Friction Welding

By D. S. MODY*

(*Continued from previous issue*)

Comparison between the Conventional and Inertia Methods of Friction Welding

Among the seven methods of friction welding developed so far, it is the conventional or continuous drive and the inertia or stored energy methods which are used quite extensively. The inertia method is more popular in the USA. Both these processes have merits and demerits of their own. It is difficult to compare both these methods as a whole, hence a comparison has been worked out in the light of the process characteristics and capabilities. A final choice as to which type of machine be employed, depends upon a combination of the factors listed below :

Conventional Friction Welding	**Inertia Welding**
1. Energy to form the weld is supplied by an electric motor. The size of the motor limits the power utilized for the weld.	The weld energy is supplied by a freely rotating flywheel. The flywheel supplies whatever power that is demanded by the weld by decelerating at the required rate.
2. The weld cycle involves two distinct phases-heating and forging, requiring about 10 to 60 secs.	The weld cycle is very short, usually from 1 to 10 secs only.
3. The HAZ is wider as a result of soaking of heat due to longer cycle time.	The HAZ is very narrow as a result of the faster heat input to the weld interface.
4. The torque reaches an initial peak value and then falls to a nearly constant value until rotation ceases. The forging is due to the axial force only.	The final peak torque value is very high resulting in torsional shear stress. This augments the shear stress due to thrust force, thus reducing the axial loading necessary for the forging action.
5. The fibre flow lines in the resultant weld area are entirely radial as a result of the forging due to the axial load.	The flow lines are predominantly circumferentially displaced. This orientation minimizes the angle at which the flow lines interesect the surface, contributing to better fatigue properties.

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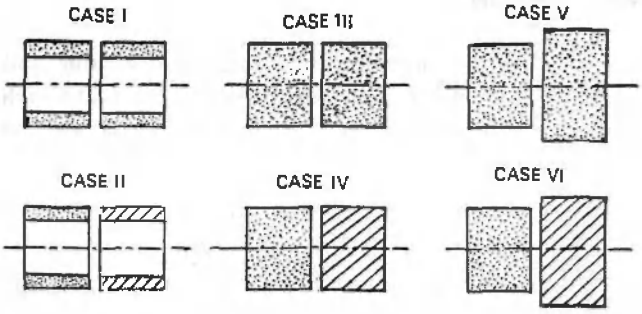
Conventional Friction Welding	Inertia Welding
6. The speed cycle involves a constant speed heating phase followed by rapid halting. Variations include a higher rotational speed at the beginning of the heating phase and then reverting to lower speed for the rest of the cycle. Also, the rate of deceleration may be varied.	The speed of rotation begins at some initial value and decreases along a parabolic curve to zero speed, at which time the weld is completed. Presently, inertia welders with preprogrammed speed control during the entire weld cycle are also available.
7. The axial load may be applied gradually and is usually increased during the forging stage . The increase may be stepped or gradual.	For most materials and interface configuration, the pre-selected pressure is built up rapidly and held constant throughout the welding cycle. Commercial machines with programmed continuous control of pressure cycle are also available.
8. The rotational speeds are relatively low. Normal bearings and work holding devices may be easily adapted. Rapid declutching and braking systems are required.	The rotational speeds are very high and the flywheel spindle system has to be accurately balanced. No braking is required.
9. For large weld diameters, the welding time would be considerably longer.	For large welds and particularly when difficult-to-heat materials (e.g. HSS) are involved, the process offers better productivity.
10. In joining of rods to plates, a projection is often necessary to ward off the heat-sink effect.	No special change in form is necessary. Flash would be produced from both the surfaces.
11. Range of welding conditions suitable for welding of metals with widely differing properties is quite narrow.	Range of welding conditions for critical material combinations is fairly large.
12. The process is found to be not quite suitable for welding of thin plates to pipes.	The flywheel process is far superior for such welds.
13. For welding of thin pipe to thin pipe the process is superior to inertia welding.	The process is not readily adaptable for welding of thin sectioned pipes.
14. The process is superior to the inertia welding method for the small diameter range usually below 10 mm.	The process is more adaptable for weld diameters larger than 10 mm.
15. The process is very good for applications where tolerance on length and alignment is critical.	Control on total welded length and concentricity is rather difficult. It is generally governed by preweld dimensions and conditions of the weld face.

7. Joint Designs

The very nature of the welding process is such that the joint face of atleast one member must be essentially round, or almost round, e.g. octagonal shaped. The rotating member should be somewhat concentric as it has to rotate at high speeds. Angular alignment of the two pieces is not always possible, without costly modifications to the machine ; except when using the orbital method of welding. Square, triangular and slightly rectangular sections are difficult but not impossible to weld.

The combinations of shapes that are most frequently encountered are shown in figure 7, along with their relative weldability. Among the other types of joints are the multiple concentric joints, conical joints-planetary and tubular type, partial conical joints, joints with centre-relief, and joints with flash traps (see Figure 8).



COMPARISON OF WELD PARAMETERS, BASE=1 FOR CASE I

CASE	MATERIALS	PART DIA., IN	THRUST	ENERGY
I	1020 Steel	1·5 O.D., 1·0 I.D.	1·00	1·00
II	1020 & 4140 Steels	1·5 O.D., 1·0 I.D.	1·25	1·25
III	1020 Steel	1·5	3·10	3·10
IV	1020 & 4140 Steels	1·5	3·90	3·90
V	1020 Steel	1·5 to 2·0	3·40	3·70
VI	1020 & 4140 Steels	1·5 to 2·0	4·30	4·70

Fig. 7. Scale of relative weldability for various shapes and materials. Parts that are cross-hatched are materials with higher strength at forging temperature.

