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Some Experiments with a New-Designed Friction Welding Machine*

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The friction welding process is developed so as to remove the flash, which protrudes from the contact area between works, by the tool as soon as it is generated.

In friction welding of plain carbon steel to plain carbon steel, stainless steel to stainless steel, plain carbon steel to stainless steel and chromium-molybdenum steel to stainless steel, the joint, which has been finished at the moment welding is formed, can be gotten. Moreover, the joint with 100 per cent joint efficiency can be formed by a considerably low welding pressure such as 2, 3 or 4 kg/mm².

1. Introduction

Since the friction welding method was developed about ten years ago, various fields have shown keen interest in the advantages and specific characteristics unique to the process. At present, this welding method is being put to practical use in many industrial countries and many applications have been studied and explored.

As is generally known, there are two methods of friction welding, namely, — the conventional method and the flywheel method. In the conventional method (Fig. 1), workpieces are aligned axially with each other and one of them is rotated against the other which is held stationary. Surfaces of workpieces are slid relatively under welding force. When heated sufficiently to accomplish a weld, a mechanical brake is applied to stop relative rotation

between workpieces. In the flywheel method (Fig. 2), one workpiece is chucked to the rotating spindle with flywheel, which has stored up desired kinetic energy. This rotating workpiece is pushed against the other workpiece held stationary under welding force. When kinetic energy of the flywheel is converted to frictional heat at the contact area, a weld is formed.

In both methods, the flash (upset) is formed at the joint. If removing of flash (upset) from joint is required, a suitable process as well as flash removing equipment must be incorporated. However, it is difficult to remove the highly hardened flash due to the quenching effect after welding. Even for the flash not so hardened, an additional flash-removing process and equipment are needed. If the flash at the joint can be removed during the welding cycle, the versatility, productivity and production efficiency of using the friction welding process will be increased considerably.

The friction welding machine introduced in this paper is designed so as to remove the flash immediately upon its forming at the joint. Thus, by the

Fig. 1 The conventional type friction welding machine

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Fig. 2 The flywheel type friction welding machine

time when welding is completed, the flash will have been removed and machined. This is the first specific feature of the process.

Since flash removing in heating phase keeps the contact area unchanged during the entire welding cycle, this results in true welding pressure at the contact area between workpieces. Therefore, a sound weld may be obtained by a lower welding force by this method than by either conventional or flywheel method for welding workpieces of same size. Consequently, this advantage makes the design and manufacturing of the machine much easier. This is the second specific feature of the process.

This paper reports (a) the mathematical aspect of the new friction welding method, (b) its new design features, (c) some interesting phenomena in welding of plain carbon steel to plain carbon steel and stainless steel to stainless steel, (d) flash removing during heating phase and (e) test results of welded joints.

2. Friction welding machine

Figures 3 (a) and (b) show the welding mechanism of the new designed friction welding machine and the process of welding.

(1) Rotational speed of one workpiece W_1

Fig. 3 The new-designed friction welding machine

chucked to the driving spindle is kept at N .

(2) The surface of the other workpiece W_2 chucked to the driven spindle contacts the workpiece stated in (1), under axial welding force. And the driven spindle, which is coupled to a free rotating mass, is stationary at this moment.

(3) By the frictional force developed at the contact area between the workpieces, the driven spindle is accelerated to some intermediate rotational speed n (where $0 < n < N$). During this phase, the contact area is heated to a forging temperature.

(4) When the rotational speed n reaches the rotational speed of N , a weld is formed.

(5) Rotation is stopped.

As stated above, both of the spindles are rotated, though the rotational speed of the driving spindle is different from that of the driven spindle in heating phase. This feature is essentially different from the conventional process and the flywheel, where one work is held stationary during welding cycle. Consequently, if one desires, the flash can be hot-machined simultaneously as it forms [phase (2)~(4) in Fig. 3 (a)], by a cutting tool at the weld, as shown in Fig. 3 (b).

Figure 4 shows a view of the friction welding machine.

The arrangements for measuring the change of rotational speed of the driven spindle, the amount of upset of workpiece during welding and the main cutting force of flash will be discussed.

