Development of Abrasion-Resistant Steel Plates with Superior Low-Temperature Toughness

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Abrasion-resistant steel plates are widely used in industries such as machinery, mining, and civil engineering, serving as essential industrial materials. However, due to the lack of domestic production capacity for abrasion-resistant plates in the past, Taiwan relied on imported steel plates to meet its demand. To address this situation, China Steel Corporation (CSC) combined rolling and direct quenching (DQ) processes to develop abrasion-resistant steel plates. In pursuit of excellent wear resistance, these steel plates incorporate a martensitic microstructure design. This design imparts ultra-high hardness to the steel, allowing it to withstand wear and enhance equipment lifespan in various application environments. On the other hand, abrasion-resistant steel plates also require low-temperature toughness to prevent damage in cold operating conditions or high-speed impact scenarios. Although martensite could offer high strength for the plates, their inherent brittleness limits practical applicability. In this study, novel alloy and process designs were adopted to overcome the need for toughness. By precisely controlling the cooling path through the DQ process, residual heat after cooling is utilized for self-tempering the martensitic structure, reducing energy consumption and producing robust abrasion-resistant plates. For the even more stringent toughness requirements in abrasion-resistant steel plates, microstructure and texture control were used to further enhance plate toughness. These plates are now applied in various fields contributing to the upgrade of domestic industries.

Keywords: Abrasion-resistant steel plate, Ultrahigh strength machine structural steel plate, Direct-quenching, Texture

1. INTRODUCTION

In recent years, with the rapid advancement of global industrialization, the demand for energy, minerals, and food has grown rapidly. The machinery industry has derived from the need for large-scale, complex, and lightweight machinery. Abrasion-resistant steel plates are often used in key parts of heavy-duty machinery, such as excavator buckets, hopper liners, and chutes, to effectively resist impact and wear during operation, extend equipment life, and therefore the industry's demand for abrasion-resistant steel plates with both strength and toughness is increasing day by day. In the past, domestic production of abrasion-resistant steel plates was lacking, so CSC set up direct quenching equipment and actively invested in the development of new products, gradually changing the industry's reliance on imported plates.

The abrasion-resistant steel plates developed by CSC are mainly products with hardness grades of 400, 450, and 500HBW, with tensile strengths ranging from 1200 to 1900 MPa. Due to the application environments of the abrasion-resistant plates, in addition to strength requirements, they also need to have sufficient toughness to cope with the impact they receive. Although martensite can be used to provide the steel plate with ultra-high strength through the interaction of carbon atoms and dislocations, it faces similar problems as other high-strength materials, such as poor toughness, which limits the application of the steel plate. To address this issue, other steel mills use the off-line reheating-quenching and tempering heat treatment process to produce martensitic steel. With this process, the grain size is further refined by controlling the temperature during the normalizing of the steel plate, and an equiaxed fine martensite structure is obtained after quenching. With the further low-temperature tempering process, excellent low-temperature toughness could be obtained. However, this process technology needs to be equipped with off-line reheating-quenching and tempering equipment, and the steel plate needs to be reheated to above Ac3 temperature which leads to significant energy consumption. To develop an energy-efficient process for abrasion-resistant steel plates, this study starts from the metallurgical strategies of improving the toughness of martensitic steel and develops steel plates with higher strength and better low-temperature toughness. The direct quenching self-tempering process developed by CSC, compared with the above-mentioned off-line heat treatment process, does not reheat the steel plate after hot rolling but directly quenches it to a specific temperature which allows the occurrence of auto-tempering. Therefore, energy usage and carbon emissions are greatly reduced. Meanwhile, this process also preserves the effects of controlled rolling, resulting in a texture conducive to low-temperature toughness.

2. NOVEL METALLURGICAL DESIGN

2.1 Alloy and Process Design

To develop abrasion-resistant steel plates with energy-efficient processes, this study focuses on alloy and process design for abrasion-resistant steel plates of different strength levels. By adjusting the carbon content, steels with different hardness can be produced. Additionally, elements such as Mn, Cr, Mo, Ni, and B are added to suppress the phase transformation of coarse-grained ferrite and bainite, resulting in steel plates with excellent hardenability. Subsequently, high-strength martensite is obtained after quenching. On the other hand, while the direct-quenching & tempering (DQT) process is already more energy-saving than the traditional RQT process, this research further advances energy efficiency by developing the even more efficient Direct-Quenching & Self-Tempering (DQST) process. Figure 1 illustrates that DQST outperforms DQT in terms of energy savings and process efficiency. The final mechanical properties of DQST plates are greatly influenced by the microstructure, therefore the precise control of process parameters such as cooling rate and finish cooling temperature is crucial.