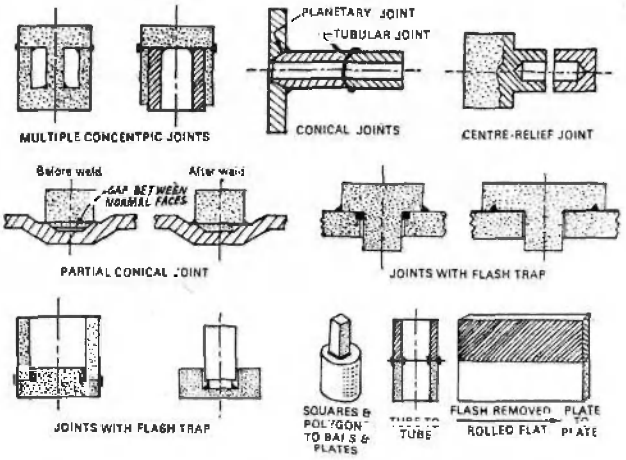


Fig. 8. Some of the weld designs used in practice.

Large chamfers, grooves, pilot diameters and the like must not be used for they prevent full contact with the mating part and obstruct complete expulsion of contamination. Sheared, flame cut, abrasive cut, or sawed surface may be utilised provided they are not excessively out of square and that adequate flash formation is allowed to even the surface irregularities and expel all inclusions. A rule of thumb is to maintain squareness within 0.01 mm per mm of weld diameter. Excessive out of squareness produces radial forces affecting resultant weld concentricity. Heavy forge or mill scale should be removed, as it acts as bearing surface and sometimes cannot be completely flashed out of the interface.

Although in the overall results, surface preparation does not have any appreciable influence on the resultant weld quality for most of the material combinations, there are certain combinations which are very sensitive even to the finger grease (e.g. Copper to Aluminium joints).

8. Materials

In principle, all forgeable materials can be successfully friction welded, provided they are not good dry bearing materials. Friction welding is usually not successful under the following conditions or for the following materials.

(a) Cast iron in any form—free graphite limits frictional heating.

(b) Bronzes and brasses having a lead content of over 0.3%.

(c) Free machining steels containing over 0.13% of sulfur, lead or tellurium, e.g. SAE 1141 (Sulfur content of 0.08 to 0.13%) is weldable whereas SAE 1144 (Sulfur content of 0.24 to 0.33%) is not.

(d) Highly anisotropic materials, e.g. beryllium having almost no transverse ductility.

(e) Wherever a distinct weak phase is present in the micro-structure e.g. graphite, manganese sulfide, free lead, tellurium etc.

Case hardened materials present some difficulty in flash explusion and in some cases it may be necesary to machine off the case over a short length. Tables 3 and 4 give weldability charts for commercially developed friction welds made by the continuous drive and inertia processes. More detailed lists of welds claimed to have been successfully made by these methods are given in Appendices I and II respectively.

9. Tolerances

Preferably, the welding should be done while there is still sufficient machining stock on atleast one of the parts. Length reduction due to upset is usually estimated as about 10 to 12.5% of the diameter at the weld for solid interfaces and may be taken as high as 44% for tubular interfaces. The actual amount of upset is controlled by the welding process and its optimum value is determined by running a few sample parts. Once the nominal upset is established, it is normally repeatable within a tolerance of ±5%. This variation is added to the size tolerance of the original pieces prior to welding and is also dependent of the joint preparation. Substantial variations in joint conditions may produce higher than normal range in length change.

With dissimilar materials, upset is unequal, with the more forgeable material having a greater length reduction. For example, in welding tool steel to SAE 1045 carbon steel, 70% of the upset is in the SAE 1045 steel and only 30% is in the tool steel.

Concentricity is largely a function of tooling rigidity. It also depends upon the accuracy of centering of the clamping device used. Initial eccentricity of parts greatly influence the concentricity of the welded assembly. Concentricity can also be controlled by keeping a minimum of overhang of the weld pieces prior to welding. The clearances necessary in the slides of the moving platen also affect the resultant concentricity. There is more of a tendency for large tube-to-tube welds in "walk" out of concentricity.

10. **Applications**

Like most new things, Friction Welding had to encounter initial problems. However, in a relatively short period, it has become an established production process in many concerns, especially in the developed countries.

There are several hundreds of friction welding machines in use in the USSR. One of the tractor parts-manufacturer is said to have ten friction welders incorporated in the production line. In 1973, there were 138 machines in about 70 companies in use in the U.K., a majority of which were put to use in the automobile industry (refer appendix III). There are no exact figures available for the number of machines in use in the USA, however it is believed that some hundreds may be in use, most of which would be of the inertia type.

The efforts made by the Japanese and the speed with which they adapted to the process in the past ten years or so is virtually second-to-none. This is very clear from the plot of the annual production of friction welders in Japan (Figure 9). As it stands today, Japan is one of the most extensive users of friction welding.

10.1 *Fabrication in Quantity Production*

A majority of the mass production applications come from the automobile industry. The most popular applicacation is for the manufacture of bi-metal engine valves. The head is made out of a high heat resistant alloy and the stem could be of alloy steel. Renault (France & Spain) has seven double head type machines used for this purpose. At Clifford Motor Components Valve Division (U.K.) some fifteen machines are employed for production of bi-metal valves with 6 to 12 mm stem diameter.

