Stud shape and joint strength for low carbon steel joints fabricated by friction stud welding with low load force requirement

Masaaki Kimura, Haru Saito*, Masahiro Kusaka and Koichi Kaizu
Graduate School of Engineering, University of Hyogo, Hyogo, Japan

ABSTRACT
This paper describes the stud shape and joint strength of low carbon steel joints fabricated by friction stud welding with low load force requirement. To reduce the load force during the welding process, the stud side with the circular hole at the weld faying surface part was used. The outer diameter of a cylindrically shaped stud side had 12.0 mm and that was welded to the circular solid bar with a diameter of 24.0 mm as the work side. The joint was made with a friction speed of 27.5 rps, a friction pressure of 60 MPa, and a forge pressure of 60 MPa, which was determined as the low force condition for obtaining good joint in the previous study. When joints were made by a cylindrically shaped stud with a hole diameter of 6.0 mm and its depth of 0.5 mm, all joints at a friction time of 0.6 s, i.e. the friction torque reached to the initial peak, had the same tensile strength as that of the base metal with the base metal fracture. All joints with flash from the initial weld interface had the fracture on the base metal, the bend ductility of over 15% with no cracking at the initial weld interface through an impact shock bending test, and a high fatigue strength of the base metal. That is, the sound joint could be successfully achieved, and that could be obtained with the same friction stud welding condition of the circularly shaped solid stud. As a conclusion, the joining technique for the friction stud welding method with low load force requirement was proposed in accordance with using a cylindrically shaped stud that has the circular hole with the shallow depth at the weld faying surface part.

KEYWORDS
Friction stud welding; low carbon steel; low load force; cylindrically shaped stud; joint strength; friction stud welding condition

1. Introduction
Stud joints, made by welding plate such as flat plates and round bars or the like, are widely used not only in large-scale structures such as buildings and ships but also in transportation equipment and the housings of electrical products and in the products themselves. Stud joints are conventionally fabricated using arc or capacitor discharge (CD) welding, which allow welding to be carried out with short operating time [1]. Also, to obtain good joint accompanying a high operational efficiency and good workability, various ingenuity is provided to arc stud welding technique [2]. However, an arc stud joint has several problems for actual welding construction such as a working reliability, so that the joint properties will be dependent on operator skill or working conditions. Furthermore, since the molten zone tends to fall away in drops due to gravity when arc stud welding is carried out, it is difficult to obtain a sound joint and the welding direction during construction demands particular attention [3], making ease of operation difficult to achieve. Therefore, to establish of the welding technique without above dependence is required for obtaining the high reliability of stud joints. It can be considered that the stud joint will be made by using friction welding technique, i.e. friction stud welding, because this welding technique has several advantages over fusion welding, e.g. high energy efficiency, narrower heat affected zone (HAZ), and low welding cost.

By the way, the same operational efficiency and excellent workability as conventional stud welding is required when friction stud welding is performed. Considered in terms of the operational convenience at construction sites and weight reduction of the work equipment and its ancillary device, it can be said to be preferable to set the axial force that is, the thrust force...
that is applied to provide friction/forge (upset) pressure, which is a welding condition, as low as possible. If it is possible to carry out joining under this constraint, it should be possible to fabricate joints simply at construction sites by stud welding, and thus to enlarge the scope of its uses and applications. Currently, however, the degree to which the load thrust can be reduced during welding and a sound joint, which has joint strength equivalent to that of the base metal and does not fracture at the weld, still be fabricated has not yet been demonstrated. It is against this background that our previous report [4] described the friction stud welding of low carbon steel. The results of this study showed that the joint had a tensile strength as that of the base metal, a fracture occurring at the base metal part, and a bend ductility of 15° or over by impact bending tests. Those joints were made with a friction pressure of 60 MPa, a friction time of 0.6 s (the time just after the friction torque reached the initial peak), and a forge pressure of 60 MPa that was an identical friction pressure. However, if the friction pressure was reduced more than this value (60 MPa), the initial weld interface did not weld sufficiently when the weld faying surfaces were first brought into contact, making it clear that the forge pressure must be increased in such cases. On the basis of these results, when welding was performed where the friction pressure and forge pressure were those that could be easily set construction sites under the same friction stud welding conditions, the pressure load had to be around 60 MPa and welding had to be performed under these conditions to create a suitable stud joint. On the other hand, if it was intended to make a further reduction in the weight of equipment used at the construction site, it would be preferable to perform welding with a reduction in friction load alone rather than changing the pressure load since, as stated above. Then a friction pressure equivalent to 60 MPa is a necessary condition at the time of welding, it is thought that a reduction in the surface area of the weld interface may be the most effective means of reducing the friction load. However, when the surface area of the weld interface is reduced, the diameter on the stud side is also reduced and this inevitably limits the size of the stud joint. Since a reduction in the diameter of the weld interface results in a limitation to the scope of application of stud joints, it cannot be said to be a desirable method. Thus, it is essential that the load thrust alone be reduced, with no change in the diameter of the weld interface on the stud side.

The purpose of the present study is to find the low force requirement condition for the friction stud welded joints with the base metal fracture. Then, this requirement condition is set as the friction load at approximately the same level as that with the spot welding equipment [5] and friction spot welding equipment [6] using in actual work sites is taken as a low load condition. In this paper, detailed observations of the joining process were made when friction stud welding, that is, friction welding, was performed with a combination of different diameters, and then tensile tests and bending tests were also performed to make a detailed study of the strength of the joints obtained. On the basis of the results, investigations were made into the possibility of fabricating sound joints, with a joint strength equivalent to that of the base metal with the base metal fracture, and into the actual cylindrical stud shapes that would make it possible for joining under the limiting condition of low force load. Also, the joining requirements for actual operation were also examined.

