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A Comparative Study on Linear Friction Welding for Dissimilar Metals

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ABSTRACT: *Linear Friction welding (LFW) is a solid state joining process in which a joint between two metals can be formed through the intimate contact of a plasticised layer at the interface of the adjoining specimens. When a stationary workpiece is pushed against another workpiece which is moving in a linear reciprocating manner, the plasticised layer is created through a combination of frictional heating between these two metals. This paper will cover the basics of the process and the fundamental aspects of operating a LFW machine using dissimilar metals.*
Keywords: *Linear friction welding, titanium, 304L stainless steel, nickel layer, microhardness structure.*

I. Introduction

Linear friction welding was first patented in 1929. However, the description of the process was vague. Some discussion of the concept was then recorded in the 1960s, but it was described as 'very doubtful' because of the difficulty in generating linear reciprocation. The Caterpillar Tractor Company was the next to mention the process in a patent. However, the patent primarily focused on the machine that generates the linear reciprocation and not the actual welding process. Indeed a patent search has shown that no currently valid patents exist that protect the fundamentals of the LFW process. However many patents protect certain aspects of LFW, such as particular applications, welding methods or tooling concepts.

It is actually a solid-state joining process that is a combination of extruding and forging and is not a true welding process. In this process a stationary part is forced against a part that is reciprocating in a linear manner in order to generate frictional heat as shown in (*Fig.1,2 & 3*). The heat, along with the force applied perpendicular to the weld interface, causes material at the interface to deform and plasticise. Much of this plasticised material is removed from the weld, as flash, because of the combined action of the applied force and part movement. Surface-oxides and other impurities are removed, along with the plasticised material, and this allows metal-to-metal contact between parts and allows a joint to form. Although the LFW of dissimilar materials has been almost totally unexplored, there has been a large amount of work on the RFW of dissimilar materials, with some good results produced. As the two processes are fundamentally similar (*i.e.* in both processes heat is generated by contact and relative movement between parts, and plasticised material is ejected by a combination of part movement and applied force), this provides hope that dissimilar welds can also be produced with the LFW process.

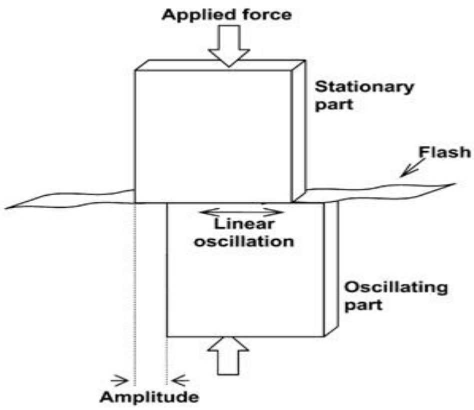


Fig.1

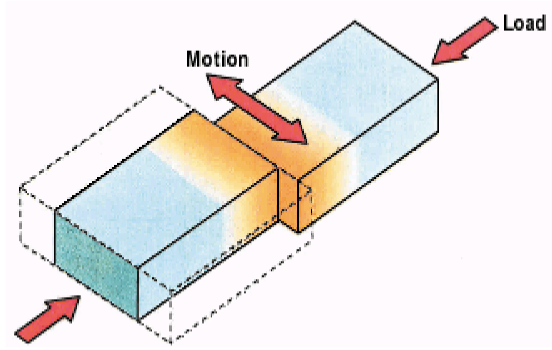


Fig.2

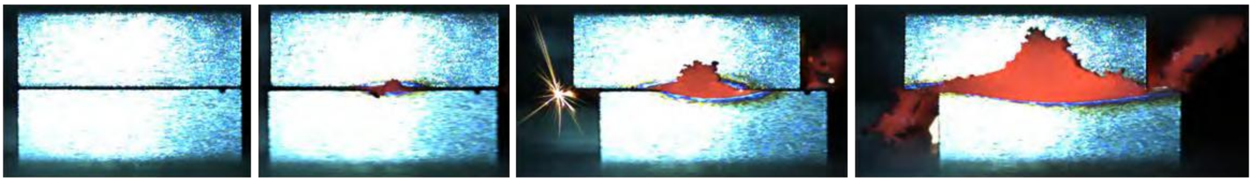


Fig.3 *1 Images taken during welding showing the different process phases*

The process can be divided into six phases: *contact* - initial advancement of actuators seating the blade onto the disc stub and applying a seating force, *ramp up* - blade oscillations start to occur, *conditioning* – maintaining the oscillations to enable frictional heat to build up, *burn-off* – material deforming plastically under compression, *ramp down* – blade decelerated to a static position, and *forging* – allowing the weld to complete under a constant pressure.

