Effect of Crystallographic Texture on Anisotropy of Mechanical Properties in High Strength Martensitic Steel

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The thermomechanical control process (TMCP) is widely applied as one of the effective processes for improving the strength and toughness of steel plates. In actual application, the anisotropies of mechanical properties arising from the crystallographic texture developed during the controlled rolling process are important issues. In this study, the effect of texture on the anisotropies of mechanical properties in an experimentally manufactured YP960 MPa class steel plate was investigated. Strength varied through the plate thickness from the surface to mid-thickness. At the surface, the strength in the longitudinal direction was higher than that in the transverse direction, and in contrast, at mid-thickness, the strength in the transverse direction was higher than that in the longitudinal direction. The major components of the texture at the plate surface were $\{110\} \langle 111 \rangle$ and $\{112\} \langle 111 \rangle$, whereas those at mid-thickness were $\{332\} \langle 113 \rangle$ and $\{211\} \sim \{311\} \langle 011 \rangle$. It is considered that the texture of the plate surface was formed by shear strain in the austenite region, whereas that at mid-thickness was formed by plane strain compressive. A crystal plasticity analysis based on the initial texture information obtained experimentally revealed that the anisotropies of mechanical properties were strongly affected by the crystallographic orientation.

KEY WORDS: TMCP; ausforming; anisotropy; crystallographic texture; crystal plasticity.

1. Introduction

The scale of welded structures has increased in recent years, and higher strength, toughness, weldability and formability are constantly demanded in the steel plates used in those structures. In order to satisfy these requirements, the thermomechanical control process (TMCP) has been widely applied as one effective process for improving the strength and toughness of steel plates in place of the conventional reheat quenching and tempering process. TMCP realizes expanded application of high strength steel plates because it has the advantages of lowering the carbon equivalent and reducing weld cracking susceptibility. The TMCP technique is applied in different ways, depending on strength requirements; one utilizes only controlled rolling, while the other employs a combination of controlled rolling followed by accelerated cooling.^{1,2)} Furthermore, in the production of ultra-high strength steel plates such as plates with tensile strength over 1 000 MPa, the modified ausforming process, which is a combined process of deformation at a lower temperature in the non-recrystallization temperature region of austenite followed by direct quenching, is used to improve tensile strength even in low-carbon steel.^{3,4)}

However, it has been reported that this rolling process might cause the crystallographic evolution of grains during

hot rolling and finally affect the anisotropy of mechanical properties.⁵⁾ Therefore, many studies have been carried out on the relationship of the texture development process and rolling pass schedule and on the relationship of textures and mechanical properties.^{6–8)} These studies usually evaluated the texture by the orientation distribution function (ODF) obtained by X-ray diffraction, and estimated mechanical properties by calculation from a single crystal to a polycrystalline structure. Recently, the crystal plasticity analysis technique, which simulates slip deformation by using an elastic-plastic model based on the ODF data measured in actual metals, has also been applied.⁹⁾

Various studies have examined the texture formation mechanism because textures induce anisotropy of mechanical properties. For example, Charnock *et al.*¹⁰⁾ used an Fe-70Ni (mass%) alloy, which had similar stacking fault energy to steels in the austenite temperature range, and Regle *et al.*¹¹⁾ analysed the orientation of retained austenite formed by the bainite transformation after rolling. The most recent research includes reconstruction of the prior austenite texture from the transformed martensite textures by calculation of electron back-scattering diffraction (EBSD) data on the basis of the K-S relationship.¹²⁾

In contrast, research focused on the texture distribution in the plate thickness direction is still insufficient. Inagaki *et al.*¹³⁾ reported on the texture formation of air-cooled steel plates after controlled rolling, and Nishimura *et al.*¹⁴⁾ reported on the texture formation of rolled plates in the

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($\gamma + \alpha$) intercritical temperature region. To date, however, no reports have discussed steel plates produced by the modified ausforming process.

In this study, the relationship between the anisotropy of tensile properties and the crystallographic texture in the thickness direction in a TS 1 000 MPa grade martensitic steel plate produced by ausforming was investigated.

