Estimation and Prediction of HAZ Softening in Thermomechanically Controlled-Rolled and Accelerated-Cooled Steel

Investigations were made into HAZ hardness and tensile strength in welds made with different heat inputs in fine-grained, ferritic-pearlitic TMCP steel

K.-S. BANG and W.-Y. KIM

ABSTRACT. In order to evaluate the degree of HAZ softening in fine-grained ferritic-pearlitic steel manufactured by TMCP, variations of HAZ microhardness and tensile strength with different heat inputs were investigated. The degree of softening was also predicted using an established microstructural evolutional model and a rule of mixtures. All specimens welded with higher than 1 kJ/mm heat input showed a softened zone that had a lower hardness than that of the base metal. Even though softened zone width increased continuously to 10 kJ/mm, the minimum hardness in a softened zone decreased slightly after a rapid decrease of up to 6 kJ/mm. Due to the softening effect, welded-joint tensile specimens were broken at the HAZ instead of the base metal. The reduction in tensile strength was similar to that for hardness and showed a maximum of 20% at 6 kJ/mm heat input. The degree of HAZ softening calculated with a modified microstructural evolution model and a rule of mixtures showed reasonably good agreement with a measured one.

Introduction

It is well known steel strength and toughness increases with the refinement of grain size. As shown in Fig. 1, extrapolation of experimental results obtained so far indicates the yield strength and fracture appearance transition temperature (FATT) of steel can reach about 800 MPa and –300°C, respectively, if its grain size is refined to 1 μm (Ref. 1). This effect results in advantages in welding high-strength steel if the reduction in strength and toughness in the heat-affected zone (HAZ) is prevented or minimized, as discussed below. In general, since high-strength steel has a relatively high carbon content and various alloying elements such as Cu, Ni, Cr, Mo, etc., to ensure its strength, it has a tendency to form hard and brittle microstructural constituents in the HAZ. Therefore, the steel has to be preheated before welding to eliminate the risk of hydrogen-assisted cracking. However, if the steel is strengthened only by the refinement of its grain size, it can be welded without preheating because of its low content of carbon and other alloying elements.

Several endeavors have been made to achieve such fine grain size. One of the most widely used techniques to refine ferrite grain size is a thermomechanically controlled-rolling and accelerated-cooling process (TMCP). The finest ferrite grain size currently obtainable by TMCP is limited to about 5 μm, as shown in Fig. 1. However, if ferrite nucleated at the grain boundaries during cooling have different orientations, they could grow without coalescence and result in an even finer microstructure. From this viewpoint, VN precipitates at the grain boundaries are being studied extensively because of the potency of nucleating ferrite with random orientations (Ref. 2). A multiaxial deformation technique has also been considered for refining steel grain size (Ref. 3). This technique is expected to introduce extra slip systems in addition to a primary slip system in a FCC crystal structure, {110}<111>, thus giving high strains in austenite grains during rolling.

One anticipated problem in welding such fine-grained steel is the reduction of HAZ strength and toughness. As the fine microstructure is lost during the weld thermal cycle, HAZ strength and toughness are expected to decrease to below that of the base metal. Therefore, it is desirable to weld it with low-heat-input welding processes such as laser beam and narrow-gap welding (Ref. 4). As it has been reported titanium oxide is very stable at high temperatures and, thus, effectively inhibits grain growth and heterogeneously nucleates ferrite in the HAZ, dispersion of fine titanium oxides in the steel has also been considered (Ref. 1). No matter which process is used, to use fine-grained steel safely in welded structures, it is important to know the degree of reduction in HAZ strength and toughness.

The objective of this study was to estimate the degree of HAZ softening in fine-grained, ferritic-pearlitic steel manufactured by TMCP. The degree of HAZ softening was also predicted using an established microstructural evolutional model and a rule of mixtures.

KEY WORDS

HAZ Softening
Hardness
TMCP Steel
Grain Size
Gas Metal Arc Welding
GMAW
Welded-Joint Tensile Test
Microstructural Evolution Model

Materials and Experimental Procedures

A fine ferritic-pearlitic microstructure with a small amount of bainite was obtained by the TMCP of carbon-manganese steel with a composition of 0.14% C-0.25% Si-1.10% Mn. After soaking a 50-mm-thick, vacuum-melted ingot for 1 h at 1100°C, its thickness was reduced to 25 mm by rolling at 950°C, and then reduced to a final thickness of 5 mm at 750°C. The accelerated cooling rate after

K.-S. BANG and W.-Y. KIM are with the Division of Materials Science and Engineering, Pukyong National University, Pusan, Korea.