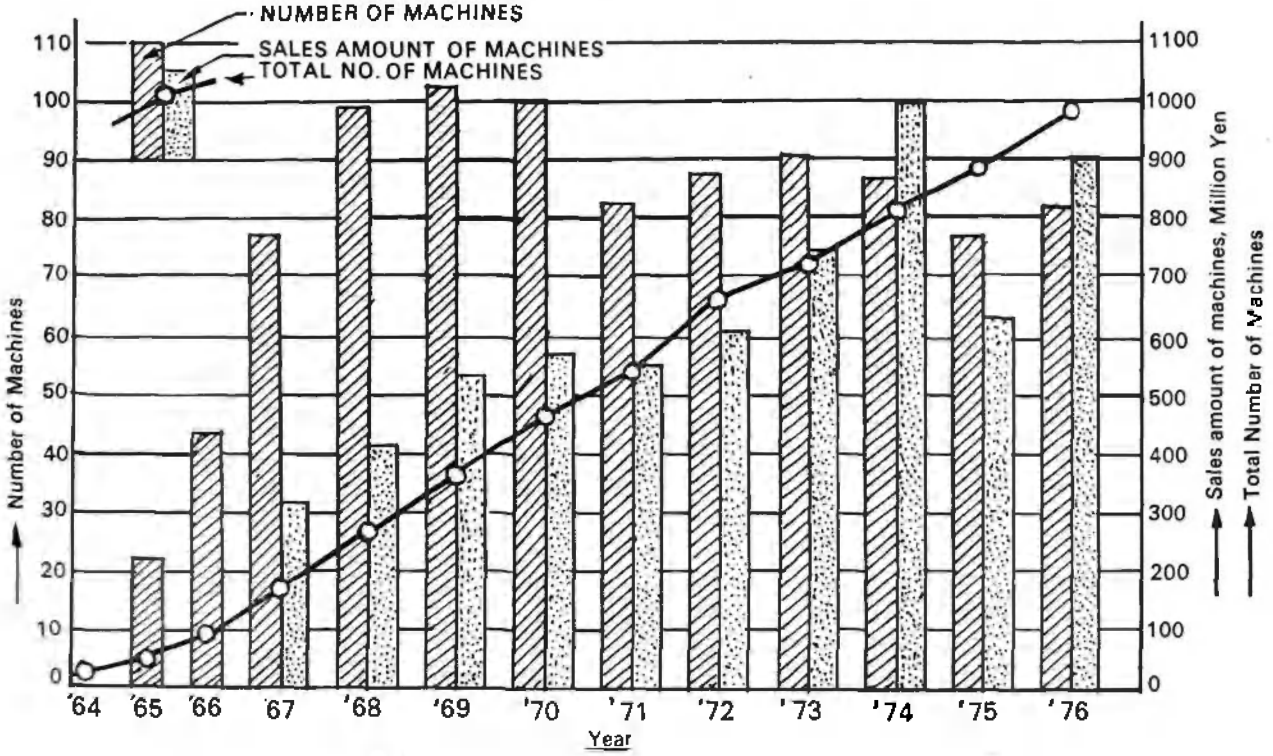
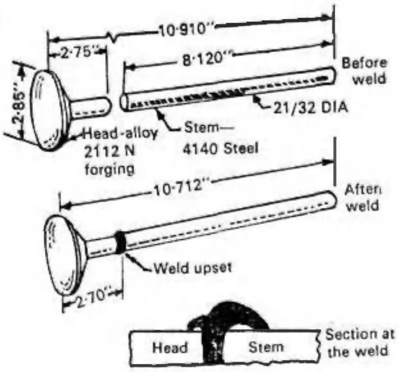


Fig 9. Annual production of friction welders in Japan



Weld Area	...	0·34 sq. in. 2/19 mm^2
Speed	...	2200 rpm.
Total Weld Time	..	10 Sec.
Heating Pressure	..	11,000 psi 773·4 kgf/cm^2
Forging Pressure	..	32,000 psi 2,245 kgf/cm^2

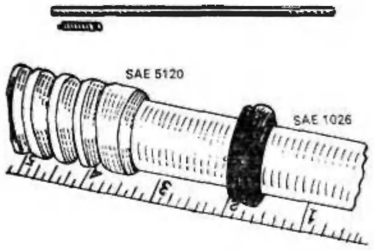
Fig. 10. Diesel Engine Exhaust made by friction welding a heat resistant alloy forged head to a low alloy steel stem.

A typical diesel exhaust valve is shown in figure 11 along with the sizes and weld parameters employed. The weld flash may be removed in an automatic lathe prior to heat treatment or may be removed on the welding machine itself by either a turning or a shearing operation following the weld cycle. It is considered by some of the users that turning off upset flash in the welding machine is uneconomic use of expensive equipment, and causes loss of production through longer work sequence. Also, upset removal by a separate turning operation is a preferred technique, because less overhang of the material from the chuck is required while welding, thus achieving better concentricity.

Other automobile parts having friction welding applications are steering shaft and worm gear, axle shaft, drive shaft, transmission output shaft, sprocket assembly, torque convertor housing, propeller shaft, suspension links, axle cases, gear change spindle, precombustion chambers, track parts, etc. Some of these are shown in figures 11 to 14.

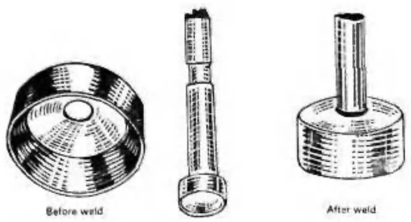
Another potential application of friction welding for large quantity production is in the manufacture of cutting tools like drills, taps, reamers and certain milling cutters. Here high speed steel body is welded to carbon steel shanks. The major advantage of using friction welding instead of the often used flash butt welding, is in the higher production rates, lower power consumption, better quality of weld and, most important, lower consumption of costly HSS material which is lost by way of flash (Please refer Appendix IV for data on savings attainable by use of friction welding in place of flash butt welding for manufacture of drills).

Considerable savings in cost are attained by use of friction welding in place of solid forged parts consisting of a bar upset at one end. Examples of this are—hydraulic piston rods, brake cams, flanged shafts, gears with shafts,



Weld Area	...	0·44 sq. in. 283·8 mm^2
Speed	...	2200 rpm.
Total Weld Time	...	8 Sec
Heating Pressure	...	7500 psi 327·3 kgf/cm^2
Forging Pressure	...	18,000 psi 1265·8 kgf/cm^2

Fig. 11. Steering Shaft and worm gear assembly



Weld Area	...	0·72 sq. in. 464·4 mm^2
Speed	...	4300 rpm
Total Weld Time	...	5 Sec.
Heating Pressure	...	8000 psi 562·5 kgf/cm^2
Forging Pressure	...	16,000 psi 1125 kgf/cm^2

Fig. 12. Transmission input shaft SAE 1310 to SAE 1141

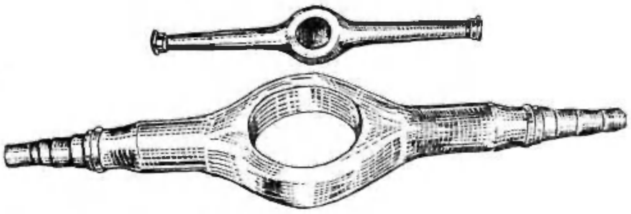


Fig. 13. Axle cases for light passenger and bulk carrying vehicles. The case centres are made from sheets by pressforming and arc welding. The ends may be friction welded individually or two at a time

