Characteristics of High Temperature Tensile Properties and Residual Stresses in Weldments of High Strength Steels

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In this study, high temperature tensile properties of high strength steels, POSTEN60 and POSTEN80, whose tensile strengths were 600 and 800 MPa respectively, were investigated through the elevated temperature tensile test. Residual stress measurements were also carried out to estimate the residual stress relaxation due to phase transformation (martensite transformation) in the process of cooling after welding. A finite element (FE) model which was able to include the volumetric changes due to the austenite → martensite phase transformation was developed on the basis of the experimental results. The three-dimensional thermal elastic-plastic FE analyses using the FE model were conducted to determine residual stresses in weldments of the high strength steels.

The results show that the extents of residual stress relaxation due to the austenite → martensite phase transformation in the process of cooling after welding are approximately 0.85 σ_0/σ_y0 and 0.75 σ_0/σ_y0 in the FZ and HAZ of POSTEN60 and POSTEN80, respectively. And residual stresses of weld line direction in the base metal (BM) which is adjacent to HAZ, therefore, do not undergo martensitic transformation increase (655 MPa < 870 MPa) with increasing tensile strength of the high strength steels (POSTEN60 < POSTEN80).

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1. Introduction

As the spans of bridges are getting longer and the stories of buildings are getting higher, there are strong demands for steels with high strength. The application of high strength steels makes it possible to design not only light weight structures, but also simple structures with simple weld details. But the fabrication of structural member using high strength steels always involves welding process. And due to the localized heating during welding, complex thermal stresses are inevitably generated. Residual stresses are stresses that remain in a material as a result of liquid-to-solid phase transformation associated with weld solidification and the subsequent non-uniform cooling of the weld altered by phase transformation (martensite transformation) in the solid state. And it is well known that, especially in high strength steel weldments, the solid-state transformation on cooling of austenite to martensite could have a major influence on the relaxation of residual stresses.¹⁻⁴

Residual stresses that develop in and around the welded joint are detrimental to the integrity and the service behavior of the welded part. High tensile residual stresses in the region near the weld might promote brittle fracture, reduce the fatigue life, and promote stress corrosion cracking during service. So, it is very important to clarify the characteristics and production mechanism of residual stress. The examination of residual stress is generally performed through numerical method due to the limitation of experimental investigation as structure becomes more complex. And the mechanical property changes depending on temperatures are required for the welding simulation by numerical method.

The present research was undertaken to determine residual stresses in weldments of POSTEN60 and POSTEN80, newly developed high strength steels for the use in bridges, pressure vessels and pipelines and offshore construction, etc. High temperature tensile properties of the high strength steels were investigated through the elevated temperature tensile test. Residual stress measurements were also carried out to investigate the residual stress relaxation due to phase transformation (martensite transformation) in the process of cooling after welding. A finite element (FE) model which was able to include the volumetric changes due to the austenite → martensite phase transformation was developed on the basis of the experimental results. The model also included the mechanical property dependence on temperatures through the elevated temperature tensile test. Three-dimensional thermal elastic-plastic FE analyses using the FE model were conducted to determine residual stresses in weldments of the high strength steels.

2. High Temperature Tensile Properties of the High Strength Steels

The elevated temperature tensile tests were carried out to determine the mechanical properties of the high strength steels at elevated temperatures which were the required input to the FE code.

2.1 Test specimens

The chemical compositions of POSTEN60 and POSTEN80 are shown in Table 1. The carbon equivalents (C_eq) of the high strength steels calculated using the formula: C_eq = C + Si/24 + Mn/6 + Ni/40 + Cr/5 + Mo/4 + V/14 are 0.40 and 0.46%, respectively. The dimensions of tensile test specimens were determined in accordance with KS D 0026 as shown in Fig. 1. There were spirals at both ends of each specimen to enable fixing to the loading shafts located at the top and bottom ends of a furnace. These spirals were designed so that they did not affect the specimen fracture that occurred in the middle of the specimen.

2.2 Test procedure

An universal testing machine equipped with a specially made electrical furnace heated by thermal rays was used for
the elevated temperature tensile tests (see Fig. 2) and a hydraulic actuator was used to apply the tension load to specimens. A load cell was used to measure the applied tension load, whereas the elongation of the specimen was measured in the middle of the specimen using a specially modified extensometer.

Tests were carried out in the elevated temperature range of 20 to 800 °C at intervals of 100 °C with a strain rate of 1 mm/min. And the temperature was controlled to within ±2 °C. In this study, thermal expansion was allowed by maintaining zero tension load during the heating process. Each specimen was held for approximately 20 min at the testing temperature before testing began to make sure the temperatures evenly distributed throughout the specimens. After each test, data for load versus displacement were converted into engineering stress versus strain curves which were analysed to determine the yield stress (YS), ultimate tensile strength (UTS), percentage elongation to fracture and elastic modulus.

