1. Introduction

Strength and toughness of steels are expected to be further increased simultaneously by refining grain size down to 1 \( \mu m \). With the steels strength-overmatching welded joints were prepared, and their mechanical properties were investigated. It is found that softening occurred in the heat-affected zone (HAZ) because of the coarsening of ferrite grains due to welding heat input. However, by using low welding heat input and strength-overmatching weld metal, the detrimental effect of softening on strength was restrained, and welded joints with strength equivalent to that of base metal were obtained. The deformability of welded joints was found to be related to the yield ratio (yield strength / tensile strength) of base metal. Low yield ratio is desirable to the deformability of welded joints. The HAZs in the welded joints of low welding heat input of 10 kJ/cm have good impact toughness for all the steels. Except for 0.14C–0.30Si–1.46Mn steel, the HAZs in the welded joints formed from the other two steels also have good impact toughness for welding heat input of 20 kJ/cm, and their fracture appearance transition temperature (\( \Delta T_{tr} \)) of the HAZs is lower than –40°C, and their Charpy impact energy at –40°C exceeds 200 J.

KEY WORDS: ultra-fine grained steel; welded joint; mechanical property; tensile property; Charpy impact test.

2. Experimental

2.1. Production of Ultra-fine Grained Steels

Three kinds of 780 MPa grade ultra-fine grained steels with different chemical composition were produced by warm rolling. The steels were characterized by ultra-fine ferrite grains (less than 1 \( \mu m \)). With the steels strength-overmatching welded joints were prepared, and their mechanical properties were investigated. It is found that softening occurred in the heat-affected zone (HAZ) because of the coarsening of ferrite grains due to welding heat input. However, by using low welding heat input and strength-overmatching weld metal, the detrimental effect of softening on strength was restrained, and welded joints with strength equivalent to that of base metal were obtained. The deformability of welded joints was found to be related to the yield ratio (yield strength / tensile strength) of base metal. Low yield ratio is desirable to the deformability of welded joints. The HAZs in the welded joints of low welding heat input of 10 kJ/cm have good impact toughness for all the steels. Except for 0.14C–0.30Si–1.46Mn steel, the HAZs in the welded joints formed from the other two steels also have good impact toughness for welding heat input of 20 kJ/cm, and their fracture appearance transition temperature (\( \Delta T_{tr} \)) of the HAZs is lower than –40°C, and their Charpy impact energy at –40°C exceeds 200 J.

KEY WORDS: ultra-fine grained steel; welded joint; mechanical property; tensile property; Charpy impact test.

1. Introduction

Strength and toughness of steels are expected to be further increased simultaneously by refining grain size down to 1 \( \mu m \). Very active researches on the development of ultra-fine grained steels are recently conducted. 1–3) 780 MPa grade steels with fine ferrite (less than 1 \( \mu m \)) and cementite particles for welded structures were successfully produced by multi-pass warm rolling with severe deformation. The mechanical behavior of parent plates was investigated elsewhere. 1) In this paper, concerns were on the mechanical properties of the welded joints formed from the developed ultra-fine grained steels. Softening in the HAZs was also discussed.

2. Experimental

2.1. Production of Ultra-fine Grained Steels

Three kinds of steel plates with chemical composition listed in Table 1 were produced. The chemical composition of steel D is similar to that of hot-rolled steel JIS grade SM490. The carbon content of steels E and F is low, which is preferable for preventing cold cracking. The \( P_{eq} \) (welding crack sensitivity) values of steels E and F are lower than 0.2, which means that they are so-called crack free steels, i.e., pre- or post-heating is not needed to prevent cold weld cracking in the heat-affected zones. 4,5) Equivalent carbon contents (\( C_{eq} \)) are also given in Table 1, which shows that steel D has the highest \( C_{eq} \) among the three steels.

The producing processes for the three steel plates are shown in Fig. 1. The processes are characterized by a warm rolling with multi-pass bi-axial reduction for obtaining uniform ultra-fine grained structures. Slabs with a cross-section of 180 mm in thickness and 120 mm in width were heated in the furnace for 1 h, respectively, at 1 100°C for steels D and E, and 1 200°C for steel F , and then water quenched. The slabs were rolled 26 passes at 500°C, and were rapidly cooled down to room temperature. The thickness (\( t \)) was reduced from 180 to 90 mm. The slabs were rotated 90°, and their thickness was prepared to 120 mm. The rotated slabs were rolled 37 passes again at 500°C, and followed by accelerated cooling. The final sizes of the steel plates were 16 mm in thickness and 100 mm in width.