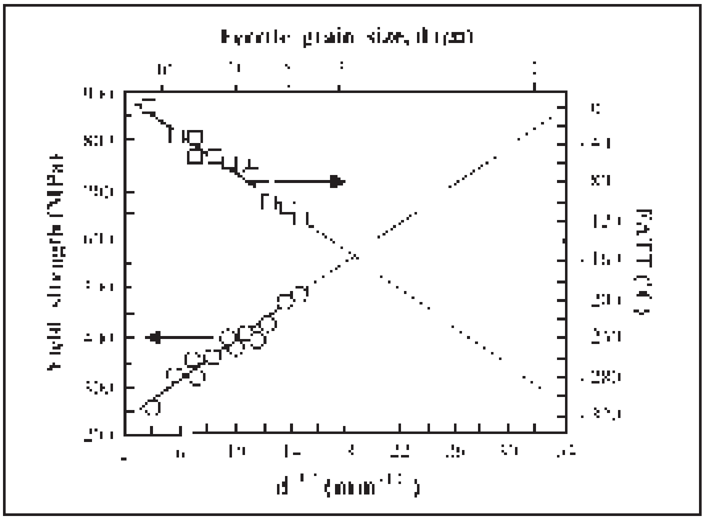

Fig. 1 — Variations in the yield strength and fracture appearance transition temperature (FATT) of steel as a function of ferrite grain size.

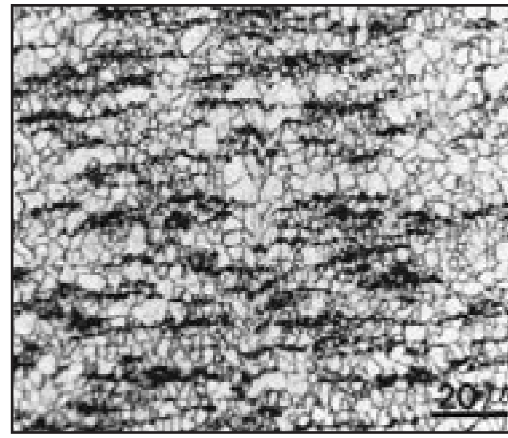

Fig. 2 — Optical microstructure of the experimental steel.

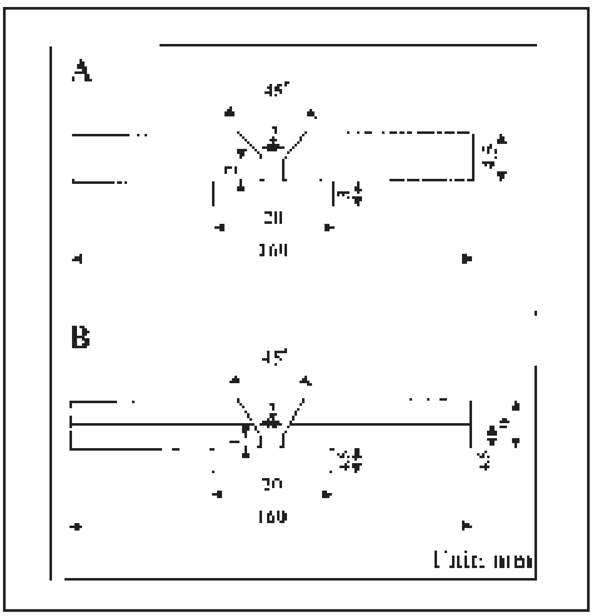

Fig. 3 — Plate preparation and joint configuration of welded joints. A — 2 kJ/mm heat input; B — 4 kJ/mm heat input.

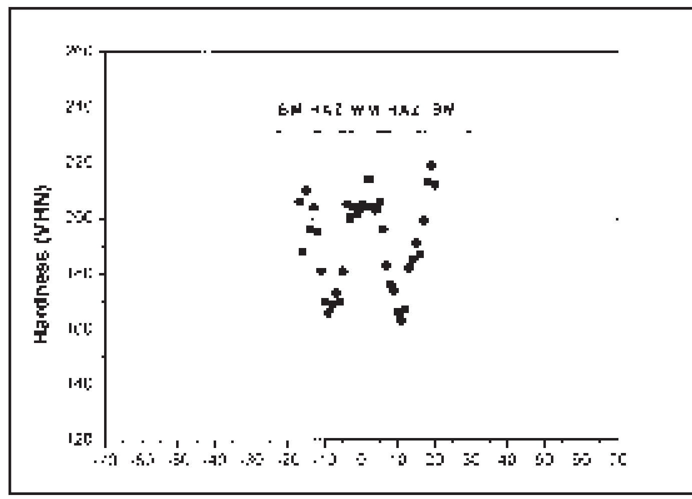

Fig. 4 — Microhardness distribution of a welded joint with 2 kJ/mm heat input.

finish rolling was 10°C/s. The ferrite grain size obtained by the process was about 4 μm (Fig. 2), which is much smaller than that of conventionally rolled steel, namely 10~20 μm. The tensile strength, yield strength, elongation (GL = 25 mm), and hardness of the steel obtained were 630 MPa, 480 MPa, 18%, and 200 VHN, respectively.