Lamp-photocell unit seen in Fig. 4 is used for measuring the change of rotational speed of the driven spindle. After the driven spindle starts to rotate, the light of lamp passing through the four holes bored equidistantly near the circumference of the disc fixed to the driven spindle is projected to a photocell, resulting in pulses. The pulses are recorded on an oscillogram. Then, by reading the pulse intervals, the change of rotational speed of the driven spindle can be found.

The amount of upset is measured as follows. As flash forms, the free end of cantilever plate, with the other end of the plate fixed to the machine

Fig. 4 View of the new-designed friction welding machine

frame, is pushed by a needle attached on the stationary part of the driven spindle, i.e. the thrust bearing enclosure [part ③ in Fig. 3 (b)]. The deflection of the plate, on which a strain gauge is attached, is recorded on an oscillogram. In this way the amount of upset in welding cycle is measured.

Magnitude of main cutting force of removing flash is calculated by the amount of deflection of the tool shank. The amount of deflection is measured by means of the strain gauge attached on the shank.

3. Mathematical aspect of new welding method

Let us consider the frictional-work done at the contact area between workpieces during the welding cycle. Here, for simplification, frictional losses at the bearings used in the machine are assumed to be negligible.

Let :

I : moment of inertia of rotating mass fitted to driven spindle (kg m sec²)

N : rotational speed of driving spindle (rpm)

Ω : angular velocity of driving spindle
 $2\pi N/60$ (rad/sec)

n : rotational speed of driven spindle (rpm)

ω : angular velocity of driven spindle
 $2\pi n/60$ (rad/sec)

At any instant in heating phase, angular acceleration of the driven spindle and the torque at the contact surface can be expressed as $d\omega/dt$, and $I(d\omega/dt)$, respectively. Then, the work done by

the frictional force, dE , can be written as follows.

$$dE = I \frac{d\omega}{dt} d\theta = I(\Omega - \omega) d\omega,$$

$$d\theta = (\Omega - \omega) dt$$

Therefore, the total energy E discharged to the contact area may be calculated as,

$$E = \int_0^{t_f} dE = \int_0^{\Omega} I(\Omega - \omega) d\omega \\ = \frac{I\Omega^2}{2} = \frac{2\pi I N^2}{3600} \text{ (kg m)}$$

where, t_f is heating time.

4. Experimental results and discussions

Welds of plain carbon steel (0.25 % C) to itself, stainless steel (18 Cr-8 Ni) to itself, stainless steel to plain carbon steel and chromium-molybdenum steel to stainless steel which have diameter of 7 mm are formed.

Basic welding parameters in this process are rotational speed of driving spindle N , moment of inertia of driven spindle system I and welding pressure* P . To select the optimum welding parameters, the workpiece dimensions, geometries and the types

Table 1 Welding parameters

Diameter of workpiece	7.0 mm
Rotational speed of driving spindle N	2 800 rpm
Angular velocity of driving spindle Ω	293 rad/sec
Moment of inertia of rotating mass I	3.09×10^{-3} kg m sec ²
Total input of friction E	132 kg m
Welding pressure P	2.0~18.0 kg/mm ²

Fig. 5 Oscillograms showing rotational speed change of driven spindle, progress of welding force, amount of upset and main cutting force of flash

* welding pressure = $\frac{\text{welding force}}{\text{original sectional area of the workpiece}}$

of materials to be welded should be considered. However, for the experiments in this report, N of 2800 rpm and I of $3.09 \times 10^{-3} \text{ kg m sec}^2$ are used. The total energy discharged at the weld interface is calculated as 132 kg m. Various welding pressures are selected for the type of materials to be welded. Welding parameters for various workpieces are tabulated in Table 1.

Figure 5 shows examples of oscillogram in which rotational speed change of the driven spindle (by counting the number of pulses), history of welding force, amount of upset and main cutting force of removing flash are shown and recorded. The upper figure in Fig. 5 shows records for welding plain carbon steel to plain carbon steel and lower figure shows those of stainless steel to stainless steel. The process, referred to as the conventional process hereafter in this paper, is the process without removing flash during the welding cycle [Fig. 3 (a)]. A constant welding force is used in the experiments, as in the case of conventional friction welding.

