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Effect of crystallographic texture on anisotropy of mechanical properties in high-strength martensitic steel

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Abstract: The thermo-mechanical controlled process (TMCP) is widely applied in the manufacture of steel plates to obtain high strength and excellent toughness. Ausforming, which means deformation at a lower temperature in the non-recrystallization austenite region followed immediately by direct-quenching, is one effective way to achieve higher strength. However, this process contributes to the development of crystallographic texture, which then affects the anisotropy of mechanical properties in the base plate. In this study, the relationship between the anisotropy of tensile properties and the crystallographic texture in a TS 1000 MPa grade martensitic steel plate produced by ausforming was investigated. Strength varied from the plate surface to mid-thickness, with surface strength in the longitudinal direction being higher than that in the transverse direction. 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}<111> and {112}<111>, whereas those at mid-thickness were {332}<113> and {211}~{311}<011>. It is considered that the texture of the plate surface was formed by shear strain during rolling in austenite region, and that of the mid-thickness was grown by plane strain. The influence of texture on the anisotropy of yield strength was considered based on the ideal orientations and K-S relationship. This study revealed that the anisotropy of tensile properties might be strongly affected by the texture derived from these different strain components and distributions in the thickness direction during rolling in the austenite region.

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 thermo-mechanical controlled process (TMCP) has been widely applied as one effective process to improve the strength and toughness of steel plates [1]. In the production of ultra-high strength steel plates such as plates with tensile strength over 1000 MPa, the ausforming process, which is a combined process of deformation in the lower temperature in the non-recrystallization austenite region and direct-quenching, is used to improve tensile strength even in low-carbon steel [2, 3]. However, it has been reported that this rolling process might cause crystallographic evolution of grains during hot rolling, and finally affect the anisotropy of mechanical properties [4].

Therefore, many studies have been performed on the relationship of the texture development process and rolling pass schedule and on the relationship of textures and mechanical properties. These studies usually evaluated 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. The most recent research includes reconstruction of the prior austenite texture from the transformed martensite textures by calculation of EBSD data on the basis of the K-S relationship [5, 6]. However, research focused on the texture distribution in the plate thickness direction is still insufficient. Only a few studies which focused on the ferrite-austenite rolling effect have been reported [7]. In this study, the relationship between the anisotropy of tensile properties and the crystallographic texture in the thickness direction in a TS 1000 MPa grade martensitic steel plate produced by ausforming was investigated.

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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 (mass%) was used. The material was reheated at 1150ºC, and the steel plate was control-rolled in the low temperature non-recrystallization austenite region down to 12mm in thickness, immediately direct-quenched, and then tempered at 630ºC. The reduction ratio of controlled rolling in the non-recrystallization austenite region was set at 60%, and the finishing rolling temperature was 820ºC.

2.2. Mechanical tests, microstructure observation and texture measurement

To investigate the anisotropy of mechanical properties, reduced-thickness tensile tests were conducted in the longitudinal direction (L-direction) and transverse to the rolling direction (T-direction). The size of the tensile specimens were 12.5 mm in width and 25 mm in gauge length. Reduced-thickness tensile specimens with 1 mm thickness were sliced at each thickness position at intervals of 1 mm from the subsurface to mid-thickness. The microstructure at the cross section in the rolling direction was observed by optical microscopy after etching with 3% nital. Thin specimens with 1 mm thickness and 20x30mm size 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.

3. RESULTS AND DISCUSSIONS

Fig.1 shows the optical microstructures of the steel plate at each position from 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, the pancake structures appeared strongly at the subsurface compared with mid-thickness, probably due to the difference of strain accumulation during hot rolling.

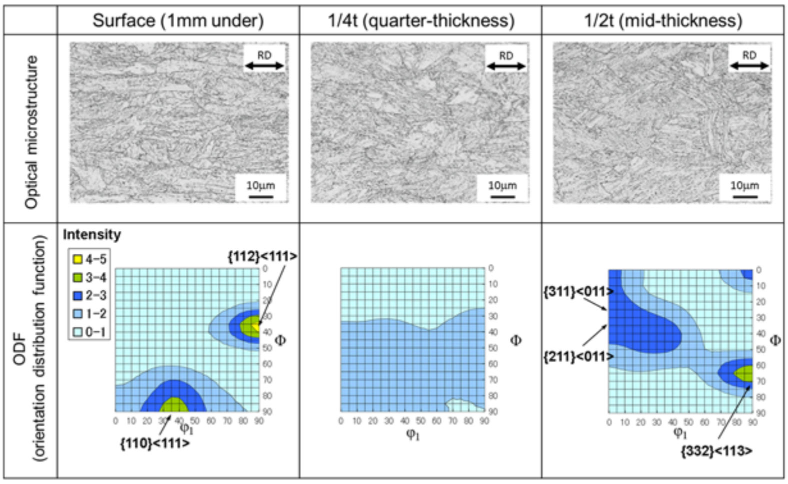

Fig.1 Optical microstructures and φ_2=45° sections of ODFs
at near-surface, 1/4t and 1/2t thickness positions.

The tensile properties at the near-surface and mid-thickness are shown in Table 1. At 1 mm under the surface, both yield strength (YS) and tensile strength (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 those in L-direction at mid-thickness. The variation of tensile properties through the thickness direction is shown in detail in Fig. 2. 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 the mid-thickness position. At quarter-thickness, the strength was nearly the same in L- and T-direction. Thus, the anisotropies of tensile properties in the L- and T-directions differed at each thickness position.