Single-pass gas metal arc welding (GMAW) using ER80S-G welding wire and CO_2 as the shielding gas was performed with heat input varying between 1 and 10 kJ/mm. While only one plate was used to weld at a heat input of 1 and 2 kJ/mm, two plates were used to weld at heat inputs from 4 to 10 kJ/mm to prevent excessive melt-through. Joint configurations for the welds made at 2 and 4 kJ/mm heat input are shown in Fig. 3.

After welding was completed, hardness and tensile test specimens were taken from the mid-thickness of the single plates. When two plates were used, specimens were taken from the mid-thickness of a lower plate. Microhardness distributions across the base metal, HAZ, and fusion zone were measured on a transverse section using a diamond pyramid indenter with a 1-kg load. Tensile specimens with a gauge length of 50 mm and a thickness of 3 mm were tested at room temperature. Synthetic HAZs were produced using an induction heating weld thermal cycle simulator to investigate the effect of cooling time on HAZ microstructural evolution. Peak temperature (T_p) of the thermal cycle was 1350°C. Cooling times at 800 to 500°C (Δt) varied from 5 to 40 s. Thermal cycle specimens were 5 x 3 mm Φ cylinders. After the thermal cycle, volume fractions of various microstructural constituents were measured from more than 1000 points using a light microscope at 500X. Classified microstructural constituents were martensite, bainite, and ferrite/pearlite.

Results and Discussion

Estimation of HAZ Softening

Measurement of microhardness distribution showed all specimens had a softened zone with a lower hardness than that of the base metal. Figure 4 shows a typical microhardness distribution of a weldment

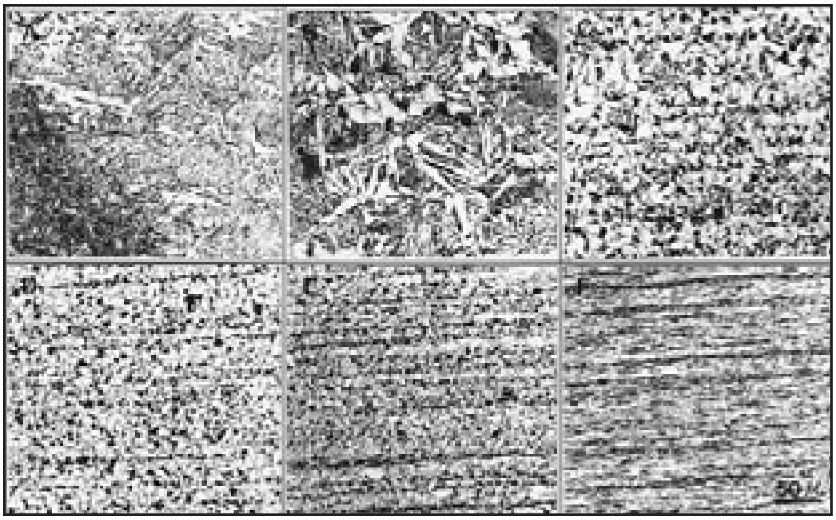

Fig. 5 — Optical microstructures at the different locations in a welded joint with 2 kJ/mm heat input. The following are distances from the fusion boundary: A — fusion boundary; B — 1 mm; C — 3 mm; D — 5 mm; E — 6 mm; F — 8 mm.

welded with 2 kJ/mm heat input. After showing a relatively constant hardness of 205 VHN in the weld metal, hardness decreased continuously to a minimum value of about 165 VHN, then increased again to 200 VHN in the base metal. The width of the softened zone extended 8~10 mm in this welding condition. Figure 5 shows the microstructures at different locations in the HAZ. With increased distance from the fusion boundary, the amount of bainite decreased and only ferrite/pearlite is shown at 5 mm from the fusion boundary, where the minimum hardness was obtained. Ferrite grain size at that location, however, is larger than that of the base metal and shows about 6 μm. With a further increase in distance, ferrite grain size became smaller and the base metal microstructure is shown at 8 mm. These variations in microhardness can be explained with the microstructural observation.

