Friction Welding

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1. Introduction

1.1 *What is friction welding*

Friction welding is a solid state welding process in which heat for welding is produced by direct conversion of mechanical energy at the interface of the weld pieces, without the application of electrical energy or heat from other sources to the weld pieces.

The frictional heat may be generated at the weld interface by imparting relative tangential motion under normal pressure.

1.2 *History of Development*

Earliest evidence of friction welding dates back to an 1891 patent issued to J. H. Bevington of Peoria. Illinois, who used friction heating for welding of cables. In 1929, Walter Richter of Mannheim, Germany, was granted a German Patent on "Friction Welded Parts". Dr. H. Klopstock and A. R. Neelands were issued a British Patent in 1945 on 'An improved method of joining or welding metals'. However, the friction welding process showed no commercial development, although "Spin Welding" of plastics was being utilised.

In 1956, fresh interest was aroused when the Russian machinist Aleksei I. Chudikov suggested using friction as a heat source for welding metals. On Sept. 5, 1957 the Scientific Research Institute of Welding Equipment (VNNIESO), USSR, was granted a Soviet Patent based on Chudikov's work. This led to an intensive study of Friction Welding by Vadim I. Vill in the USSR, who first published on the subject in 1957.

The Russian work was first described in American literature by Tesmen in 1959. This inspired a number of studies in friction welding in USA and UK. The process was introduced to the USA in 1960 by American Machine & Foundry Company.

In 1964, Caterpillar Tractor Company, USA., set up its first "Inertia Welder" based on the principles of friction welding utilising stored flywheel energy. The process was introduced to trade and general public in 1965, and was patented in Sept. 1966.

The B.W.R.A. (now The Welding Institute) developed "Micro Friction Welding" process in 1968. This is a scaled down version of the original Russian method of friction welding, applicable to the miniature component fabrication field.

In 1970, the Friction Welding Company Ltd., Walsall developed "Orbital Friction Welding" technique based on the principles announced by

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the Mechanical Engineering Department of University of Leeds. This has extended the application of friction welding to non-circular interface configurations as well.

The Welding Institute, U.K., last year developed the "Radial Friction Welding" technique, which is suitable for welding of long tubular sections using an intermediate rotating ring.

As it stands today, the Friction Welding process is undergoing continued research in the developed countries like USSR, USA, UK, Germany, Japan, China, Czechoslovakia, France, etc.

1.3 *Friction Welding in India*

Although friction welding has received wide acceptance in the developed countries, it is yet to find any significant applications in our country. There are reports of friction welding being used by a few companies in India employing imported machines.

To achieve technological self-reliance in the field of friction welding, work was started at MERADO (Welding) on the campus of Central Mechanical Engineering Institute, Durgapur, some time during 1971. In August 1974, a 12 ton friction welding machine, based on the Russian (continuous drive) principle was completed. Many successful welds between similar and dissimilar materials have been made on this machine.

Friction welders are likely to enter the Indian market as a substitute for flash butt welder, particularly where consistently good welds are to be made between dis similar materials. For wider acceptance and application of friction welding in India, it would be necessary to educate and enlighten the probable users on the capabilities of this technique.

Equally important is the development of indigenous machines for friction welding. It has been reliably learnt that many organisations/institutions are working independently on the development of machines for friction welding. To start with, the machines could be made much simpler than the very sophisticated type of machines available in the foreign market, involving automatic loading, unloading, flash removal, and quality monitoring systems. Such simple and consequently cheaper machines would find an easier access into the industry.

An indigenous manufacturer of welding equipment has taken the first step towards commercial production of friction welding machines. Successful welds have been made with the development machine between similar and dissimilar materials with quite encouraging results.

2. Methods of Friction Welding

The following are the different methods of welding by friction as developed till today.

(a) Conventional friction welding (Continuous drive friction welding)

(n) Inertia Welding (Stored energy welding)

(c) Flywheel friction welding.

(d) Micro friction welding.

(e) Orbital friction welding.

(f) Heat under power (HUP) welding.

(g) Radial friction welding.

2.1 *Conventional Friction Welding*

This is the original method of friction welding as developed in USSR. Here mechanical energy is converted to heat energy by rotating one workpiece while pressing it against a non rotating workpiece. After a specific period of time (or a pre-set burn-off length), rotation is suddenly stopped and the pressure is increased and held for another specified period of time, producing a weld.