2. Materials and experimental procedure

2.1. Materials and specimen shapes

Materials used were JIS SS400 steel round bars (referred to as SS400) φ16mm in diameter, and φ28mm in diameter. Those were similar materials as described in our previous report [4]. The tensile strength of these materials were 458 MPa for the φ16mm diameter bars and 438 MPa for the φ28mm diameter. As shown in Figure 1(a), a φ15mm diameter grip part was lathe machined in the φ16mm round bar and the weld interface surface was lathe machined to a diameter of φ12mm. Also, as stated above, it is necessary to reduce the faying surface area of the weld interface for welding to be performed with a low load thrust. A hole of depth Lmm and diameter φdmm, as shown as the values in red in Figure 1(a), was made in the centre of the weld faying (contacting) surface so that the weld faying part alone was cylindrical shape and a range of shapes was prepared by varying these values. The holes were machined so that they were flat-bottomed, and the corners machined to R0.2 or less. Also,
the grip part was machined as the flat along its three directions to prevent rotation during welding. Then, this shape was used as the stud side specimen that was the small diameter side when joints is made. By the way, when the friction welding with the ratio of the large diameter to the small diameter was 1.75 or over, this combination of specimen diameter was able to consider the friction stud welding, because the large diameter side specimen had hardly deformation. Also, when the longitudinal length from the faying surfaces (the specimen length) is extremely short, the peripheral area of the weld interface may undergo shear fracture in the circumferential direction during welding, terminating the friction welding [7]. Accordingly, it is necessary that the work side, the side with larger diameter, is of a sufficient thickness to ensure that the length of the specimen is such that no shear fracture is caused during the friction process. The round bar used in the present study, in which these factors are taken into account, had a diameter of \( \varnothing 28 \text{mm} \) on the work side with a \( \varnothing 27 \text{mm} \) diameter grip part machined into it, as shown in Figure 1(b). And then, the diameter of the weld faying surface was machined to \( \varnothing 24 \text{mm} \), which is twice the diameter of the stud side specimen, as shown in Figure 1(a). All the weld faying surfaces were surface-ground to a finish with an arithmetic average roughness in the range of 0.05~0.14 \( \mu \text{m} \) and were immediately rinsed with acetone before welding.

2.2. Welding method

A brake-type (continuous or direct drive) friction welding machine was used for the welding. It was necessary to remove the deformation caused in the joint during the braking to elucidate the effects of friction time on joining phenomena and joint strength. Accordingly, in the present study, an electromagnetic clutch was used and welding was performed by a welding method similar to the previously reported experimental method [8]. When the clutch was released, the relative speed between both specimens instantly decreased to zero. By the way, stud joints were a combination of plate and round bar, in many cases it was unsuitable for the plate to be rotated. In actual operations, a friction stud welding is performed by the stud side being rotated while being pressed against the work side, it would seem appropriate for each specimen to be positioned and joined in this way. However, the specimens were made set conversely in this study, because the durability of used jig was considered during the experiment. It has been confirmed, however, that if welding is performed with the specimens attached in the opposite way, as in the method of the present study [4,9], this produces results that are no different from the results obtained when welding is performed with the parts attached as in conventional friction stud welding.

During the friction stud welding operations, the friction stud welding conditions in this study was set to a friction speed of 27.5 rps (1650 rpm), friction pressure of 60 MPa and forge pressure of 60 MPa. This friction stud welding condition was established in the previous study [4], and the friction stud welded joints had good joint properties as a conventional stud joint. Then, joints were prepared with a range of different friction times. Measurement of the thrust force at this friction pressure/forge pressure (60 MPa) when the internal diameter of the cylindrical part was \( d = \varnothing 6.0 \text{mm} \) showed that this was approximately 519 kgf, approximately the same as the thrust that can be set for the above-described spot welding apparatus [5] and friction stir welding apparatus [6]. The specimen appearance during the friction process was photographed using a digital video camera and recorded along with the friction torque at a sampling time of 0.001 s by a PC via an A/D conversion board.
2.3. Test methods

After a joint was fabricated, the burn-off (axial shortening) was measured and the appearance was inspected, the flash expelled from the initial weld interface and the grip part were removed with machining into a tensile test specimen with a parallel part length of 60 mm and a diameter of \( \phi 12 \) mm. Tensile tests were performed on the joint at room temperature using an Amsler universal testing machine. Also, the impact bending test, that the impulsive force through a steel hammer was applied to the joint having the flash, was carried out \[1\]. In actual impact bending test, the work side was set to a vice, and the impulsive force was applied to the stud side. Fatigue tests were also performed on a base metal specimen with a shape which simulated the joint after welding as in Figure 2 and the as-welded joint. The corners of the virtual initial weld interface surfaces of the base metal specimen shown in Figure 2 were prepared by machining them into a shape (R0.1 or less) which could be regarded as approximately a right angle. Fatigue tests were performed using a hydraulic servo tensile compressive fatigue tester, and a sine wave with a frequency of 10 Hz was applied with stress ratio of 0.1, to the base metal or joint, and the number of fatigue cycles was measured at room temperature either to failure or up to 10 \[10\] cycles.