Variations in softened zone width as a function of heat input are shown in Fig. 6. After showing 6~8 mm at 1 kJ/mm, the width increased continuously with an increase in heat input and reached 23~24 mm at 10 kJ/mm. However, the variation of minimum hardness in the HAZ was different from that of the softened zone width. It decreased slightly after a rapid decrease to 153~160 VHN at 6 kJ/mm — Fig. 7. Observations showed all except one specimen that was welded with 1 kJ/mm heat input had only a ferrite/pearlite microstructure at the location of minimum hardness, but ferrite grain size was different at each heat input. It grew with increased heat input and showed about 6.8 μm at 6 kJ/mm and then grew a little more with an increase in heat input. Therefore, it can be seen that even though the width of the softened zone increased continuously up to 10 kJ/mm in this experiment, the degree of softening in the HAZ is almost saturated at 80% at 6 kJ/mm.

In general, a welded structure is designed for fracture to occur in the base metal. If, however, severe HAZ softening occurred after welding, fracture would occur in the HAZ instead of the base metal. Tensile tests were carried out to confirm the softening effect. After machining tensile test specimens, the location of the HAZ in each specimen was identified through macroetching and microhardness measurements and then indicated on the specimen. The tests showed all specimens broke at the HAZ except one welded with 10 kJ/mm heat input. Figure 8 shows typical broken specimens. Tensile specimens welded with 10 kJ/mm were broken in the weld metal; their weld metal hardness was as low as 140 VHN due to the high heat input. As this was lower than the minimum hardness of the softened HAZ (150~158 VHN, as shown in Fig. 7), fracture occurred in the weld metal instead of the softened HAZ. Figure 9 shows the variations in measured welded-joint tensile strength as a function of heat input. After having shown 564~568 MPa at 1 kJ/mm, it decreased continuously with increased heat input up to 6 kJ/mm and then changed little. This trend was similar to that of the minimum hardness shown in Fig. 7. It can be seen again that the maximum degree of softening in terms of tensile strength was also about 20%. According to Ito's works (Refs. 5–7),

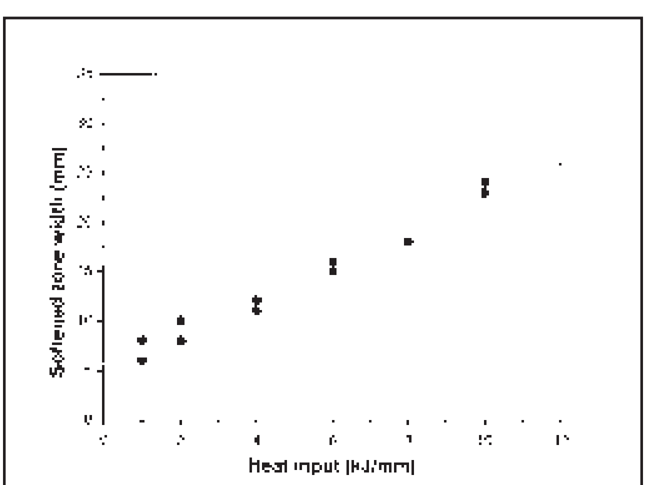

Fig. 6 — Variations in softened zone width as a function of heat input.

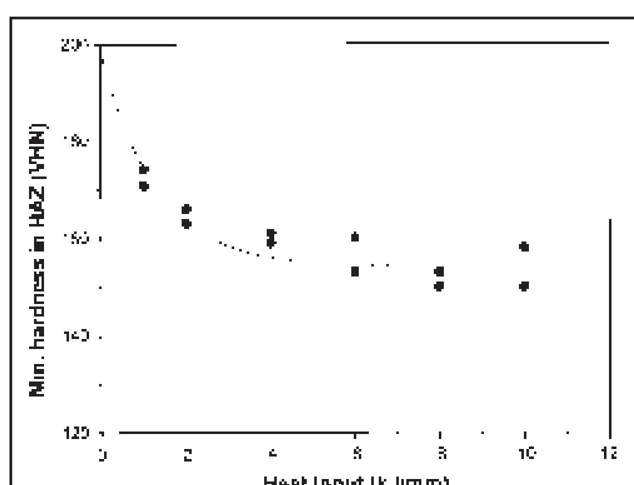

Fig. 7 — Variations in minimum HAZ hardness as a function of heat input.

