Friction Welding of Incompatible Materials

The feasibility of using a metal interlayer to friction weld certain similar and dissimilar metals was established

BY F. SASSANI AND J. R. NEELAM

ABSTRACT. A modified method for friction welding of incompatible materials was investigated. Friction welding of brass to copper, bronze to steel and titanium to nickel with different interlayer materials was performed, and varying degrees of success and mechanical joint strengths were observed.

Metallurgical analyses and observations of the extent of metallic bonding and diffusion showed that incompatible materials can be friction welded with an interlayer and mechanically improved joints obtained.

Introduction

Friction welding has become a widely used process for joining both similar and dissimilar materials in such industries as the automotive industry. In the majority of cases, there are no problems relating to different melting points, cast structure at the interface, inclusions and microsegregation. One-hundred-percent efficient welds are common (Ref. 1), and with some dissimilar materials, the strength obtained in the joint can be better than the strength of the weaker material (Ref. 2). For these reasons and for those of manufacturing economics, friction welding is a preferred process when size and geometry of the workpieces permit.

Although friction welding is inherently a versatile process, it does not result in a joint of acceptable quality in some cases, such as the welding of titanium to nickel where no weld is formed, and in silver alloys to themselves where a brittle weld is formed. Such combinations, in this paper, have been termed "incompatible." While some other methods arrive at a good metallic bond between these materials, the possibility of using friction welding has advantages ranging from simplicity and efficiency to quality and productivity.

The objective of the research discussed here is to examine the potential of a modified friction welding process (referred to as the "three-element method") in joining incompatible materials. This paper considers the outcome of this method that has been used to overcome some of the situations which result in a brittle weld or no weld at all.

KEY WORDS

Friction Welding
Incompatible Metals
Brass to Copper
Bronze to Steel
Titanium to Nickel
Interlayer Materials
Dissimilar Materials
Three-Element Weld
Copper Interlayer
Aluminum Interlayer

Three-Element Friction Welding

The method involves the use of a third element, the "interlayer" or the "intermediate material," which is placed as a buffer in a small premachined recess between the two incompatible base materials being welded—Fig. 1. The element welds with both of the base materials and, by remaining as a thin metallic bonding layer between them, forms a joint. From tabulated weldability data compiled by The Welding Institute, England (Ref. 3), Table 1 was setup. For given combinations of incompatible materials, this table immediately provides some possible interlayers. Several other materials can also be thought of as interlayers, but many can be ruled out as being ineligible due to lack of certain physical properties and inability to create conditions conducive to bonding. An ideal intermediate material should generally:

A) Be able to create conditions amenable for metallic bonding to occur.

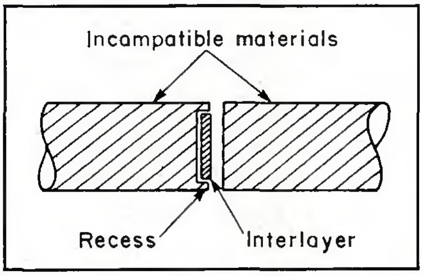

Fig. 1—Schematic of component arrangement in three-element friction welding

Table 1—Incompatible Material Combinations, Type of Weld and Possible Interlayers

Material Combination	Type of Weld Formed	Possible Interlayer
Aluminum alloys/magnesium alloys	No weld	Aluminum
Brass/copper	No weld	Aluminum
Bronze/plain carbon steel	No weld[a]	Aluminum, bronze(s)
Bronze/steel alloy	No weld	Aluminum
Magnesium alloys/magnesium alloys	No weld	Aluminum
Magnesium alloys/stainless steel	No weld	Aluminum
Nickel/titanium	No weld	Aluminum
Niobium/stainless steel	No weld	Aluminum
Niobium/zirconium alloys	No weld	Aluminum
Silver/titanium	No weld	Copper
Plain carbon steel/titanium	No weld	Aluminum, copper
Plain carbon steel/tungsten carbide, cemented	Brittle weld	Aluminum
Stainless steel/titanium	Brittle weld	Aluminum
Stainless steel/zirconium alloy	Brittle weld	Aluminum

(a) The tests conducted resulted in brittle welds.