2.3 Deterioration of mechanical properties with increasing temperature

The variations of YS and UTS of high strength steels with testing temperature are shown in Fig. 3. It is seen that both YS and UTS of POSTEN60 steel decrease at 100 °C and then increase with increasing temperature up to 300 °C due to blue brittleness, after which they decrease for all conditions. On the other hand, YS and UTS of POSTEN80 steel decrease with increasing temperature up to 200 °C and then increase at 300 °C due to blue brittleness, after which they decrease slowly until 600 °C. Elevated temperature also leads to the deterioration of elastic modulus. Figure 4 shows the variations of elastic modulus at elevated temperatures. From this figure, it can be seen that elastic modulus of POSTEN60 steel decreases with increasing temperature.
decrease slowly with increasing temperature up to 400 °C and then decrease radically at higher temperatures. On the other hand, elastic modulus of POSTEN80 steel decrease radically with increasing temperature up to 400 °C and then decrease slowly until 600 °C, after which they decrease radically. The stress–strain curves obtained at elevated temperatures are also shown in Fig. 5. As like room temperature, POSTEN60 specimens show higher strain hardening rate than that of POSTEN80 specimens and strain hardening rate decrease radically after 400 °C for both specimens.

3. Experimental Investigation into Residual Stresses in Weldment of High Strength Steels

Residual stress measurements together with metallographic observations were performed to investigate the microstructures and the extent of residual stress relaxation due to phase transformation in the FZ and HAZ of high strength steels. Rolled plates of 30 mm thickness have been used as the base materials. Double ‘V’ butt joint configuration, as shown in Fig. 6, has been prepared for joining the plates. The joint for the specimen of POSTEN60 was welded in the flat position with six passes using flux cored arc welding (FCA) procedure with SUPERCORED81 electrode of 1.2 mm in diameter and the joint for the specimen of POSTEN80 was welded with five passes using gas metal arc welding (GMA) procedure with MGS-80 electrode of 1.2 mm in diameter. The chemical compositions and mechanical properties of the weld metals are presented in Tables 2 and 3, respectively. The welding conditions and process parameters used in the fabrication of the joints are given in Table 4.
3.1 Microstructure

Microstructures were analyzed using an OLYMPUS PME3 optical microscope after welding. Samples used for microstructural analysis were cut from the FZ and HAZ. They were finally polished with 1 μm diamond paste on a cloth polishing wheel, and etched with Nital’s etchant for about 20–30 s. Results are shown in Fig. 7. Figures 7(a) and (b), representing FZ and HAZ of POSTEN60, exhibit a dual phase structure (ferrite-plus-martensite). On the other hand, welding of POSTEN80 produced a microstructure nearly wholly martensitic in the FZ and HAZ [refer to Figs. 7(c) and (d)]. Therefore, it can be inferred that the FZ and HAZ heated over the austenitic temperature during welding undergo martensitic transformation and the extent of martensitic transformation in POSTEN80 is larger than that of POSTEN60.

3.2 Residual stress measurements

Residual stress measurements were carried out on the two-axis strain gauge with the saw cutting method. Figure 8 shows the measurement positions which are located on the specimen. Gauges were intensively attached at the FZ and HAZ in order to investigate the residual stress relaxation due to phase transformation. Residual stresses were measured by calculating the difference between initial strains and residual strains after saw cutting. Figure 9 shows the residual stresses
of weld line direction perpendicular to the weld line. A solid line represents the results of three-dimensional thermal elastic-plastic FEM analysis for the experimental model without taking into account the phase transformation effects. The calculating conditions for the analysis are the same as those used in the fabrication of the experimental model. Considerable differences between the experimental values and the analysis results in the FZ and HAZ are shown. Lower stresses in the FZ and HAZ can be explained by the volume change of the materials that undergo the austenite → martensite phase transformation. And the extents of residual stress relaxation in POSTEN60 and POSTEN80 are approximately \(0.85 \sigma_y/\sigma_{0.2}\) and \(0.75 \sigma_y/\sigma_{0.2}\), respectively.

4. Numerical Investigation into Residual Stresses in Weldments of High Strength Steels

4.1 Model for analysis

Figure 10 shows the coordinate systems and sizes for the analysis. Two \(1000 \text{mm} \times 500 \times 7 \text{mm}\) plates were assumed to be welded by one pass with a heat input of \(1200 \text{J/mm}\) and welding velocity of \(6 \text{mm/s}\).

The residual stress distribution was computed using an uncoupled thermo-mechanical FE formation\(^6\) to incorporate the phase transformation effects in the thermal and mechanical analysis. The computation employed three-dimensional, eight-noded, hexahedral elements in a full model and used temperature-dependent thermo-physical and mechanical properties of the BM. Figures 11(a) and (b) show the temperature dependency of physical\(^6\) and mechanical properties. The thermal analysis was based on the three-dimensional non-steady heat conduction formulation with the moving heat input. In thermal analysis, the heat conduction into the surrounding solid materials as well as the convective heat transfer in ambient temperature was considered. Thermal and mechanical analyses were uncoupled and conducted sequentially. First, the thermal analysis was carried out calculating the transient temperature distributions during welding. The mechanical part relied on the thermal analysis results and calculated the stress–strain distribution on the basis of the temperature history. The same FE mesh as in the thermal analysis was used in the mechanical model, except for the applied boundary conditions. The movement of bottom plate was restrained to approximately model the actual welding conditions.