II. Linear Friction Welding Machine Operation

The machine operation of the LFW process can be broken down into six separate stages. These are:

Part clamping: The parts are held using tooling designed to withstand the forces experienced during the process. Specimen and tooling preparation is critical to the process, with accurate sides and edges needed on the specimen, and a tight-fit needed between the specimen and the tooling. This generally means that the tooling is custom built to fit particular specimen geometries.

Datum and retract: The clamped parts are brought together under a small compressive force in order to determine the location of the parts and set the machine datum to zero. The parts are then retracted to leave a small separation distance between the work pieces.

Conditioning phase: Oscillation of one of the parts is increased and stabilized over a set period (usually very quickly) and the parts are brought together under a small force for a predetermined time (*Fig.4*).

Frictional phase: The compressive force (friction force) is increased to a set level and heat is generated at the interface. The material at the interface becomes plastic and flows out of the weld, as flash, because of the shearing motion between the two parts and the applied force. This loss of material from the weld causes the parts to shorten (or burn-off). This phase usually ends, and the next is triggered, when a predetermined loss of length, or burn-off distance, is reached. However, the next phase can also be triggered after the frictional phase has continued for a predetermined time (burn-off time) or number of oscillation cycles (burn-off cycles). The LFW process is always carried out under load control, but other parameters also play a role in controlling the welding process. For example when using a burn-off distance the load is controlled throughout the welding process, however the burn-off is also monitored (although not controlled) and at a set burn-off distance the next phase (forge phase) is triggered. Similarly with burn-off time or cycles the load is controlled throughout welding and the amount of time or cycles determines the transition to the next phase.

Forge phase: The amplitude is decayed to zero over a predetermined time to ensure good alignment (usually very quickly), and a forge force is rapidly applied and held for a set time to consolidate the joint. The forge force can either be the same as or higher than (more common) the friction force.

Release phase: The welded parts are released from the clamps and removed from the machine.

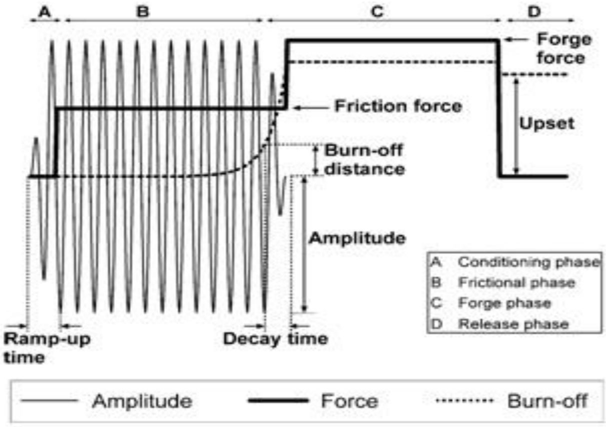


Fig.4. *Schematic diagram of the parameter traces that are obtained during the linear friction welding process A number of input variables are defined in the diagram. Burn-off is defined as the loss of length occurring as the process continues, whilst upset is the total loss of length measured after the weld has been produced*.

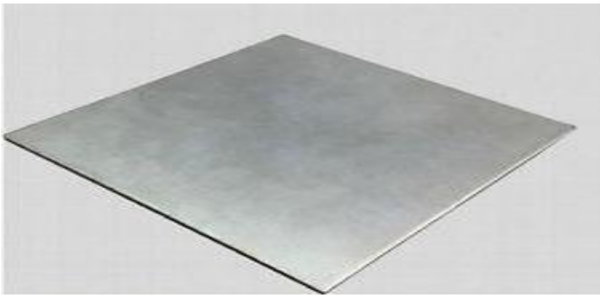
III. Linear Friction Welding Of Titanium-Stainless Steel Joints with a Nickel Interlayer Nickel Alloys