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Table 2—Composition of Materials Used in the Experiments

Material	Composition (%)
Aluminum (6061)	0.6 Si, 1 Mg, 0.25 Cu, 0.25 Cr, Al (balance)
Brass	65 Cu, 35 Zn (yellow brass)
Copper	99.9 Cu (commercially pure)
Naval brass	60 Cu, 0.75 Sn, 29.25 Zn
Nickel	99.9 N (commercially pure)
Phosphor bronze	90 Cu, 10 Sn
Steel (1025)	0.25 C, 0.45 Mn, 0.04 P (max), 0.04 S (max)
Titanium	99.9 Ti (commercially pure)

Table 3—Experimental Conditions and Results for Ti-Ni Combination with Cu Interlayer

Speed: 1120 rpm

Friction Time (s)	Forge Time (s)	Friction Pressure ×1000 psi (MPa)	Forge Pressure ×1000 psi (MPa)	Ultimate Tensile Strength ×1000 psi (MPa)
7	7	5.0 (34.47)	10.0 (68.95)	Failed on dropping
5	7	5.0 (34.47)	10.0 (68.95)	Failed by slight bending
5	7	6.25 (43.1)	10.0 (68.95)	9.38 (64.70)
5	7	6.25 (43.1)	12.5 (86.2)	19.65 (135.48)
5	14	6.25 (43.1)	12.5 (86.2)	4.13 (28.53)
5	7	6.25 (43.1)	10.0 (68.95)	2.78 (19.16)
3	7	6.25 (43.1)	10.0 (68.95)	4.45 (30.69)
3	7	6.25 (43.1)	10.0 (68.95)	11.07 (76.32)
5	7	6.25 (43.1)	10.0 (68.95)	6.85 (47.29)

Table 4—Experimental Conditions and Results for Al-Al Combinations

Speed: 1120 rpm, No Interlayer

Friction Time (s)	Forge Time (s)	Friction Pressure ×1000 psi (MPa)	Forge Pressure ×1000 psi (MPa)	Ultimate Tensile Strength ×1000 psi (MPa)
3.0	10.0	6.25 (43.1)	7.5 (51.71)	26.41 (182.14)
3.5	10.0	6.25 (43.1)	10.0 (68.95)	25.79 (177.82)
3.5	10.0	6.25 (43.1)	17.5 (120.66)	28.47 (196.30)
3.5	10.0	6.25 (43.1)	17.5 (120.66)	27.13 (187.06)
Speed: 1120 rpm, Al Interlayer				
4.0	10.0	6.25 (43.1)	10.0 (68.95)	26.41 (182.14)
3.5	10.0	6.25 (43.1)	12.5 (86.2)	25.79 (177.82)
3.0	10.0	6.25 (43.1)	12.5 (86.2)	28.47 (196.30)
3.0	10.0	6.25 (43.1)	3.75 (25.85)	8.41 (57.99)

B) Be compatible with both of the base materials.

C) Have the passivity to the formation of brittle intermetallics at the temperatures encountered.

D) Flow at the same temperature and pressure ranges as those of the base materials.

With regard to item A, some materials, such as brass, flake away in the form of chips and thus adhesion, alloying or continuous plastic deformation does not take place. In such cases, conditions for metallic bonding do not occur.

Qualitative Considerations

These four properties set the guidelines for the selection of a material as an interlayer. Materials such as lead or aluminum are immediately excluded when tungsten is welded, for they cannot create conditions to promote metallic bonding, since they flow at much lower stresses and temperatures than tungsten does. In other cases, however, the reasons for elimination are not so evident. For example, bronze may have been considered as a suitable intermediate material between copper and brass (which do not weld) as it has a melting point close to the melting point of the two. However, the results of the preliminary experiments indicated that this reasoning was not entirely adequate.

Preliminary Experiments

For all the experiments conducted in this work, the specimens were 0.5 in. (12.7 mm) in diameter. The interlayers were 0.04 in. (1 mm) thick and 0.4 in. (10 mm) in diameter. The compositions of the materials and the interlayers used are given in Table 2. The purpose of the preliminary experiments was to obtain an overview of the interaction between different material combinations and set the groundwork for main experiments. For example, because of similar melting points and the base materials' close resemblance, copper was expected to form a good metallic bond with its own alloy brass, but the experiments proved otherwise. Another example was steel (melting point 1450°C/2642°F) when used as an interlayer between nickel (mp 1455°C/2651°F) and titanium (mp 1820°C/3308°F). The conditions required for metallic bonding did not materialize and it was titanium, with a higher melting point, that was completely extruded away because of its low hot strength.

For the same material combination, copper, with a lower melting point of 1083°C (1981°F), was used as the interlayer instead of steel. While copper formed a good weld with titanium by the conventional friction welding process, it did not form a satisfactory weld with it in the three-element method. Experimental conditions and results of the tensile tests are given in Table 3. The inconsistency of the ultimate tensile strength is apparent, particularly with multiple experiments under identical conditions. Under the tensile test, the specimens always failed or separated at the copper/titanium interface.

