independent of strain rate (stress-strain curve would be same for all strain rates) If m ~ 0.2 for common metals If m | 0.4 to 0.9, the material may exhibit super plastic behaviour. If m = 1 material behaves like a viscous liquid

$$m = \left. \frac{\partial \ln \sigma}{\partial \ln \dot{\varepsilon}} = \frac{\dot{\varepsilon}}{\sigma} \frac{\partial \sigma}{\partial \dot{\varepsilon}} \right|_{\varepsilon,T}$$

Like strain hardening, thermal softening is also defined. Thermal softening coefficient ( ) is also defined as below:

$$\nu = \frac{\partial \ln \sigma}{\partial \ln T}$$

What is the importance of „m" and „ v"

We have seen that below recrystallization temperature „v" is „the" important parameter. Above recrystallization temperature it is „m" which is important. We have also noted that it is necking which limits the ductility in uni-axial tension.
Necking implies that there is locally more deformation (strain) and the strain rate is also higher locally. Hence, if the „locally deformed" material becomes harder (stronger) then the deformation will

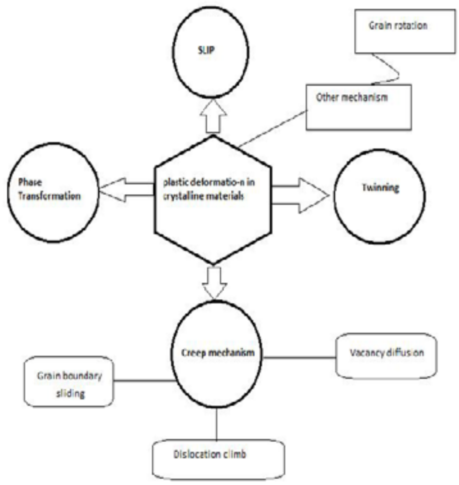


Figure 5 : Other plastic deformation mechanisms

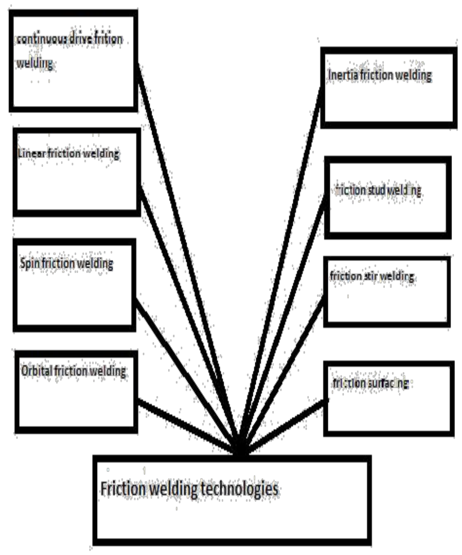
„spread" to other regions along the gauge length and we will obtain more ductility.
Hence having a higher value of „n" or „m" is
Beneficial for obtaining good ductility. Variation of strength and plastic strain with temperature are indicated in Figure 6 and 7.From the above discussion, it is clear that at high temperatures, may plastic deformation mechanisms may act contributing increased strains which is measured by softening coefficient. Materials having higher softening coefficient can be easily friction welded.

Metallurgical characteristics of the interface

Yet another aspect that requires careful examination is the metallurgical aspects of the friction weld interface. Many a times formation of inter-metallic compounds particularly when dissimilar materials are

welded. In the case of friction weld between Al and Cu, micro-structural observations showed that a mixed layer of aluminium and copper that includes brittle inter-metallic compounds such as $CuAl_2$, CuAl, and Cu_9Al_4 are formed in a dissimilar aluminium alloy/copper weld

Similar problems are encountered during Friction Stir Welding between Al and Steel. Figure 9 shows the morphologies of the joint produced by Friction Stir Welding : (*a*) using pin tool A at axial force of 15.6 kN, rotational speed of 200 rpm, travel speed of 1.06 mm/s and (*b*) using pin tool B at



18.7 kN Figure 11: Different Friction Welding Technologies

axial force, 200 rpm rotational speed, 1.06 mm/s travel speed, respectively. Parametric investigation showed that welds between Al/steel had a very limited process window. The best quality welds with good surface appearances were made under those two conditions. Lap welds with both pin tools showed two distinct stir zones with typical FSW weld zones (stir zone, HAZ on advancing and retreating side).