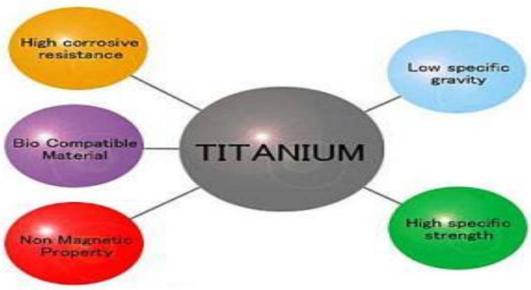
Linear Friction Welding is particularly suited to joining materials that have good high temperature properties, especially compressive yield and shear strength, and a low thermal conductivity. The good high temperature mechanical properties allow a high level of frictional heat generation, whilst the low thermal conductivity helps confine heat to the interface. This makes titanium and nickel alloys, with their good high temperature mechanical properties and low thermal conductivities, particularly suitable for the process.

The joining of titanium to steel by using conventional fusion welding techniques is resulted in major metallurgical problems. He et al. (1999). Sun et al. (1996) studied on dissimilar metal joint by convectional arc welding processes reported that the joints between Ti and Steels unsuccessful due to involve in melting of base materials.

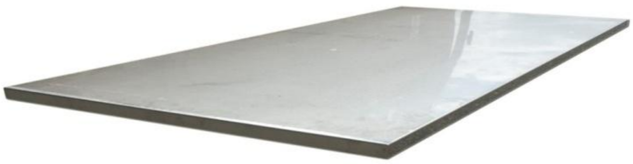
Titanium:

Titanium possesses high strength when alloyed with additional metals and elements. It is highly resistant to most types of corrosion. Most metals will corrode in the presence of salt water, acids, and other chemical solutions, however titanium shows surprising resilience to these. Titanium is also very resistant to stress corrosion cracking unlike stainless steel.



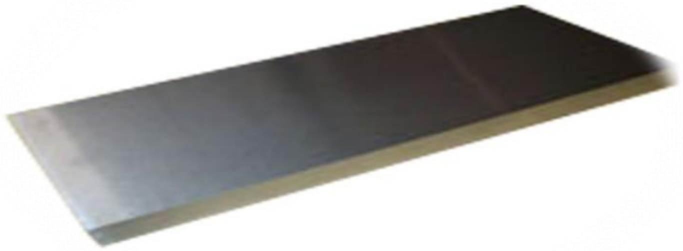


Stainless Steel (304L): 304L is a low carbon version of type 304 stainless. 304L is used almost interchangeably with 304 but is preferred for welding operations. It offers a good combination of strength, corrosion resistance and fabric ability.



Nickel:

Nickel metal has been used for many purposes and applications because of its high melting point, its resistance to corrosion, and its catalytic properties. It is face centered cubic and undergoes no phase changes as it cools from melting point to room temperature; similar to a stainless steel. All the conventional welding processes can be used to weld nickel and its alloys and matching welding consumables are available.



IV. Experimental procedure

The materials used in the present experiment were titanium and 304L austenitic stainless steel metal which are machined respectively. The contact surfaces of titanium and stainless steel specimen were polished by using a range of emery papers and alumina cloth polishing to maintain an equal surface roughness. The interlayer material such as Nickel was deposited by electro plating on the stainless substrates. The substrates were cleaned with acetone to remove the grease and enduring contaminants before performing friction welding. The welds which were made between and 304L stainless steel with nickel interlayer by linear friction welding process, each deform resistance differs greatly, in that the titanium base metal deforms by plastic deformation during joining. The titanium metal maintained as a oscillating member and stainless steel positioned in a stationary side. The produced friction weld were resulted in the physical appearance of titanium linear flash is greater than the stainless metal.