4.2 Numerical reproduction of phase transformation

Phase transformation is occurred by the temperature changes due to rapid cooling after welding and temperature history is changed by the increase of specific heat due to the volumetric expansion originated in the phase transformation. And the volumetric expansion eventually becomes the cause of residual stress relaxation. Thus, while it is very difficult to reproduce the effect of phase transformation on residual stress relaxation, it is necessary to develop a FE model which is able to include the volumetric changes due to the austenite → martensite phase transformation for the accurate prediction of the mechanical behavior in welds.

The correlation between temperature and metallography is largely dependent on specific heat (SH) change and the correlation between stress–strain field and metallography is largely dependent on coefficient of thermal expansion (CTE) change. Figure 12 shows the change of specific heat and coefficient of thermal expansion in the region of phase transformation with respect to temperatures. Residual stress relaxation due to the austenite → martensite phase transformation in the process of cooling after welding was simulated by obtaining the value of \(C_p\) and \(\alpha\) which yield a good agreement with the experimental results through iterative analyses assuming specific heat and coefficient of thermal expansion were varied linearly in the transformation temperature range. The \(C_p\) and \(\alpha\) used to numerically model the volumetric expansion in the process of cooling after welding were \(5.0 \times 10^{-1} \text{ (cal/g·°C)}\) and \(-1.5 \times 10^{-5}\) respectively for the case of POSTEN60 and \(8.0 \times 10^{-1}\) (cal/g·°C) and \(-2.5 \times 10^{-5}\) respectively for the case of POSTEN80.

The thermo-physical and mechanical properties of the materials were used for the entire model during heating.
Depending on the peak temperature that a particular point reached during the heating transient, the decision was made whether the point underwent the martensitic transformation or not. The temperature of the materials transformed into the austenitic phase was determined from the equilibrium phase diagram. The volume change was approximated by introduction of a modified specific heat and coefficient of thermal expansion. The analysis distinguished between the heating and cooling cycle of each point and the modified CTE and SH curves were used (Fig. 12). Note that the part of the CTE and SH curves that represent the austenite → martensite phase transformation were only used on the cooling cycle for the points that satisfied the transformation criteria explained above.

The onset temperature of phase transformation is determined through the empirical formulae of Andrews: 12: \( T = 539 - 423C - 30.4Mn - 12.1Cr - 17.7Ni - 7.5Mo \).

### 4.3 Results and discussion

Figure 13 shows the residual stress distribution perpendicular to the weld line at the center of the weldments \( (x = 500 \text{ mm}) \). Figures 13(a) and (b) show the results of POSTEN60 and POSTEN80 respectively. The residual stresses of weld line direction in the FZ and HAZ which undergo martensitic transformation are as high as 470 and 545 MPa respectively, which correspond to each degree of residual stress relaxation due to the volume expansion by phase transformation. Stresses in the BM adjacent to HAZ increase significantly (655 and 870 MPa, respectively) and then gradually decrease to compressive stress in the far BM. The temperature in the BM adjacent to HAZ do not reach the transformation temperature, therefore, no phase transformation occurs there, which means no volume change to offset high stresses. The results presented in Fig. 13 take into account...
account the phase transformation effects. Another analysis was carried out without considering these effects, and the results are shown in Fig. 14. The results show a significant effect of phase transformation on residual stresses. This can be explained by the microstructural changes (Fig. 7) that occur during the austenite $\rightarrow$ martensite phase transformation in the FZ and HAZ that affect the SH and CTE which have a significant effect on the residual stress.

5. Conclusions

This study presented high temperature tensile properties and a FE model for residual stress analysis in weldments of high strength steels which accounts for the phase transformation effects. Three-dimensional thermal elastic-plastic FE analyses using the FE model were conducted to determine residual stresses in weldments of high strength steels. The following conclusions can be made.

(1) Both YS and UTS of POSTEN60 decrease at 100°C and then increase with increasing temperature up to 300°C due to blue brittleness, after which they decrease for all conditions. On the other hand, YS and UTS of POSTEN80 decrease with increasing temperature up to 200°C and then increase at 300°C due to blue brittleness, after which they decrease slowly until 600°C.

(2) Elastic modulus of POSTEN60 decrease slowly with increasing temperature up to 400°C and then decrease radically at higher temperatures. On the other hand, elastic modulus of POSTEN80 decrease radically with increasing temperature up to 400°C and then decrease slowly until 600°C, after which they decrease radically.

(3) The extents of residual stress relaxation due to the austenite $\rightarrow$ martensite phase transformation in the process of cooling after welding are approximately 0.85 $\sigma_s/\sigma_Y$ and 0.75 $\sigma_s/\sigma_Y$ in the FZ and HAZ of POSTEN60 and POSTEN80, respectively.

(4) Residual stresses of weld line direction in the base metal (BM) which is adjacent to HAZ, therefore, do not undergo martensitic transformation increase (655 MPa < 870 MPa) with increasing tensile strength of the high strength steels (POSTEN60 < POSTEN80).

REFERENCES