2.2 Toughness Enhancement by Texture Control

For decades, grain refinement has been the main approach to enhance the low-temperature toughness of martensitic steels. Researchers have begun researching the possibility of enhancing the low-temperature toughness of steel through extrinsic factors recently. Kimura et al[1, 2]. found that tempered martensite with a pronounced <110>||RD texture exhibits improved toughness. In impact tests, cracks continuously bifurcate as they propagate along neatly aligned {100} cleavage planes between elongated fibrous grains. This phenomenon increases the crack propagation distance significantly, resulting in enhanced toughness. In this study, we

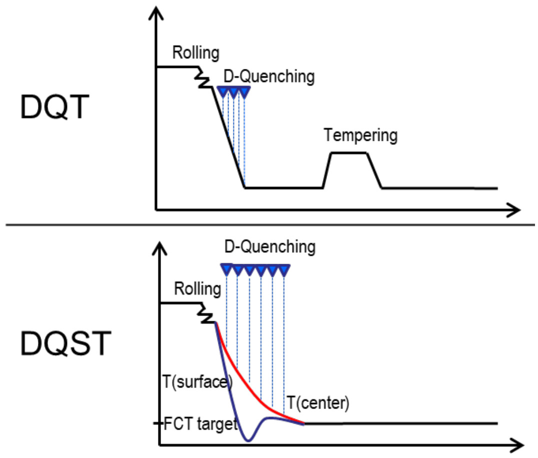


Fig.1. Schematic illustration of processes of DQT and DQST.

attempted to improve the toughness of the HB400-grade abrasion steels by microalloying elements and rolling the austenite phase at temperatures below recrystallization, leading to the development of RD||<111> texture in the rolled austenite. Subsequent quenching produced martensite with an RD||<110> texture, further enhancing its toughness.

3. RESULTS AND DISCUSSION

3.1 Effects of Finish Cooling Temperature in the DQST process

The precipitation behavior of auto-tempered martensite is deeply influenced by the cooling path[3]. Therefore, the effect of the finish cooling temperature in PA500H steel was investigated by the quenching-deformation dilatometer. Figure 2(a)~(c) shows the SEM micrographs of different finish cooling temperatures. In Figure 2(a)~(c), fine carbides were dispersed evenly in the martensite lath. It indicates that all of them underwent auto-tempering during and cooling simulation. The morphologies of carbide become smoother with the increasing FCT imply the extent of tempering could be controlled by the FCTs. However, in Figure 2(a) and (b), a thin film of carbide (as indicated by white arrows) also formed during the quenching and cooling process. The presence of thin carbide film may cause tempered martensite embrittlement[4, 5] and is deleterious to the toughness. Figure 2(d) shows the relation between hardness and FCTs. The hardness decreases slightly with increasing FCT. The hardness curve shows a greater extent of self-tempering occurs at higher FCT. Therefore, the combined effects of microstructure evolution and tempering on hardness and toughness must be taken into consideration when deciding the optimal process parameters.

The mechanical properties of PA500H of different FRT produced by the DQST process in plate mill were also evaluated and listed in Table 1. The hardness values are nearly identical for plates of FRT 180℃ and 210℃. Once the FRT reaches 250℃, the hardness starts to decrease. As for the low-temperature toughness, the (L-T) Charpy absorption energy at -40℃ reaches the optimal value while the FRT is equal to 180℃. The Charpy absorption energy also exhibited a significant drop when the FRT increased to 250℃.

The microstructure of the plate of FRT 180℃ was examined by electron microscopes. The low-magnification SEM micrograph of PA500H is shown in Figure 3(a). From the SEM image, the microstructure is mainly composed of tempered martensite with dispersed fine carbides. In Figure 3(b), the high magnification bright field TEM image shows that the carbides are evenly spread inside the site lath. The sizes of the carbides are about 100nm in length and 30nm in width.