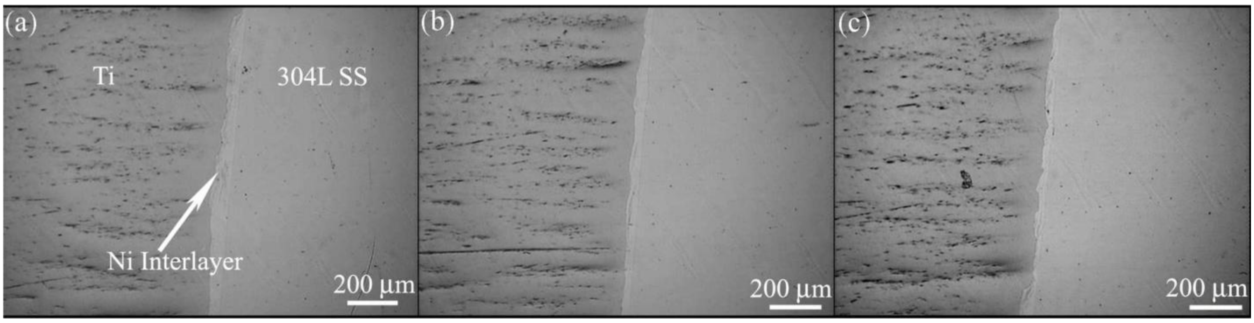


Fig.5. Different interlayer thickness of joints

The evaluation of joint strengths was conducted after making joints immediately performed a drop test for all the welds at various welding parameters. After completion of welding the resulted weld are taken out from the machine and tensile specimen was prepared as per ASTM-E8 standard. Ti was experienced to plastic deformation at higher temperature; hence the existed dynamic recrystallization had resulted in fine equi-axed grains closed to the weld interface. The thermal conductivity of stainless steel is larger than that of titanium substrate. Thus the formation of heat at interface by frictional effect is mainly produced on titanium side because of its low thermal conductivity temperature. However there is no noticeable change of recrystallization effect at the stainless side. The weld interface between titanium nickel interlayer is characterized by thin transition layer revealed at the interface region. The transition layer thickness increases with increasing friction time. The linear depends of the transition layer thickness on the square root of the friction time implies that the growth of interface caused by the diffusion.

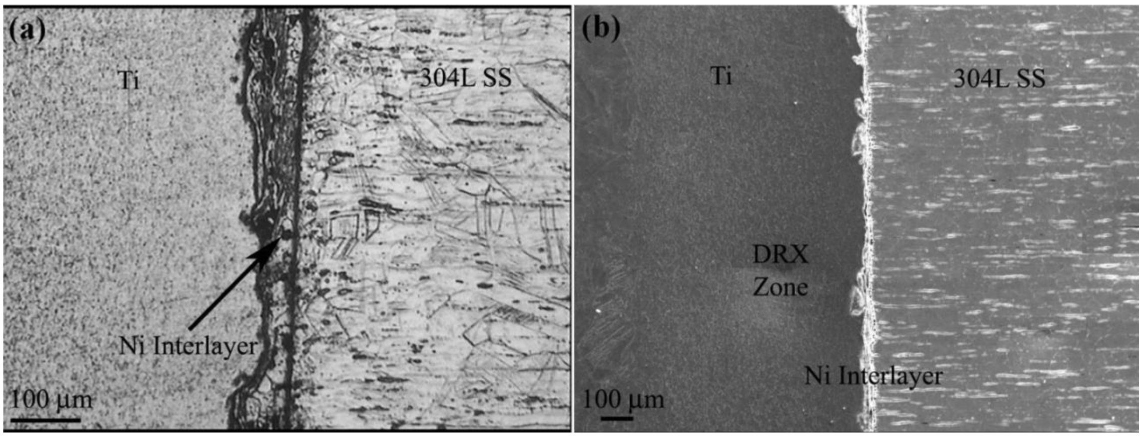


Fig.6. linear friction welded piece of titanium-stainless steel joints with a nickel interlayer.