This involves two distinct phases, viz. the heating phase—when the interface is bought upto the welding temperature—, and the forging phase—when the actual welding takes place. The softened plastic interfacial zone of the weld material is forced out into the characteristic flared flash of a friction weld, under constant forging load. This method of welding is also referred to as the continuous drive friction welding (See Fig. 1).

In conventional friction welding, the variables to be controlled are:—

(a) Friction Speed.

(b) Friction force.

(c) Friction time or the burn-off length.

(d); Deceleration time.

(e) Forge force.

(a) *Friction Speed:* The most widely used speed cycle is one where a constant speed is maintained during the friction heating phase followed by rapid halting. The rotational speed is often specified in terms of sliding speed at two-thirds of the radius at the faying surface.

From the standpoint of an intensification of the process and improvement of weld quality—particularly for welding of metals sensitive to overheating—, it is desirable to use relatively low rotational speeds. This, however, leads to a necessary increase in the power of the installation.

For low carbon steels, a relation has been established between the speed in RPM(n) and the outside diameter of the welded cross section in mm (d) as,

$$n.d. = (1.2 \text{ to } 6.0) \times 10^4$$

The lower limit refers to hard welding procedures with a high intensity of heat liberation, whereas the upper refers to soft welding procedures with moderate intensity of heat liberation.

(b) *Friction Force:* This is the longitudinal force applied to the faying surfaces during the time that there is relative movement between the components. Low values of friction force result in proportionately low unit thermal energy liberation, greater heat dissipation and consequently an increased width of heat affected zone (HaZ).

If very high friction forces are employed, the softer metal at the interface would be squeezed out leaving relatively cooler metal at the interface, which again would be detrimental for weld formation.

(c) *Friction time or burn-off length:* Friction time is that time during which relative movement between the components takes place at friction speed and under application of the friction force. Burn-off length is the overall length loss of the components during the application of the friction force. Either of these may be used for controlling the process.

When burn-off length is used for controlling the process, the wear of large & randomly distributed irregularities—e.g. large burrs, central projections left after improper facing operation, or when the friction surfaces are not perpendicular to the axis of rotation, —is often wrongly taken to be the biginning of the burn-off. This could result in non-fusion or lack-of-bond defects. This condition is overcome to some extent by allowing more than optimum burn-off to take place.

Controlling the process according to friction time rather than burn-off length would have the same drawback unless relatively high rotational speeds are employed to obviate the influence of irregularities of the faying surface. In the event of contamination of the faying surfaces or inadequate finish, the process should be controlled by upset and not by time.

(d) *Deceleration time:* This is the time required by the moving component to decelerate from friction speed to zero speed. It was believed for long that relative movement at the friction surfaces must be halted in the shortest possible time—instantaneously, if possible, in order to produce sound welds. Gradual reduction of speed to zero value was believed to preclude weld formation. Recent experiments have established that in continuous drive friction welding, it is not essential to use a brake and very good welds can be produced without a brake.

When a brake is used, the deceleration could be of the order of about 2500 rad/Sec^2 and high axial pressure and/or low rotational speeds are required to produce a weld of adequate strength. The use of very low values of deceleration (60 rad/Sec^2 or less) produces risk of developing cracks in the HaZ. The burn-off collar would also be large and very high terminal torques may result.

(e) *Forge Force:* This is the longitudinal force applied to the faying surfaces at the time when relative movement between the components is ceasing and/or has ceased. This is usually higher than the friction force. Here, clean, pure surfaces are pressed into intimate contact for a resultant atomic bonding. For low carbon steels the forging pressure is about 530 Kg/sq cm.

While it is desirous to specify optimum welding parameters for every material combination that is to be welded, it is not always possible to do so. Typical weld cycles used in the conventional process are shown in Table 1. Satisfactory welds have been made with parameters quite different from those indicated in the table.