2. Experimental Procedure

2.1. Material

Low carbon steel with a chemical composition of 0.15C-0.4Si-1.2Mn-0.5Cr-0.4Mo-0.02Nb (wt%) was used. The base composition of this steel is 0.15C-0.4Si-1.2Mn (wt%), and Cr and Mo are added to improve hardenability. A 150 kg ingot was cast by high-frequency vacuum furnace melting, and the slab was prepared by breakdown rolling to a thickness of 100 mm after reheating at 1 100°C for 2 h. The material was then reheated at 1 150°C, and a steel plate was control-rolled to a thickness of 12 mm in the low temperature non-recrystallization region of austenite, immediately direct-quenched and then tempered at 630°C. The reduction ratio of controlled rolling in the non-recrystallization region of austenite was set at 60%, and the finishing rolling temperature was 820°C.

2.2. Mechanical Tests

To investigate the anisotropy of mechanical properties, full and reduced-thickness tensile tests were conducted in the longitudinal direction (L-direction) and transverse to the rolling direction (T-direction). The dimensions of the tensile specimens were 12.5 mm in width and 25 mm in gauge length. Reduced-thickness tensile specimens with a thickness of 1 mm were sliced at each thickness position at intervals of 1 mm from the subsurface to mid-thickness. In this article, yield strength was evaluated by 0.2% proof stress.

2.3. Microstructure Observation and Texture Measurement

The microstructure at the cross section in the rolling direction was observed by optical microscopy after etching with 3% nital. Thin specimens with a thickness of 1 mm and size of 20 mm $\times$ 30 mm were prepared for texture measurement at each thickness position. The crystallographic textures were measured by X-ray diffraction in the form of (110), (200) and (211) pole figures, and orientation distribution functions (ODF) were calculated from these pole figure data. In addition, in order to investigate the texture development in detail, SEM/EBSD observation was also conducted using cross-sectional microstructure observation samples. The martensite orientations were measured by EBSD at an accelerating voltage of 20 kV using a step size of 0.3 μm and area size of 200 μm $\times$ 200 μm to obtain average information on the textures by measuring multiple grains. The EBSD measurements were conducted in a cross section in the longitudinal direction and converted to the normal direction by OIM. The prior austenite textures were evaluated by the reconstruction method from the transformed martensite textures by calculation of the EBSD data on the basis of the K-S relationship.^{12,15)}

3. Experimental Results

3.1. Microstructures

Figure 1 shows the optical microstructures of the steel plate at each position from the near-surface to the quarter-thickness (1/4t, 3 mm under surface) and mid-thickness (1/2t, 6 mm under surface) positions. The microstructures consisted of tempered lath martensite and had an elongated structure in the longitudinal direction. Especially, pancake structures appeared strongly at the subsurface compared with mid-thickness, probably due to the difference of strain accumulation during hot rolling.

3.2. Tensile Properties

The tensile properties of the full-thickness specimens are shown in Table 1. Both yield strength (YS) and tensile

Fig. 1. Microstructure of plate. (a) 1 mm from plate surface, (b) 1/4t, (c) 1/2t.

strength (TS) are higher in the L-direction.

Next, the tensile properties at the near-surface and mid-thickness are shown in **Fig. 2**. At 1 mm under the surface, both YS and TS in the L-direction were about 50 MPa higher than those in the T-direction. On the other hand, at mid-thickness, both YS and TS were higher in the T-direction than in the L-direction. The strength in the L-direction decreased drastically from the surface to the mid-thickness position. However, the strength in the T-direction increased slightly from the surface to mid-thickness. At the quarter-thickness position, the strength was nearly the same in the L- and T-directions. Thus, the anisotropies of the tensile properties in the L- and T-directions differed at each thickness position.

3.3. Textures

To evaluate the reason for the different anisotropies of tensile properties observed in the thickness direction, the crystallographic textures were measured at each thickness position, *i.e.*, 1 mm under the surface, 1/4t and 1/2t. The respective analyzed ODFs in the cross section of $\varphi_2=45^\circ$ are also shown in **Fig. 3**. The observed textures differed at each of the plate thickness positions. The major components of the texture near the plate surface were the $\{110\}\langle 111 \rangle$ and $\{112\}\langle 111 \rangle$ orientations, whereas those at mid-thickness were $\{332\}\langle 113 \rangle$ and $\{211\}\sim\{311\}\langle 011 \rangle$. At the quarter-thickness position, a relatively random texture was observed.