The joint was cut at positions at distances of approximately 10 mm in the longitudinal direction of the initial weld interface and then cut along the plane that passed through the axial centre, the central line of the initial weld interface, and in a direction perpendicular to the initial weld interface. Then, the observation surface was buffed and the etched with Nital solution and the cross-section of the adjacent region of the initial weld interface was subjected to the observation at this portion. Vickers hardness was measured on the axial centre of the stud side cutting perpendicularly across the initial weld interface and at positions on the axial line on the periphery 0.5 mm towards the central axis from the outer surface.

3. Results and discussion

3.1. Observations of joining behaviour during the friction process

In order to understand the appearance of the joint with a cylindrical section at the weld faying part, as shown in Figure 1(a) the joining behaviour during the friction process was observed using a stud specimen in which the inner diameter of the cylindrical part was \( d = \phi 6.0 \) mm and the depth was \( L = 20.0 \) mm. Figure 3 show the relationship between the joining behaviour and friction torque curve during the friction process. Photos (1)~(6) in Figure 3(a) correspond to (1)~(6) in Figure 3(b). Photo 1 shows the instant at which the weld faying surfaces come into contact and the
friction torque immediately after this rises abruptly to reach the initial peak torque peak shown in (3). This value was approximately 50Nm and the elapsed time at which this was reached was approximately 0.3 s. The entire initial weld interface was becoming red at photo 2, and then, the peripheral part of the stud side was greatly deformed at photo 3, i.e. exhibiting a state in which flash was beginning to be expelled. In the photos 4 and 5 the quantity of flash being expelled from the stud side is increasing, but the friction torque has remained almost constant. Subsequently, the friction torque decreases and shifts to the steady torque range of (6) showing an almost constant value. There was also almost no observable deformation on the work side and no flash expulsion was observed. When compared with the solid stud with no cylindrical part, as described in our previous report [4], that is, when \( L = 0 \) mm, although there was almost difference in the initial peak torque, the time at which this was reached was shorter. Also, the changes in friction torque shown in (4) and (5) in Figure 3(b), where an almost constant value was attained and held immediately after the initial peak torque had been reached, were not observed at \( L = 0 \) mm.

### 3.2. Effects of friction time on the tensile strength of the joint

Joints were fabricated at various friction times using stud specimens with the inner diameter of the cylinder being \( d = \varnothing \) 6.0 mm and the depth \( L = 20.0 \) mm and these were subjected to tensile tests. Figure 4 gives the joint efficiency, found by comparing the tensile strength of the joint thus obtained and the tensile strength of the base metal plotted on the friction torque curve is shown in Figure 3(b). And examples of the appearance of joints after the tensile tests are shown in Figure 5. Also, since the shape of the stud side cylinder is comparatively long, it was possible to predict that base metal fracture would be shown by fracture occurring at the cylindrical part. Accordingly the joint efficiency in Figure 4 was found on the basis of the tensile strength of the base metal on the stud side. Figure 4 shows that at a friction time of 0.3 s, when the friction torque is close to the initial peak torque, the tensile strength of the joint is approximately the same as the base metal and that has a joint efficiency of approximately 100\% and two types of fracture morphology were obtained: a mixed mode fracture at both the initial weld interface and base metal part, as shown in Figure 5(a) and a base metal fracture as shown in Figure 5(b) (at this depth, the fracture location was the cylindrical section). At a range of friction time of 0.4 ～ 1.0s, the joint efficiency was also approximately 100\%, and all the joints showed base metal fracture, as shown in Figure 5(b). However, when joints were made with a friction time of 1.5 s, although the joint efficiency was approximately 100\% the joints obtained showed mixed mode fracture as in Figure 5(a) or a base metal fracture with
cracking at the weld interface as in Figure 5(c) with no evident differences in fracture morphology. Due to this, when the depth of the cylindrical section was \(L = 20.0 \text{ mm}\), it was found that the joint showed base metal fracture when welding was performed, within a range where the friction torque shown as (4)\textsuperscript{−}(5) in Figure 3(b) was approximately constant, i.e. within the range between a friction time of 0.4 s, after the initial peak torque was reached, to 1.0 s, where the friction torque began to decrease. Also, all joints showed base metal fracture when \(L = 0 \text{ mm}\), i.e. when there was no cylindrical section, at a friction time of 0.6 s after the initial peak torque was reached [4]. Hence, it was clear that when welding was performed with a cylindrical stud, at a friction time close to the initial peak torque, similar results were obtained as when welding was performed with a solid stud.