2.2 *Inertia Welding*

Here, one work piece is held in a non-rotating clamping device. The companion workpiece is held in a rotating holding device which is coupled to a flywheel spindle system driven by a power source. The spindle is accelerated to a predetermined speed, at which time the power source is disconnected from the spindle assembly and the workpieces are brought into contact under a rapidly applied constant axial welding force. The fly-

TABLE—1

Representative Friction Welding Parameters**

	Diameter (in)	*Relative Rotational Speed (rpm)*	*Contact Pressure (PSI)*		*Total Time (Sec.)*
			Heating Phase	*Forging Phase*	
Carbon Steel (a)	0.5	9000	5000	5000	7
	1.0	1500	7500	7500	15
Stainless Steel (b)	1.0	3000	12000	16000	7
	5.5 o.d. 4.5 i.d.	800	20000	20000	35
Stainless Steel to Carbon Steel	0.75	3000	7500	15000	10
Tool Steel (c)	0.75	4000	15000	20000	10 (d)
Copper (ETP) (e)	1.0	6000	5000	10000	18
Aluminium-Commercially Pure(e)	0.75	3800	4000	6500	6
Alloy Steel (f)	0.375	5000	25000 (g)	40000	10 (d)
Alloy Steel to Carbon Steel (h)	1.75 p.d. 1.25 i.d.	6800	2500 (i)	6000	42 (d)
	4.5 p.d. 3.25 i.d.	3000	5500 (j)	16000	26 (d)

(a) AISI 1010, 1020, 1030, 1045 steels
(b) Series 300 and 400
(c) Type T-1 or equivalent
(d) Post-heat treatment required.
(e) Small amounts of alloys can alter the parameters considerably.
(f) AISI 3140 to 21% Cr-4% Ni-9% M_n steel
(g) Pressure built-up from 0 to 25,000 psi in 3 secs.
(h) AISI 4140 to 1035 steel; pre-heat the AISI 4140 steel to 600°F.
(i) Pressure built-up from 0 to 2500 psi in 20 secs.
(j) Pressure built-up from 0 to 5500 psi in 26 secs.

**Reproduced from "The Welding Handbook", published by AWS.

wheel energy is rapidly converted to heat at the interface and welding occurs as rotation ceases (see Fig. 1).

The flywheel makes it feasible to develop thermal energy at the weld interface at a rate equivalent to from 20 to 200 Hp/Sq.in. of weld area. The weld cycle time is also much shorter, usually from 1 to 10 seconds only. High energy input, together with forging action produced by a combination of high torque and high axial thrust, results in sound welds, free from oxides and voids.

Three interrelated parameters control the character of the weld. These are:—

(a) Initial sliding velocity at the faying surface.

(b) Moment of inertia of the flywheel-spindle system.

(c) Axial thrust force at the welding interface.

All these depend upon the combination of materials and the configuration at the weld. The effects on weld patterns when these weld parameters are varied are explained in figure 2.

