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Effect of weld faying part groove shape on reduction of inner flash in steel pipe joints fabricated by friction welding

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Abstract The groove shape of the weld faying part was investigated to obtain an ideal pipe friction-welded joint that had a fracture in the base metal and no inner flash of it. The steel pipe had inner and outer diameters of 8.0 mm and 13.5 mm, respectively, and the weld faying surface was of a basic flat shape (butt) type. Moreover, stepped and tapered groove shapes were prepared. Pipe groove shapes were welded with a friction speed of 27.5 s^{-1} and a friction load of 2.79 kN. Joining phenomena during the welding process were observed, and the tensile strength of joints was evaluated. The joints, that fabricated with flat or step groove shapes, made with a friction time at which the friction torque reached the initial peak did not have the tensile strength of the base metal nor a fracture in the base metal. However, the joints fabricated with a friction time that reached past the initial peak had a large flash, and they contained a fracture in the base metal. In contrast, when joints were made with a gently tapered groove shape with a friction time reaching the time of the initial peak, they achieved a fracture in the base metal, despite having an extremely small inner flash. Therefore, the shape at the weld faying part was capable of reducing the flash exhausted from the weld interface.

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1 Introduction

The use of pipes is widespread in various industrial components such as plants, pipelines, vacuum vessels, and a variety of sensors or actuators. To fabricate these components, it is necessary to join pipes to each other or plates. Generally, the joining of pipes made of metallic material including non-ferrous metals is accomplished by fusion welding methods such as shielded metal arc welding, tungsten inert gas (TIG) welding, and laser welding. For pipes, however, these are not convenient fusion welding methods as they give rise to some problems in the actual welding construction, such as sound weld bead formation [1]. In particular, the welding of a thin pipe is difficult, since the joint properties depend heavily on the operator skill and working conditions [2, 3]. Hence, establishing a joining method to enable the mass-production of thin pipe joints with high reliability is desirable.

Friction welding is a well known solid state joining method, whose welding process is easily automated. It has several advantages compared to fusion welding methods, such as high energy efficiency, a narrower heat-affected zone (HAZ), and low welding cost, as described in Refs. [4, 5]. Friction welding can easily fabricate joints with high reliability, and it is widely employed in the automobile industry to fabricate crucial components such as drive shafts and engine valves. Furthermore, this method can also produce circular joints in pipes (referred to as pipe) as well as a circular solid bar. Eberhard et al. [6] studied the steel pipe joint with a wall thickness of 12.7 mm. Kumar and Balasubramanian [7] investigated the austenitic stainless steel pipe joint with a wall thickness of 3.5 mm with relatively good joint strength. A similar steel pipe joint with a wall thickness of 3 mm was demonstrated by Ogawa et al. [8]. Palanivel et al. [9] investigated the tensile properties of a titanium pipe joint with a wall thickness of 3.9 mm. Kawai et al. [10] and Ohkubo et al. [11] provided the results of a pipe joint with a combination of steel and aluminum alloys and a wall thickness of 3 mm. Balta et al. [12] proposed a method and the friction welding conditions for dissimilar steel pipe joints with a wall thickness of 4 mm. Hence, several researchers reported that the joining of pipes by friction welding could be successfully achieved, obtaining relatively good joints.

The pipe joint made by friction welding, inevitably has a flash (burr or collar) at the outer and inner parts, and the flash is exhausted from the weld interface during the welding process (see Fig. 1). Hence, generating the flash in a good joint cannot be avoided, and its final shape and size depend on the friction welding condition [13]. The inner flash of the joint cannot be removed in some cases, whereas the outer flash is easily removable by a machine tool, such as a lathe. It is desirable that the inner flash at the weld interface of pipe joints is not having for its application, since various liquids or cables are inserted in pipe joints. Several studies attempted to reduce the inner flash at the weld interface. The characteristics of titanium pipe friction-welded joints at various friction speeds were demonstrated by Palanivel et al. [14]. Luo et al. [15] showed the results of a bell-shaped joint at the pipes edge. Rovere et al. [16] investigated the mechanical properties of pipe joints, fabricated by the radial friction welding method. Faes et al. [17] studied the characteristics of a pipe joint using a solid ring as filler material. Pissanti et al. [18] applied friction welding for a duplex stainless steel pipe with a rotating ring. Nevertheless, it proved difficult to achieve a joint that had both the tensile strength of the base metal and no inner flash, as the flash of the joint was assumed to be enough exhausted at the weld interface to obtain completely welding. However, the joining mechanism of the friction welding for pipe shapes is not completely clarified, and the friction welding conditions are determined by trial and

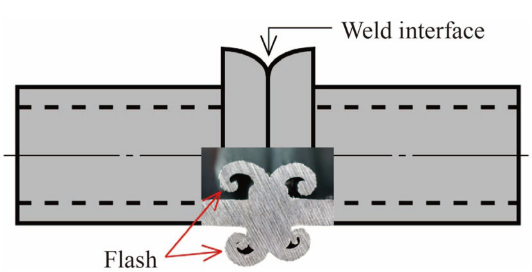

Fig. 1 Example of flash in circular joint of pipe produced by friction welding

error, since the research on the friction welding of pipes is lacking in comparison with that on circular solid rods. Therefore, determination of theoretical friction welding conditions for the ideal pipe joint that has the tensile strength of the base metal with no inner flash and clarification of the joining phenomena during the friction process is strongly required. In the search of relevant solutions, we noticed the groove shapes of the weld faying surface, as several researchers investigated joint performance improvement by altering the shape at the weld faying part. Shi et al. [19] proposed a groove shape designed by the principle of 3D tool radius compensation. Li et al. [20], Wan and Huang [21] attempted to decrease the intermetallic compound layer of the welded joint between aluminum alloy and some steels. The joint strength of friction-welded joint between aluminum alloy and steel solid bars by changing of the shape at the weld faying part was demonstrated by Ashfaq et al. [22]. According to the above reports, reducing the flash from the joint by changing of the shape at the weld faying part is a possibility. However, the effective shapes that led to the decrease of the inner flash of the pipe joint were not investigated. Moreover, the suitable groove shape for obtaining the ideal pipe joint with no inner flash and no fracture at the weld interface was not demonstrated. Hence, the effects of shape changes at the weld faying part on reducing the flash for a pipe friction-welded joint should be clarified.