4.1 Friction phenomena

Rotational speed change of the driven spindle in welding can be easily found by checking the pulse intervals against the standard interval of 0.01 sec, shown in Fig. 5. If the rotational speed change of the driven spindle is known, the torque generated at the weld interface at any time can be calculated using the equation, $I(d\omega/dt)$. The energy input at the contact area at that instant can be calculated as $I(d\omega/dt)d\theta$, where $d\theta = (\Omega - \omega)dt$. The results of these calculations for welding plain carbon steel to plain carbon steel and stainless steel to stainless steel are plotted in Figs. 6 and 7. Here, welding pressures of 3 and 6 kg/mm² are used, respectively. It can be seen from these figures that the rotational acceleration of the driven spindle, the

torque and energy input at the contact area in both tests follow almost the same pattern. Torque continues to increase gradually after workpieces make the contact, keeping nearly constant value for a while, reaches the peak immediately before the welding cycle is completed and then dwindles to zero. Energy input at the contact area continues to increase after welding starts and attains the maximum value and diminishes. Histories of torque and energy input in welding cycle by the conventional process, too, have the same trend as those obtained by this process. However, the welding time by this process is found to be 10 to 20 per cent longer than that by the conventional.

In welding the materials other than the above, similar histories of friction process are observed.

4.2 Removing of flash

Figures 8 (a), (b), (c), (d) and (e) show the progress of flash removing in the welding of plain carbon steel to stainless steel under N of 2800 rpm and welding pressure of 6 kg/mm². These photographs are reproduced from the film taken by a high-speed camera. Figure (a) shows the moment at which the workpieces contact. Figures (b), (c) and (d) show the states at 0.66, 1.06 and 1.20 sec after welding starts, respectively. In these photographs, it is observed that the high temperature flash is being cut continuously as soon as it is formed. Under the conditions used in the experiments, removing of flash begins at the point of time when the rotational speed of driven spindle increases to 500 ~ 600 rpm, that is, the surface velocity of one of the workpieces reaches about 0.18 m/sec. As a result, the cutting speed of the flash is 0.18 ~ 1.03 m/sec (surface velocity of workpiece chucked to the driving spindle is kept at 1.03 m/sec). Figure (e) shows the state of welding finish, so the rest will

Fig. 6 Histories of rotational speed change of driven spindle, torque and energy input for welding plain carbon steel to itself

Fig. 7 Histories of rotational speed change of driven spindle, torque and energy input for welding stainless steel to itself

be left over for stopping of spindle. Figure 9 shows the chip formed in the welding process.

Since the main cutting force shows considerable fluctuations as seen in Fig. 5, the values shown in Table 2 are the maximum values. In any case the main cutting force is found to be lower than 50 kg. From these results, it may be understood that removing of the flash in heating phase of welding cycle is done with ease.

Tool edge used in this experiment is DIN 4975, cemented carbide tip, and its shape is shown at the bottom of Table 2. Throughout the experiments, no tool edge damages are found.

Figure 10 shows the appearance-comparisons of friction welded joints of stainless steel to stainless steel and plain carbon steel to stainless steel, with the flash removed in heating phase, against those without removing the flash. It can be seen that when the welding cycle is completed, a welded joint with finished surface can be obtained at the same time.

Now, some part of main cutting force acts as resistance to acceleration of the driven spindle. As a result, to find the true torque at the weld interface, the effect of main cutting force upon the torque should be investigated. From Table 2, the peaks of main cutting force in removing the flash for welding plain carbon steel and stainless steel are 45 and 23

kg, respectively. Assuming that a half of the main cutting force is attributed to cutting of the flash protruding from the workpiece chucked to the driven spindle, the maximum retarding torque (resistance to acceleration of the driven spindle) becomes 0.08 kg m for welding of plain carbon steel to plain carbon steel and 0.04 kg m for that of stainless steel to stainless steel, whereas the diameter of every workpiece is 7 mm. On the other hand, from Figs. 6 and 7, the torques at this moment in welding of plain carbon steel to plain carbon steel and stainless

Table 2 Main cutting force of flash in welding of various materials

Materials	Welding pressure of kg/mm ²	Amount of upset mm	Main cutting force (Max.) kg	Rotational speed at flash removing start rpm
Plain carbon steel-plain carbon steel	6	3.1	45	520
Stainless steel-stainless steel	6	2.7	23	500
Plain carbon steel-stainless steel	6	2.2	19	560
Chromium-molybdenum steel-stainless steel	6	2.0	17	580