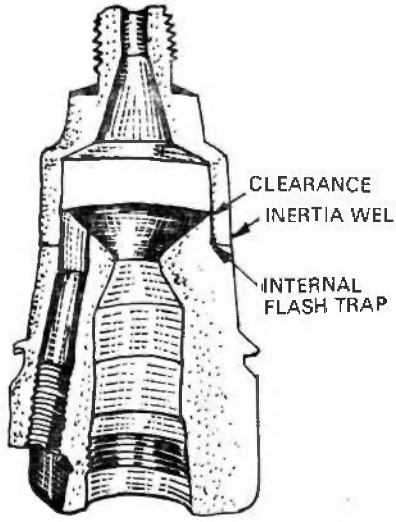


Fig. 14. Precombustion Chamber for diesel engines produced by inertia welding. The original design was to have a press fit followed by copper braking. The inertia welded joints were much stronger and the joint was simplified by eliminating the press fit. An internal flash trap was provided to ensure a clean inside surface

axles with flanges, etc. A smaller forging can be welded to the required size of round stock. The rough forging inventory costs also go down in some cases e.g. one user of hydraulic piston rods (Fig. 15) used to stock rods having a range of eye sizes and for each size of eye he had different lengths of rods. Thus he was stocking over 150 different forgings. With use of friction welding, he now stocks only 28 smaller eye forgings which could be welded to the required length of rod (As per reports given by the Joliet Plant of Caterpillar Tractor Company, USA, this change over generated a savings of $ 85,000 per year).

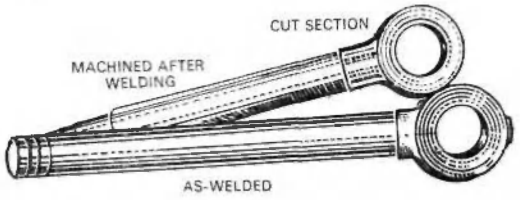


Fig 15. Piston rods for large earthmoving machines made by welding small eye forgings to bar-stock. Parts stock for piston rods was reduced from 150 one piece forged items to 25 basic eye forgings which were then welded to rods of required length

10.2 *Batch Applications*

For many parts the quantity required is too small to warrant the use of an expensive machine with automatic loading/unloading and flash removal attachments. For these, machines with standard easily interchangeable work holding devices are available which can be adapted to the job involved. There are certain special cases where the throughput of various parts is too small; in such cases, the services of a sub contractor are used. (In 1973, there were six sub contractors having 17 machines in the U.K.).

One of the very popular batch applications is the production of Copper-Aluminium electrical distribution connectors. In many electrical distribution systems, copper has gradually been replaced by aluminium. The use of aluminium created some problems, like the growth of insulating oxides, creep under points of high stress (e.g. Screws) and susceptibility to corrosion when in contact with copper (which could be in the form of conductor or parts of electrical equipment). Aluminium conductors are also larger than their copper equivalents and sometimes present problems of accomodating in equipment designed for copper conductors. All these difficulties can be overcome by use of copper aluminium transition pieces. The aluminium end is usually crimped onto the aluminium cable and the copper end is used for connections. The weld configurations most commonly used are shown in figure 16.

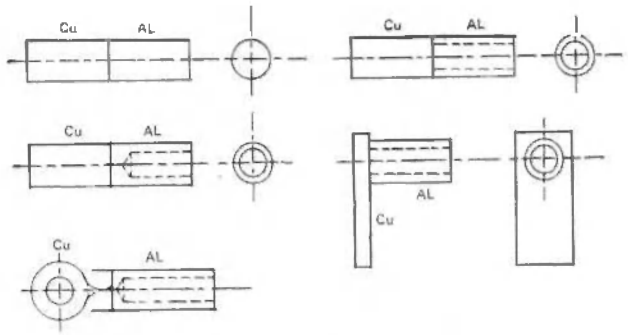


Fig. 16. Some configurations of copper-aluminium transition pieces used in electrical distribution systems

An interesting application where friction welding has replaced submerged arc welding is in the manufacture of track rollers for caterpillar type equipments (see Fig, 17). Formerly, after forging the track roller rim halves it was necessary to machine a bevel and a male and female joint for proper centering. The rim halves had to be preheated and welded by submerged arc process. Presently, the halves are welded on an Inertia Welder. Because of the inherent centering capability of the welding machine, it is only necessary to face off the halves of the roller rims before welding.

Sometimes friction welding can be used to advantage by a slight re-design of existing parts. An example of this is the stop valve shown in figure 18. By the change of design, the advantages obtained were—standardisation of valve body (i.e. the same body could be used for flange type, union nut type, tapered screw type, direct welding type, etc.), avoiding of the angular drilling operation and saving in material cost by use of round or square bars instead of steel forging for the valve body.

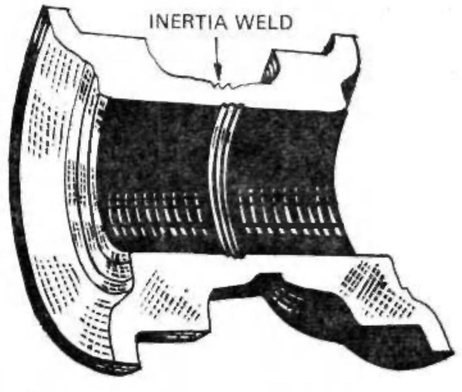
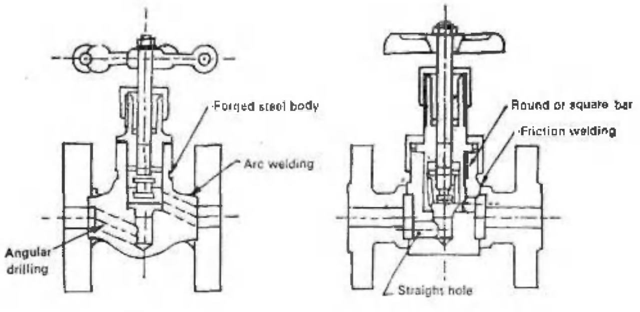


Fig. 17. Track roller halves welded by inertia welding. Here submerged arc welding was being done after bevelling the mating edges and machining a pigot for correct centering. The material involved is SAE 103B or 1046. The diameter at the weld is 150 to 200 mm



Original Design

Designed for Friction Welding

Fig. 18. Friction welding of stop valve. The forged body was replaced by a round or square bar, angular drilling was avoided and standardization was achieved, the same body could be used for flange type, union nut type, tapered screen type etc.