In previous studies [23, 24], we obtained a successful weld of thin-walled pipes. Those cases applied a welding technique, where the stationary (fixed) side specimen was simultaneously rotated in conjunction with the rotating side specimen when the set friction time was finished, i.e., the relative speed at the weld interface was instantly decreased to zero. This friction welding technique did not generate the final peak torque of the friction torque curve during the welding process. More specifically, the joint fabricated by this welding method has less flash compared with the conventional friction welding method [25]. Furthermore, the joints of circular solid bars of some carbon steels made with this friction welding method had the fatigue strength of base metal [26] and the tensile strength of the base metal with a fracture in its base metal at the friction time just after the occurrence of the initial peak of the friction torque [27]. Hence, repeat-ability and durability of joining was achieved in this welding technique [28]. The possibility of fabrication of the ideal pipe joint with no inner flash existed, since one could consider that both weld faying surfaces were joined owing to the new (fresh) surface generated seizure when the friction torque reached at the initial peak [25, 26].

This study presents research conducted to describe joining behavior of the friction welding process to obtain an ideal pipe joint with no inner flash, which had a fracture in the base metal and the same tensile strength as the base metal. Firstly, we show the relationship between the friction time and the generated inner flash of steel pipe joints with a flat groove shape. Then, the conditions required for obtaining a good joint are clarified. Secondly, we present the results of the groove shape at the weld faying part and the influence of reducing the inner flash in steel pipe joints. We also demonstrate the effect of a friction time on the tensile strength of those joints, and determine a suitable friction time for the joint fabrication with a fracture in the base metal. Through those investigations, we suggest a suitable groove shape of the weld faying part for decreasing the inner flash of pipe joints.

2 Experimental

2.1 Materials and specimen shapes

The material used was seamless cold-drawn carbon steel pipe for high temperature service (JIS STPT410-S-C) with inner and outer diameters of 7.8 mm and 13.8 mm, respectively. The chemical composition of this material was 0.20%C-0.22%Si-0.53%Mn-0.022%P-0.011%S (mass fraction); the ultimate tensile strength was 484 MPa; the 0.2% yield strength was 297 MPa; and the elongation was 35%, respectively. Pipes were machined by a lathe to the length of 80 mm, and then those were machined to inner and outer diameters of 8.0 mm and 13.5 mm, respectively. In this study, five different groove shapes at the weld faying (contacting, edge) parts were prepared as shown in Fig. 2. The basic groove shape was the flat (square edge, butt) type (see Fig. 2a, referred to as the flat groove shape). In addition, two kinds of groove shapes, namely the stepped and tapered types were prepared in this study. Step groove shapes had one step at the inner part of the weld faying surface. Specimens with the Step-A groove shape had a step height of 0.3 mm and the area at the outer part (initial contact part) of the weld faying surface was about 86% of that of the flat groove shape (see Fig. 2b). Specimens with the Step-B groove shape had a step height of 0.3 mm and the area of the initial contact part at the weld faying surface was about 70% (see Fig. 2c). In contrast, the taper groove shapes had a concave slope on the inner part (single-bevel edge) of the weld faying surface. The area at the outer part of the weld faying surface and the slope angle of that concave slope (taper angle) differed, although the height of the slope was equal to 0.5 mm. Specimens with the Taper-A groove shape had a tapering angle of 29.1° and an area at the outer part of the weld faying surface of about 73% of the flat groove shape (see Fig. 2d). Specimens with the Taper-B groove shape had 15.5° tapering angle and about 40% area of the initial contact part at the weld faying surface (see Fig. 2e). All specimens with various groove shapes were inserted into the thin pipe jig made of steel as shown in Fig. 3, and then the opposite sides of the weld faying part were unified by TIG welding to prevent rotation in the chuck during the friction process.

2.2 Friction welding method

A continuous (direct) drive friction welding machine was employed for the joining. During friction welding operations, the friction welding conditions were set as follows: a friction speed of 27.5 s^{-1} (1 650 r/min), a friction load of 2.79 kN (a value equivalent to a friction pressure of 30 MPa for the flat groove shape), a range of friction times from 0.1 s to 0.9 s, a forge load of the same value as (identical to) friction loads, and a forge time of 6.0 s. In this study, the same groove shapes of friction welding specimens were joined to each other. The joining behavior during the friction process was recorded by a digital video camera. The friction torque was measured with a load-cell recorded with a personal computer through an A/D converter with a sampling time of 0.001 s. When joints are made by the conventional friction welding method, the rotation of the specimen does not instantly stop. That is, a braking time is required for rotation stop, as rotation of the specimen does not stop completely at set friction time. To prevent deformation due to the braking during the rotation stop, the stationary side specimen was fixed with an electromagnetic clutch as shown in Fig. 4. Figure 5 shows the schematic illustration of the welding process in this study. The rotating side specimen was rotated (see Fig. 5a), and

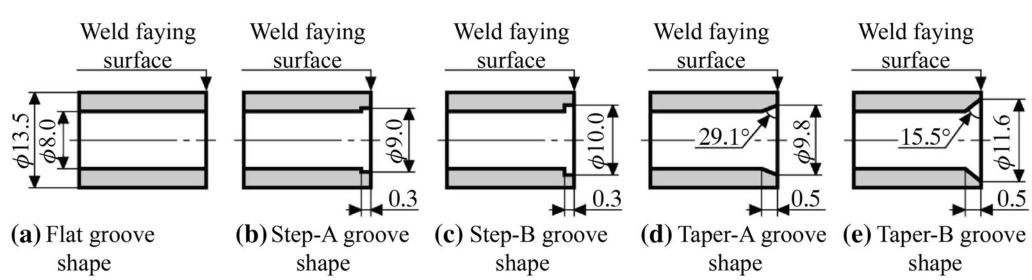

Fig. 2 Shapes and dimensions of different weld faying parts in friction welding specimens (unit: mm)

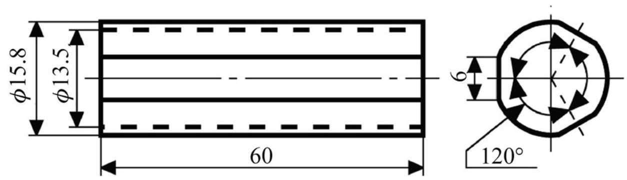

Fig. 3 Shape and dimension of a thin pipe jig (unit: mm)