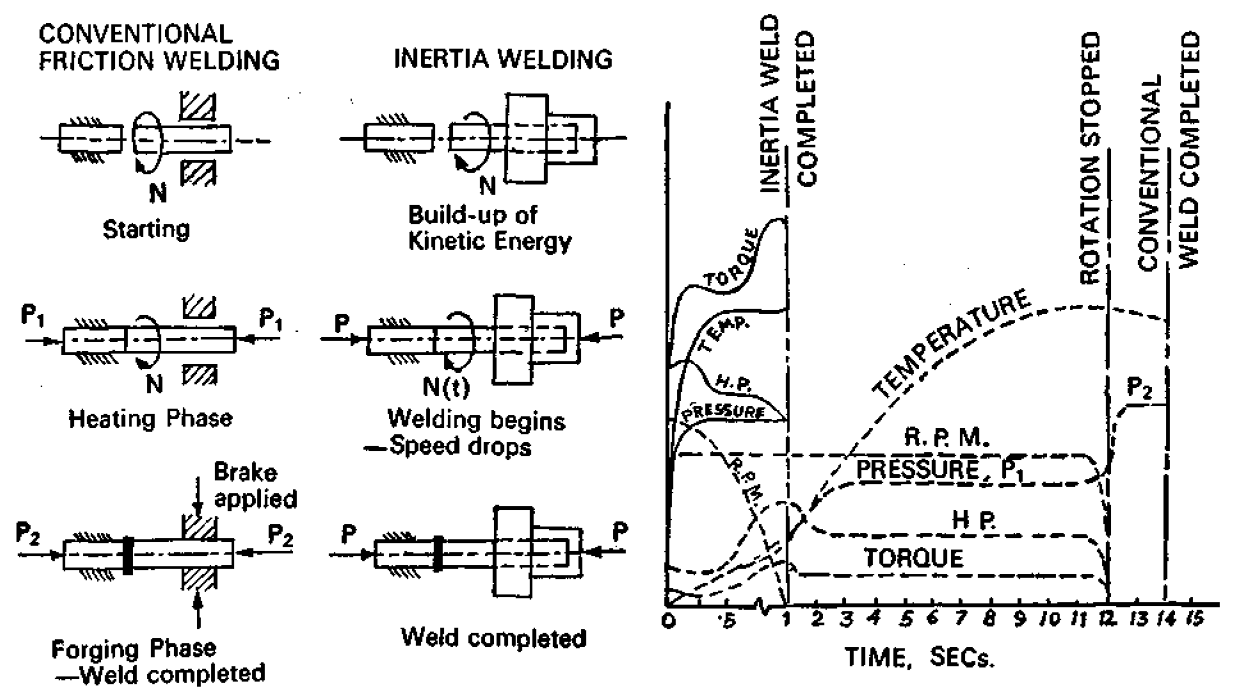

Fig. 1. Conventional and Inertia methods of friction welding.

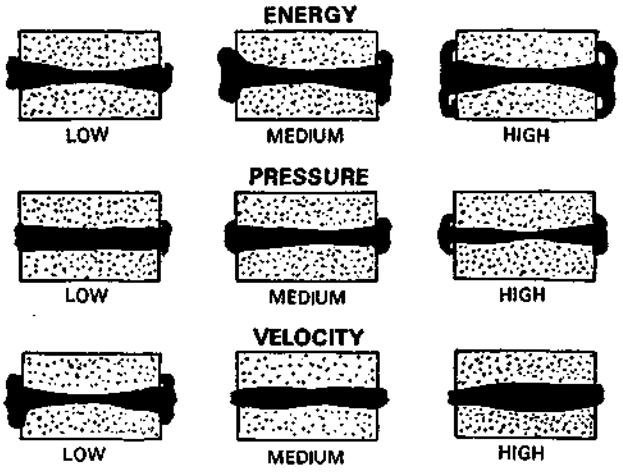

Fig. 2. Effect of change in weld parameters on HAZ and flash pattern for Inertia welding of steel bars.

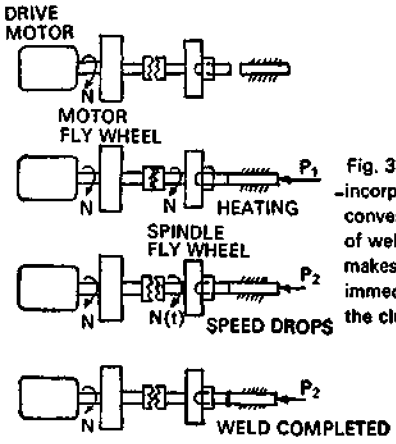

Fig. 3. Flywheel Friction welding incorporating features of the conventional and inertia methods of welding. The motor flywheel makes the weld energy almost immediately available. Once the clutch is engaged.

Representative parameters for inertia welding of different materials are given in Table 2. Here again, departures from the recommended values may be adopted without seriously affecting the quality of welds.

2.3 *Flywheel Friction Welding*

This incorporates features of both the conventional and inertia process. Flywheels are connected to the drive motor and to the spindle, and are coupled through an integral clutch. The drive motor-flywheel system rotates continuously and is coupled to the flywheel-spindle system to bring the rotating workpiece to a pre-determined speed. The stationary workpiece is pressed against the rotating workpiece, generating heat at the flying surfaces. At a pre-determined time, the motor-flywheel is disengaged from the spindle flywheel. The weld is completed as the spindle flywheel, which has a low moment of inertia, comes to rest without application of a brake (see Fig. 3).

The controlling parameters in flywheel friction welding are:

(a) Rotational speed.
(b) Moment of inertia of spindle flywheel.
(c) Cut-out speed.
(d) Axial Pressure