Before the three-element method was pursued further with incompatible materials, experiments were conducted on other materials that were generally considered to be suitable for the friction welding process. The first set of experiments involved joining pairs of aluminum alloy (6061) specimens with an interlayer of the same alloy. The properties of the joints obtained were similar in all respects to those of the conventional two-piece joints. Table 4 shows the results for both cases. Even after the flash was turned down, there were no indications of their being three-element specimens. When subjected to a tensile test, the specimens failed across the interface after necking in a ductile mode of fracture. In several cases, such as shown in Fig. 2, the failure took place outside the weld plane. In the next set of preliminary experiments, an intermediate material dissimilar to one of the base materials was used. In two different sets of experiments, 1025 plain carbon steel was friction welded to 6061 aluminum with aluminum and steel as interlayers, respectively. The aluminum interlayer produced a joint that failed adjacent to the steel interface, but not in the plane of the weld. The failure was similar to that of a two-piece joint. The steel interlayer, however, did not produce a good metallic bond for it did not adequately interact at the steel-to-steel interface to create the required conditions for bonding. The third trial

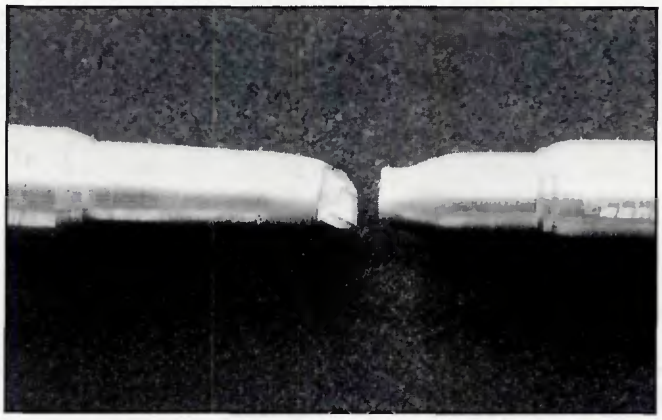

Fig. 2—A three-element friction welded specimen (all aluminum) failed in tension in the base material. The weld plane is at the middle of the machined recess

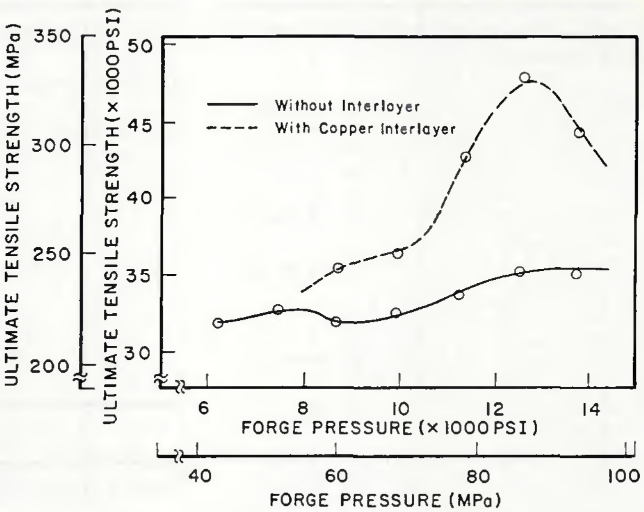

Fig. 3—Variation of UTS versus forge pressure for bronze/steel combination welded at 3600-psi (25-MPa) frictioning pressure and 3-s frictioning time

used a totally dissimilar material as the interlayer. In this case, nickel was used between two steel rods. During the experiments, most of the nickel was usually expelled. These specimens, under the tensile test, failed along the weld plane after necking at a strength of almost equal to that of a pure steel specimen. Tables 3 and 4 show representative results from preliminary experiments.

Main Experiments

After the preliminary experiments, the feasibility of the method was established, and further experiments were carried out with incompatible material combinations. Of the several combinations of materials that do not weld, three combinations were selected as base materials for these experiments: brass/copper, bronze/steel and titanium/nickel.

From Table 1, aluminum was considered a suitable element for use as the intermediate material since it forms a good weld with each of the six materials. In addition to aluminum, several other materials that were not evident from Table 1 were also used, and results of the experiments are discussed later.

While it is accepted that the tensile test does not evaluate a specimen's impact strength or fatigue properties (Refs. 4, 5), it was used as the sole quantitative criterion test for all the friction welded specimens, though occasional qualitative bending tests were also performed. More advanced in-process and nondestructive testing of friction welded joints has been under investigation (Refs. 6–8) and will become more common in the coming years. In all the experiments, the process parameters were manipulated to improve (not necessarily maximize) the tensile strength.