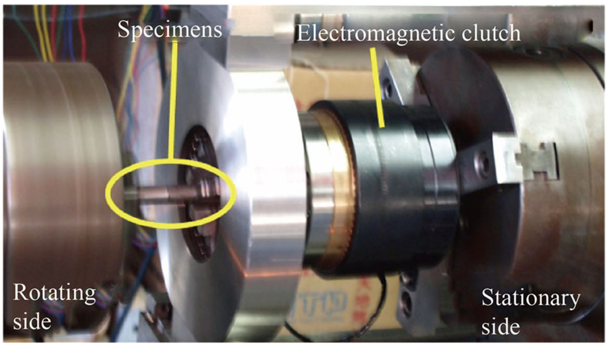

Fig. 4 Photograph of clutch part at stationary side of friction welding machine

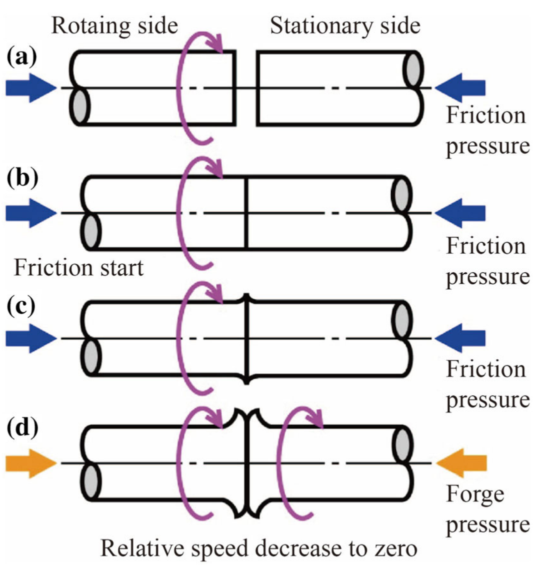

Fig. 5 Schematic illustration of friction welding method in this study

subsequently the stationary side specimen was contacted by the rotating side (see Fig. 5b). This state was maintained until the completion of the set friction time (see Fig. 5c). When the time reached the set friction time, the relative speed between both specimens simultaneously decreased to zero by release of the clutch (see Fig. 5d). Thereafter, the welding was completed. Moreover, as the braking time for this experimental method was smaller than 0.04 s, i.e., one rotation of the specimen, its influence was negligible. The details of this welding method for appropriate pipe welding were described in Refs. [23, 24].

2.3 Mechanical test method

The joint tensile test specimen had retained the inner and outer flashes that were expelled from the weld interface during the welding process. Hence, all flashes were never removed, although all thin pipe jigs were removed from joints, as shown in Fig. 3. The joint tensile test was performed in the as-welded condition at room temperature using Amsler universal testing machine. It was evaluated with three or more joints per one friction time, and the repeat-ability of results was verified. Subsequently, the joint tensile strength was evaluated in terms of the joint efficiency, which was defined as the ratio of joint tensile strength to the ultimate tensile strength of the base metal. The Vickers hardness test at a low test force, i.e., the Vickers microhardness (referred to as Vickers hardness), was carried out at room temperature for further clarification of joint properties. The hardness distribution was measured in the zigzag pattern, and its center line corresponded to the half-thickness location of the pipe part on the adjacent region of the weld interface. The measuring load was 9.81 N, and the measuring range was about 7 mm from the weld interface to both sides of the joint. The measuring intervals in the longitudinal and radial directions were 150 μm and 50 μm, respectively.

3 Results

3.1 Flat groove shape results

Primarily, the combination between two flat groove shapes was welded to clarify the joining phenomena and the tensile strength of joints. Figure 6 shows the relationship between the joining behavior and the friction torque curve during the friction process. Photos (1)–(6) in Fig. 6a correspond to the friction torques (1) to (6) in Fig. 6b, respectively. Photo (1) shows the state at the faying surfaces as they contact each other, and the friction torque is increased. Sparks are produced from the weld interface because of the generation of the seizure, as shown in Photo (2). Subsequently, the adjacent region of the weld interface is slightly deformed. The softened part is exhausted as a flash from the weld interface, as shown in Photo (3). When the friction torque reaches the initial peak of (4) in Fig. 6b, the initial peak torque was about 50 N·m, and the elapsed time for the initial peak was approximately 0.5 s. Thereafter the friction torque was maintained nearly constant from peak (4) in Fig. 6b, and the flash increased with friction time, as shown in photo (5). Afterward, the friction torque decreased as shown in peak (6) in Fig. 6b.

Figure 7 depicts the relationship between the joint efficiency and the friction time of joints, which were plotted

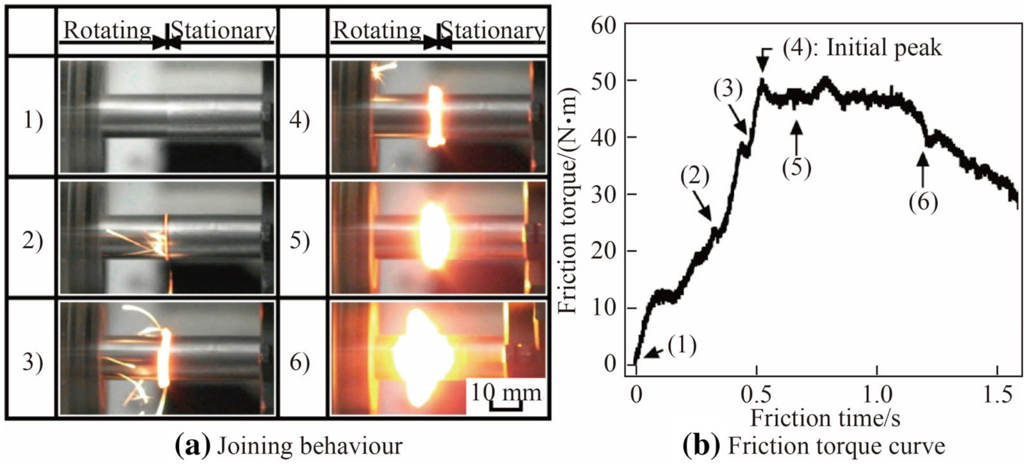

Fig. 6 Joining behavior and friction torque curve during friction process for joint with the flat groove shap