3.3. Relationship between the tensile strength of the joint and the depth of the cylindrical part

In order to investigate the effect on joint strength of the depth \(L\) of the cylindrical section, a case was investigated in which the cylindrical part depth was shallower than that shown in Figure 4. The relationships between joint efficiency and cylindrical section depth when the inner diameter of the cylindrical part was fixed at \(d = \phi 6.0 \text{ mm}\) and the depth varied within the range \(L = 0 \sim 5.0 \text{ mm}\) are shown in Figure 6. Also, an example of the joint appearance after the tensile test is shown in Figure 7. Since, in the present study, there was the limiting condition that welding was performed without the load thrust being changed, at \(L = 0 \text{ mm}\), when there was no cylindrical section, the friction/forge pressure was equivalent to approximately 45 MPa, and this pressure lower than 60 MPa was a condition for the surface area of the weld interface to increase. Also, in many cases, the joint shows base metal fracture at the solid part as shown in Figure 7. With the used materials used in the present study, as noted in 2.1 above, the tensile strength on the work side was lower than that on the stud side, when these were combined for calculation of joint efficiency; this was found on the basis of the tensile strength of the base metal on the work side where the base metal strength was lower. It is clear from the results at a friction time of 0.4 s, as shown Figure 6(a), that since the friction pressure for \(L = 0 \text{ mm}\) was equivalent to 45 MPa, not all the joints had the same tensile strength as the base metal and the fracture was mixed mode, as shown in Figure 5(a). This agrees with the results in the previous report [4]. Although a joint efficiency of approximately 100% was obtained at a cylindrical section depth of \(L = 0.5 \text{ mm}\), all of the joints showed mixed mode fracture. At a cylindrical section depth of \(L = 1.0 \text{ mm}\), all joints showed base metal fracture, as shown in Figure 7 (with the fracture located in the solid section). Also, no cracks or other defects were observable near the initial weld interface after the tensile tests. However, as the cylindrical
section became longer, it became less possible to obtain a 100% joint efficiency and the fracture became base metal fracture with cracks at the initial weld interface, as shown in Figure 5(c). At a friction time of 0.5 s as in Figure 6(b), all joints with a cylindrical section depth of $L = 0.5$ mm showed base metal fracture. And then, at a friction time of 0.6 s, as in Figure 6(c), all joints with a range of depth of $L = 0.5 \sim 1.0$ mm showed base metal fracture as in Figure 7. For all friction times, however, as the cylindrical section became longer (as the hole became deeper) it became impossible to obtain joints showing base metal fracture. Further, cases where the friction time was 1.0 s, as in Figure 6(d), although there was some variance, a larger number of joints with base metal fracture were obtained up to a cylindrical section depth of $L = 3.0$ mm. Since in our previous study [4], the results showed that when the friction pressure was 60 MPa and the depth was $L = 0$ mm, having no cylindrical section, all joints showed a base metal fracture at a friction time of 0.6 s after the initial peak torque was reached; hence, it was clear that the joints would show base metal fracture even when a cylindrical stud into which a hole of a depth of $L = 0.5$ mm had been made in the weld faying part was used. It was also clear when welding could successfully be performed under friction stud welding conditions that were the same as those when a solid stub with no cylindrical part was welded. A joint efficiency of 100% was also shown in the results of the tensile tests shown in Figure 6 and this was due to the parallel sections of the tensile test specimens being subjected to plastic constraint due to hardening of their weld interface region.

3.4. Investigation of the optimal cylinder depth

It is clear from the results in the preceding sections that, when performed under friction stud welding conditions identical with those used for a solid stud with no cylindrical section [4]. That is, a friction pressure of 60 MPa and a friction time of 0.6 s, welding a round bar with a cylindrical section having an internal diameter of $d = \phi 6.0$ mm and a depth within the range $L = 0.5 \sim 1.0$ mm produced joints that invariably fractured at the base metal as shown in Figure 6(c). In this section, in order to discover the optimal depth for the cylindrical section, joints were prepared with the depth in the range $L = 0.5 \sim 1.0$ mm and these joints with the flash expelled from the initial weld interface, were subjected to strength evaluation and impact bending tests to make a detailed investigation of the optimal depth for the cylindrical section.

3.4.1. Tensile strength of joints with flash

It is assumed that the stud joints are used in a state in which the flash expelled from the weld interface is still remained, that is, in an as-welded condition [2]. Since the results described above were obtained with joints from which the flash had been removed from the initial weld interface by machining, there is a possibility that they differ from strength assessments of joints having flash. Accordingly, the joint strength of joints with flash was evaluated. Figure 8 shows the joint efficiency and burn-off of joints with a friction time of 0.6 s for the hole depths of $L = 0.5, 0.75,$ and $1.0$ mm. Also, Figure 9 shows an example of the appearance of each of the fracture modes after the tensile test. The result for joint efficiency in Figure 8 show that all joints had a joint efficiency of at least 100%. With a cylindrical depth of $L = 0.5$ mm, however, the fracture was in the base metal, as shown Figure 9(a). Then, when the hole was deeper than this, it was a mixed mode fracture, as shown in Figure 9(b). Thus, although joints with a cylindrical depth of $L = 0.5$ mm and with flash showed base metal fracture when the cylindrical section was longer, there were differences between the fracture appearance of joints with flash and those from which it had been removed. This was
thought to occur at the friction time of 0.6 s with the same friction stud welding conditions. The results shown in Figure 8 show that the burn-off was approximately 1 mm when the hole depth was \( L = 0.5 \text{ mm} \) and thus was greater than the depth of the hole, so that welding reached the bottom of the hole at a friction time of 0.6 s. When, however, the cylindrical section was longer than this, it is thought that the bottom of the hole became increasingly difficult to weld, since the burn-off increased negligibly.

### 3.4.2. Impact bend strength of the joints

One method of assessing the strength of a stud joint is the impact bending test [1]. An impulsive force is applied to the joint using a steel hammer for example and the joint is judged acceptable if it has a bend of at least 15° without any cracks being observed in the joint section. Accordingly, the joints were subjected to this impact bending test. In the example shown in Figure 10 welding was performed with a cylindrical hole depth of \( L = 0.5 \text{ mm} \) and a friction time of 0.6 s. As shown in Figure 10, the joint reached a bend angle of 15° or over. No cracks or defects were observed in the initial weld interface at the photo which was taken in the direction in which the impulsive force had been applied, as in Figure 10(b). Although the data are not shown here, similar results were also obtained with hole depths of \( L = 0.75 \text{ mm} \) and 1.0 mm. Thus, a bend angle of at least 15° was obtained at each of the hole depths and it was judged that these joints were welded in a state that could be used as a stud joint.