The textures at mid-thickness are the same type as those already reported, which are formed by the rolling process in the non-recrystallization temperature region of austenite.^{16–18)} On the other hand, the surface textures are similar to the copper or brass textures, which have frequently been reported in rolling of FCC metals. However, it was confirmed separately that the specimens investigated here do

not contain retained austenite, and there are few examples of reports of these surface textures in BCC metals.

4. Discussion

4.1. Texture Formation Mechanism at Each Thickness Position

First, we will discuss the mechanism of the development of the textures observed in this study. The microstructure of the steel plate was tempered martensite which did not contain recrystallized grains during tempering, since it was control-rolled in the low temperature non-recrystallization region of austenite and then immediately direct-quenched and tempered. Because recrystallized grains were not observed in the microstructure after tempering, it is considered that the microstructure maintained the relationship between the prior austenite grains and transformed martensite. In the martensite transformation, the K-S orientation

Table 1. Full-thickness tensile properties of steel used.

Direction	YS/MPa	TS/MPa	t.El/%
L	1 037	1 065	24
T	997	1 053	21

Fig. 2. Variation of tensile test properties through thickness direction.

Fig. 3. Variation of crystallite orientation distribution function through thickness direction ($\varphi_2=45^\circ$). (a) 1 mm from the plate surface, (b) 1/4t, (c) 1/2t. (Online version in color.)

relationship between austenite and martensite is well known, as shown by the following equation.¹⁹⁾

$$\{111\}\gamma // \{011\}\alpha'$$

$$\langle 101 \rangle \gamma // \langle 111 \rangle \alpha'$$

Table 2 shows the prior austenite texture estimated from the transformed martensite observed in this research by supposing K-S relationship. It is thought that the subsurface textures were transformed from $\{111\}\gamma$ and $\{100\}\gamma$ textures, and the mid-thickness textures were transformed from $\{110\}\gamma$ textures.

To confirm this estimation, the prior austenite textures were reconstructed from the EBSD data of the transformed martensite by calculation based on the K-S relationship.¹²⁾

Table 2. Crystal orientations in austenite region estimated by K-S relationship from transformed ODF images.

Thickness position	Main strain introduced by hot rolling	Martensite (Observed)	Austenite (Estimated)
Surface	Shear strain	$\{110\}\langle 111 \rangle$ $\{112\}\langle 111 \rangle$	$\{111\}\langle 110 \rangle$ $\{100\}\langle 110 \rangle$
Mid-thickness (1/2t)	Compressive strain	$\{332\}\langle 113 \rangle$ $\{211\}\sim\{311\}\langle 011 \rangle$	$\{110\}\langle 112 \rangle$ $\{311\}\sim\{211\}\langle 111 \rangle$

Fig. 4. Inverse pole figure of reconstructed austenite orientation. (a) plate surface, (b) mid-thickness of plate. (Online version in color.)

Figure 4 shows the inverse pole figures of the reconstructed austenite textures. These figures prove that $\{100\}$ and $\{111\}$ textures were developed at the surface and $\{110\}$ and $\{311\}\sim\{211\}$ textures were developed at mid-thickness.

Strains introduced by the rolling process usually have variations in the plate thickness direction. It is known that shear strains are stronger at the plate surface, and in contrast, the plane strain compressive component becomes larger at mid-thickness. In FCC metals, Calnan *et al.*²⁰⁾ reported that the (100) and (111) textures are developed by crystal rotation of shear strains, and the (110) texture is developed by plane strain compressive. Accordingly, in steel plates rolled in the austenite temperature region, the (100) and (111) textures are developed by shear strain, and the (110) texture is developed by plane strain compressive.

Therefore, as estimated above, the textures observed in this study originated from the rolled textures in the austenite temperature region.