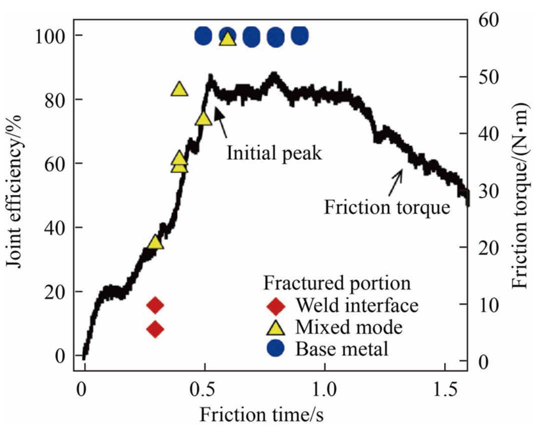

Fig. 7 Relationship between friction time and friction torque (black line), joint efficiency of joints with the flat groove shape (symbols)

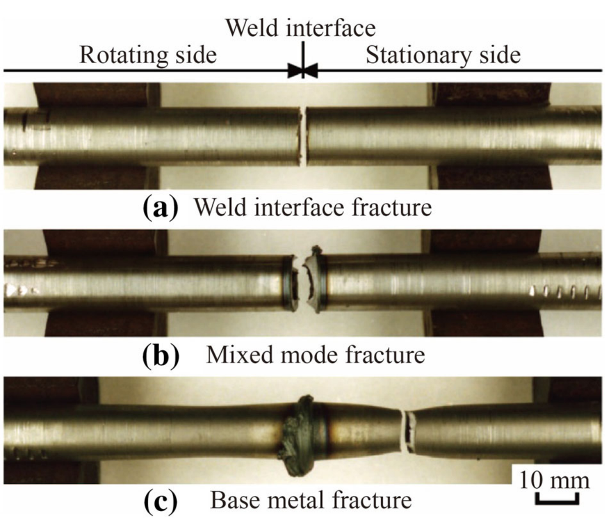

Fig. 8 Appearances of different fractures of joint tensile tested specimens

alongside the friction torque curve shown in Fig. 6b. Figure 8 shows the appearances of joint tensile tested specimens. When the joints were fabricated with a friction time of 0.3 s, i.e., the time with sparks at the weld interface, the joint efficiency was approximately 20%. Almost all joints fractured from the weld interface (see Fig. 8a), though one of the joints fractured between the weld interface and the base metal (mixed mode fracture), as shown in Fig. 8b. The joint efficiency increased with the friction time. When joints were fabricated with a friction time of 0.5 s, i.e., when the friction torque reached its initial peak, almost all joints had a joint efficiency of 100% with a fracture in the base metal, as shown in Fig. 8c. However, one of the joints had a joint efficiency of approximately 74%, and a mixed mode fracture. Hence, the repeat-ability and durability of joining could not be achieved at this friction time (0.5 s). When joints were fabricated with a friction time of 0.7 s, all joints had a joint efficiency of 100% with a fracture in the base metal. The joint efficiency with a friction time of 0.7 s or longer was kept at 100% with all joints having a fracture in the base metal. Hence, a good joint could be obtained at this friction time (0.7 s).

Figure 9 shows examples of the cross-sectional appearances of joints at various friction times. When the joint was fabricated with a friction time of 0.3 s (before the initial peak), the weld interface was not completely joined. The flash of this joint was hardly exhausted, as shown in Fig. 9i. Hence, the joint was fractured at the weld interface as shown in Fig. 8a, since it did not have enough friction heat for joining during this friction time (0.3 s). Inner and outer flashes increased with friction time (see Figs. 9ii and iii). All joints at a friction time of 0.5 s (initial peak) did not contain a fracture in the base metal (see Fig. 7), although they contained slight inner and outer flashes. Thus, it could be considered that the weld interface did not join completely at this friction time. In contrast, when the

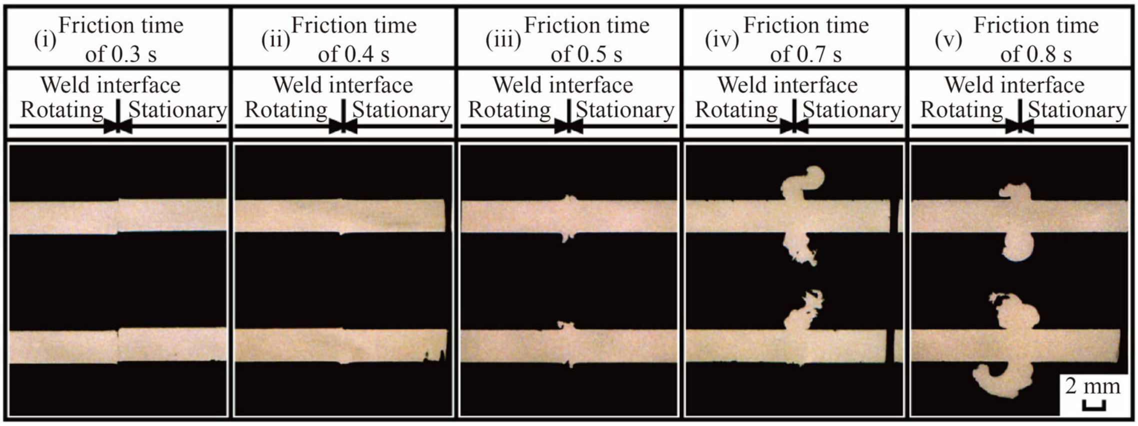

Fig. 9 Cross-sectional appearances of weld interface regions of joints with the flat groove shape at various friction times

joint was fabricated with a friction time of 0.7 s as shown in Fig. 9iv, the inner flash partially closed the hole of the pipe, even though all joints had a fracture in the base metal. Then, the inner and outer flashes further increased, as shown in Fig. 9v. These results indicated that the joint had sufficient inner and outer flashes to obtain a joint efficiency of 100% and a fracture in the base metal. In this study, this friction time was 0.7 s.