Brass/Copper

Three materials were thought of as interlayers for this combination: aluminum, phosphor bronze and naval brass. The experiments with the first two were unsuccessful. Although aluminum welds well with copper (Ref. 9) in conventional friction welding, it did not work as an interlayer (Ref. 10). The remaining experiments were carried out with naval brass. The naval brass interlayer between copper and brass resulted in joints of a tensile strength as high as 30,000 psi (207 MPa). In the tensile tests, the failures took place mostly at the brass/naval brass or the naval brass/copper interface, and occurred indiscriminately at both interfaces. Table 5 shows some results under different experimental conditions. A closer look at the failed surfaces showed that the failure had taken place largely by interface separation. In a particular case which failed at the copper/naval brass interface, some copper patches were exposed on the fracture surface especially towards the periphery. Examination under the scanning electron microscope (SEM) showed that the failure across these copper patches had been through a ductile mode of fracture, as numerous small dimples could be seen. The rest of the area had failed largely by interface separation. However, a 1000X magnification of this area showing some patches of localized ductility indicated that a fair amount of metallic bonding had also taken place. General observation was that in these areas the base copper was the weakest part.

Some problems, such as inconsistency of the weld results, were encountered with this combination of materials, as is evident from Table 5. One factor was thought to be the randomly varying relative motions between the three elements, which resulted in an uneven rate of heat generation. Due to this uneven rate of heat input, the amount of melt-off for each cycle varied so that workable conditions for welding this combination of materials could not be established with certainty.

Bronze/Steel

Welding experiments were performed with 1025 steel and bronze specimens.

Table 5—Experimental Conditions and Results for Brass-Copper Combination

Speed: 1120 rpm; Naval Brass Interlayer

Friction Time (s)	Forge Time (s)	Friction Pressure ×1000 psi (MPa)	Forge Pressure ×1000 psi (MPa)	Ultimate Tensile Strength ×1000 psi (MPa)
7	10	6.25 (43.1)	10.0 (68.95)	22.70 (156.51)
7	10	6.25 (43.1)	10.0 (68.95)	15.10 (104.11)
7.5	10	6.25 (43.1)	10.0 (68.95)	10.69 (73.70)
8	10	6.25 (43.1)	10.0 (68.95)	10.70 (73.77)
8	10	6.25 (43.1)	11.25 (77.57)	8.26 (56.95)
8	10	5.0 (34.47)	11.25 (77.57)	19.43 (133.90)
9.5	10	5.0 (34.47)	11.25 (77.57)	13.58 (93.63)
10.5	10	5.0 (34.47)	11.25 (77.57)	30.29 (208.85)

The welds obtained were brittle and weak in tension and bending. An interlayer of copper was used, and the improvement in the tensile strength was substantial. The rates of heat generation and melt-off were more uniform with this material combination than they were with brass and copper. The variation in the melt-off was less than 0.0625 in. (1.6 mm). The metallic bond strength also responded to the change in one of the process parameters, the forge pressure. The tensile strength increased with an initial increase in the forge pressure and then decreased, as shown in Fig. 3. The strength of the joints made without an interlayer was less affected by forge pressure. The experimental conditions are given in Table 6.

The tensile test specimens with copper interlayer separated at the interface without necking and the maximum ultimate tensile strength obtained was 47,770 psi (330 MPa), about a 40% improvement over the strength obtained without an interlayer. The failures that appeared to have taken place in the copper interlayer left a layer of copper on both surfaces. A low magnification of the steel specimens showed a general tendency for interface separation, especially at the center of the specimen where the welding is usually worst — Fig. 4. A 200X magnification (Fig. 5) shows some areas with original machining marks present on the unbonded steel surface and adjacent dimpled areas. The dimpled areas are macroscopic evidence of fracture in the copper metallic bonding layer. The bronze counterpart surface showed more uniform bonding all over the surface, and ductile fracture had taken place both in the copper and in the bronze.

Titanium/Nickel

The third combination of materials for the experiments was titanium and nickel. An attempt to weld these two materials directly resulted in a joint of a very low strength. Even though titanium has a much higher melting point than nickel, it starts to flow at a much lower temperature. The result is a complete extrusion of titanium without any reasonable joint being formed.