| Table 1. Chemical composition of steels examined (mass%). |
|---|
| \( \% \) | C | Si | Mn | P | S | Cu | Al | N | Nb | Ti | \( C_{eq} \) | \( P_{eq} \) |
| D | 0.140 | 0.30 | 1.46 | 0.005 | 0.001 | 0.032 | 0.0013 | 0.442 | 0.223 |
| E | 0.095 | 0.30 | 1.45 | 0.005 | 0.001 | 0.032 | 0.0015 | 0.395 | 0.178 |
| F | 0.093 | 0.30 | 1.45 | 0.005 | 0.001 | 0.033 | 0.0018 | 0.016 | 0.007 | 0.393 | 0.176 |

\( P_{eq} \) = \( 0.4(C) + 0.2(Mn) + 0.15(Si) + 0.15(Al) + 0.05(Nb) + 0.05(Ti) \)

\( C_{eq} \) = \( C + \frac{(Nbr+\sqrt{(C)+(Cr+Mo+V+5Ni+0.5Nb)})}{15} \)
For improving the tensile properties, steel plates were annealed at 470°C for steels D and E, and 530°C for steel F for 1 h.

2.2. Preparation of Welded Joints

Welded joints were prepared from steels D, E and F by MAG welding with the welding conditions given in Table 2. The welding groove is X-type with the dimensions shown in Fig. 3. The two sides of the X-type groove were, respectively, welded by one pass without gouging and pre-/post-heating. Welding wires of 980 MPa grade produced by Kobe Steel were used to intend to obtain strength over-matching welded joints (i.e., the welded joints in which the strength of weld metal is larger than that of base metal). The details about the welding wire are listed in Table 2. The weld bead is normal to the rolling direction of base metal. Welding heat input was calculated to three digits in this work, which shows that the welded joints have the order of about 10 kJ/cm and 20 kJ/cm. The welded joints formed from steels D, E and F were, respectively, denoted as JD1, JE1 and JF1 for the heat input of 10 kJ/cm, and JD2, JE2 and JF2 for the heat input of 20 kJ/cm.

2.3. Preparation of Specimens

Round tensile specimens of 8 mm in diameter and 40 mm in length of parallel part, and Charpy impact specimens of 10 mm (t)×10 mm (W)×55 mm (L) were prepared from steel plates D, E and F. The longitudinal direction of specimens is parallel to the rolling direction.

Plate type tensile specimens for welded joints were prepared as shown in Fig. 2. The gage length is 240 mm, and the thickness is the initial thickness of parent steel plates (~16 mm). To measure local deformation in tensile specimens, 13 measuring points were punched uniformly along the gage length in a welded joint (see Fig. 2). The interval between two neighboring points is 20 mm. Charpy impact specimens for the heat-affected zone (HAZ) were also prepared. The notch location is as shown in Fig. 3. Because of the inclined HAZ, ~50% weld metal is involved in addition to HAZ.

2.4. Experimental Methods

Tensile tests were conducted at a crosshead speed of 0.4 mm/min and at room temperature for base metal and welded joints. Charpy impact tests were carried out for base metal and HAZ at several temperatures (from room to low temperature). Hardness distributions in welded joints were measured at a load of 500 gf. Microstructure of base metal and HAZ was examined by scanning electron microscopy (SEM).

3. Results and Discussion

3.1. Base Metal

3.1.1. Microstructure

Figure 4 shows the SEM micrographs of steel plates D–F on transverse sections. The microstructures of the
three steels consist of ferrite and cementite particles. The average ferrite grain size is less than 1 μm. The distribution of cementite particles can be recognized to be nearly uniform.

3.1.2. Mechanical Properties

Mechanical properties of steel plates D, E and F are given in Table 3. The tensile strength of steel plates D and E did not attain 780 MPa while steel plate F exceeded, which indicates that adding a small amount of Nb and Ti is effective to increase the tensile strength (see Table 1). The yield ratio of steel F is highest among the three steels.

Stress versus elongation curves in tensile tests are shown in Fig. 5. Except for high yield ratio, steel plates D–F have good combination of strength and elongation. The uniform elongation exceeds 7% for the three steels.