3.2 Step groove shape results

To clarify the joining phenomena and the tensile strength of joints, the step groove shapes shown in Figs. 2b and c were welded to each other. Figure 10 shows the relationship between the joint efficiency and the friction time of joints, of which were plotted alongside the friction torque curves. When joints were fabricated with the Step-A groove shape as shown in Fig. 10a, the friction torque had the initial peak of about 51 N·m, and the elapsed time for the initial peak was approximately 0.45 s. The elapsed time for the initial peak was slightly reduced, although the initial peak maintained similar values in comparison with the flat groove shape of Fig. 6b. The joining behavior resembled that of the flat groove shape (data not shown). The joint efficiency at a friction time of 0.3 s was approximately 63%, and all joints contained a mixed mode fracture. The joints at a friction time of 0.4 s (just before the initial peak), almost had a joint efficiency of 100% with a fracture in the base metal (see Fig. 8c). However, one of the joints at this friction time (0.4 s) had a joint efficiency of approximately 79% and a mixed mode fracture (see Fig. 8b). Thus, all joints had a joint efficiency of 100% and a fracture in the base metal when these were fabricated with a friction time of 0.5 s or longer. In contrast, when joints were fabricated with the Step-B groove shape as shown in Fig. 10b, the friction torque had the initial peak of about 51 N·m and the elapsed time for the initial peak of approximately 0.3 s. The elapsed time for the initial peak was reduced, although the initial peak maintained similar values in comparison with the Step-A groove shape. In this instance, the joining behavior also resembled that of the flat groove shape (see Fig. 6a). When the joints were fabricated at a friction time of 0.3 s, i.e., the friction torque reached the initial peak, one of the joints had a joint efficiency of 100% and a fracture in the

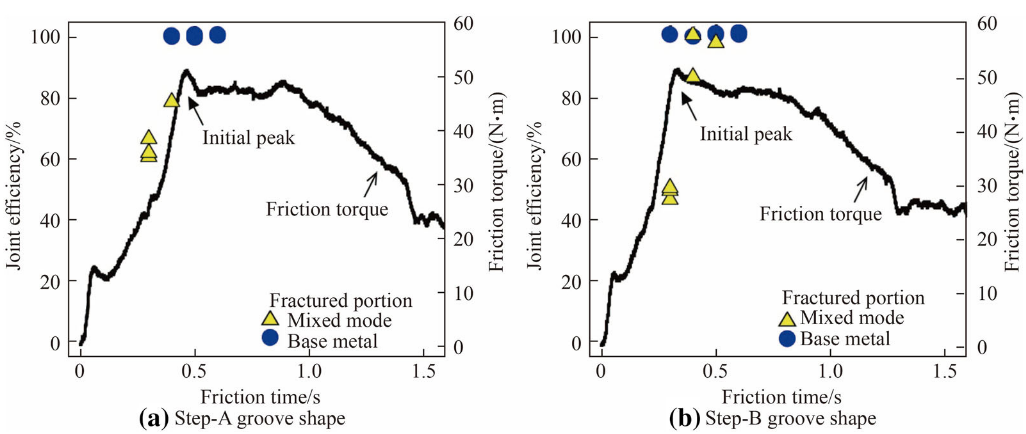

Fig. 10 Relationship between friction time and friction torque (black line), joint efficiency of joints with the step groove shape (symbols)

base metal (see Fig. 8c). However, almost all joints at this friction time (0.3 s) had a joint efficiency of approximately 50% and a mixed mode fracture (see Fig. 8b). Hence, the joint efficiency of all joints with the Step-B groove shape did not achieve 100% at the initial peak. The joint efficiency increased with the friction time, and all joints had a joint efficiency of 100% and a fracture in the base metal when fabricated at a friction time of 0.6 s.

Figure 11 shows examples of the cross-sectional appearances of joints at various friction times. When the joints were fabricated with the Step-A groove shape as shown in Fig. 11a, the weld interface of the joint with a friction time of 0.3 s was not completely joined and the flash was hardly exhausted (see Fig. 11a-i). Moreover, part of the step groove was observed at the inner part of the pipe. Hence, this friction time (0.3 s) was insufficient for complete joining at the pipe part. The inner and outer flashes increased with friction time. However, all joints at a friction time of 0.4 s did not have a fracture in the base metal (see Fig. 10a). When the joint was fabricated with a friction time of 0.5 s as shown in Fig. 11a-iii, i.e., the friction torque reached the initial peak, it contained inner and outer flashes. All joints with this friction time had a fracture in the base metal as shown in Fig. 10a. Moreover, a part of the hole of the joint with a friction time of 0.6 s or longer as shown in Figs. 11a-iv and v, was closed by the inner flash. In contrast, when the joints were fabricated with the Step-B groove shape as shown in Fig. 11b, the weld interface with a friction time of 0.3 s (just reaching the initial peak) was not completely joined (see Fig. 11b-i). The inner and outer flashes increased with friction time, however not all joints with a friction time of 0.4 s had a fracture in the base metal (see Fig. 10b). Thereafter, one part of the hole of joints with a friction time of 0.5 s or longer were closed by the inner flash, although all joints (see Figs. 11b-iii to v) obtained a fracture in the base metal. Thus, a requirement was that the joint had sufficient inner and outer flashes to obtain a joint efficiency of 100% and a fracture in the base metal. In particular, the joint with a Step groove shape for obtaining a fracture in the base metal could not be achieved at the initial peak, as the step part was not completely joined.