### 3.4.3. Observation of the cross-section at the initial weld interface region

In order to find the optimal depth of the cylindrical section, the cross-sections of the initial weld interface region of the joints with cylinder section depths of \( L = 0.5, 0.75, \) and 1.0 mm and a fixed friction time of 0.6 s were subjected to the observation of those sections after welding had been performed as shown in Figure 11. Figure 11(a) shows a joint with a cylinder section depth of \( L = 0.5 \text{ mm} \). The cylindrical section contacted to the stud side was completely lost and also shows a HAZ as a black-coloured area around the axis. As shown in Figure 8, when the cylinder section depth was \( L = 0.5 \text{ mm} \), the burn-off was approximately

---

Figure 9. Examples of appearances of tensile tested specimens for joints with flashes.

Figure 10. Example of appearances of impact shock bending tested specimen for joint with flash: hole diameter of \( d = \varphi 6.0 \text{ mm} \), depth of hole of \( L = 0.5 \text{ mm} \) and friction time of 0.6 s.

Figure 11. Cross-sectional appearances of initial weld interface region of joints at various depth of holes: hole diameter of \( d = \varphi 6.0 \text{ mm} \) and friction time of 0.6 s.
1 mm, which was larger than the hole depth. And, it was clear that, at this depth, the bottom of the hole was welded. No travelling phenomena of the weld interface [4,9,11,12] was observed in this friction stud welded joints. On the other hand, the cylinder section of the joint with a hole depth of $L = 0.75$ mm (Figure 11(b)), was lost, and the width of the longitudinal HAZ (HAZ width) around the axis was narrower than that of $L = 0.5$ mm (Figure 11(a)). Furthermore, at a cylinder hole depth of $L = 1.0$ mm, although it was not possible to observe the cylinder section clearly, the HAZ width around the axis was even narrower, as shown in Figure 11(c). The burn-off of these joints was approximately 1 mm in all cases and, as shown in Figure 8, this very little differed from joints with a cylinder section depth of $L = 0.5$ mm, it can be determined that the HAZ width of these joints was narrowed. Therefore, when the joint made with a friction time of 0.6 s and a cylinder section depth of $L = 0.5$ mm, the bottom of the hole of that was completely welded with all of the fractures in the base metal, as shown in Figure 9(a). And then, as shown in Figure 10, it is clear that they attained a bend angle of 15° or over. Also, as shown in Figure 6(b) all joints with a cylinder section depth of $L = 0.5$ mm showed base metal fracture when welding was performed at the shorter friction time of 0.5 s. And, the fracture of joints with flash was in the base metal, as shown in Figure 9(a). Furthermore, a bend angle of joint at least 15° was obtained, as in Figure 10. Hence, it is evident that the bottoms of the holes were welded even at this friction time (0.5 s) and was determined that the optimal cylinder section depth was $L = 0.5$ mm.

3.5. Investigation of the optimal cylinder inner diameter

It was clear from the results up to the previous section, when the inner diameter of the cylinder part was $d = \phi 6.0$ mm, the optimal cylinder hole depth was $L = 0.5$ mm. Here, when the necessary load thrust at this inner diameter was calculated, as shown in Figure 1(a), since the diameter on the stud side is $\phi 12.0$ mm, this was found to be approximately 519 kgf. Since it is approximately 692 kgf for a solid round bar of $\phi 12.0$ mm, it is clear that there was a reduction in load thrust due to the use of a cylindrical stud of approximately 25%. Also, this reduction in a lower load thrust would result in a reduction in the weight of the ancillary equipment at the work site, which could be expected to improve usability. Accordingly, the size of the hole made at the stud side, i.e. the inner diameter $d$, was varied during the investigations in this section in order to investigate whether it is possible to fabricate a joint which fractures in the base metal even if the welding is performed with the load thrust further reduced. Figure 12 shows the results for joint efficiency and burn-off with the inner diameter of the cylinder section at $d = \phi 8.5$ mm and 9.5 mm, which joints were made with a friction time of 0.6 s and a cylinder section depth $L = 0.5$ mm. In this section, tensile tests were performed after the joints had been machined into tensile specimens and the results for $d = \phi 6.0$ mm are the same as shown in Figure 6(c). Since the joints were fabricated with the friction/forge pressure of 60 MPa when the inner diameter of the cylinder section was $d = \phi 6.0$ mm, the load thrust was found at each of the internal diameters. At $d = \phi 8.5$ mm, it was approximately 347 kgf (equivalent to a friction pressure of 30 MPa in the case of a solid stud) and at $d = \phi 9.5$ mm, it was approximately 258 kgf (equivalent to a friction pressure of 22 MPa). As shown in Figure 12, when the inner diameter of the cylinder section was $d = \phi 6.0$ mm, the joint efficiency was 100%. And, as shown in Figure 7, all joints showed base metal fracture with no crack at the initial weld interface. However, when the cylinder section was $d = \phi 8.5$ mm the joint efficiency remained the same, but the joints obtained showed mixed mode fracture, as
shown in Figure 5(a) and thus the results showed differences in their fracture mode. Further, when the cylinder section was \( d = \phi 9.5 \text{ mm} \), a joint efficiency of 100% was not obtained and all joints showed mixed mode fracture. On the other hand, the burn-off of these joints became less as the inner diameter of the hole became greater, as shown in Figure 12.