Friction welding for cryogenic applications is used for making aluminium to stainless steel tube welds. British Oxygen Company Limited has used such joints in 12, 25, 37 & 50 mm diameters in batch quantities usually around twenty pieces.

Feed tubes for rock drilling are manufactured by friction welding tubes to male and female threaded end pieces at either ends (Fig. 19). Holman Broomwade Ltd. U.K., have been using this technique to their advantage.

The nuclear industry often requires welds in special materials in one-off or very limited numbers. Examples of such applications are a 100 mm o.d. Zirconium-aluminium-stainless steel tube, stainless steel to aluminium tube joints used in containment vessels (Fig. 20) etc.

Perhaps the largest friction welding application is the production of ancde hanger assemblies by The British Aluminium Co. Ltd. The machine employed has a 200 HF driving motor and a thrust capacity of 140 tons Here, 4.50 in. x 4.75 in. crossection, by 8 to 10 ft. long. aluminium bar is friction welded to an 8 in. diameter X 17 in. long steel billet.

11. Machines

The early developed machines were based on the lathe configuration and incorporated necessary provisions for friction welding parameters. The machines were generally composed of separate units-a welding section, a hydraulic or pneumatic section and an electric section. The next step was to incorporate all these three units into one neater looking unit utilizing lesser floor space.

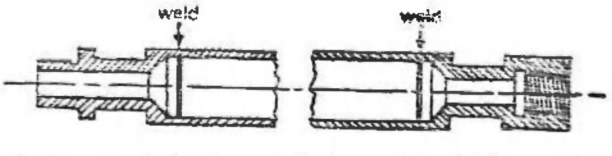


Fig. 19. Feed tubes for rock drilling made by friction welding of male and female threaded coupling ends to standard lengths of tube. The tubes are usually 64 to 82 mm dia. and obout 3 mm long.

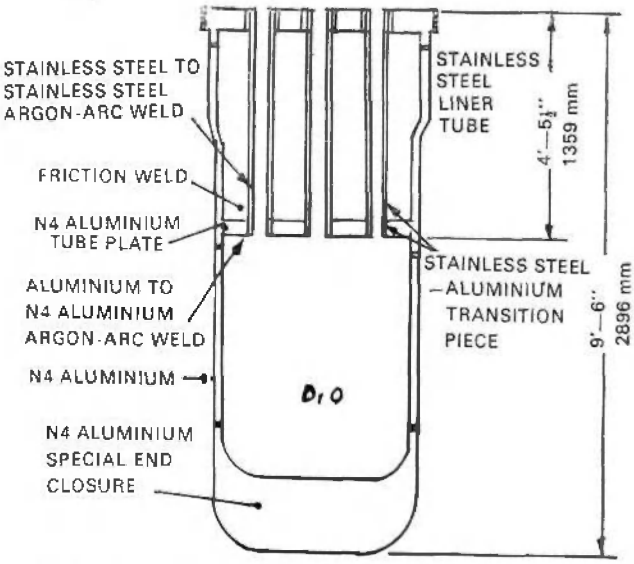


Fig. 20. A containment vessel used in nuclear industry utilising stainless steel to aluminium transition pieces

This was followed by modular construction giving a choice between horizontal and vertical units. As the production potential started growing, double headed machines capable of making two welds simultaneously were introduced. Automatic loading (and unloading) of piece parts into the work holders was adopted to completely automate the operation. The twin head inertia type machine with fully automatic operation for production of bi-metal valves for diesel engines can give a throughput of 1200 valves per hour.

The trend of high production automatic machines in certain developed countries like USA & Germany is largely attributed to chronic labour shortage. The utmost if not impossible—is usually expected of the machine manufacturer while the necessary involvement and expenditure in providing the required automation and precision is often overlooked.

Customers invariably demand high standards of concentricity between the welded pieces not realising how inaccurate their components are. It is no use demanding a concentricity of 0.1 mm or better if the parts to be welded are eccentric by 0.5 mm. Production must always be considered with the most economically attainable tolerance rather than the finest attainable tolerance.

TABLE—3 : RELATIVE WELDABILITY OF SOME OF THE MATERIALS THAT HAVE BEEN FRICTION WELDED TO DATE *

	ALUMINIUM	AL. ALLOYS	BRASS	BRONZE	CADMIUM OXIDE	CAST IRON	CERAMIC	COBALT	COPPER	CUPRO-NICKEL	IRON-SINTERED	INVAR	LEAD-DISP. HDN	MAGNESIUM	Mg. ALLOY	MOLYBDENUM	MONEL	NICKEL	NICKEL ALLOYS	NIMONIC	NIOBIUM	NIOBIUM ALLOY	SILVER	SILVER ALLOY	STEEL, PLAIN—C	STEEL ALLOY	STEEL MARAGING	STEEL, S. S.	TANTALUM	THORIUM	TITANIUM	TUNGSTEN	CEM. W-CARBIDE	URANIUM	VANADIUM	ZR. ALLOYS
ALUMINIUM	■	■	■				■		■					☒	■			■							■	■		■			■		■			■
AL. ALLOYS	■	■					■							☒	☒										◪			◪								
BRASS	■		◪						☒			☒													■											
BRONZE				◪																					☒	☒										
CADMIUM OXIDE									◪																											
CAST IRON						☒																			☒											
CERAMIC	■	■																																		
COBALT								☒																							☒					
COPPER	■		☒		◪				■									■					■		■			■								
CUPRO-NICKEL										■																										
IRON-SINTERED																									■											
INVAR			☒																																	
LEAD-DISP HDN													■																							
MAGNESIUM	☒	☒												☒	☒			☒													☒					
Mg. ALLOY	■	☒												☒	☒													☒								
MOLYBDENUM																☒													☒		☒					
MONEL																	■									■		■								
NICKEL	■								■					☒																	☒					
NICKEL ALLOYS																			■																	
NIMONIC																				■					■	■		■								
NIOBIUM																																				☒
NIOBIUM ALLOY																						■														
SILVER									■																						☒					
SILVER ALLOY																								◪												
STEEL. PLAIN—C	■	◪	■	☒		☒			■		■									■					■	■	■	■			☒		◪			◪
STEEL ALLOY	■			☒													■			■					■	■	■	■								
STEEL MARAGING																									■	■	■	■								
STEEL. S. S.	■	◪							■						☒		■			■					■	■	■	■	☒		◪				☒	◪
TANTALUM																☒												☒			■					
THORIUM																														◪						
TITANIUM	■							☒						☒		☒		☒					☒		☒			◪	■		■					
TUNGSTEN																																◪				
CEM. W-CARBIDE	■																								◪											
URANIUM																																		◪		
VANADIUM																												☒								
ZR. ALLOYS	■																				☒				◪			◪								