TABLE—2

Representative Conditions for Inertia Welding 1" Dia Bars

Material	*Weld Parameters*			*Resultant Weld Conditions*		
	Speed *RPM*	*Thrust Load* *Lb.*	*Inertial Mass* *lb—ft²*	*Energy* *ft—lbs*	*Upset* *in.*	*Weld Time* *Secs.*
Low C steel (1018)	4600	12,000	6.7	24,000	0.10	2.0
Medium C steel (1045)	4600	14,000	7.8	28,000	0.10	2.0
Low alloy steels (4140)	4600	15,000	8.3	30,000	0.10	2.0
Superalloy-Inconel 718	1500	50,000	130.0	50,000	0.15	3.0
Maraging Steels	3000	20,000	20.0	30,000	0.10	2.5
S. S. 410 (Ferritic)	3000	18,000	20.0	30,000	0.10	2.5
S. S. 302 (Austenitic)	3500	18,000	14.0	30,000	0.10	2.5
Copper-commercially pure	8000	5,000	1.0	10,000	0.15	0.5
Cartridge Brass (70%)	7000	5,000	1.2	10,000	0.15	0.7
Titanium alloy (Ti-6AL-4V)	6000	8,000	1.7	16,000	0.15	2.0
Aluminium (1100)	5700	6,000	2.7	15,000	0.15	1.0
Aluminium (6061)	5700	7,000	3.0	17,000	0.15	1.0
Copper-C Steel (1018)	8000	5,000	1.4	15,000	0.15	1.0
M2 Tool steel-steel (1045)	3000	40,000	27.0	40,000	0.10	3.0
Inconel 718—steel (1045)	1500	40,000	130.0	50,000	0.15	2.5
S. S. 302—steel (1020)	3000	18,000	20.0	30,000	0.10	2.5
Sintered high C steel-steel (1018)	4600	12,000	8.3	30,000	0.10	2.5
Aluminium (6061)—S. S. 302	5500	5,000 *15,000	3.9	20,000	0.20	3.0
Copper—Aluminium (1100)	2000	7,500	11.0	7,500	0.20	1.0

*The lower thrust load is applied during the heating stage of the weld and then increased to the higher load near the end of the weld.

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The effects of variations in these parameters (except cut-out speed) on the weld pattern are the same as those for intertia welding.

2.4 *Micro Friction Welding*

This method of friction welding is a scaled-down version of the conventional friction welding method, with the parameters extrapolated accordingly. This has extended the use of friction welding to the work in very small diameter range. The diameter range being from 0.75 mm to 2 mm. Very high speeds, of the order of about 65,000 to 100,000 rpm are employed. Alignment between the two axes and the end preparations are of particular importance.

The parameters to control weld quality and the effect of change in these on the resultant weld condition are same as those for the conventional method of friction welding.

2.5 *Orbital Friction Welding*

This method of friction welding overcomes some of the major limitations of the friction welding technique, viz. its application to circular or nearly circular components, difficulty in attaining angular alignment and non-uniform pattern of heat generation over the interface.

Here, one component is stationary and the other pursues a circular path with an orbit radius 'e' (see figure 4) without rotating about its own axis. The two components are pressed together and, when sufficient heat has been generated all that is done is to reduce

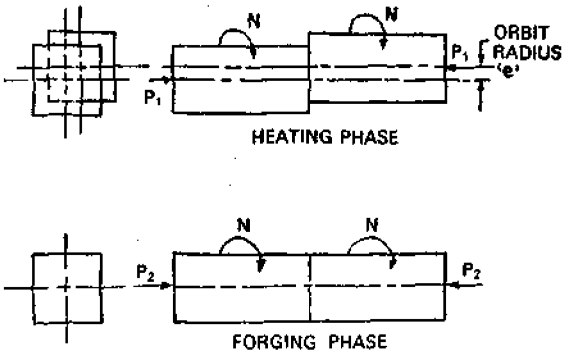


Fig. 4. Orbital Friction Welding —both components are rotated with their axes off-set, resulting in relative orbital motion. When sufficient heat has been generated the axes are realigned and the forge force is applied.

the orbit radius 'e' to zero, i.e. to centre the moving component on the stationary one, to achieve alignment.

In practice, such an orbital motion would result in very high centrifugal forces on the work holder. A simple operating principle to achieve relative orbital motion involves rotating both the components in the same direction with their axes offset. Heating is effected by applying an axial friction force. When sufficient heat has been generated, the axes are realigned and a forge force is applied to the still rotating components.

2.6 *Heat-Under-Power (HUP) Welding*

The HUP method of friction welding offers advantages of both the continuous drive and the inertia methods, with few of their limitations. Here, the first part of heating phase is performed like the continuous drive method—the spindle rotated by the drive motor. The difference is that this phase is continued until control equipment physically detect the attainment of an optimum interface condition, this being a criterion of control (see Fig. 5).