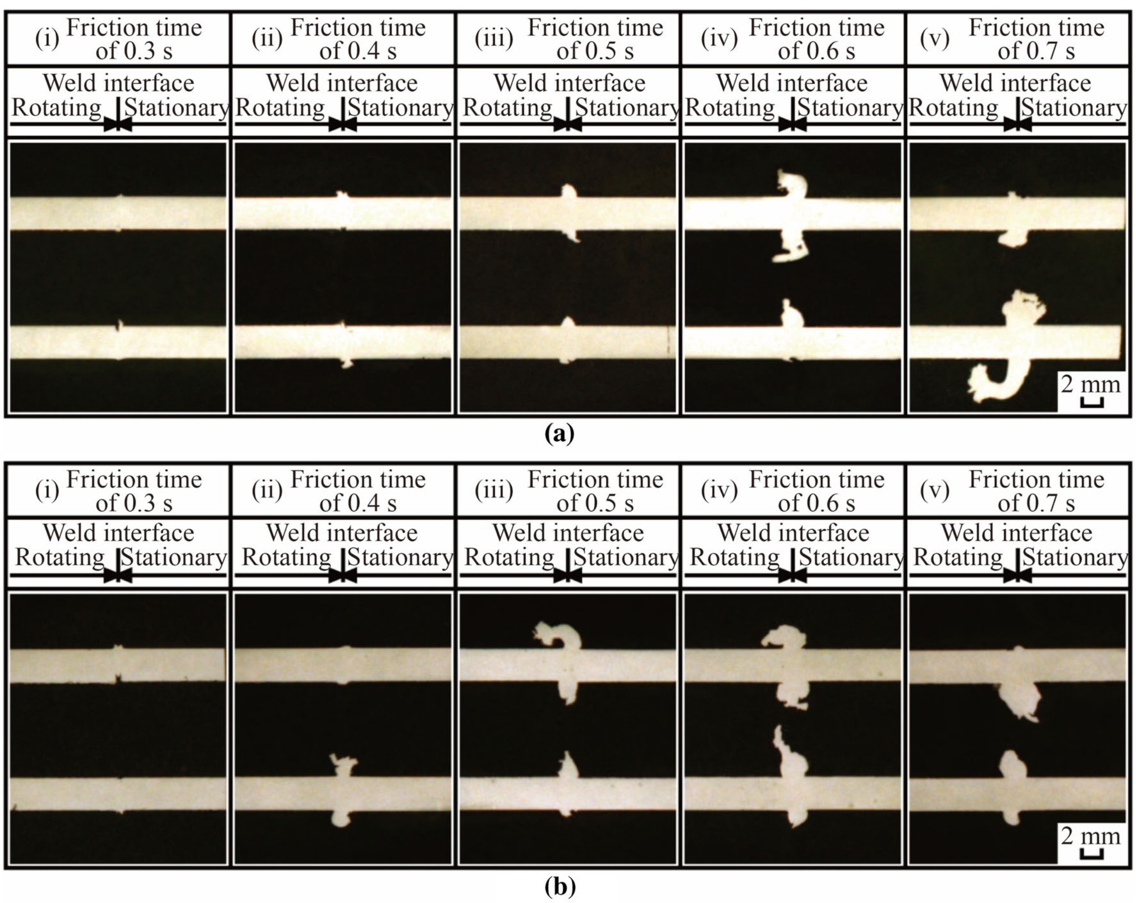

Fig. 11 Cross-sectional appearances of weld interface regions of joints with the step groove shape at various friction times **a** Step-A groove shape, **b** Step-B groove shape

3.3 Taper groove shape results

To clarify the joining phenomena and the tensile strength of joints, the taper groove shapes shown in Figs. 2d and e were welded to each other. Figure 12 shows the relationship between the joint efficiency and the friction time of joints, of which were plotted alongside the friction torque curves. When the joints were fabricated with the Taper-A groove shape as shown in Fig. 12a, the friction torque had the initial peak of about 50 N·m, and the elapsed time for the initial peak was approximately 0.35 s. The elapsed time for the initial peak was reduced, although the initial peak had similar values in comparison with the flat groove shape of Fig. 6a. In this instance, the joining behavior also resembled that of the flat groove shape. The joint efficiency at a friction time of 0.2 s was approximately 13%, and all joints were fractured from the weld interface (see Fig. 8a). The joint efficiency increased with friction time, and it was approximately 95% when joints were fabricated with a friction time of 0.35 s, i.e., the friction torque reached the initial peak. One of the joints had the mixed mode fracture (see Fig. 8b), whereas the others had a joint efficiency of 100% and a fracture in the base metal (see Fig. 8c). Hence, the joint efficiency of all joints with the Taper-A groove shape did not achieve 100% at the initial peak. Subsequently, all joints with a fracture in the base metal were fabricated with a friction time of 0.4 s. This friction time occurred after the initial peak. In contrast, when joints were fabricated with the Taper-B groove shape as shown in Fig. 12b, the friction torque had the initial peak of about 53 N·m and the elapsed time for the initial peak of approximately 0.25 s. The elapsed time for the initial peak was shorter than that of the Taper-A groove shape as shown in Fig. 12a, although the initial peak had a similar value. In this instance, the joining behavior also resembled that of the flat groove shape (see Fig. 6a). The joint efficiency at a friction time of 0.1 s was approximately 32%, and all joints fractured from the weld interface. With a friction time of 2.5 s, i.e., the friction torque just reached the initial peak, a joint efficiency achieved 100%, and all joints had a fracture in the base metal as shown in Fig. 13. Hence, the joint with the Taper-B groove shape could achieve a fracture in the base metal with this friction time, i.e., the time of the initial peak. Furthermore, all joints had a fracture in the base metal after this friction time (0.25 s).

Figure 14 shows examples of the cross-sectional appearances of joints at various friction times. When joints were fabricated with the Taper-A groove shape as shown in Fig. 14a, the weld interface of the joint with a friction time of 0.2 s was not completely joined, and the flash was hardly exhausted (see Fig. 14a-i). Moreover, part of the taper groove was observed at the inner part of the pipe. Hence, this friction time (0.2 s) was also insufficient for the complete joining of the pipe part. The inner and outer flashes increased with friction time. When the joint was fabricated with a friction time of 0.35 s (initial peak), it contained inner and outer flashes, as shown in Fig. 13a-iii. However, all joints at this friction time (0.35 s) did not have a fracture in the base metal (see Fig. 12a). When joints were fabricated with a friction time of 0.4 s or longer as shown in Figs. 14a-iv and v, a part of the hole at the pipe was closed by the inner flash, although these obtained a fracture in the base metal. In contrast, when joints were fabricated with the Taper-B groove shape as shown in Fig. 14b, the weld interface of the joint with a friction time of 0.1 s was not completely joined (see Fig. 14b-i). When the joint was fabricated with a friction time of 0.25 s (initial peak), it had a small inner flash (see Fig. 14b-iii), and all joints were fractured at the base metal (see Fig. 12b). The inner and outer flashes increased with friction time. Thus, it was clarified that the joint with the Taper-B groove shape had a fracture in the base metal when the joint was fabricated with a friction time at same

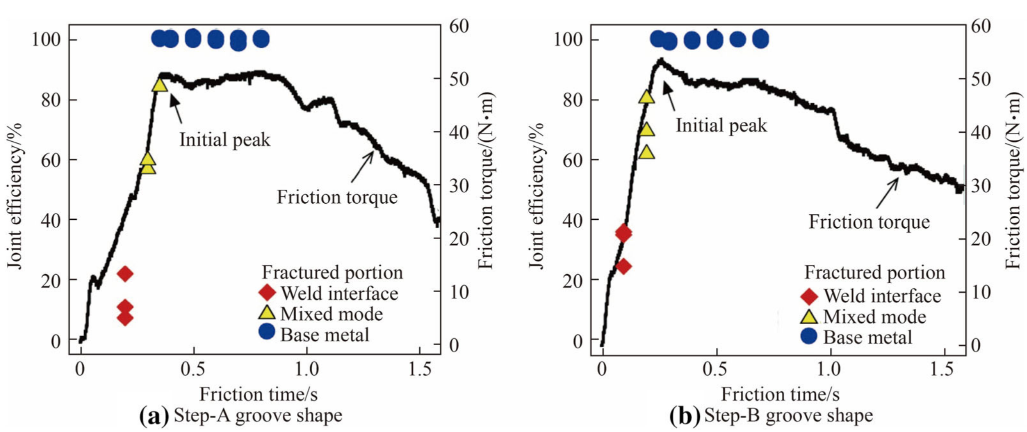

Fig. 12 Relationship between friction time and friction torque (black line), joint efficiency of joints with the taper groove shape (symbols)