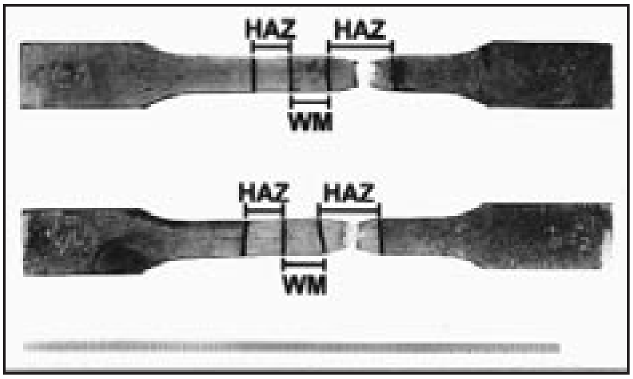

Fig. 8 — Typical fracture appearance of tensile specimens broken in the weld HAZ.

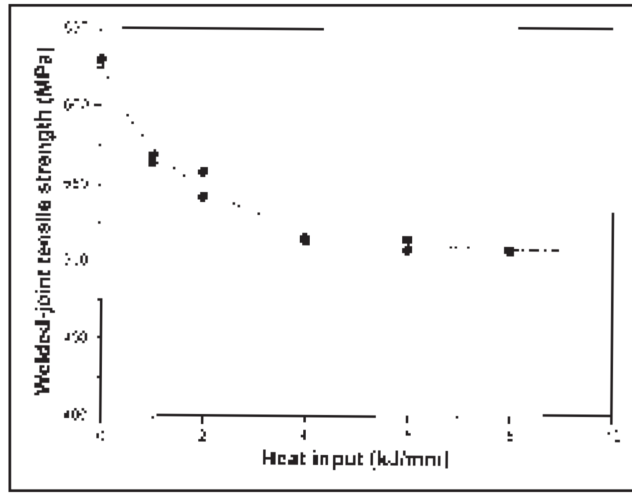

Fig. 9 — Variations in tensile strength of the weld joint as a function of heat input.

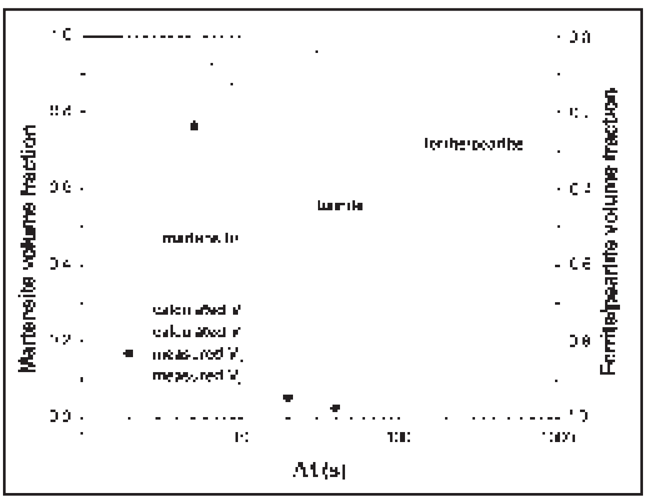

Fig. 10 — Variation of calculated and measured volume fractions of microstructural constituents in the HAZ with Δt (peak temperature 1350°C.)

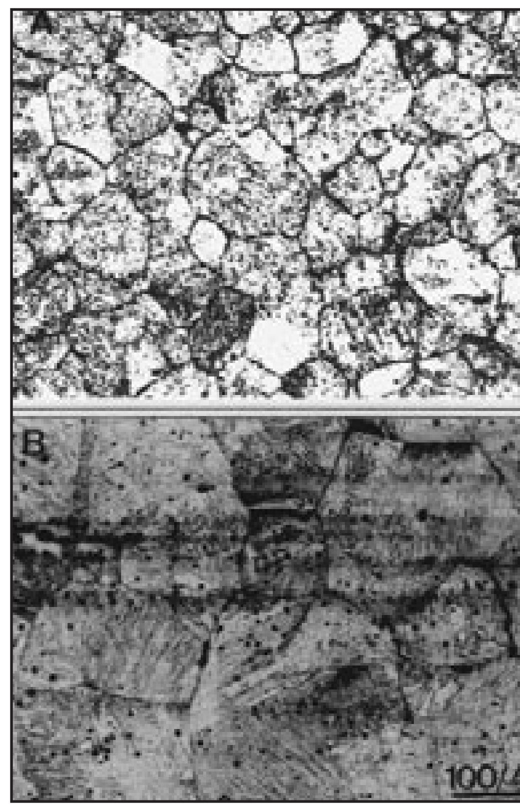

Fig. 11 — Typical optical microstructures of steel quenched at 1350°C. A — Experimental steel; B — conventionally rolled steel.

strength of a welded joint with a softened HAZ can increase up to the base metal value because of the constraints of plastic deformation on the softened HAZ by a hard base metal if the thickness and/or width of the tensile specimen is large enough compared to the softened zone width. The reason why the effect of plastic deformation constraints on the softened HAZ is not seen in this experiment is believed to be because the tensile specimen's thickness was small, 3 mm, compared to the softened zone's width of 6~24 mm. In fact, this was confirmed by the theoretical considerations reported elsewhere (Ref. 8).