■ FULL STRENGTH METALLURGICAL WELDS. (IN SOME CASES APPROPRIATE POST-WELD TREATMENT IS REQUIRED TO REALISE FULL WELD STRENGTH)

◪ CAN BE WELDED, BUT SOME OR ALL WILL NOT PRODUCE FULL STRENGTH BOND.

☒ NO WELD

☐ MOST NOT ATTEMPTED-MANY ARE ASSUMED TO BE WELDABLE .

* Based on the chart published in Metal Const. & British Welding Journal, May 1970, "Friction Welding"—C. R. G. Ellis.

TABLE—4 : WELDABILITY OF METALS BY INERTIA WELDING *

	ALUMINIUM & ALLOYS	BRASS	BRONZE	CARBIDES CEMENTED	COBALT ALLOYS	COLUMBIUM	COPPER	COPPER NICKEL	LEAD	MAGNESIUM ALLOYS	MOLYBDENUM	NICKEL ALLOYS	STEEL ALLOYS	STEEL CARBON	STEEL-FREE MACH'G	STEEL MARAGING	STEEL SINTERED	STEEL STAINLESS	STEEL TOOL	TANTALUM	TITANIUM ALLOYS	TUNGSTEN	VALVE MATERIALS	ZIRCONIUM ALLOYS
ALUMINIUM & ALLOYS	■	◢	◢		◢		◢	◢				◢	◢	◢				◢			◢			◢
BRASS	◢	■	■																					
BRONZE	◢	■	■											■										
CARBIDES CEMENTED														■					■	■				
COBALT ALLOYS	◢				■								■	■										
COLUMBIUM						■																		
COPPER	◢						■							■				◢			■			■
COPPER-NICKEL	◢							■						■				■						
LEAD									■															
MAGNESIUM ALLOYS										■														
MOLYBDENUM											■											◢		
NICKEL ALLOYS	◢											■	■	■	◢	■	■	■	■				◢	
STEEL- ALLOY	◢				■							■	■	■	◢	■	■	■	■		■		■	
STEEL-CARBON	◢		■	■	■		■	■				■	■	■	◢	■	■	■	■		■		■	
STEEL-FREE-MACH'G												◢	◢	◢	◢	◢	■	◢	◢				◢	
STEEL MARAGING												■	■	■	◢	■	■	■	■				■	
STEEL-SINTERED												■	■	■	■	■	■	■	■				■	
STEEL STAINLESS	◢						◢	■				■	■	■	◢	■	■	◢	■		■		■	
STEEL—TOOL				■								■	■	■	◢	■	■	■	◢				■	
TANTALUM																				■				
TITANIUM ALLOYS	◢						■						■	■				■			■			
TUNGSTEN											◢											■		
VALVE MATERIALS												◢	■	■	◢	■	■	■	■				■	
ZIRCONIUM ALLOYS	◢						■																	■

■ INDICATES FULL STRENGTH METALLURGICAL BONDS (IN SOME CASES, POST WELD TREATMENT IS NEEDED TO PRODUCE FULL STRENGTH.

◢ INDICATES BOND OBTAINED IS LESS THAN FULL STRENGTH IN SOME OR ALL CASES

* Reproduced from Publication of Manufacturing Technology, Inc., Mishawaka, Indiana, U.S.A., 1976

Some customers demand attachments on the welding machine itself for removal of the weld flash. The flash is either sheared off or turned on the welding head. It is the opinion of some that removal of weld flash on the welding machine itself is an uneconomic use of an expensive equipment and causes loss of production through longer work sequence. Incorporating too wide a range of possibilities into a machine leads to high costs and limited applications.

12. Conclusion

Friction welding has now reached a stage when it can be applied for joining of metals with a view to attain technical as well as economic advantages. Within the inherent limitations of the process (which are far outweighed by the advantages), one can find many applications where friction welding can be adopted readily. In order to attain greatest economy, parts should be designed with friction welding in mind as the production process.

Friction welding has not yet received the desired acceptance by the Indian engineering industry although a number of potential applications are obvious. One of the reasons could be the lack or insufficiency of knowledge of this welding technique. Another reason could be the low throughputs of welded parts not justifying the high investment. In such cases sub-contracting of parts should be undertaken.

In U.K., by 1973, there were six sub-contractors, having seventeen machines among them. However, considering the high potentials of the technique, friction welding is bound to receive good acceptance by the industry very soon.