3.2 Effects of Rolling Temperature on the Texture and Low-Temperature Toughness

The DQST process cannot enhance the toughness of martensite in the same way as the traditional RQT process, which controls grain refinement through normalizing temperature and increases high-angle grain boundaries. For the AR400F abrasion-resistant steel with a higher toughness requirement, this study employs

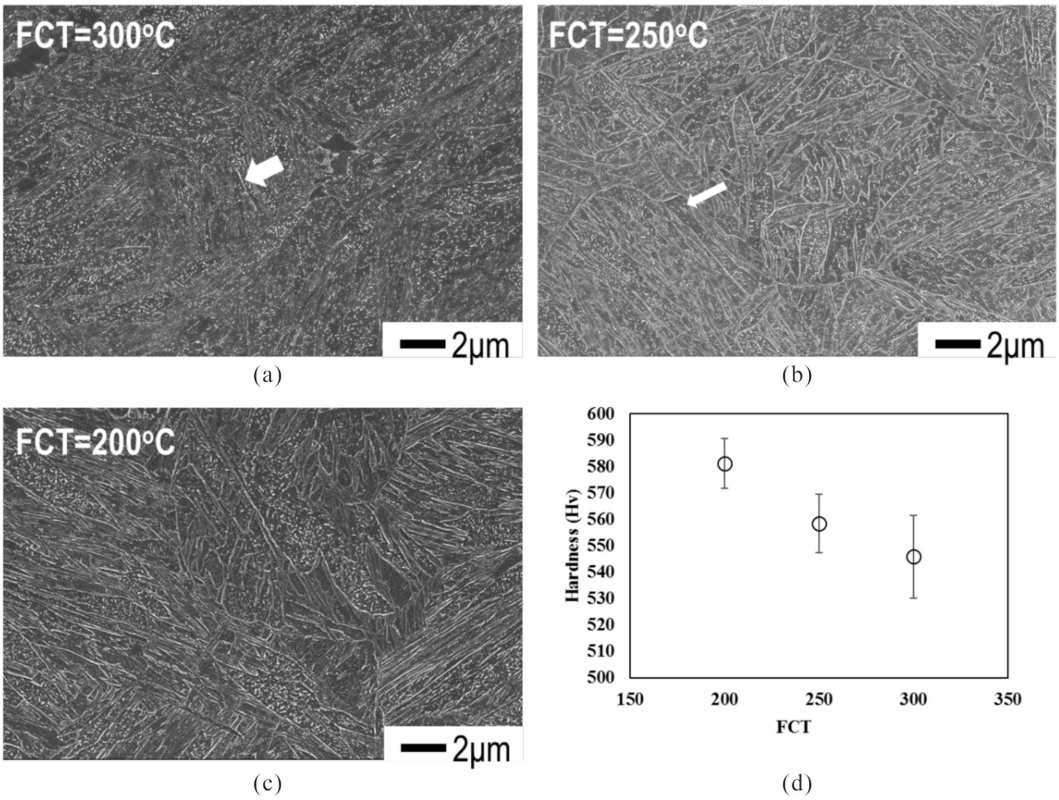
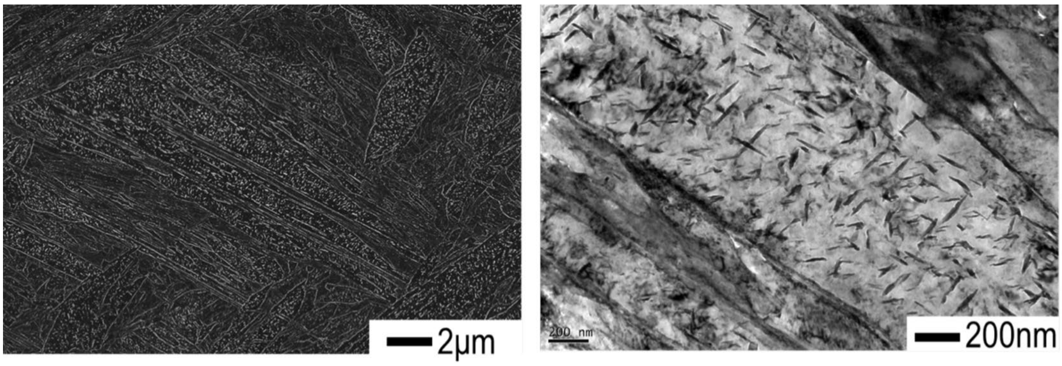


Fig.2. SEM micrographs of different finishing cooling temperatures: (a) FCT=300℃ (b) FCT=250℃ (c) FCT=200℃; (d) relation between hardness and finishing cooling temperature.

Table 1 Mechanical properties of the PA500H steel plate of different FRT.