The results of Charpy impact tests are summarized in Fig. 6. Shear area fraction is ~80% even at −150°C, and the fracture surfaces are fully ductile at −40°C. Figure 7 gives the fractographs of impact specimens of steel plate F. It can be seen that a great quantity of secondary cracks (denoted as “separation”) are present on the fracture surfaces. Separations are also present in steel plates D and E. The separations were caused by texture structure formed in warm-rolling process with severe deformation. The occurrence of separation decreases the absorbed energy of the three steels.
3.2. Welded Joint

3.2.1. Softening in HAZs

The configurations of the welded joints of steel F for heat input 20 kJ/cm and 10 kJ/cm are, respectively, shown in Figs. 8(a) and 8(b). The hardness distributions in the welded joints of 10 kJ/cm or 20 kJ/cm at 1/2\(t\) and 1/4\(t\) (\(t\): thickness) are shown in Figs. 9 and 10, respectively. J\(_{D1}\)–J\(_{F1}\) and J\(_{D2}\)–J\(_{F2}\) correspond with 10 kJ/cm and 20 kJ/cm, respectively. Figures 9 and 10 show that the strength of weld metal is larger than that of base metal. This indicates that all the welded joints are so-called “strength over-matching welded joints”. However, the difference in strength between weld metal and base metal for heat-input 10 kJ/cm differs from that for 20 kJ/cm. Figures 9 and 10 show that the extent of strength mismatch in the welded joints of 10 kJ/cm is severer than that in the welded joints of 20 kJ/cm. Take steel F as an example, the hardness ratio of J\(_{F1}\) (Hv of weld metal/Hv of base metal) is \(\sim 1.4\) while the hardness ratio of J\(_{F2}\) is \(\sim 1.2\).

It is seen from Figs. 9 and 10 that softening occurs in the HAZs of all the steels tested. The width of softened region for 20 kJ/cm is obviously larger than that for 10 kJ/cm. The decrease in hardness in the HAZ increases with heat input. The most softened region in the HAZ was examined by SEM. SEM micrographs of the most softened regions of steel plate F are shown in Fig. 11. By comparing Fig. 11 with Fig. 4, it is seen that ferrite grains have grown significantly due to the welding heat input. Softening in the HAZ is attributed to the coarsening of ferrite grains.

3.2.2. Strength of Welded Joint

A welded joint is composed of base metal, heat-affected zone and weld metal. Because of different microstructure, mechanical properties in the three regions are different. The strength of welded joint is, therefore, generally determined by the three parts. It has been shown that the tensile strength of welded joints with strength discontinuity depends on the specimen size, and the specimen width \(W\) should be as wide as possible to avoid the size effect. The strength of welded joint is recognized to be independent of specimen size if \(W\) is larger than 5\(t\) (\(t\): specimen thickness).
In this work, the width of the parallel part was maximally taken as 60 mm because of the size limitation of parent steel plates (see Fig. 2). 0.2% proof stress is defined as the apparent yield strength of welded joint. The results of tensile tests are listed in Table 4.

The presence of softened regions in the HAZ will decrease the strength of welded joint. However, previous work has shown that this detrimental effect can be restrained to some extent by using weld metal with high strength (larger than that of base metal) for the welded joints of ultra-fine grained steels. The HAZ has the lowest strength in the three welded joints for the same heat-input. This indicates that the strength of welded joints formed from the developed ultra-fine grained steels can be improved by using strength over-matching welded joints. Significant differences in failure elongation between 10 kJ/cm and 20 kJ/cm welded joints are found. The ductility of welded joints decreases with heat input.

Table 4. Tensile results for welded joints.

| Joint No. | Heat Input (kJ/cm) | Proof Stress (MPa) | Apparent Yield Stress (MPa) | Tensile Strength (MPa) | Failure Elongation (%) | BM Tensile (MPa) | TR |
|-----------|--------------------|--------------------|---------------------------|-----------------------|------------------------|-----------------|----|
| J101      | D                  | 737                | 745                       | 11.4                  | 751                    | 0.992           |
| J101      | 10                 | E                  | 699                       | 704                   | 9.6                    | 705             | 0.999 |
| J101      | F                  | 770                | 777                       | 8.3                   | 787                    | 0.987           |
| J101      | 20                 | E                  | 671                       | 692                   | 10.3                   | 751             | 0.999 |
| J101      | F                  | 744                | 767                       | 4.2                   | 787                    | 0.975           |

Note: H, heat input; PS, parent steel; AYS, apparent yield strength; TS, tensile strength; FE, failure elongation; BM TS, TS of base metal; TR, TS/BM TS

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3.2.3. Deformability of Welded Joint

Weld metal and HAZ are the regions in which defects are most likely present. If deformation concentrates in these regions, it is harmful to the security of welded structures. Therefore, deformation is expected taking place over the whole region, not in weld metal or HAZ merely.