4.1 Micro hardness distribution

The micro hardness measurement were made across the welds to identify the microstructural strength on heat affected zone, base metals, interlayer materials and both interfaces are shown in Fig. 7. The hardness profile gradually increasing from the substrates to the respective weld interface. Virtually the similar tendency of hardness distribution is identified for the two welded material are considerably increases in the dynamic crystallization zone and the highest hardness value is attained near the weld interfaces. This is due to the grain size in dynamic crystallization zone is finer than that of heat affected zone, so the dynamic crystallization zone has a higher hardness value rendering to the Hall-Petch relationship, Sato et al., (2003) . It is observed that the hardness profile in Fig.7 showing a steep increase in hardness in titanium side near the weld interface is directly related to the microstructure formed in the welds as a result of strain hardening effect during the friction welding process. The increase in hardness at stainless steel side is very less compare to titanium side, it is indicating the strain hardening effect is less and extent of deformation is limited in stainless steel compare to titanium. Based on the distribution of hardness profile it can be declared that the hardness values of the combination of intermetallic compounds were newly generated in the welds has higher value than that of substrates. The highest recorded at titanium-nickel interface can be attributed to the formation of intermetallics of titanium and nickel. All the above discussed factor can together impact and result in the hardness profile may directed that the weld interfaces is the weakest region when experienced to load. The formation Ni/Ti intermetallics at weld interface are came to the degradation of weld strength of the joints.

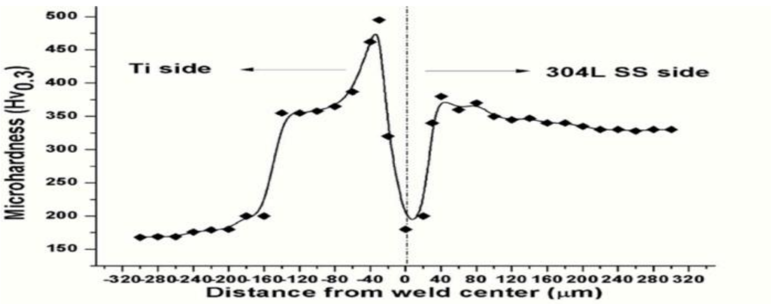


Fig. 7: Micro hardness distribution across the joints

V. Weld Ability

Most of the publicly available work on weld ability and welding parameters has been conducted on Ti-64, however similar concepts should be equally applicable to other materials. Vairis and Frost showed that for sound linear friction welds to be formed in Ti-64, a specific power input parameter must be exceeded. It was shown that frequency; amplitude and pressure have an effect on this parameter, which was defined as:

$$w = \frac{\alpha f P}{2\pi A}$$

with α being the amplitude, f the frequency, P the pressure and A the weld area. From this equation it can be seen that the power input can be increased by increasing the frequency, amplitude or pressure. A similar critical power input has also been suggested to exist for linear friction welds in 304L stainless steel.

Wanjara and Jahazi showed that another parameter, the upset, was also important in forming sound welds and demonstrated that a minimum level of upset was necessary to consolidate the weld. Therefore the power input parameter devised by Vairis and Frost cannot be used as an exclusive criterion for obtaining sound welds.

VI. Effects of Welding Parameters

The influences of various welding parameters on the size of recrystallised β grains in the near weld line region of Ti-64 welds have been reported. This work gives a good insight as to how the interface temperature varies as welding parameters are changed, as the β grain growth will be dependent on it. It was shown that an increase in frequency or pressure increases the size of the prior β grains (Fig .8). This is thought to be because an increase in power input, associated with an increase in frequency or pressure, causes the temperature at the interface to be greater. However, the increased prior β grain size could also be related to slow cooling rates when high parameters were used.