FRT (℃)	$CVN_{-40℃ L}$ (J)	HBW
180	43.8	513
210	38.9	513
250	27.7	498



(a) (b)

Fig.3. (a) low magnification SEM micrograph (b) high magnification TEM micrograph of the PA500H steel plate.

texture control to enhance its toughness. Martensite with the {112}<110> crystallographic texture possesses two characteristics that benefit steel toughness(6), both related to its RD||<110> orientation. Firstly, when RD||<110>, martensite is more likely to activate the BCC structure's slip systems upon impact. This allows energy absorption through dislocation movement, preventing a transition from dislocation deformation to {001} transgranular cleavage due to slip systems being less prone to activation. Secondly, when RD||<110>, the {001} cleavage planes are perpendicular to it. If fracture mechanisms shift from dislocation deformation towards cleavage, these {001} planes, while susceptible to cleavage, can generate delamination to release stress in the vicinity of the crack tip, thereby enhancing toughness.

Theoretically, by microalloying elements and controlling rolling, it's possible to roll austenite into a pancake shape with a {112}<111> crystallographic texture. When combined with quenching during the DQST process, the resulting martensite can exhibit a {112}<110> texture favorable for toughness. In this process, the finishing rolling temperature significantly affects the geometry and crystallographic structure of the austenite, which in turn impacts the low-temperature toughness of the steel plate.

In this study, AR400F steel plates were produced using Nb-alloyed controlled rolling and the DQST process. The effect of finishing rolling temperature (FRT) on the steel plate's low-temperature toughness was analyzed. Figure 4 shows the impact energy at -40°C for different finishing rolling temperatures. High-temperature rolling results in an impact energy of approximately 50 J, while lowering the finishing rolling temperature increases the low-temperature impact energy to around 130 J, highlighting the significant impact of finishing rolling temperature on toughness.

Further analysis of the microstructures under high-temperature and low-temperature finishing rolling conditions (Figure 5) reveals that high-temperature rolling leads to a random distribution of grain orientation, whereas low-temperature rolling results in RD||<110> texture with more pronounced {112}<110> texture. Additionally, EBSD analysis of the {100} cleavage planes (Figure 6) shows that low-temperature rolled

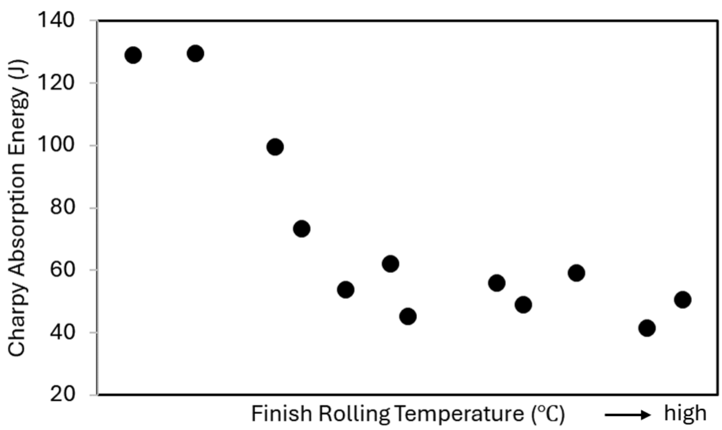


Fig.4. Influences of finish rolling temperature on the (L-T) Charpy absorption energy of AR400F at -40°C.

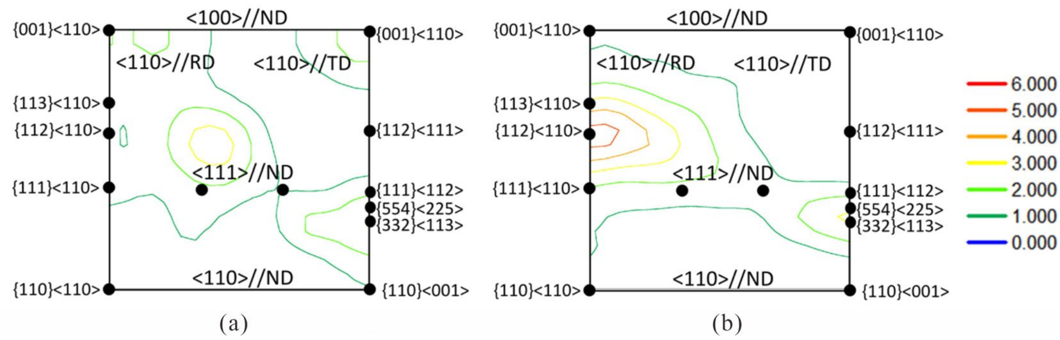


Fig.5. Orientation Distribution Function (ODF) in $\varphi 2=45^\circ$ of (a) high FRT (b) low FRT AR400F steel plates.