This optimum condition is the state of equilibrium, when the heat input is balanced by heat dissipation. As the state of equilibrium can be continued as long as desired correction of length variation in initial parts can be accomplished, i.e. by using a 'burn-off-to-length' control which is dependent on a relationship attached between datums on the fixed and moving part holders.

If a rotating mass or flywheel, which can be varied in size is added to the rotating spindle, an exactly repeatable amount of stored energy is provided when the motor is disconnected, acting on an exactly repeatable interface condition. The size of the flywheel required is smaller than that for inertia welding as it has only to supply energy to create a bond from an already prepared and heated interface. Also, the flywheel does not have to rotate at high speeds and standard bearings and holding devices can be used.

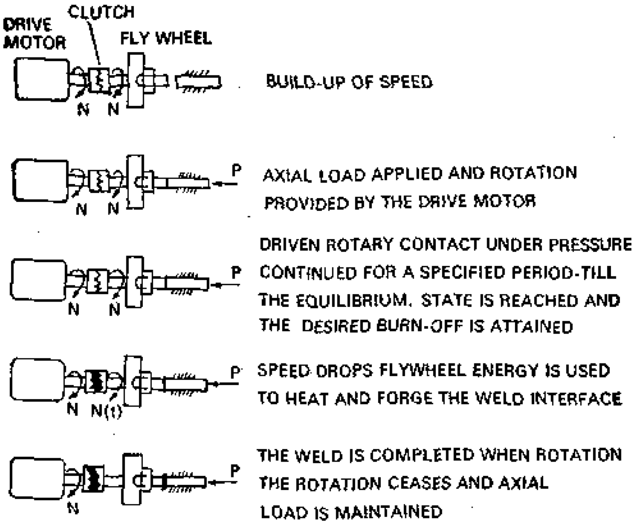


Fig. 5. Heat Under Power (HUP) method of friction welding.

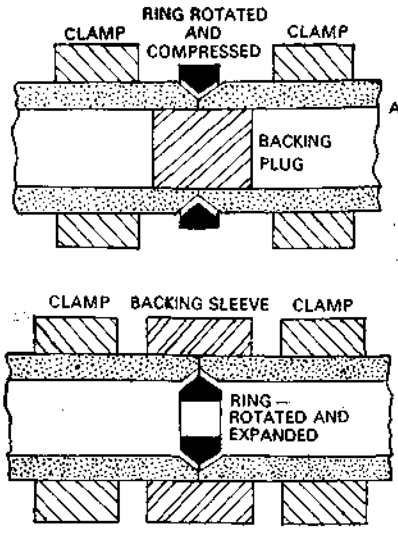
The flywheel also assists in the heating phase as it is rotating with the spindle and therefore provides inertia to assist the motor over cold state contact peak torque. Use can either be made of a smaller drive motor (than that required for conventional method of welding) or a larger interface area can be welded.

2.7 *Radial Friction Welding*

When the usual methods of friction welding are applied for butt welding long pipe lengths, the necessity to rotate and provide axial displacement while maintaining adequate work holding and force reaction present a problem. Also the removal of internal flash collar becomes impracticable. Radial friction welding method has been developed to resolve these problems.

Here, the two tubes to be butt welded are bevelled (see figure 6—a) and held in axial alignment, A special welding ring with its sides similarly bevelled is placed in position between the tube ends. This ring is rotated and radially compressed. The tubes are clamped so that they can not move apart in axial direction or rotate about their common axis. Interaction of the compressing ring against the tube ends provides the necessary welding force. As a result of relative motion and force, thermal energy is developed, which results in metal displacement taking place at the faying surface.

To terminate the heating cycle, rotation of the ring is arrested while the radial compression rate (welding



A. Radial Friction welding -using a compression ring and an internal backing plug.

B. Radial friction welding -using an expansion ring and an external backing sleeve

Fig. 6. Schematic arrangements for Radial friction welding.

force) is either maintained or increased to complete the weld.

A non-consumable backing plug is employed to prevent any internal flaring or restriction. This leaves the bore of the tubes undisturbed, eliminating the necessity for flash removal.

The technique works equally well if the rotating ring is radially expanded, using a backing sleeve on the outside diameter (Fig. 6—B).

3. Mechanics of Friction Welding

Friction welds are solid phase welds, in which there is no melting of either of the materials being welded. Even if excess energy were put into the welds, the plastic material would flow out under axial pressure before the melting point could be reached. The weld is formed as a result of fresh clear sub-surface materials coming into intimate contact at atomic level to form a metallurgical bond after the contaminated original surface layers are cracked and forged out into the flash.