The results of cross-section of the initial weld interface region of the joints are shown in Figure 13. The results of the inner diameter of the cylinder section Figure 13(a) was \( d = \phi 6.0 \text{ mm} \) were as in the same photo of Figure 11(a). The width of the HAZ in the axial centre region reduced as the inner diameter of the hole increases. Therefore, when the weld faying surface area of the weld interface at the initial contact was small, the load thrust reduced, with the result that it became difficult to generate sufficient friction heat for welding at a friction time of 0.6 s and it is thought that a not joined region would remain and the burn-off would be smaller. The problem of welding the bottom of the hole could be solved by lengthening the friction time to longer than 0.6 s but these conditions were different from the friction stud welding conditions under which good joints could be obtained with solid studs with no cylindrical section [4]. Since it thus became necessary to re-set the friction stud welding conditions to suit the size of the stud used, this method could not be readily used without determining the friction stud welding conditions under which good joints can be obtained. Therefore, it was preferable for welding to be performed with cylindrical studs under the same welding conditions as with solid studs. And then, it seems evident that the internal diameter of the hole made on the stud side must be of an appropriate size. In the present study, it was determined that this should be \( d = \phi 6 \text{ mm} \), which is half the diameter of the stud side weld interface (\( \phi 12 \text{ mm} \)).

### 3.6. Fatigue strength of the joint

In the circumstances in which stud joints are used, it is assumed that various parts and members are attached to the stud side during use. Since it is assumed that load and vibration act repeatedly on these various attachments to the stud side when the joints are in use, it is considered necessary to carry out fatigue tests to evaluate the soundness of the joint. In the case of stud joints, since the thickness of the plate forming the work side is specified [13], a method of fatigue test in which stress is applied in a direction perpendicular to the axial direction of the stud side is generally used [14]. In many actual stud joints, however, a screw groove for bolt fixing is formed on the stud side and the parts on the stud side are hung from this for use. That is, it is assumed that the joints will be used with a load applied in the axial direction on the stud side. Also although the fatigue strength of friction welded joints [15–17] and friction stud welded joints [18,19] is usually found by rotary bending fatigue strength in the axial direction is rarely investigated. Accordingly, it is necessary to find the fatigue strength in the axial direction of the joint. In the form of the joints described above, however, the grip section on the stud side is narrow, as shown in Figure 1(a), making it difficult to perform fatigue strength tests. Accordingly, joints were fabricated with the same diameter as the grip section on the work side used for the part corresponding to the grip section on the stud side, base metal fatigue test specimens simulating joints without flash at the position equivalent to the initial weld interface shown in Figure 2 were prepared. And then, fatigue test was performed on these by loading a tensile-compressive force in the axial direction. In one case, a joint was prepared with a cylinder section \( d = \phi 6.0 \text{ mm} \) in diameter and \( L = 0.5 \text{ mm} \) in depth, welded with a friction time of 0.6 s. The same material was used for the work side and stud side of the joint and the

![Figure 13](image13.png)

**Figure 13.** Cross-sectional appearances of initial weld interface region of joints at various hole diameters: depth of hole of \( L = 0.5 \text{ mm} \) and friction time of 0.6 s.
base metal of the test specimens. The results are shown in Figure 14. In the case of the form shown in Figure 2, fracture did not occur at stress amplitudes up to 110 MPa even after the number of cycles to failure repetitions reached $10^7$, at higher amplitudes, although fracture occurred from the corner of the assumed initial weld interface, as shown in Figure 15(a) before the number of cycles to failure repetitions reached $10^7$, in the results for the base metal shown in red as in Figure 15(a). It was judged from these that the fatigue strength of the base metal was 110 MPa. On the other hand, the joint with a stress amplitude of 150 MPa which stress amplitude was higher than that of the base metal reached a number of cycles to failure of $10^7$, in the results shown in open blue symbol. Furthermore, all joints below a stress amplitude of 135 MPa reached a number of cycles to failure of $10^7$, in the results shown in solid blue symbols. Those joints had no fracture. Also, one joint did fracture at the initial weld interface at 175 MPa as shown in Figure 15(c), although one joint at a stress amplitude of 150 MPa and most of the joints at 175 MPa were in a state where fracture occurred at the corner between the stud part and the grip of the initial weld interface as in Figure 15(b). Furthermore, the stress amplitude of this joint at a number of cycles to failure of $10^7$ achieved an approximately quadruplicate value of the base metal. On the basis of the results that fracture occurred at a corner part, not at the initial weld interface, as shown in Figure 15(b), apart from the single joint described above where the stress amplitude was 175 MPa, it was thought that the joint had a higher fatigue strength than the base metal.

The results for Vickers hardness distribution across the initial weld interface regions are shown in Figure 16. At all measurement points over the initial weld interface and for a width of 3 mm in its periphery, the hardening was greater than the base metal, but the hardened...
proportion of the axial centre was lower than that of the periphery. It has been reported that fatigue crack growth is slower in the hardened zone in a friction welded joint than in the unhardened zone [20]. Even if the shape of the flash expelled from the initial weld interface as well as the stress concentration and residual stress will be generated by a complex situation in the joint, it was clarified that the joint had a fatigue strength at least equivalent to that of the base metal due to hardening in the vicinity of the initial weld interface.