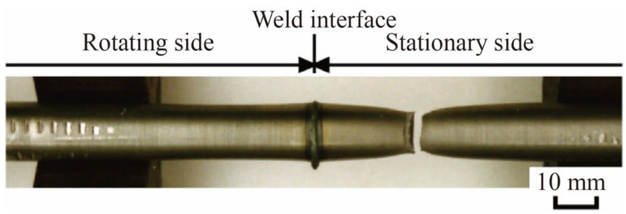

Fig. 13 Appearance of joint tensile tested specimen of joint with the Taper-B groove shape at a friction time of 0.25 s

time of the initial peak. Nevertheless, the joint had very slight inner and outer flashes, as shown in Fig. 14b-iii.

4 Discussions

4.1 Comparison of friction torque at various groove shapes

The above results described that the elapsed time for the initial peak was reduced by changing groove shapes at the weld faying part, although the initial peak had similar values as in that of the flat groove shape. Table 1 shows the set and measured values in the experiment at various groove shapes. In this study, the friction and forge loads were constant at 2.79 kN, which was the same value for a friction pressure of 30 MPa for the flat groove shape. The area of the initial contact part at the weld faying surface was small, and the true friction pressure at the initial contact part was increased in comparison with that of the flat groove shape. In particular, the elapsed time for the initial peak was reduced in comparison with that of the flat groove shape. This result was due to increasing friction pressure. Therefore, the time until the initial seizure at the weld interface from the contact of both weld faying surfaces was reduced, and the quantities of heat input per time was increased by increasing friction pressure [29]. Nevertheless, the initial peak had similar values in all groove shapes since it was obtained after the entire pipe part welded. In friction welding, the friction torque reached the initial peak torque when a fresh surface generated the seizure to the entire of the weld interface, as shown in Fig. 6. Then, the friction torque decreased with reducing yield strength of the base metal due to the increasing

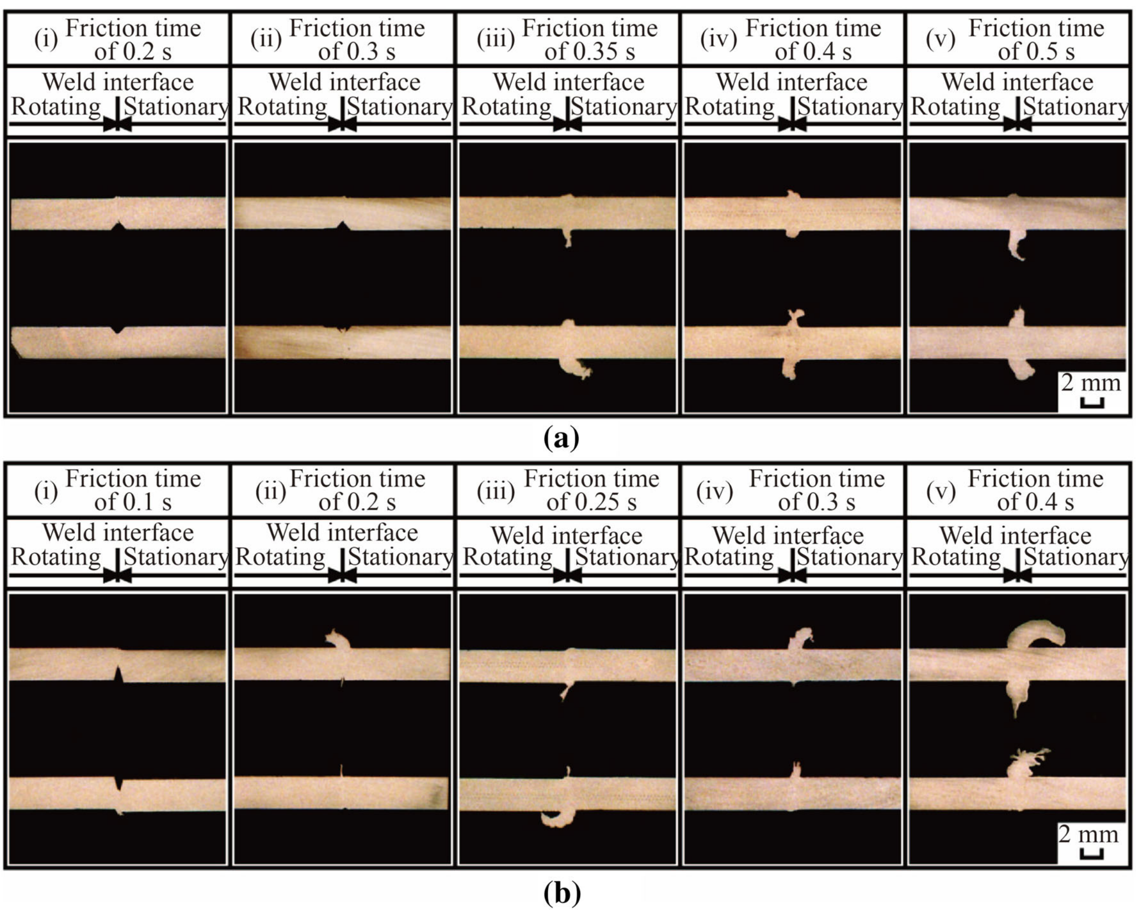

Fig. 14 Cross-sectional appearances of weld interface regions of joints with the taper groove shape at various friction times **a** Taper-A groove shape, **b** Taper-B groove shape

Table 1 Experiment parameters at various groove shapes

Groove shape	Friction force/kN	Area of initial contact part at welding surface/mm^2	True friction pressure/MPa	Elapsed time for initial peak/s	Initial peak/(N·m)
Flat	2.79	92.9	30	0.5	50
Step-A	2.79	79.5	35	0.45	51
Step-B	2.79	64.6	43	0.3	51
Taper-A	2.79	67.7	41	0.35	50
Taper-B	2.79	37.5	74	0.25	53

temperature at the weld interface [30]. In this study, two pipes with the same inner and outer diameters were welded. Hence, the initial peak had identical values, because the inner and outer diameters of pipe were same, regardless of groove shapes. Thus, the difference of the area of the initial contact part at the weld faying surface, namely the initial friction pressure was increased by decreasing the area of the initial contact part at the weld faying surface.