Local deformation in tensile specimens was investigated in this study, and the local elongations between two neighboring measuring points uniformly distributed along the gage length of tensile specimens (see Fig. 2) are shown in Figs. 12 and 13. The heat inputs of Figs. 12 and 13 are, respectively, 10 kJ/cm and 20 kJ/cm. The tensile specimen is divided into twelve uniform local regions by the 13 measuring points within the gage length. The abscissas in Figs. 12 and 13 represent the number of the 12 local regions. It is seen that the deformability of base metal away from the HAZ in the three welded joints for the same heat-input is different. The base metal in J101 has good deformability. The effect of YR of base metal on the deformability of welded joint obtained coincides with the results of Ref. 7. Steel D has the lowest yield ratio among those of heat input 20 kJ/cm except steel plate D. The values of TR (tensile strength of welded joint/tensile strength of base metal) in Table 4 shows that the welded joints of heat input 10 kJ/cm have higher apparent yield and tensile strength than those of heat input 20 kJ/cm except steel plate D. The values of TR (tensile strength of welded joint/tensile strength of base metal) in Table 4 indicates that the strength of welded joint almost attains that of base metal despite of heat input. This indicates that the strength of welded joints formed from the developed ultra-fine grained steels can be improved by using strength over-matching welded joints. Significant differences in failure elongation between 10 kJ/cm and 20 kJ/cm welded joints are found. The ductility of welded joints decreases with heat input.

Fracture morphologies of tensile specimens are also shown in Figs. 12 and 13. It is noticed that failure positions...
are different in the welded joints of 10 kJ/cm and 20 kJ/cm. Fracture occurred from base metal in the welded joints of 10 kJ/cm while the welded joints of 20 kJ/cm failed in the HAZ. The HAZs in the welded joints tested have the lowest strengths, failure therefore takes place most easily from them. However, because the HAZ is constrained from the neighboring high strength base metal and weld metal, the strength of HAZ is increased. As mentioned above section, the constraint in the welded joints of 10 kJ/cm is much stronger than that in the welded joints of 20 kJ/cm. As a result of different constraint extent, failure occurred in different positions, respectively, in the welded joints of 10 kJ/cm and 20 kJ/cm. For the welded joints in which failures take place in the HAZs, deformation is furthermore not expected concentrated in the HAZ, and sufficient deformation in base metal prior to fracture is expected. It can be seen, therefore, that low YR is very important for these types of welded joints.

### 3.2.4. Impact Behavior of HAZ

The results of Charpy impact tests on the HAZs of the welded joints of 10 kJ/cm and 20 kJ/cm are given in Figs. 15 and 16, respectively. Comparing with base metal, upper shelf energy of the HAZs is very high because separation disappeared in the HAZs owing to the effect of welding heat. Comparison between Fig. 15 and Fig. 16 indicates that the effect of heat input only appears in steel D. Fracture appearance transition temperature, $T_{trs}$, of the HAZs is lower than $-40^\circ C$ except $J_{D2}$. Except for $J_{D2}$, the values of absorbed energy at $-40^\circ C$ exceed 200 J, which is enough for general steel structures.

In the welded joints tested, only $J_{D2}$ has low toughness. To reveal the reason for this result, weld bond microstructure that is usually recognized as the weakest in toughness in the HAZ was simulated. Welding thermal cycle of weld
bond of heat input 20 kJ/cm was experimentally measured with welding current 369 A, welding voltage 30.2 V and welding speed 33 cm/min. The experimental result is shown in Fig. 17. The cooling time, $t_{8/5}$, from 800 to 500°C is 19.4 s. By simulating the welding thermal cycle given in Fig. 17 with ultrafine grained steel bars with the same chemical compositions as steels D and E, simulated weld bond microstructures of steels D and E of heat input 20 kJ/cm were obtained. Charpy impact tests on simulated specimens were conducted, and the experimental results are given in Fig. 18. It is known from Fig. 18 that the $T_{bs}$ of steel D is 60°C while the $T_{bs}$ of steel E is $-9°C$, which indicates that the toughness of the bond of steel D is extremely low. The weld bonds of both steel D and steel E are composed of bainite. Significant difference in microstructure between the bonds of steel D and steel E should be attributed to the difference in equivalent carbon content (see Table 1). The presence of weld bond region with extremely poor toughness leads to low toughness of $f_{U}$. 

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4. Conclusions

The mechanical properties of the welded joints formed from three developed ultra-fine grained steels were investigated. The following conclusions were obtained.

(1) Combination of low welding heat input (10 kJ/cm or 20 kJ/cm) and strength overmatching weld metal enables the welded joints to have strength equivalent to that of base metal despite the presence of softened regions. If the softened heat-affected zone is constrained sufficiently from base metal and weld metal, failure occurs in base metal not in the heat-affected zone.

(2) Deformability of the welded joints depends on the yield ratio of base metal. Low yield ratio is desirable to the deformability of welded joints.

(3) The heat-affected zones of the 0.1% C ultra-fine grained steels have good toughness. Their fracture appearance transition temperature ($T_{pa}$) is lower than $-40^\circ$C, and their Charpy impact energy at $-40^\circ$C is larger than 200 J.

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