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APPENDIX I

Successful Welds by Continuous-Drive Friction Welding Process*

(1) Carbon & Low Alloy Steels

SAE 1018/SAE 1018
SAE 1020/SAE 1020
SAE 1021/SAE 1021
SAE 1035/SAE 1035
SAE 4147/SAE 4147
C1008 C1008
C1020 C1020
C1022 C1022
C1026 C1026
C1030 C1030
C1040 C1040
C1040 C1020
C1040 C1038
C1040/C1010
C1038/C1038
C1042/C1042
C1027/C1027
C1027/1524
Jalloy 1/Jalloy 1
Jalloy 1/C1020
Jalloy 1/C1040
5140/5140
4140/4140
4140/C1020
4140 C1042
4340 4340
4340 C1020
4340 C1040
C1050 C1050
C1040/C1040
C1046/C1050
C1046 5140
C1046/C1046
6150/6150
6150/C1020
6150/C1040
4118/C1020
4320/4320
C1042/C1042
C1045/C1030
C1060/C1060
C1040/C1030
C1039/C1039
1330/C1035
C1055/C1055
C1010/C1010
C1020/5120
C1030/C1020
C1049/C1049
4130/4130
5115/5115
1340/1340
4140/1335
4150/4150
4320/4320

(2) Stainless Steels

410/410
410/C1020
410/4140
431/C1020
431/321
321/C1020
316/C1020
316/C1026
316/C1040
316/316
316/C1009

(3) Heat Resistant Materials

Dreadnought 30BW/Dreadnought 30 BW
Carpenter 20/C1020
Hastelloy B/C1020
Hastelloy C/C1020

Vacon IST/St330TS
Stellite G60/C1020
Stellite G60/C1040
Stellite G60/AIS316
Monel/Monel
Monel/C1020
Incolloy/Incolloy
Incolloy/C1020
Ni/Ni

(4) **Powder Products**

Iron Powder/9255
Iron 2% copper/C1008

(5) **Case Hardening and Nitriding**

C1009/C1009
C1016/C1027
C1016/316
0C116/C1016
4615/C1040
1019/1019
4718/4718
4781/C1020
Nitralloy 125 (H)
8622/8622

(6) **Nonferrous**

Al/C1020
Al/C1040
Al/Cu
Al/Al
Ti/Ti
Ti/Al
Cu/316
Cu/Cu
CA260/CA260
Cu Zn 37 Mn 2 Al.
Niobium/Niobium

(7) **High Speed Steel**

M2/C1055
T1/C1055

Note : The material specifications in the list are closest U.S. equivalents converted from the original British specifications by the New Britain Machine Co.

* Reproduced from WRC Bulletin No. 204, April 1975, "Friction Welding" by K. K. Wang.

APPENDIX II

Successful Welds by Inertia Welding Process*

(1) **Carbon & Alloy Steels**

SAE 1008 to 1037, 1052
SAE 1010 to self, **113, 1213,** 8620
SAE 1013 to 1010, 1018, **1117**
SAE 1017 to 1085
SAE 1018 to self, 1013, 1117, 5130, 8620, sintered 1024, 1080, ausformed 1060.
SAE 1020 to self, 1037, 1052, 1095, **1141, 1144, 1215** 4140, sintered 1080
SAE 1025 to self
SAE 1025 to **51204**
SAE 1035 to 4130, 4140
SAE 1036 to Inconel 713C
SAE 1037 to 1008, 1020
SAE 1040 to 52100
SAE 1045 to self, **1141,** 4150, 8620
SAE 1047 to 21-4N
SAE 1049 to self
SAE 1052 to self, 1008, 1020
SAE 1060 ausformed to 1018
SAE 1070 to M-I
SAE 1080 to self
SAE 1085 to 1017
SAE 1095 to self 1020
SAE 1113 to **416SS**
SAW 1117 to **self, 1013, 1018**
SAE 1137 to self
SAE 1141 to **self, 1144, 1018 1020, 1045**
SAE 1144 to **self 1141, 1020**
SAE 1213 to **1010**
SAE 1215 to **1020**
SAE 14B36 to self
SAE 3140 to SilSB
SAE 4032 to self
SAE 4038 to self
SAE 4115 to self
SAE 4130 to self, 1035
SAE 4140 to self, 4020, 1035, T-1
SAE 4142 to self

SAE 4150 to self, 1045
SAE 4340 to self
SAE 5120L to self, 1026
SAE 5130 to 1018
SAE 5140 to self
SAE 521000 to self, 1040, 8620, 8630
SAE 6150 to 8650
SAE 8150 to Sil 10
SAE 8615 to self
SAE 8620 to self, 1010, 1018, 1045, 8820, 52100
SAE 8625 to self
SAE 8630 to self, 52100
SAE 8645 to Inconel X
SAE 8650 to 6150
SAE 8740 to self
SAE 8822 to 8620
SAE 9310 to self
SAE 98BV 40 to self
USST-1 to 4140

(2) Sintered Steels

SAE 1024 to wrought 1018
SAE 1080 to self, wrought 1018, 1020

(3) Maraging Steels (18% Nickel)

250 to self, Waspaloy
300 to self, 4340
350 to self

(4) Stainless Steels

302 to self, 404, 410, 1020, 1045, 8620, 8630.
304 to self, 1020, 1045 nickel-copper
309 to 1010
310 to 17-4 Ph
316 to 1018, 1020
321 to self, 8630
347 to 17-4 Ph
404 to 8655
410 to 1045
416 to self, 440 ,1018, 1045, 1113
440C to self
17-4 Ph to self, 310, 347
Ca-5 (Centrif, cast) to self
Ca-20 to 1020, 1045
HK to self

(5) Tool Steels

M-1 to 1040, 1045, 1050, 1070, 1080, 8645, 8650
M-2 to 1045
M-4 to carbides (with a minimum of 10% Co)
M-7 to 1045
M10 to 1045
M50 to self
S-1 to 1080