4.2. Analysis of Anisotropies of Tensile Properties by Crystal Plasticity Model

To evaluate the influence of crystal orientation on tensile stress anisotropy, a crystal plasticity analysis was performed. The crystal plasticity analysis technique is based on the assumption that plastic deformation proceeds along specific shear vectors on certain slip planes.²¹⁾ The plastic strain in the crystal plasticity analysis is represented as the summation of the shear slip in slip systems. The DAMASK framework (DAMASK: the Düsseldorf Advanced Material Simulation Kit, 2014) was used for the crystal plasticity analysis in this work.²²⁾ The strain rate in each slip system is expressed by the rate-dependent model²³⁾ shown in Eq. (1) and the hardening development equation shown in Eqs. (2) and (3).

$$\dot{\gamma}^\alpha = \sum_{\alpha=1}^{24} \dot{\gamma}^\alpha h_0 \left| 1 - \frac{S^\alpha}{S_\infty} \right|^w \operatorname{sgn} \left(1 - \frac{S^\alpha}{S_\infty} \right) h_{\alpha\beta} \dots \dots \dots (1)$$

$$\dot{\gamma}^\alpha = \dot{\gamma}_0 \left| \frac{\tau^\alpha}{S^\alpha} \right|^n \operatorname{sgn}(\tau^\alpha) \dots \dots \dots (2)$$

$$L_p = \sum_{\alpha=1}^{24} \dot{\gamma}^\alpha (\mathbf{b}^\alpha \otimes \mathbf{n}^\alpha) \dots \dots \dots (3)$$

where $\dot{\gamma}$ is the shear strain rate and the superscript α ($= 1, 2, \dots, 24$) is the slip system index, S^α is the slip resistance in the α^{th} slip system, S_∞ is the saturation slip resistance, h_0 is the initial hardening rate, $h_{\alpha\beta}$ is the interaction parameter, w is a fitting parameter, $\dot{\gamma}_0$ is the reference shear strain rate, τ^α is the resolved shear stress on the α^{th} slip system and n is a strain rate exponent. L_p is the plastic strain, the vectors $\mathbf{b}^\alpha$ and $\mathbf{n}^\alpha$ are unit vectors describing the slip direction and the normal to the slip plane, respectively. A body-centered cubic crystal structure with $\{110\}\langle 111 \rangle$ and $\{112\}\langle 111 \rangle$ slip system families was applied.

Table 3 shows the material parameters used in the crystal plasticity simulation. The elastic constants of martensite described by Kim *et al.*²⁴⁾ were used. The critical resolved shear stress at each thickness position were estimated from the macroscopic stress-strain curves in the longitudinal

Table 3. Mechanical parameters used in crystal plasticity analysis.

Parameter	Symbol	1 mm from plate surface	Mid-thickness
Elastic constants	C_{11}	268 100 MPa	
	C_{12}	111 200 MPa	
	C_{44}	79 060 MPa	
Reference shear strain rate	$\dot{\gamma}_0$	0.001 s ⁻¹	
Slip resistance	S^α	385 MPa	405 MPa
Saturation slip resistance	S_∞	410 MPa	430 MPa
Initial hardening rate	h_0	563 000 MPa	
Interaction parameter	$h_{\alpha\beta}$	1.0	
Strain rate exponent	n	20	
Hardening exponent	w	2.00	

direction. The ratio between the macroscopic yield stress and the critical resolved shear stress is given by the Taylor factor.²⁵⁾ Therefore, the slip hardening behavior can be estimated by rescaling the macroscopic stress-strain curve using the Taylor factor. The average Taylor factor for the body-centered cubic crystal structure was set to 2.5. The other constitutive parameters of the martensite were set with reference to the mechanical properties of martensite described by Tasan *et al.*²⁶⁾

In this study, a spectral solver was used in the crystal plasticity analysis.^{27,28)} Based on the Green's function method, the equilibrium equations for the first Piola-Kirchhoff stress were solved so as to satisfy both the strain compatibility equations and the boundary conditions. The speed of this calculation is increased by using a fast Fourier transform-based solver for the equilibrium and constitutive equations. This solver can achieve a higher numerical efficiency than the more common finite element method. In addition, the use of the spectral solver in combination with a nonlinear numerical library improves the convergence of the simulation. The boundary conditions are based on the periodic boundary conditions because trigonometric polynomials were used as the basis functions. The simulation model had 3D polycrystalline microstructures, and the total number of voxels was $16 \times 16 \times 16$. Each voxel was considered to be a grain.