Prediction of the Degree of HAZ Softening

If the effect of plastic deformation constraint is not expected in a welded structure, it is important to predict how much of the HAZ is softened during welding. The degree of HAZ softening was calculated and compared with a measured one. After predicting volume fractions of microstructural constituents in the HAZ using an established microstructural evolution model, HAZ hardness was calculated using a rule of mixtures. J. Ion, *et al.* (Refs. 9, 10), modeled HAZ microstructural evolution after analyzing continuous cooling transformation (CCT) diagrams for a wide range of conventionally rolled structural steels. This study showed the model could be used for fine-grained steel as well if the effect of fine grain size was considered. According to the model, the volume fractions of martensite (V_m), bainite (V_b), and ferrite/pearlite (V_{fp}) in coarse-grained HAZ (T_p 1350°C) that form during cooling time Δt are given by the following equations:

$$V_m = exp\left[-0.69\left(\frac{\Delta hr\, t}{\Delta hr\, t_{1/2}^{\;m}}\right)^2\right] \qquad (1)$$

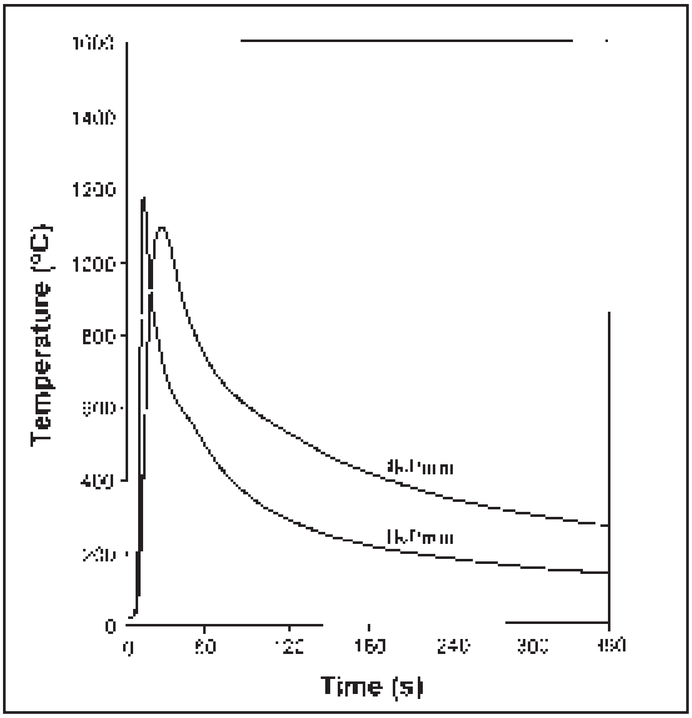

Fig. 12 — Thermal cycles measured at the location of minimum hardness when welded with 1 and 4 kJ/mm.

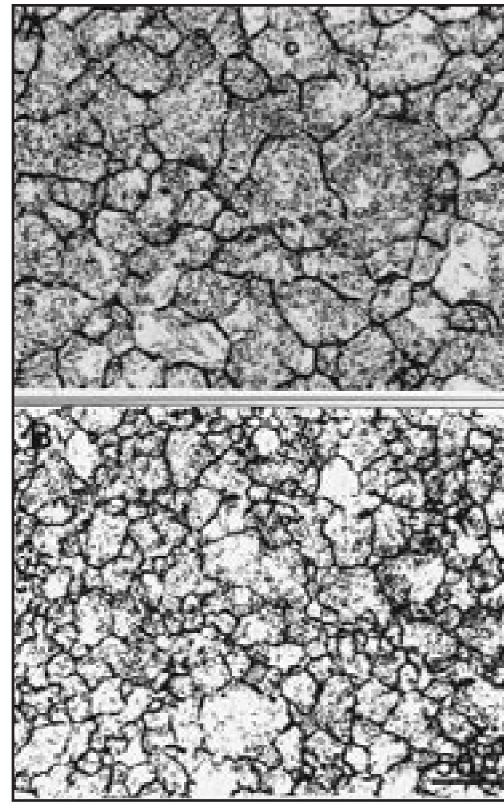

Fig. 13 — Optical microstructures quenched at different peak temperatures. A — 1150°C; B — 1100°C.