Welding was attempted between the two with several interlayer materials. Although steel appeared to be a reasonable candidate due to its strength, melting point, etc., it did not form a good metallic bond with titanium. Titanium also flows at much lower pressures than steel does. Copper by itself welds well with titanium, but the joints obtained between titanium and nickel with the copper interlayer failed at the copper/titanium interface in the tensile tests. This combination has not yet been fully investigated. However, failure at the copper/titanium interface is thought to have been caused by the presence of brittle intermetallic compounds. The best results obtained for this incompatible nickel and titanium combination were with the use of aluminum as the interlayer. Table 7 shows the experimental conditions when the aluminum interlayer was used. The most influential parameters in this case were the forge pressure and the frictioning time. Figure 6 shows that when the forge pressure was increased from 5000 psi (34 MPa) to 16,000 psi (110 MPa) the ultimate tensile strength increased from about 20,100 psi (139 MPa) to 41,800 psi (288 MPa). The experimental conditions and the plot between the ultimate tensile strength for tests of different frictioning times are shown in Table 8 and Fig. 7, respectively. For each set of experimental conditions, three tests were performed. Every data point on Fig. 7 indicates the maximum, minimum and the average value of the ultimate tensile strength. With the increase in the frictioning time, the strength peaks at a frictioning time of 2 s, followed by a sudden drop, and then there is a gradual increase in strength rising to give another peak of the UTS at 15 s, the maximum frictioning time available with the present setup of the machine used.

Table 6—Experimental Conditions for Results Shown in Fig. 3

	Without Interlayer	With Interlayer
Friction time (s)	4	5
Friction-pressure ×1000 psi (MPa)	7.5 (51.7)	8.75 (60.3)
Forge time (s)	10	
Speed, rpm	1120	

Table 7—Experimental Conditions for Results Shown in Fig. 6

Friction time (s)	15
Friction-pressure ×1000 psi (MPa)	7.5 (51.7)
Forge time (s)	15
Speed, rpm	1120

The reason for this variation in strength is due to a number of factors:

1) Mode of bonding
   a) Mechanical interlocking
   b) Metallic bonding
2) Thickness of the interlayer (not investigated)
3) Physical properties of interlayer
4) Extent of the formation of brittle intermetallic phases.

The mode of bonding is purely mechanical in the initial stages as the asperities become interlocked and some of the harder material plows into the softer. This was noticed by the fact that

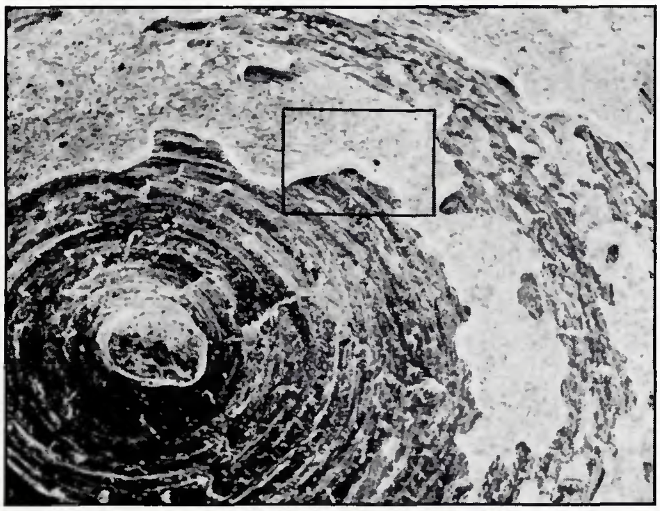

Fig. 4 — Failed steel surface from bronze/copper/steel combination showing mottled copper over some areas (40X)

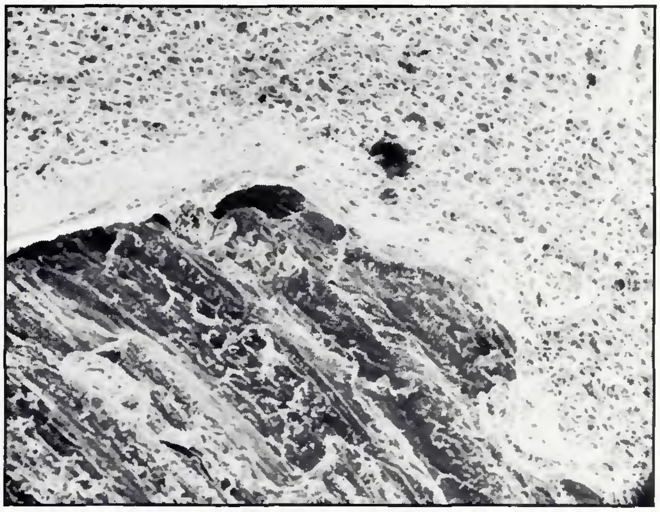

Fig. 5 — 200X of outlined area in Fig. 4 showing flow lines on the steel surface and fine dimples on the copper layer