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 analysed ODFs in the cross section of φ_2=45° are also shown respectively in Fig. 1. The observed textures differed at each of the plate thickness positions. The major components of the texture near the plate surface were the {110}<111> and {112}<111> orientations, whereas those at mid-thickness were {332}<113> and {211}~{311}<011>. At quarter-thickness, a relatively random texture was observed.

Inagaki [4] reported that calculation of the theoretical relative yield strength from ODF data based on the Taylor-Bishop-Hill model was effective to analyse the anisotropy of tensile properties derived from crystallographic textures. The relative yield strength versus the angle from the rolling direction was analysed using this calculation model. The calculated results for both the near-surface and the mid-thickness positions are shown in Fig.3. The texture observed at the near-surface, for example {110}<111>, shows relatively higher strength in the L-direction than in the T-direction. On the other hand, the {332}<113> orientation observed at mid-thickness shows higher strength in the T-direction than in the L-direction. Therefore, the anisotropies of the tensile properties at each thickness position could be explained from the observed textures.

Table 1. Tensile test results at surface and mid-thickness.

	Direction	YS [MPa]	TS [MPa]	El [%]
Surface	L	1048	1097	11.6
	T	990	1054	11.6
1/2t	L	963	1036	12.7
	T	1029	1093	13.4

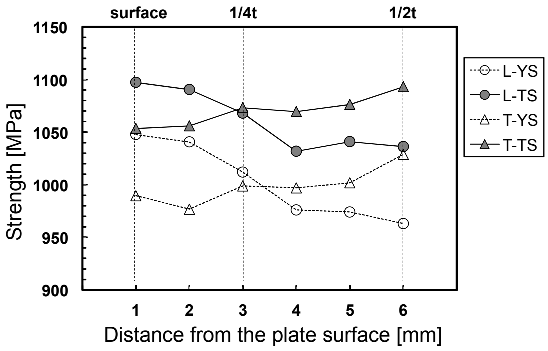

Fig.2 Variation of tensile properties in thickness direction. (L-direction, T-direction)

To investigate in detail the mechanism of texture development at the near-surface and mid-thickness in this study, SEM/EBSD measurements were conducted using the samples of the cross sections in the L-direction at the near-surface and mid-thickness. Miyamoto [5, 6] reported a calculation method for reconstructing the austenite grain structure in steels based on the ferrite orientation maps of lath martensite or bainite obtained by EBSD data through the K-S relationship. The calculated results of the reconstructed austenite textures using this method are shown in Fig. 4, compared with the measured textures of the lath martensite at both the surface and mid-thickness positions. The predicted austenite textures at the surface are nearly the same as the reported shear-induced textures in the austenite region, and those at mid-thickness are close to the compression-induced textures in austenite in the hot rolling process [8, 9]. Therefore, it is considered that the anisotropy of tensile properties might be strongly affected by the textures derived from these different strain components and distributions in the thickness direction during rolling in the austenite region.

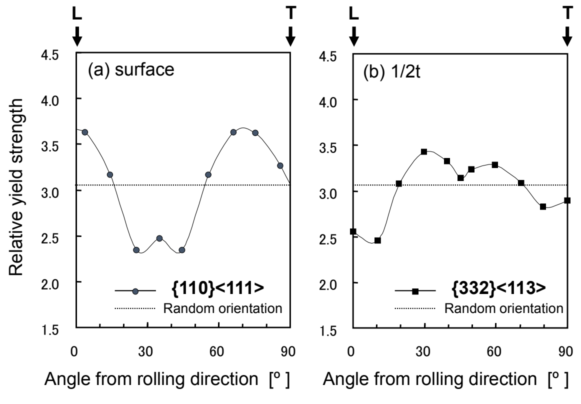

Fig.3 Plot of theoretical relative yield strength versus angle from rolling direction calculated from measured major components of textures.

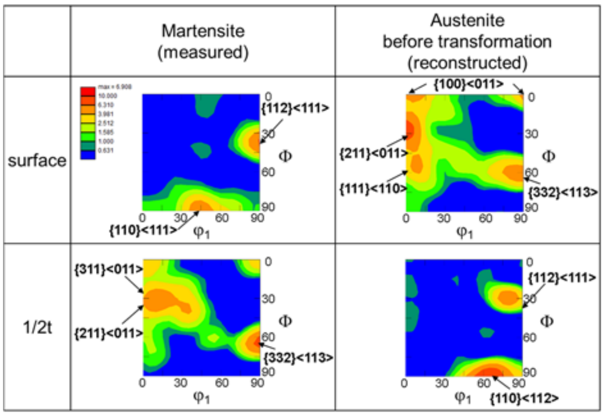

Fig.4 Austenite textures before martensite transformation reconstructed by K-S relationship from EBSD data. (φ_2=45° sections of ODFs)

4. SUMMARY

The anisotropy of the tensile properties in a high strength tempered martensitic steel plate produced by ausforming, which is a controlled rolling and direct-quenching process, was analysed in terms of 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}<111> and {112}<111>, whereas those at mid-thickness were {332}<113> and {211}~{311}<011>. It is suggested that the anisotropies of tensile properties in the longitudinal and transverse directions at the surface and mid-thickness positions could be explained by the calculated results of relative yield strength based on the measured textures at each thickness position.
(3) 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 compression strain during rolling in austenite region.

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