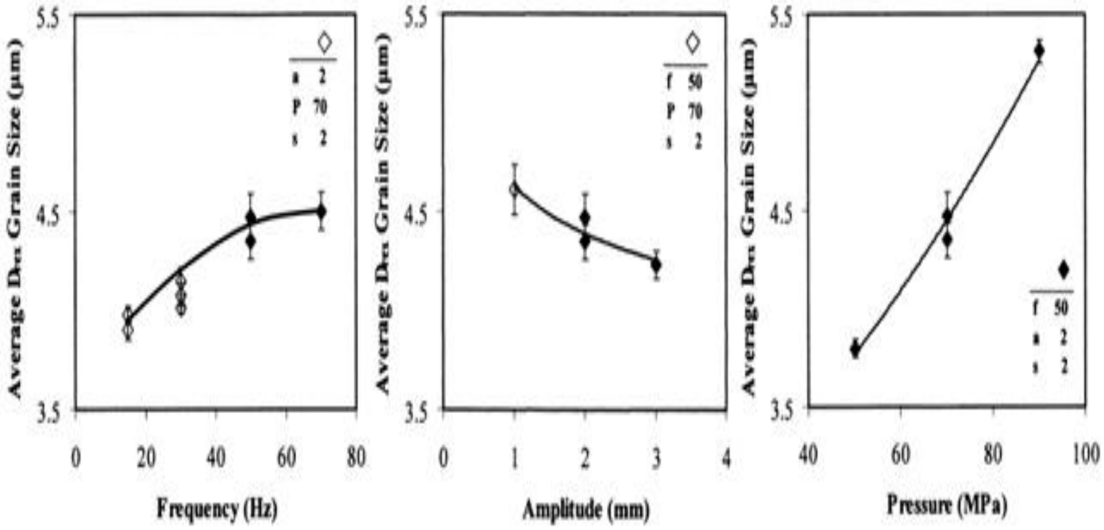


Fig.*8* *Effects of frequency, amplitude and pressure on average prior β grain size in the weld zone of Ti-64 linear friction welds. a: amplitude, P: pressure, f: frequency, s: burn-off distance. Open markers indicate poor welds.*

More recent work, however, has shown that the prior β grain size actually decreases at high pressures, which has been interpreted as a reduction in the peak welding temperature, although changes in the overall weld thermal cycle may also have contributed to producing these effects. This proposed decrease in temperature was attributed to a large amount of flash expulsion at high pressures, which caused large heat rejection, and short welding times.

VII. Equations of Power Input And Modeling of Linear Friction Welding

The heat input power per unit area in this model was defined as:

$$q_A = \tau * \upsilon = \frac{F_S}{A} * \upsilon = \frac{\mu F_N}{A} * \upsilon$$

$$= \frac{\mu F_N}{D(W - \alpha \sin(\omega t))} * \alpha\omega\cos(\omega t)$$

Equation.1

where T is the shear stress, ν is the sliding velocity, F_S is the shear force, μ is the co-efficient of friction, *F*N the force normal to the interface, α is the amplitude, Ω is the angular frequency (2Π*oscillation frequency), *t* is the time, *D* is the thickness, and *W* is the width of the specimen (weld area = *DW*). *A* is the contact area, which is not constant and will change during the oscillatory cycle.

Although the equation of power input into the weld (equation (1)) is likely to be sufficient for a retrospective analysis of heat input, it may not satisfy requirements for a forward, predictive, analysis from a given set of initial welding parameters (*i.e.* pressure, force, frequency, amplitude and burn-off distance). This is largely because of the difficulty in predicting the shear force (force in the reciprocating direction) that results from the initial parameters. The shear force will be dependent on both sliding velocity and the real (or true) contact area (area of contact of microscopic asperities), and this is not brought out in equation (1). Although equation (1) does have a shear stress that is contact area dependent, this is solely a result of dividing a constant shear force by an area that is changing due to the oscillation. Therefore, the model is not an accurate depiction of the welding process as the shear force also oscillates with both contact area and velocity14. This unsatisfactory representation of the shear force may also mean that there is an inadequate representation of the power generation, and better models may be needed to accurately describe the power generation and temperature profiles produced by the LFW process.

Despite the criticism of the LFW process models currently available in the open literature, it is important to remember that the development of any reliable process model is difficult. It will largely depend on the accurate knowledge of friction coefficients and forces, and will rely on an accurate material data base over a wide temperature range and for exceptionally high strain rates.

VIII. Conclusion

In the present study, titanium-stainless steel joints with a nickel interlayer were welded successfully. With the wider application of titanium and stainless steel, the dissimilar welding technique for joining titanium to stainless steel will become more and more important. The sustainabilty properties of dissimilar metals capable of resisting high temperatures and low thermal conductivity has its applications in various manufacturing industries. The process is currently established as a niche technology for the fabrication of titanium alloy bladed disk (blisk) assemblies in aero-engines, and is being developed for nickel based superalloy assemblies.

Due to the complexity of Linear Fricrtion Welding, it is clear that it could help to significantly improve our understanding of the process, and in this way provide strategies to further improve welding parameters for LFW.

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