$$V_b = exp\left[-0.69\left(\frac{\Delta t}{\Delta t_{1/2}^{\ b}}\right)^2\right] - V_m \quad (2)$$

$$V_{fp} = 1 - V_m - V_b \quad (3)$$

where $\Delta t_{1/2}{}^m$ is the time required for 50% martensite/50% bainite transformation to occur and $\Delta t_{1/2}{}^b$ is the time required for 50% bainite/50% ferrite/pearlite transformation to occur. After analyzing CCT diagrams for a number of steels, they obtained empirical relationships between $\Delta t_{1/2}{}^m$ and $\Delta t_{1/2}{}^b$ and steel composition as follows:

$$log\,\Delta t_{1/2}{}^m = 8.79C_{eq} - 1.52 \quad (4)$$

$$log\,\Delta t_{1/2}{}^m = 8.84C_{eq} - 0.74 \quad (5)$$

where $\Delta t_{1/2}{}^m$ and $\Delta t_{1/2}{}^b$ have units of second and C_{eq} is calculated using the IIW formulation. $\Delta t_{1/2}{}^m$ and $\Delta t_{1/2}{}^b$ for the steel used in this experiment are 19.62 and 122.69, respectively. Figure 10 shows variations of calculated volume fractions for each microstructural constituent with Δt using the above equations. Solid and open circles in the figure represent experimentally determined values at Δt 5, 20, and 40 s. It shows the measured values are different from the calculated ones. It is believed this discrepancy is due to the fine ferrite grains of the steel used. As mentioned previously, the empirical relationships obtained by Ion, *et al*., in Equations 4 and 5 are based on conventionally rolled steels that do not have as fine grain size as 4 μm. Therefore, $\Delta t_{1/2}{}^m$ and $\Delta t_{1/2}{}^b$ for the experimental steel should be smaller than the calculated values, 19.61 and 122.69, since the hardenability is lower because of the fine grain size. To confirm the lower hardenability of experimental steel, the prior austenite grain size of the steel was measured and compared with that of conventionally rolled steel. Ferrite grain size of the conventionally rolled steel was 12 μm. Figure 11 shows the austenite grain size of both steels when quenched at 1350°C. It is clear the average grain size of the experimental steel, 86 μm, is much smaller than that of the conventionally rolled steel, 160 μm. In fact, if $\Delta t_{1/2}{}^m$ and $\Delta t_{1/2}{}^b$ of the experimental steel are corrected as only half the calculated values of conventionally rolled steel, we obtain the best agreement between measured and calculated volume fractions. This means if ferrite grain size is refined to 4 μm, phase transformation during cooling in the HAZ is accelerated to make the time required for half the transformation to occur to be only half that of conventionally rolled steel.

For calculation of volume fractions in HAZ with any T_p other than 1350°C, the transformation time was corrected as follows (Refs. 9, 10):

$$\left(\Delta t_{1/2}{}^m\right)_p = \frac{g_p}{g}\left(\Delta t_{1/2}{}^m\right) \quad (6)$$

$$\left(\Delta t_{1/2}{}^b\right)_p = \frac{g_p}{g}\left(\Delta t_{1/2}{}^b\right) \quad (7)$$

where $(\Delta t_{1/2}{}^m)_p$ and $(\Delta t_{1/2}{}^b)_p$ are the time required for half the transformation to occur in HAZ with any T_p other than 1350°C. g and g_p are austenite grain size at 1350°C and any T_p other than 1350°C, respectively. By incorporating Equations 6 and 7 into Equations 1 through 3, V_m, V_b, and V_{fp} in HAZ with any T_p and Δt can be calculated. V_m, V_b, and V_{fp} at the location of minimum hardness in the HAZ welded with 1 and 4 kJ/mm heat input were calculated first. T_p and Δt at the location of minimum hardness in each heat input were measured directly by embedding a thermocouple in the HAZ. Figure

12 shows typical measured thermal cycles; T_p and Δt at the location are about 1150°C and 30 s in 1 kJ/mm and 1100°C and 60 s in 4 kJ/mm. Austenite grain sizes at T_p of 1150°C and 1100°C were measured by gas quenching from the temperatures. They are 35 and 27 μm, respectively, as shown in Fig. 13. Using all this information, it is possible to calculate the volume fractions of each microstructural constituent. The calculated V_m, V_b, and V_{fp} are 0, 0.369, 0.631 in 1 kJ/mm and 0, 0.002, and 0.998 in 4 kJ/mm. This indicates ferrite/pearlite constituent is predominant at the location of minimum hardness when welded with 4 kJ/mm, which was confirmed by the optical microstructural observation mentioned previously. Now the hardness of the location can be calculated using a rule of mixtures:

$$H = H_m V_m + H_b V_b + H_{fp} V_{fp} \quad (8)$$

where H_m, H_b, and H_{fp} refer to Vickers hardness (VHN) of the martensite, bainite, and ferrite/pearlite microstructures, respectively. The following relationships were used for the hardness of each microstructure (Ref. 11):

$$H_m = 127+949C+27Si+11Mn +8Ni+16Cr+21logV' \quad (9)$$

$$H_b = -323+185C+330Si+153Mn +65Ni+144Cr+191Mo +(89+53C-55Si-22Mn-10Ni- -20Cr-33Mo)logV' \quad (10)$$

$$H_{fp} = 42+223C+53Si+30Mn +12.6Ni+7Cr+19Mo +(10-19Si+4Ni+8Cr+130V) logV' \quad (11)$$

where V' is the cooling rate at 700°C (K/h) and it is about 58,000 and 27,000 K/h in each heat input, as shown in Fig. 12. The final calculated hardness is 176 VHN for 1 kJ/mm and 143 VHN for 4 kJ/mm. These values are in reasonably good agreement with measured values, 171~174 for 1 kJ/mm and 159~161 VHN for 4 kJ/mm, within a 10% error. Therefore, it can be seen the degree of HAZ softening in fine-grained steel can be predicted using an established microstructural evolution model and a rule of mixtures if the time required for half the transformation to occur in the HAZ is corrected adequately.

Conclusions

In order to evaluate the degree of HAZ softening in fine-grained ferritic-pearlitic steel manufactured by TMCP, variations of HAZ microhardness and strength with heat input were investigated. The degree of softening was also predicted using an established microstructural evolutional model and a rule of mixtures. The important results obtained are as follows:

1) Even though the softened zone width increased continuously to 10 kJ/mm, the minimum hardness in the softened zone decreased slightly after a rapid decrease up to 6 kJ/mm. Due to the softening effect, welded-joint tensile specimens were broken at the HAZ instead of in the base metal. The reduction of tensile strength was similar to that of hardness and showed a maximum of 20% at 6 kJ/mm.

2) As a consequence of the acceleration of phase transformation in HAZ due to fine grain size, the time required for half the transformation of the steel to occur was only half that of conventionally rolled steel.

3) The minimum hardness in a softened zone calculated with a modified microstructural evolution model and a rule of mixtures showed reasonably good agreement with a measured one within a 10% error when welded with 1 and 4 kJ/mm heat inputs.

Acknowledgments

The authors wish to acknowledge the financial support of the Pohang Iron and Steel Co., Ltd., Pohang, Korea. They would also like to thank H.-K. Jung and S.-W. Jung for their contributions to this research.

References

1. Takahashi, T. 1997. High-strength steels aimed at research project on ultra structural steels. *Journal of the Japan Welding Society* 66(8): 601–608.

2. Ishikawa, F., and Takahashi, T. 1995. Effect of vanadium nitride precipitated at austenite grain boundary on behavior of ferrite phase transformation. *Materials and Process* 8: 1497.

3. Nemoto, M., Horita, Z., Furukawa, M., and Langdon, T. 1998. Equal-channel angular pressing: A novel tool for microstructural control. *Metals and Materials* 4(6): 1181–1190.

4. Shiga, C., Ohta, A., Hiraoka, K., and Tsukamoto, S. 1997. Welding in research project on frontier structural materials. *Journal of the Japan Welding Society* 66(8): 609–614.

5. Satoh, K., and Toyoda, M. 1970. Static strength of welded plates including soft interlayer under tension across a weld line. *Transactions of the Japan Welding Society* 9: 146–153.

6. Satoh, K., and Toyoda, M. 1971. Effect of mechanical heterogeneity on the static tensile strength of welded joint. *Quarterly Journal of the Japan Welding Society* 40(9): 885–900.

7. Satoh, K., Doi, T,. and Toyoda, M. 1968. Size effects on static tensile properties of welded joints including soft interlayer. *Quarterly Journal of the Japan Welding Society* 37(11): 1214–1226.

8. Bang, K.-S., and Jung, S.-W. 2000. Variation of welded-joint tensile strength of GMA welded accelerated-cooled steel. *Journal of the Korean Welding Society* 18(6): 83–88.

9. Ion, J. C., Easterling, K. E., and Ashby, M. F. 1984. A second report on diagrams of microstructure and hardness for heat-affected zones in welds. *Acta Metall.* 32(11): 1949–1962.

10. Ashby, M. F., and Easterling, K. E. 1982. A first report on diagrams for grain growth in welds. *Acta Metall.* 30(11): 1969-1978

11. Blondeau, R., Maynier, P., Dollet, J., and Viellard-Baron, B. 1976. *Heat Treatment '76.* London, U.K.: Metals Soc., p. 189.