In the case of Friction Stir Welding between Al and Mg, again the interface is heterogeneous as can be seen in Figure 10

Such inter-metallic compound formation at the interface may seriously hamper the soundness of the joint.

Advantages of Friction Welding technologies

Weld complex shapes or circular shapes at all stages of components: finished, semi-finished, and raw stock and Optimizes material usage; near net-shapes or for cost containment and Solution-based manufacturing and machining process to reduce material cost, reduce tooling cost, reduce R&D cost, reduce weight, and/or reduce machining cost, Solution-based manufacturing and machining process to increase quality, increase manufacturing through-put, and/or increase speed-to-market and Readily join combinations of steels & non-ferrous metals and also Dissimilar metal combinations can be joined also Powder metal components can be welded to other powder metals, forgings, casting or wrought materials which yields in High production rates there by Joint strength equal to or greater than parent metal which is also Self-cleaning action reduces or eliminates surface prep time and cost, Joint preparation is not critical; machined, saw cut, and even sheared surfaces are wieldable and Integrity of welded joints is very reliable, Highly precise & repeatable process and also 1OO% metal-to-metal joints yield parent metal properties also No filler metals, fluxes, or protective gases needed, Joints can withstand high temperature variations and Reduced scrap parts rate.

Types of Friction welding technologies

Different Friction welding technologies in vogue are depicted in Figure 11. In each case, the way friction is imparted and also the occurrence of plastic deformation is different.

Rotary Friction Welding (Direct drive)

This is most commonly used method in Friction welding. Figure 12 indicates the

rotary type of Friction welding both continuous drive and inertia welding.

In continuous drive friction welding, rotating component is continuously driven

by a motor and this component is pressed by a stationary component as indicated in Figure 13.

During friction and upsetting stage, rotation is imparted and a brake is applied after the joining is completed. Different events that take place are indicated in the figure. This type of welding is suitable for carbon steel and other metal applications. Dissimilar materials can also be joined by this technique.

Rotary Friction Welding (Inertia)

In Inertia Friction Welding, the required energy for the joining of components is obtained from the stored energy of fly-wheel. One component is held stationary while the other is attached to the rotating fly-wheel (Figure 12). As soon as the components are brought into contact the energy of the fly-wheel is converted into frictional heat that is used for the welding of components (Figure 14). During contact the speed of the fly-wheel is lowered and heat is generated and during this period, axial force is increased. The process is complete, once the fly-wheel stops. Inertia Friction Welding has a broad range of applications across the manufacturing industry. Some of the benefits are listed below:

Strong welds for all geometries, No matter what type of weld interface configuration you need - combinations of tubes, bars, plates, discs, etc. - Inertia Friction Welding produces strong, consistent joints and allows you to develop complex parts that would otherwise be difficult or cost-prohibitive to create. Narrowest heat affected zones among rotational friction welding applications, More parent material properties are retained in joints with narrower heat affected zones - leading to more uniform properties throughout the part, higher joint efficiencies, and stronger welds. Short weld times save you time and money, Fast cycle times mean that more parts can be welded in less time. Using submerged arc welding, a large diameter cylinder rod can take upwards of 20 minutes to weld - with Inertia Friction Welding, joining takes less than five minutes. Increased mechanical strength due to helical flow of weld, In Inertia Friction Welding, the use of a flywheel causes a helical flow pattern in the joint. This increases the joint's mechanical strength and the part's overall material strength. Easy to manage with only two quality control parameters - RPM and Pressure, Because RPM and Pressure are machine controlled, the Inertia Friction Welding process is uniformly consistent and independent of the operator's skill level. No other welding process has as few control variables, making quality control, monitoring and troubleshooting much easier, faster, and cost effective. Pre-calculable parameters allow process to be mathematically scaled, Because energy, load and weld area have an exact mathematical relationship, we can build and run feasibility tests on reduced scale models at less cost and with less risk