3.7. Effect of mill scale on the steel surface

There is a work-hardened surface layer, which colour is black, on the surface of steel plate. This layer, also known as ‘mill scale’, is dense and repels oxygen infiltration, it is intentionally created to prevent corrosion and the like. However, as this layer is irregular, hard and brittle, it is usual to remove it by chemical dissolution or grinding [21] before use. The results of previous experiments refer to welding performed after this layer had been completely removed and it is thought that the welded state differs according to whether or not there is mill scale on the weld interfaces on the work side. In particular, since there is little or no flash expulsion from the work side of the friction stud welded joints as shown in Figure 11(a), the presence of mill scale evidently has a major effect on joint strength. Also, since mill scale is often present on the steel plate surfaces in structures, in operation processes in the construction site, workability would be improved, even if welded with mill scale present on the steel plate surface, as such processing before welding could then be omitted, if a good joint with fracture in the base metal could be fabricated. It was thus necessary to clarify the preparation process of mill scale removal operations before welding was a requirement for on-site welding. Accordingly, a work side specimen with mill scale on the weld facing surface was prepared and the necessity of removing mill scale as one of requirements for welding this to the stud side was investigated. Thus, in the experiments described in this section, 110 mm block SS400 steel plate with mill scale (the initial mill scale thickness was approximately 130µm and the base metal tensile strength in the plate thickness direction was 434 MPa) was prepared, and this was machined in the plate thickness direction into the form shown in Figure 1(b). Then, work side specimens with mill scale remaining solely on the weld interface surface were prepared. Joints fabricated by welding these with stud specimens with the internal diameter of the cylinder section \( d = \phi 6.0 \text{ mm} \) and the depth \( L = 0.5 \text{ mm} \), for a friction time of 0.6 s, were evaluated. As a result, several joints were joined, showing the appearance of a welded state as in Figure 17(a). However, most of them were unjoined as shown in Figure 17(b). Also, when joints compared between the united joints of Figure 17(a) and those welded without mill scale as in the photograph shown in Figure 11(a), the flash expelled from the initial weld interface had decreased and the burn-off was 0.5 mm similar to the hole depth. On the other hand, the unjoined joint shown in Figure 17(b) shows the cylinder section remaining on the stud side and no observable HAZ in the axial centre region. Furthermore, although the data are not shown here, the joint as in Figure 17(a) the result was that the tensile strength was not equivalent to that of the base metal and fracture occurred in the initial welding interface. From these results, it was not possible to generate sufficient friction heat by welding with a friction time of 0.6 s when mill scale was present on the weld facing surfaces because the mill scale would remain at the initial weld interface, even if welding were possible, since this would be via the mill scale.

Figure 17. Cross-sectional appearances of initial weld interface region of joints with mill scale on weld facing surface of work side: hole diameter of \( d = \phi 6.0 \text{ mm} \), depth of hole of \( L = 0.5 \text{ mm} \) and friction time of 0.6 s.
It would thus seem unlikely that it would be possible to obtain a joint strength equivalent to that of the base metal. Therefore, it was clearly necessary that welding should be performed after the mill scale had been removed by, e.g. machining the weld interface/faying surfaces at the work site and this then becomes a welding requirement.

On the basis of the above results, when low carbon steel was friction stud welded with the limiting condition of a low thrust load, it was found that as follows: a sound joint which showed base metal fracture even when welded with the same friction stud welding condition requirements for a solid stud \[4\] could be obtained simply by making a shallow hole at the centre of the weld faying surface on the stud side, i.e. by making a section into a cylinder. By the way, since the results show that this cylinder section disappeared during welding and the bottom of the hole was completely welded, it seems evident that the weld faying surface area increased to be greater when the bottom of the hole was in a welded state than immediately after the weld faying surfaces came into contact. Thus, when the cylinder section disappeared, the joint was welded at a friction pressure/forge pressure lower than the friction pressure that was applied. Additionally, it was found in the case of mild steel, it was possible to fabricate sound joints even under conditions whereby the forge pressure was lower than the friction pressure.

4. Conclusion

In order to investigate whether it is possible to easily fabricate friction stud joints of low carbon steel (JIS SS400) under the limiting condition of low thrust load, the joint was made with hollow cylindrical studs at the weld faying surface on the stud side, in the present study.

Then, the relationship between joint strength and friction time was examined, the cylindrical stud shape with which it was possible to fabricate sound joints under low thrust load conditions was investigated and also the welding requirements for on-site work were examined. The findings thus obtained were as follows.