The actual mechanism of bonding is different for similar and dissimilar metal combinations as studied by McMullar and Bahrani.

3.1 *Similar Materials*

When a rotating component slides over the unlubricated surface of the stationary component, adhesion junctions are formed at points of real contact under the influence of an axial force. At some of the junctions, the adhesion between the surface is stronger than the metal on either side and shearing takes place at a short distance from the interface. Fragments of metal get transferred from one surface to the other and vice versa.

As the rubbing continues, the temperature rises and eventually reaches a value at which the transferred fragments and the material in the annular rubbing region become soft and under the applied high shear stresses, it starts to flow resembling a high viscosity liquid.

The plasticised material from both sides of the interface merge with each other. Thus the condition at the interface changes from two solid surfaces rubbing against each other to that of two solids separated by a viscous fluid which is being churned between them. The drop in torque curve is due to this plasticised condition.

It is believed that the hot and severely worked metal in the plasticised layer forms the joining medium between the two parts being welded. Thus, if welding conditions are such that a continuous plasticised layer is formed at the interface then sound welds are produced.

3.2 *Dissimilar Materials*

The mechanics of friction welding dissimilar materials is different from that for similar materials in that the adhesion junctions formed are sheared either at the interface or at a short distance from the interface in the softer material only. Fragments of the softer specimen get transferred to the surface of the harder specimen until the surface of the harder material is completely covered with a layer of the softer material.

As the layer formation progresses, the plane of rubbing moves axially into the softer material component. Thus rubbing becomes between two similar materials and eventually a plasticised annular zone is developed on the rubbing plane, composed of the softer material. The harder specimen does not participate in the formation of the plasticised layer or the upset collar. This phenomenon is particularly apparent for welds between aluminium alloys and mild steel or copper.

4. Advantages of the Friction Welding Process

(a) Ability to join dissimilar materials, e.g. M.S. to copper, S.S. to aluminium etc.

(b) No metallurgical disturbance of the weld is caused and the joints are metallurgically sound.

(c) Flux, filler metals or protective atmospheres are not necessary.

(d) The weld is free from defects like voids or slag inclusions.

(e) The process is neat and clean. There is no spatter, and no arcs, fumes or scales are developed.

(f) The operating cycle is very short, particularly for inertia welding (1 to 10 Secs. only).

(g) A very narrow HAZ is present due to optimum heat input and short cycle time.

(h) Post-weld annealing of the weld zone is seldom necessary.

(i) The weld zone is mechanically worked and free of soft spots. The grain structure in the HAZ is refined, not coarsened. The grain size in the HAZ is frequently smaller than that in the base metal.

(j) There is very little loss of material in the form of flash expulsion.

(k) The weld joints show good mechanical properties and consistent quality.

(l) Simplicity of the equipment—the elements of machine manipulation are easily mastered.

(m) The operation being simple, labour can be easily and quickly trained.

(n) Lower power consumption. Friction welding requires only 1/10 to 1/5 of the power required for flash welding. The power factor is around 0.85 as against 0.4 to 0.6 for flash welders. Unlike the flash welders, the friction welders use a steadier load and there is no high peak loading.

(o) The process is equally suitable for small batch and large quantity production by automation.

5. Limitations

Like all manufacturing processes, friction welding too has its own limitations. These are:

(a) One workpiece must be round (or nearly round) at the interface and must have a size/shape that can be clamped and rotated at high speeds. However this limitation is not applicable to orbital friction welding.

(b) The workpiece must be strong enough to withstand heavy torque and shock loads during welding.

(c) The work holding devices too must be rigid.

(d) The process is restricted to flat and angular butt welds that are concentric with the axis of rotation (—not applicable to orbital friction welding).

(e) Final angular alignment is not always possible. Expensive modifications are necessary to achieve final angular alignment (—not applicable to orbital Friction welding).

(f) There is a limit to the maximum size that can be welded. This limitation is imposed because of the very high axial thrust that would be required to accomplish the weld, which in turn requires machines of gigantic proportions.

(g) The process is unsuitable for materials which have very low coefficient of friction, e.g. cast iron, bronzes and brasses having a lead content of over 0.3%. Even free machining steels having over 0.13% of lead, sulfur or tellurium cannot be successfully welded.

(To be continued)