Spin or Orbital Friction welding

This type of welding is generally used for thermoplastics where the material in the vicinity of the interface softens and moves outwards as a result of spinning and pressure. Once a homogenous layer of soft material is available at the interface sufficient force is applied to join the parts together. The spindle speed can range from 100 to 1000 rpm depending on the size of the part and materials to be joined. Spin or Orbital friction welding is similar to rotary friction welding but both welded parts are rotated in the same direction and at the same speed, but with their axes offset by up to 3mm (Figure 15). At the end of a weld the relative movement is ended by returning both parts to the common axis of the machine and the welding force is maintained or increased. For continuous drive rotary friction welding the surface velocity increases from the centre of the contact area to its outside edge, however, orbital friction welding has the benefit of a uniform surface velocity over the whole contact area. It is possible to join non-round components and a number of separate parts in one friction weld sequence. Although it has been demonstrated for many materials and joint configurations, there are no known industrial users.

Linear Friction welding

Linear friction welding (LFW) has many advantages over conventional welding processes. It is robust, repeatable, fast, and is capable of producing high quality joints in many engineering metals and metal combinations. Despite these benefits, the number of industrial applications is limited and confined to the aerospace industry. Due to the process being applied primarily to titanium alloys, most articles relate to the welding of this material, although there are exceptions. The linear friction welding process is rapidly developing into an important manufacturing technology for high quality joining of engineering materials. The energy required for Linear Friction Welding is an important issue due to economic and environmental reasons, but is not currently fully understood. A comprehensive evaluation of the energy input during Linear Friction Welding of a medium carbon steel with different process parameters. This calculation is based on an analysis of force and displacement data from the machine, which takes momentum into account. The analysis shows that energy input to the weld is minimized with high frequencies and rubbing velocities, however there is a considerable amount of energy lost in oscillating the machine tooling under these conditions. Furthermore, analysis of the force indicates that a peak load occurs just prior to the samples being aligned which is probably caused by ploughing of the samples during welding. The LFW process works by holding one component stationary and oscillating another component against it under an applied load this is shown in the schematic diagram of the equipment used for the process in Figure 16. 1(a). The motion between the parts generates heat which causes the material at the interface to plasticize and soften. As the process progresses, the applied load causes extrusion of the material from the joint, and any surface impurities are removed in the flash. One of the advantages of this process is that the parts can be of arbitrary shape, unlike the related process of rotary friction welding where the parts must be cylindrical. Much of the early reported work on the process describes how the process may be divided into four phases:

Phase I

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Initial phase. During this phase heat is produced by columbic friction between the rubbing surfaces. Asperity contact exists between the two surfaces, and as heat is generated, the asperities soften and deform, increasing the true area of contact between the parts.

Phase II

Transition phase. During this phase the true area of contact increases to 100% of the cross-sectional area. This transition is accompanied by an increase in the force required to oscillate the parts.

Phase III

Equilibrium phase. During this phase the shear force reaches a steady state value and significant axial shortening occurs through the generation of flash. The plastic zone gets progressively larger during this phase.

Phase IV

Deceleration phase. The relative motion is ceased and the two parts are aligned. In some applications an additional forging force may also be applied.

Ploughing mechanism in LFW

Rubbing velocity: Under high temperatures and pressures a sticking condition often exists between the two rubbing surfaces. Therefore the rubbing causes shearing of the material and the flow stress is dependent on the strain-rate of the material. Hence, higher velocities increase the strain-rate leading to a greater flow stress which requires a higher interfacial force to cause the deformation. Interfacial area: The interfacial area between the two parts varies linearly with the displacement. Hence the maximum area is obtained when the two parts are aligned and is minimum at the maximum amplitude or displacement. This effect will lead to higher values of the interface force when the parts are aligned. Ploughing effects: This effect is explained in the diagrams shown in the Figure 17. This ploughing effect would also explain why the flash is produced in pulses rather than being a continuous flow which has been observed by several authors.