4.2 Comparison of joint performance at various groove shapes

According to the above results, the joints at various groove shapes had a fracture in the base metal, although the friction time differed. To clarify the relationship between exhausted flash and friction time, the joints with a fracture in the base metal at short friction time were compared for each groove shape. The step groove shape did not achieve a joint efficiency of 100% and a fracture in the base metal at the initial peak, since the joint with this fracture had large inner and outer flashes when the bottom surface (step part) of that shape was completely joined (see Fig. 11). Moreover, the joint with that fracture was obtained when it was made with a long friction time after the initial peak (see Fig. 10). Thus, the step groove shape was not suitable for obtaining a fracture in the base metal at the initial peak. In contrast, the taper groove shapes had relatively small exhausted inner flash in comparison with the flat and step groove shapes within the same friction time (see Fig. 14). When the joint was fabricated with a suitable taper groove shape, such as the Taper-B groove shape, it achieved 100% joint efficiency and a fracture in the base metal as shown in Fig. 13 at the initial peak. Particularly, the real friction pressure at the initial contact part of the Taper-B groove shape was larger than that of the Taper-A groove shape, as shown in Table 1. The joint with 100% joint efficiency and a fracture in the base metal was easily obtained by increasing friction pressure [26]. Hence, the joint with the Taper-B groove shape easily obtained 100% joint efficiency and a fracture in the base metal. In this connection, the joint may be fabricated with higher friction pressure. Nevertheless, the joint in the higher friction pressure condition was difficult to weld, as it buckled during the friction process [23]. Hence, it is desirable that the joint with a small inner flash is made with a suitable taper groove shape, such as the Taper-B groove shape.

4.3 Characteristics of joint with Taper-B groove shape

According to the above results, it was clarified that the joint with the Taper-B groove shape had a joint efficiency of 100% and a fracture in the base metal when the friction torque reached the initial peak. To clarify the characteristic of the joint with the Taper-B groove shape in detail, the hardness distribution across the weld interface of the joint was measured. Figure 15 shows the corresponding Vickers hardness distribution. The joint had a hardened area that extended about 4.0 mm in the longitudinal direction including the weld interface, and the maximum hardness was approximately 250% of the base metal. The weld interface and its adjacent region of the low carbon steel joint also had a hardened area, which was fabricated at the initial peak by continuous drive friction welding and described in a previous report [31]. This joint in the previous report also had the same fatigue strength as the base

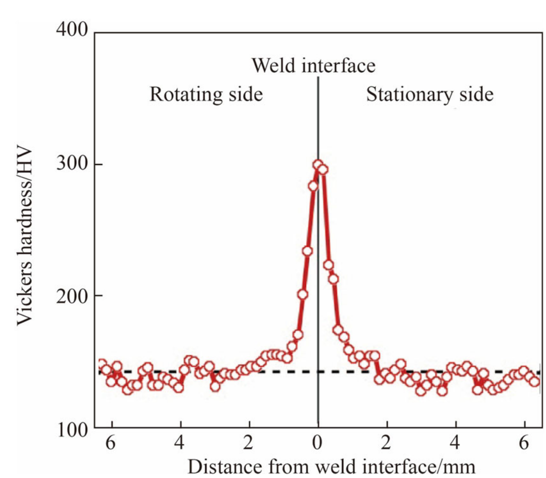

Fig. 15 Vickers hardness distribution across weld interface of joint with the Taper-B groove shape at friction time of 0.25 s

metal [26]. Hence, a hardened area in the joint appeared not to have any influence on the joint strength, although further investigation was needed to elucidate detailed characteristics of the weld interface and the joint strength such as fatigue strength because the grain size at the adjacent region of that interface affected these joint properties.

Based on the above results, it was clarified that the flash of the joint with the Taper-B groove shape at a friction time of 2.5 s was smaller than that of the flat groove shape, as shown in Fig. 8c. In particular, the axial shortening of the joint with the Taper-B groove shape at a friction time of 2.5 s was about 1.1 mm, which was smaller than that of the flat groove shape at a friction time of 0.7 s (about 2.4 mm). Moreover, further investigation was needed to fabricate an ideal pipe joint with no inner flash, as the joint with the Taper-B groove shape contained a small inner flash. In contrast, the opportune taper groove shape could be designed by a simulation technique [32]. These, along with other results, will be described in a subsequent report. In conclusion, it is suggested that the pipe joint with a small inner flash is achieved with a suitable taper groove shape. A pipe with a suitable taper groove shape can be welded into significant lengths.

5 Conclusions

This study described the effect of the groove shape of the weld faying part on the decrease of the inner flash for steel pipe joints fabricated by friction welding. The pipe had inner and outer diameters of 8.0 mm and 13.5 mm, respectively. The types of the weld faying surfaces of these joints had flat, two step groove shapes, and two taper groove shapes. The following conclusions are provided.

(i) When joints are fabricated with the flat groove shape at a friction time of 0.5 s (when the friction torque reaches the initial peak), they do not achieve a fracture in the base metal and the tensile strength of the base metal. However, the inner flash partially closes the pipe hole at this friction time. All joints at a friction time of 0.7 s achieve a fracture in the base metal.

(ii) The elapsed time for the initial peak is reduced using step and taper groove shapes, although the initial peak has similar values to the flat groove shape. This is because of the increasing friction pressure at the initial contact surface when using these groove shapes.

(iii) When joints are fabricated with step groove shapes, those with the time at which the friction torque reaches the initial peak do not have the tensile strength of the base metal and a fracture in the base metal. However, when joints are fabricated with a gently tapered groove shape at the time of the initial peak, they achieve a fracture in the base metal, despite the extremely small inner flash.

(iv) The suitable joint with no inner flash and a fracture in the base metal can be obtained with the Taper-B groove shape with the taper angle of 15.5° and an area of about 40% of the flat groove shape.

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