Note: Welding parameters;

Rotational speed of driving spindle

N : 2800 rpm

Moment of inertia

of rotating mass

I : 3.09×10^{-3} kgm sec²

Shape of tool used

to cut the flash is

as follows;

(Tip of tool: DIN 4975)

(a) Workpieces contact

(b) State at 0.66 sec after welding start

(c) State at 1.06 sec after welding start

(d) State at 1.20 sec after welding start

(e) Welding finish

Fig. 8 Progress of flash removing in welding of plain carbon steel to stainless steel

Fig. 9 Chip formed in welding process

(a) Weld by this process (b) Weld by conventional process
Stainless steel-stainless steel

(c) Weld by this process (d) Weld by conventional process
Plain carbon steel-stainless steel

Fig. 10 Appearance-comparisons of friction welded joints

steel to stainless steel are 1.4 kg m and 1.1 kg m, respectively. Thus, the peaks of retarding torque are only several per cent of the values of torque. The results shown in Figs. 6 and 7 are the torque values without compensation for the afore-mentioned retarding torques by the main cutting force.

4.3 Strength of welded joint

Figure 11 shows the relationship between welding pressure and strength of welded joints of stainless steel to stainless steel with the flash removed in heating phase, against those without the flash removed. From this figure, it can be seen that a welding pressure higher than 8 kg/mm² is necessary for the conventional process to get a weld with 100 per cent joint strength. However, by this process with the flash removed in heating phase even a joint welded under a pressure of 3 kg/mm² is fractured at base metal in tensile test.

For welding of stainless steel to plain carbon steel, only a welding pressure as low as 4 kg/mm² is sufficient to obtain a satisfactory weld using this process. On the other hand, when welded by the conventional process, a joint welded under the welding pressure of the same value is fractured at the weld interface.

Figure 12 shows the fracture-appearances of stainless steel to stainless steel and stainless steel to plain carbon steel, subjected to tensile tests. Joints of stainless steel (a-1), (a-2), welded under the welding pressure of 6 and 3 kg/mm² by this process, are fractured at base metal. On the contrary, when welded by the conventional process (without removing the flash in heating phase), the joint (a-3) welded under the pressure of 6 kg/mm² is fractured at the

weld interface, though it has the strength almost equal to base metal. Furthermore it was found that the welding pressure has to be increased to 8 kg/mm² (a-4) to fracture at base metal in tensile test. As for stainless steel to plain carbon steel, similar results were obtained, as can be seen in (b-1) and (b-2).

Table 3 shows the lowest welding pressure for each of various combinations of workpiece materials, under which satisfactory welds can be obtained. A welding pressure used in this process can be considerably lower than that in the conventional process.

If the geometry of the joint is retained unchanged throughout the entire welding cycle, then (by cutting the flash in welding cycle) the welding force acts effectively on the contact area at all times. On the contrary, in the conventional process, the flash continues to increase and the shape of flash becomes divergent toward the contact interface. Especially in the final phase of welding cycle, where the effective welding pressure is important to obtain a sound weld, the decrease in effective welding pressure will result in poor weld. This is why when this welding process is used, it is possible to get a sound weld by a lower welding pressure than that used in the conventional process for welding workpieces with same diameters.

Figure 11 shows the relationship between welding pressure and amount of upset for welding stainless steel to stainless steel. Amount of upset by this process is found to be larger than that by the

Fig. 11 Tensile strength of joint, amount of upset and welding pressure (Stainless steel to stainless steel)

Fig. 12 Typical fractures of friction welded specimens under tension

Table 3 The lowest welding pressure to weld various materials

Materials	Lowest welding pressure kg/mm ²		Location of fracture*
	Process in question	Conventional process	
Plain carbon steel-plain carbon steel	2	18	Plain carbon steel
Stainless steel-stainless steel	3	8	Stainless steel
Plain carbon steel-stainless steel	4	6**	Plain carbon steel
Chromium-molybdenum steel-stainless steel	3	8	Stainless steel

Note:

Welding parameters:

Rotational speed of driving spindle N : 2 800 rpmMoment of inertia of rotating mass I : 3.09×10^{-3} kg m sec²

* Each specimen is fractured at base metal in tensile test.