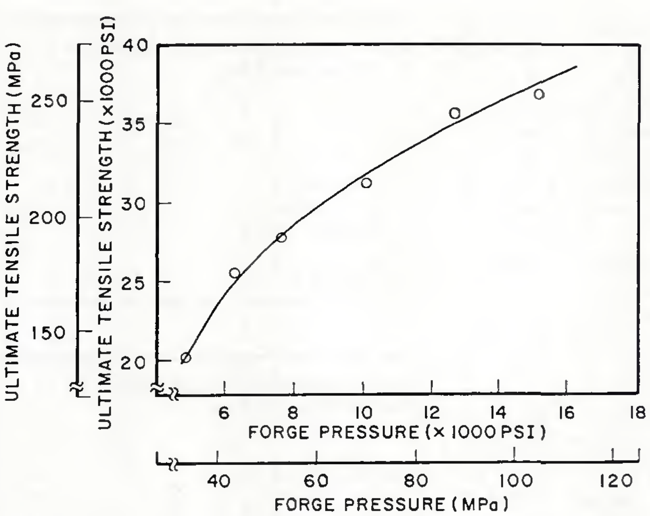

Fig. 6 — Variation of UTS versus forge pressure for titanium/nickel combination with an aluminum interlayer. Frictioning pressure was 4000 psi (27.5 MPa) with frictioning time of 15 s

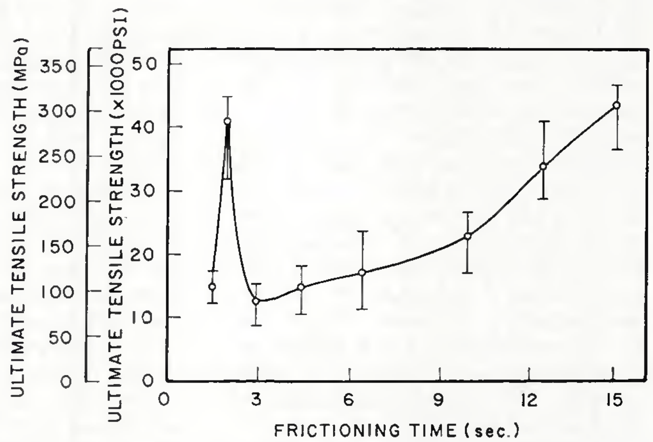

Fig. 7 — The effects of frictioning time for a titanium-aluminum-nickel joint welded at 4000-psi (27.5-MPa) frictioning pressure and 16,000-psi (110-MPa) forging pressure

when the specimens welded at around 2 s of frictioning time were subjected to the tensile test, clickings were heard as the separation of the interlockings took place. Titanium, like aluminum, has a very stable oxide coating which generally prevents further oxidation and protects it from the environment. With longer frictioning time, it is thought that more oxide is displaced, thereby exposing unoxidized titanium and aluminum and encouraging metallic bonding to occur.

When subjected to tensile tests, most of the failures occurred by interface separation either at the nickel or the titanium junctions with the aluminum interlayer. Some traces of aluminum always adhered to the base material's surface where the interface separation had taken place. As the frictioning time is quite substantial (15 s) for the 0.5-in. diameter specimens being welded, a possibility exists for the formation of intermetallic compounds (Ref. 4). The intermetallics in general are brittle and are weak in tension, fatigue and bending properties. The formations and growth of these phases can be controlled by varying the friction welding process parameters, such as decreasing the speed and increasing the axial pressure during the frictioning period, etc. The rate of heat input is higher at lower speeds over a certain minimum limit. Similarly, by having large loads, the heat input rate can be increased to reduce the process time, but both of these have limitations. Low speeds generate high torques, which can lead to work-holding problems. Too high friction pressure results in high rates of melt-off, an unnecessary extrusion of metal that can cause localized, unrecrystallized plastic damage, which adversely affects fatigue and fracture toughness.

Extended Analysis

In the titanium-aluminum-nickel joint, there is a possibility of diffusion of aluminum into nickel or titanium, titanium into aluminum or nickel into aluminum.

An electron microprobe analyser was used on longitudinally cut and polished welded specimens to determine the incidence and, if any, the extent of diffusion. Analysis was done on three types of joints that arise from this combination (Fig. 7): Type I joints, seemingly good joints resulting at low frictioning time of about 2 s; Type II joints, bad joints occurring at times greater than 2 s, with these particular joints obtained at around 6 s; and Type III joints, good joints obtained at about 15 s of frictioning time.