1. It was possible to make stud joints using a cylindrical stud in which a hole is formed in the centre of the weld interface surface on the stud side.
2. In order to obtain a good joint with a tensile strength equivalent to the base metal and without cracks in the weld interface after tensile tests, when the cylinder section had an internal diameter of \(\phi 6.0\)mm and a depth of 20.0mm, welding must be performed as following condition: the appropriate friction time after the friction torque has reached initial peak torque is within the range 0.5~1.0s.
3. When the diameter of the cylinder section was \(\phi 6.0\)mm and the hole depth was varied under the same friction stud welding conditions as for solid studs, a good joint was obtained with a tensile strength equivalent to that of the base metal when the cylinder section depth was 0.5~1.0mm.
4. When welding was performed with the depth of the cylinder section being 0.5mm and the internal diameter varied, it was not possible to obtain a good joint under the same friction stud welding conditions as for a solid stud even if the internal diameter was increased to be greater than \(\phi 6.0\)mm.
5. When joints fabricated under the same friction stud welding conditions as for a solid stud with no cylinder section, that had the flash expelled from the initial weld interface, were subjected to tensile testing, all joints fractured in the base metal when the internal diameter of the cylinder section was \(\phi 6.0\)mm and the depth 0.5mm.
6. When impact bending tests were performed on the joints having the flash expelled from the initial weld interface, all of the joints had a bend angle of at least 15°.
7. When fatigue tests were performed on the joints having the flash that expelled from the initial weld interface, the joints had a fatigue strength at least equivalent to that of the base metal.
8. When welding was performed with the mill scale remaining on the weld faying surface on the work side and a cylindrical stud, good joints were not obtained even under the same friction stud welding conditions as for solid studs. Accordingly, it was found to be necessary to perform welding after the mill scale had been removed from the steel surfaces.
9. Sound joints were obtained even under the same friction stud welding conditions as for solid studs when a shallow hole was formed at the centre of the weld faying surface on the stud side and in this study it was possible to reduce the load thrust by approximately 25%.

Acknowledgements

We thank Mr. Hiroshi Taniguchi in President of TRUST, Inc. and Mr. Takumi Kawakami in President of Kawakami Seisakusho Ltd. for their assistance in the study. We also thank the staff members of the Machine and Workshop Engineering at the Graduate School of Engineering, University of Hyogo. Additionally, we wish to thank the alumnus Mr. Rui Takahashi at the University of Hyogo for his devoted contributions to this research project.

References

[1] Association of Stud Welding, Japan. Guide of stud welding construction for weld technician. Tokyo, Japan: Association of Stud Welding; 2012.
[2] Nishikawa W. The principal and application field of stud welding. J Jpn Weld Soc. 2002;71(8):575–580.
[3] Nakaseko Y, Sakai T, Suzuki J, et al. Reducing the defects of joints welded in the horizontal position using a large diameter steel stud. Q J Jpn Weld Soc. 2017;35(2):57–62.
[4] Kimura M, Kusaka M, Kaizu K. Joint strength of low carbon steel joints and its selection guide of friction welding conditions for low force requirements made by friction stud welding method. Q J Jpn Weld Soc. 2018;36(2):135–144.
[5] European Aluminium Association. EAA aluminium automotive manual– joining 7. Solid state welding; 2015.
[6] Fukunaga K. Friction spot joining (FSJ) robot technology. J Jpn Weld Soc. 2016;85(7):652–656.
[7] Kimura M, Fuji T, Utsumi D, et al. Development of autocompleting friction welding method. Sci Technol Weld Joining. 2008;13(2):184–191.
[8] Kimura M, Kusaka M, Seo K, et al. Relationship between the friction time, friction torque, and joint properties of friction welding for the low heat input friction welding method –study of joining mechanism of friction welding (report 3)–. Q J Jpn Weld Soc. 2002;20(4):559–565.
[9] Kimura M, Kusaka M, Kaizu K. Effect of friction welding condition on joint properties of austenitic stainless steel joints by friction stud welding. Q J Jpn Weld Soc. 2016;34(2):102–111.
[10] Okita K, Aritoshi M, Kishimoto W, et al. Study on the friction welding of different diameter bars (report 1) –effect of relative difference of bar diameter on the friction welding phenomenon. J Jpn Weld Soc. 1981;50(2):189–195.
[11] Fukakusa K. On real rotational contact plane in friction welding of different diameter materials and dissimilar materials –fundamental study of friction welding. Q J Jpn Weld Soc. 1996;14(3):483–488.
[12] Shinoda T, Takegami H. Friction stud welding of small diameter aluminum alloy for automobile use. Proceedings of International Symposium on Joining Technologies in Advanced Automobile Assembly; 2005. p. 27–35.
[13] Masuda T, Takada Y, Miyachi S, et al. A consideration of relationship between stud diameter and steel plate thickness. Kawada Tech Rep. 2005;24:14–19.
[14] Japan Society of Steel Construction. Fatigue design recommendations for steel structures. Tokyo: Gihodo shuppan; 2012. p. 31–35.
[15] Nakayama H, Ohhira K, Okita K, et al. Fatigue strength characteristics and fractographic features of SUS 304/SUS 304 friction welded butt joint. J Soc Mater Sci Jpn. 1984;33(367):447–453.
[16] Hasegawa M. Effect of friction welding conditions on the fatigue strength of steel welded joints with flash. Q J Jpn Weld Soc. 1995;13(3):463–469.
[17] Kimura M, Kusaka M, Seo K, et al. Properties of low carbon steel joint by low heat input friction welding method. Proceedings 57th Assembly of IIW, Osaka, Japan, International Institute of Welding, Doc.III-1290-04, July 2004, 139–149.
[18] Morikawa K, Kawai G, Ochi H, et al. Strength of 2017 aluminum alloy stud joints by friction welding. J Light Metal Weld Construct Jpn. 2010;48(10):390–395.
[19] Ochi H, Morikawa K, Moritani T, et al. Strength of 5083 aluminum alloy stud joints. J Jpnse Soc Streng Frac Mater. 2013;47(1):1–6.
[20] Morimoto T. Preventive means of porosity on gas shielded arc welding. J Jpn Weld Soc. 2004;73(8):559–564.
[21] Okita K, Fukuchi Y, Aritoshi M. Fatigue crack growth behavior in friction welded butt joints of free cutting stainless steel. J Soc Mater Sci Jpn. 1989;38(432):1033–1039.