This column shows the base metal at which fracture occurs.

** Specimen is fractured at plain carbon steel base metal in tensile test, but surface cracks are observed at welded joint.

(a) Plain carbon steel-plain carbon steel

(b) Plain carbon steel-stainless steel

Fig. 13 Macro-structures of welded joints

conventional process under the same welding pressure.

4.4 Structure of welded joint and chip

Figures 13 (a) and (b) show macro-structures of the welded joints of plain carbon steel to plain

(a) Part close to circumference of joint

(b) Part close to circumference of joint

(c) Center of joint

(d) Center of joint

Fig. 14 Micro-structures of welded joint (Plain carbon steel-stainless steel)

carbon steel and plain carbon steel to stainless steel. The white zone seen in plain carbon steel workpiece is the heat affected zone.

Figures 14 (a), (b) and (c), (d) show structures of the parts close to the circumference of the joint of plain carbon steel to stainless steel and those of the center, respectively. As seen in Fig. (c), flow of structure occurs at the contact area and its vicinity. The flown zone coincides with the heat affected zone observed in the macro-structure of the joint, e.g., in Fig. 13 (b).

The structure of plain carbon steel at the joint consists of very fine ferrite and sorbite. And it is recognized that mechanical mixture of both materials of workpieces (plain carbon steel and stainless steel) takes place at the contact area and moreover the workpieces are bound sufficiently.

In welding of plain carbon steel to plain carbon steel, the structure composed of fine ferrite and sorbite is observed continuously from the part close to the circumference of the joint to the center, as seen in Figs. 15 (a) and (b).

Figures 16 (a) and (c) show cross sections of the chip formed in the early stage and the later stage in welding cycle, in which the flash protruding from stainless steel adheres to the one from plain carbon steel. And according to observation of Figs. (b) and (d), the more magnified photographs of these sections, it becomes clear that the materials of both workpieces are welded perfectly even in the chip.

Figures 17 (a) and (c) show cross sections of the chip formed in the early stage and the later

stage in welding of plain carbon steel to plain carbon steel. These photographs also show that a perfect weld of workpieces is obtained in the chip formed in welding cycle. And it may be recognized that

(a)

(b)

(c)

(d)

(a) Part close to circumference of joint

(b) Center of joint

Fig. 15 Micro-structures of welded joint (Plain carbon steel-plain carbon steel)

Fig. 16 Cross-sections of chip (Plain carbon steel-stainless steel)

Fig. 17 Cross sections of chip (Plain carbon steel-plain carbon steel)

the structure of fine grain sizes is obtained at the area welded in the chip.

5. Conclusions

A friction welding machine, incorporating flash removing in heating phase of welding cycle, is produced. The machine is constructed as follows.

(A) Welding machine

(1) Driving spindle, in which one workpiece is chucked, is coupled to the driving system. The driving spindle is rotated at a constant speed (angular velocity Ω) throughout the entire welding cycle.

(2) Driven spindle, which clamps the other workpiece, is free of rotation.

(3) Rotating mass (moment of inertia I) is fitted to the driven spindle. At the contact area, the effective frictional energy ($I\Omega^2/2$) is developed by relative rotation between workpieces and welding force.

(B) Flash removing mechanism

Flash machining mechanism, which is mounted on the above-stated machine, removes the flash as soon as it forms during welding.

Using the above-stated welding machine, experiments are conducted for welding plain carbon steel to plain carbon steel, stainless steel to stainless steel, stainless steel to plain carbon steel and chromium-molybdenum steel to stainless steel.

(1) The flash is machined off with continuous chips. The main cutting force is found to be less than 50 kg. Therefore, flash removing in heating phase of welding cycle can be done with ease.

(2) A finished welded joint with flash removed (machine-finished) can be obtained upon completion of welding cycle.

(3) The joint with 100 per cent joint strength can be obtained with a considerably lower welding pressure by this process than that by the conventional process.

(4) By this welding process, the actual total production time of finished joints (flash removed and machined) can be shortened considerably. In other words, in contrast to the conventional process, where flash removing step must be added after welding, this process eliminates this additional step and thus increases the production efficiency.

(5) The fact that a lower welding pressure can be used and still yield an excellent joint by this process makes the design and manufacturing of the welding machine simpler and easier.