The concentration profile at the aluminum-nickel and aluminum-titanium interface gave a sharp transition without any indication of movement of aluminum into either of the two base materials. This was the case with all the joints, Types I, II and III. As expected, no diffusion of either nickel or titanium into aluminum was observed for Type I joints. But in Type II joints there was some evidence of movement of nickel into aluminum, while titanium showed no diffusion at all. An

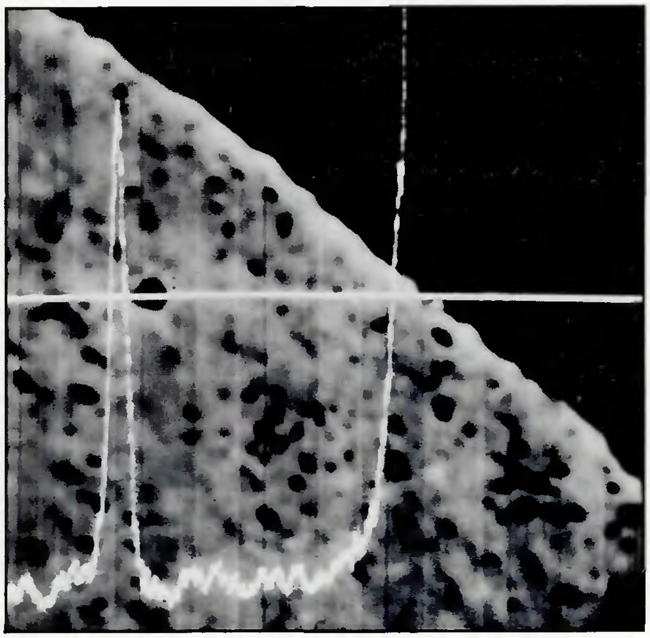

Fig. 8 — A nickel scan for a Type II joint over a spotted area suspected to be nickel rich. The dark area on the top-right portion is nickel (1200X)

Table 8—Experimental Conditions for Results Shown in Fig. 7

Friction-pressure ×1000 psi (MPa)	7.5 (51.7)
Forge time (s)	15
Forge pressure ×1000 psi (MPa)	12.5 (86.1)
Speed, rpm	1120

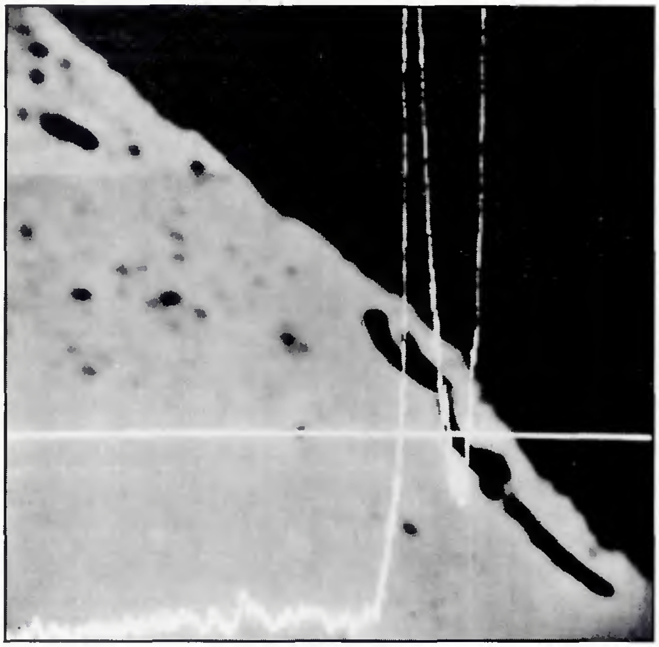

Fig. 9 — Nickel scan for a Type III joint at a region close to the center at 200X. Nickel is seen as the dark area

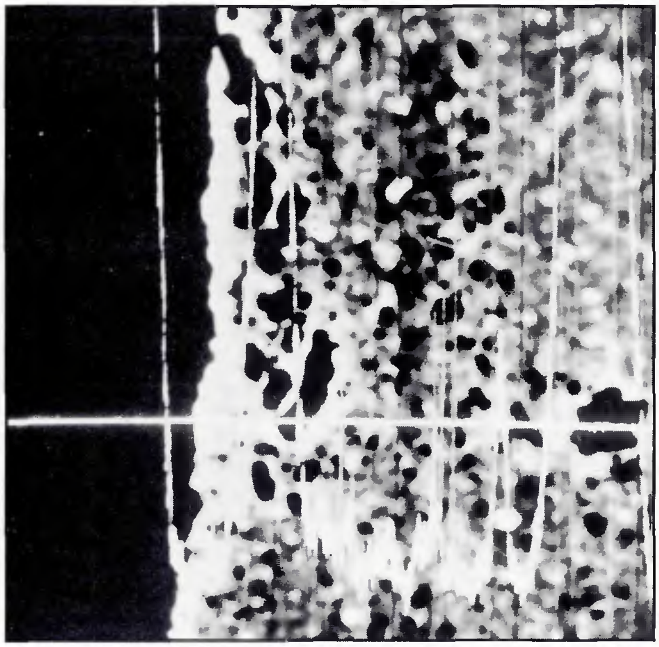

Fig. 10 — Nickel scan for a Type III joint at a region close to the periphery. Numerous dark regions indicate extensive movement of nickel into aluminum at long frictioning times