The embedded crystal orientations in the voxels were generated from the measured ODFs by using the method developed by Morawiec *et al.*²⁹⁾ The Bunge Euler angles were generated randomly as

$$\begin{aligned} \varphi_1 &= 180^\circ \times \text{rand}(\) \\ \Phi &= \cos^{-1} \{ \text{rand}(\) \} \dots\dots\dots (4) \\ \varphi_2 &= 90^\circ \times \text{rand}(\) \end{aligned}$$

and the intensities of the ODFs corresponding to the generated Euler angles were extracted. The $\text{rand}(\)$ function returns a pseudorandom integer in the range 0 to 1. The crystal orientation is regenerated when the intensity of the ODFs satisfies

$$f(\varphi_1, \Phi, \varphi_2) \geq f_{\text{MAX}} \times \text{rand}(\) \dots\dots\dots (5)$$

Fig. 5. Strain-stress curve obtained from experiment and crystal plasticity analysis. (a) 1 mm from plate surface, (b) mid-thickness of plate.

where f_{MAX} is the maximum intensity of the ODFs. After the initial crystal orientation was embedded in each element, tension was applied in the rolling and width directions. The strain rate and simulation time were set to $1.0 \times 10^{-3} \text{ s}^{-1}$ and 100 s, respectively. In this simulation, uniaxial tensile strain was added in L- or T-direction.

Figure 5 shows the stress-strain curves obtained from the tensile test and the crystal plasticity analysis. In this figure, Figs. 5(a) and 5(b) show the flow curves at the thickness position 1 mm from the plate surface and the mid-thickness of the plate, respectively. The solid and dashed flow curves correspond to the curves obtained from the tensile test of the martensite steel and the crystal plasticity analysis, respectively. At the thickness position 1 mm from the plate surface, the tensile stress in the L-direction is larger than that in the T-direction, and at the mid-thickness position, the tensile stress in the T-direction is larger than that in the L-direction. Since these results correspond to the experimental results, it is assumed that the martensitic texture distribution contributes to the anisotropy of mechanical properties in each thickness direction.

In Fig. 5, the slight difference between the results of the crystal plasticity analysis and the experimental results in the small plastic strain region was considered. As the grains are not recrystallized completely, they are likely to have an elongated form. The major elongation direction should be longitudinal direction so this morphology effect should be imposed to the difference in S-S curves. However, even one

uses a 3-dimensional FFT analysis, this elongation effect seems to be difficult to analyse because the FFT method uses the discrete points which are not related to the real distances. A deformation anisotropy analysis considering 3-dimensional grain information (e.g. 3D-EBSD) is an issue for future work.

5. Summary

The anisotropy of the tensile properties in a high strength tempered martensitic steel plate produced by ausforming, which was a controlled-rolled from 30 mm to 12 mm in thickness at a temperature under 930°C in the non-recrystallization region of austenite, followed by direct-quenching and tempering at 630°C, was analysed in terms of the crystallographic texture. The results are summarized as follows.

(1) Tensile properties differed at each position in the plate thickness direction. At the plate surface, the strength in the longitudinal direction was higher than that in the transverse direction. On the other hand, at mid-thickness, the strength in the transverse direction was higher than that in the longitudinal direction.

(2) The major components of the texture at the plate surface were $\{110\}\langle 111 \rangle$ and $\{112\}\langle 111 \rangle$, whereas those at mid-thickness were $\{332\}\langle 113 \rangle$ and $\{211\}\sim\{311\}\langle 011 \rangle$.

(3) It is suggested that the anisotropies of the tensile properties in the longitudinal and transverse directions at the surface and mid-thickness positions could be explained by the calculated results of the relative yield strength based on the measured textures at each thickness position. From the calculated results of the austenite textures before the martensite transformation reconstructed through the K-S relationship, it is estimated that the observed textures at the near-surface and mid-thickness are derived from the textures developed respectively by shear strain and plane strain compressive during rolling in the austenite region.

(4) A crystal plasticity analysis was carried out with the textures regenerated from the actual ODFs. At the thickness position 1 mm from the plate surface, the strength in the L-direction was larger than that in the T-direction. In contrast, at the mid-thickness position, the strength in the T-direction was larger than that in the L-direction. These results suggest that the martensitic texture distribution contributes to the anisotropy of mechanical properties in each thickness direction.

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