(6) Special Alloys & Nonferrous Materials

Aluminium
AA1100 to self, 6061, copper
AA2024 to **self**
AA6061 to self, 6063, 1100, Cast 356 **copper**
AA6063 to self, Cast 356
AA 7075 to self
Cast 356 to 6061, 6063
S A286 to GMR 235
S AMS6304 to Inconel 713 LC, Waspaloy
S Astralloy to self
S B1910 to SAE 4340
Brass (70-30) to self
Bronze (alum) to self, SAE 1020, 1045
Carpenter 5 SS (Centrif. Cast) to self
Carpenter 20 SS to SAE 1020, 1045
Copper (pure) to SAE 1020, 1045,
AA1100, 6061 alum, chrome copper, Zircalloy
Copper (leaded) to **AA1100 aluminium**
Copper-beryllium 25 to self
Copper-nickel to nickel-copper
Copper-tungsten to chrome-copper,
Chrome-copper to copper tungsten,
 silver tungsten, pure copper
D979 to Inconel 713 LC
S GMR 235 to SAE 1040, 4130, 8620, 8630 A286
S Hastelloy to self
V Hastelloy X to SAE 1045
Inconel 100 to 718
Inconel 600 to self, 305 SS, SAE 1018
S Inconel 713C to SAE 1036, 1040, 4140,
5140, 8630, EN24, Nitralloy J
S Inconel 713 LC to 718, SAE 4140, 5140, D979, EN 24,
 Nitralloy J
S Inconel 718 to self, 100, 713LC, 901, AMS6304,
 Waspaloy.
V Inconel 751 to SAE 1045, 4140
S Inconel 901 to self, 718, Waspaloy
V Inconel X to SAE 8645
Lead (lead oxide dispersed) to self
S Mar M246 to SAE 5140
Molybdenum (sintered) to self
Monel 400 to self
Nickel 200 to self
Nickel (thorium dispersed) to self
Nickel-copper to self, copper-nickel 304 SS, SAE 1018
Nitralloy to self
Nitralloy J to Inconel 713C, 713LC

S Rene 41 to self, SAE 4340
V Silcrome//1 to SAE 3140, Stellite 5
V Silchrome//10 to SAE 8150
V Silcrome SB to SAE 3140
Silver tungsten to chrome copper
V Stellite 6 to SAE 3140, 4140, 8645, Silcrome//1
Stellite 21 to self
S Stellite 31 to SAE 1036, 8630
S Stellite 151 to SAE 8630
Stellite 220 to self.
Tantalum to self, **302 SS, SAE 1018**
V Thompson VMS-488 to SAE 1041
Titanium (pure) to self
Titanium (6Al-4V) to self, pure titanium
Tungsten (sintered) to self
Tungsten carbide to **SAE 1018, 1020, M4 Tool Steel**
S Udimet 700 to self
S Udimet 710 to SAE 4140
V Valve meterial 21-4N to SAE 1045, 1047, 3140
V Valve material 21-12to SAE 3140
V Valve material 21-55N to SAE 8650
Vascomax 250 (maraging steel) to Waspaloy
S Waspaloy to self, SAE 8545, AMS 6304, Inconel 901, Vascomax 250
Zircalloy 2 to self
Zircalloy 4 to self, copper

Notes : 1. All material combinations listed above have been inertia welded and in all cases a sound metallurgical bond was formed. For materials in bold type, however, the bond does not possess inherent 100% parent metal strength. In other cases appropriate post-weld treatment may be required to develop full weld-zone strength in materials that have been quenched and tempered, precipitation hardened or work hardened. Stress relieving may be required in hardenable materials.

2. V denotes valve materials and S denotes Superalloys.

* Reproduced from "Inertia Welding Applications Principles", published by Manufacturing Technology, Inc., Indiana, U.S.A.

Appendix III

Location of friction welding machines in UK industry (1973)*

Industry	*No. of Machines*		
Automobile :			
Structural parts	18		
Engine parts	24		
Transmission parts	13		
Steering parts	2		
Other components	4		
	61	61	44%
Hydraulic		3	2%
Wire		8	6%
General		12	9%
Dissimilar metal (electrical, chemical, twist drill)		18	6%
Plastics		12	9%
Sub-contract, development and research organisations.		34	24%
		138	100%

*Reproduced from "Friction Welding Application in the U.K."
CRG Ellis, Metal Const. Nov 1973.

APPENDIX IV

A. DRILL COST COMPARISON USING 12 TON MACHINE**

Drill data	*Drill A*	*Drill B*
Diameter (mm)	12.50	20.0
Overall length	182.00	238.0
Flute length	101.00	140.0

Welding data	*Flash*	*Friction*	*Flash*	*Friction*
Total burn-off	9.6	4.5	12.4	4.5
High speed steel burn-off	5.8	2.0	7.5	2.0
Production rate/hour	120.0	160.0	100.0	130.0
Cost data/100 pieces (pence)				
Flute stock	1686	1626	5962	5740
Shank stock	207	203	640	625
Welding labour	264	200	320	246
Cut-off labour	126	126	160	160
Scrap loss	11	11	35	34
	2294	2166	7117	6805
Savings with friction welding/100 drills	128p		312p	

Values used in calculations

High speed steel cost	165.0p/Kg	Labour	£1.00/hr.
EN9 material	25.4p/Kg	Overheads	220%
Scrap rate	0.5%	Labour efficiency	80%

B. DRILL COST COMPARISON USING 40 TON MACHINE

Drill Data	*Drill C*	*Drill D*	*Drill E*
Diameter (mm)	32.0	50.0	70.0
Overall length	334.0	396.0	437.0
Body length	185.0	220.0	250.0

Welding Data	*Flash*	*Friction*	*Flash*	*Friction*	*Flash*	*Friction*
Total burn-off	17.0	5.0	23.6	5.0	31.0*	5.0
High speed steel burn-off	10.2	2.0	14.2*	3.0	18.7*	3.0
Production rate/hour	80.0	100.0	30	60.0	12.0	25.0
Cost data/100 pieces (pence)						
Flute stock	20201	19352	59171	56341	133060	124790
Shank stock	2466	2413	6160	5911	15345	114833
Welding labour	400	320	1066	533	2666	1280
Cut-off labour	187	187	320	320	640	640
Scrap loss	166	111	334	315	758	706
Total cost/100 pieces.	23370	22383	67051	63420	152469	141899
Savings with friction welding/100 drills	987p		3631p		10570p	

Values used in calculations

High Speed Steel cost	165.0p/Kg	Labour	£1.00/hr
EN9 material	25.4p/Kg	Overheads	22%
Scrap rate	0.5%	Labour efficiency	80%

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*Extrapolated data

**Reproduced from "Friction Welding as a Production Tool", Seminar Handbook The Welding Institute, U.K., Oct. 1974.