absorbed electron image of this joint is shown in Fig. 8, the image is magnified 1200 times. Figure 8 also shows the microprobe scan of the Ni peak. A high Ni response is apparent in the dark upper corner, decreasing rapidly to zero at the nickel-aluminum interface. Localized regions of high Ni are apparent within the aluminum layer, probably indicative of the formation of a nickel-aluminum intermetallic compound. All the small dark areas are nickel-rich regions though the occurrence of spots of the size showing the peak were not as common as the smaller spots.

The Type III, aluminum-nickel junction also showed evidence of nickel diffusion into the aluminum layer. The shape and the location of this transfer varied along the radius. At locations nearer to the center (Fig. 9), the nickel-rich regions were of plate-like structure and were close to the interface. At locations nearer to the periphery, the spots were more widely dispersed and were globular. The absorbed electron image, with the concentration profile as the scan passes over some of these spots, is given in Fig. 10, which shows numerous small peaks all of them having some nickel.

A quantitative analysis of the electron microprobe results provided approximate stoichiometric compositions of the nickel-rich region within the aluminum layer. For the sake of simplicity, the count taken was assumed to be of 100% aluminum, even though the aluminum used had alloying elements (1% silicon, 0.6% magnesium). The nickel and aluminum intensities were taken at different positions within the aluminum layer under a steady operating condition of the equipment. The results are shown in Table 9. The concentration percentages were obtained after atomic number correction, absorption correction and fluorescent enhancement using a computer program MAGIC (microprobe analyzer general intensity corrections). Since only two elements were being analyzed and were predominant, the concentration of aluminum was determined by difference.

A light-shaded region was also found along the nickel-aluminum interface, but this region could not be analyzed due to its thinness (approximately 1 to 2 microns thick) and the difficulty in obtaining counts accurately because of substantial difference in the atomic weights of the elements being analyzed.

Conclusions

A method of using an intermediate layer of a same or different composition in the conventional friction welding process was investigated for both compatible and incompatible materials. Compared to the two-element method, the

Table 9—Quantitative Analysis of the Nickel and of a Polished Type III Specimen at Various Locations

Spot Number	Element	Weight Percent	Atomic Percent	K-Ratio	Unknown Intensity	Standard Intensity	Unknown Background	Standard Background	Iterations
1	Ni (Kα)	73.33	55.82	0.7203	56829	78896	109	189	2
	Al (a)	26.67	44.18						
2	Ni (Kα)	57.88	38.71	0.5269	44411	78896	109	189	2
	Al (a)	42.12	61.29						
3	Ni (Kα)	78.48	62.63	0.7735	61026	78896	109	189	2
	Al (a)	21.52	37.37						
4	Ni (Kα)	69.77	51.47	0.6838	53937	78896	109	189	2
	Al (a)	30.23	48.53						
5	Ni (Kα)	57.20	38.05	0.5560	43870	78896	109	189	2
	Al (a)	42.80	61.95						
6	Ni (Kα)	39.97	23.43	0.3842	39314	78896	109	189	2
	Al (a)	60.03	76.5						

(a) Determined by difference.

three-element method resulted in 100% efficient welds (in terms of tensile strength) when welding aluminum to aluminum with a similar interlayer, and over 95% when welding steel to steel with a nickel interlayer.

Attempts to weld a number of incompatible material combinations using several intermediate materials achieved different degrees of strength. A 40% improvement in strength was observed for joints obtained between bronze and steel using a copper interlayer. The strength of the joint obtained between the incompatible combination of titanium and nickel with an aluminum interlayer was stronger by 13% than the joint obtained between the interlayer material to itself. The variation of the strength of this joint with friction time was attributed to different metallic bonding mechanisms.

In the titanium-aluminum-nickel combination, a microprobe analysis showed movement of nickel into aluminum when the frictioning time was long. The nickel-rich areas in the aluminum layer, when analyzed quantitatively, showed the presence of several phases, most compositions being in agreement with phases shown on the aluminum-nickel phase diagram. Further analysis is required to determine the effect of these phases on the strength of the joint. Future studies are directed toward determining the functional relationships between material properties, process parameters and the strength of the welded joints.

This study established the feasibility and practicality of the three-element friction welding of incompatible materials.

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