Friction Stir Welding

Friction Stir Welding is achieved by a non-consumable tool that does not soften during the operation. The tool is pressed on the interface of the components to be welded together. The tool softens both of the components around the interface and mixes the softened material from both of the components around the interface to provide bonding. The mechanisms occurring are indicated in Figure 18.

The two halves to be joined must be rigidly fixed before the welding operation. The pin, which is an integral part of the tool, is plunged into the metal to help stir it up; the shoulder of the tool generates much of the heat. As the weld is completed, the tool is withdrawn. Leaving behind a hole. The weld is designed so that such regions can be discarded from the component. The presence of a hole may not be appropriate when welding pipes or storage vessels. The hole can be avoided by designing the tool such that only the pin can be retracted automatically and gently into the shoulder, leaving behind an integral weld.

Friction Stud Welding

In this welding process a high speed rotating stud is pressed against a stationary substrate. Thus the frictional heat softens the region of contact and provides the joint. Friction stud welding is suitable for special applications whether other conventional welding techniques may not be applicable such as underwater welding. However the cost of this kind of welding is high and therefore the applicability is limited.

This technology may be considered for the retro fitting of existing structures such as steel bridges or for joining materials with different properties. In this way, for example, a hard wear resistant plate can be welded to the softer mild steel structure.

Friction Surfacing

A coating material is used in the interface of the component to be joined for this type of welding. The frictional heat generated turns the coating material into a plastic layer which consequently joins the components together when the joint is cooled (Figure 19). Since the type of material used as the coating layer the metallurgical and physical properties could be very different from those of the base component.

The deposit is inherently homogenous and has good mechanical strength and

Adherence. The interface region usually remains intact, even after resisting loads equal to the ultimate tensile strength of the weaker material. However, the bond quality at the edges of the deposit is generally poor, and this area may need to be removed. With high strength surfacing materials, the thickness of the deposit is generally small. The surface appearance depends on the material deposited, and the parameters used. Special combinations of material properties can be achieved which cannot usually be realized in monolithic materials. This reduces usage of more expensive or strategic materials. The process has been extended to deposit metal matrix composites (MMCs) by inserting hard particles into one or more holes or slots machined in the consumable bar. The material of the bar becomes the matrix, with the hard particles distributed throughout it.

Comparison of types of Friction Welding Technologies

1. Friction welding (Continuous drive):-

Salient features

One of the component has to have surface of revolution Brake system has to be very effective Parameters: Rotational speed, Heating pressure, Forging pressure, Heating time, Braking time, Forging time Applications: Cable lugs, engine valves, drill bits, electrical components

2. Friction welding (Inertia drive):-Salient features

Flywheel supplies rotational speed. No brake system Parameters :Mass of the flywheel ; Friction force ; Friction time ; Spindle speed ; Upset force ; Upset time Applications: Axle to shaft, dissimilar material combinations,

3. Orbital Friction Welding:-

Salient features: both components are rotated Size limitations Parameters: Friction force; Friction time; Spindle speed; Upset force; Upset time Applications: Rectangular rods to rectangular rods

4. Spin Friction welding:-

Salient features : One component rotated to a pre-set speed. The fixed “tail” stock is then forced against the remaining component. Mainly for thermoplastics.

Parameters: Spindle speed; Friction time Applications: Back flow Preventers,

Pressure Relief Valves, Access Covers, Petcocks, Bulkhead Fittings (up to 4")

5. Linear Friction Welding:-

Salient features: Both components are rotate size and limitations Parameters ;Friction force ; Friction time Linear speed ; Upset force Upset time Applications ; Blisk to blade, intricate lugs

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