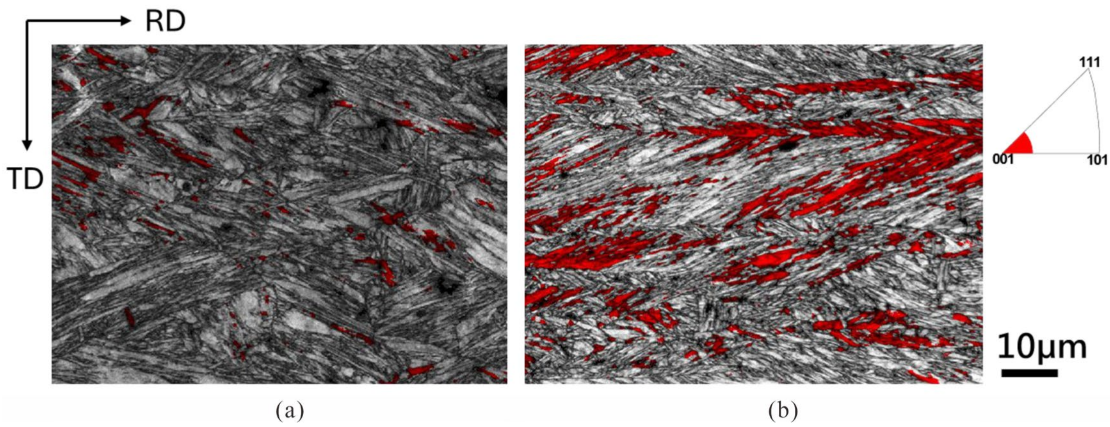


Fig.6. {100}⊥RD texture plots for (a) high FRT and (b) low FRT AR400F steel plates.

steel plates exhibit {100} cleavage planes predominantly perpendicular to the RD, accounting for 15.7% of the microstructure. However, the high FRT steel plates exhibit randomly distributed {100} cleavage planes, comprising only 4.2% of the microstructure.

The differences in these textures can cause the steel plate to split along these specific orientations for the low FRT steel plate when subjected to impact. These delamination cracks guide the propagation of crack tips, thereby preventing cracks from penetrating the steel plate and enhancing its low-temperature toughness. Figure 7 shows the fracture surface of a low FRT steel plate that has been tempered within the temperature range of tempered martensite embrittlement. From the appearance, it is evident that the steel plate exhibits crack-divider delamination (as the arrows indicate in the photo). The presence of delamination could prevent the occurrence of tempered martensite embrittlement and enhance the toughness of the plate.

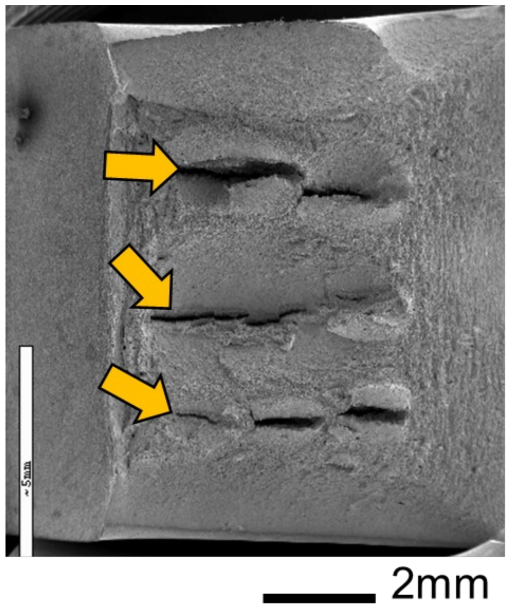


Fig.7. The fracture surface of the low FRT AR400F steel plate which was tempered in the temperature of tempered martensite embrittlement.

4. CONCLUSIONS

Conventional processes for abrasion-resistant steel plate often rely on repeated heat treatments to enhance impact toughness and widen its applications. However, this process results in high energy consumption and carbon emissions. In this study, an innovative metallurgical design known as Direct-Quenching Self-Tempering (DQST) was developed to lower carbon emissions for producing abrasion-resistant steels. By controlling the finishing cooling temperature in the direct-quenching process, the effects of martensite self-tempering could be controlled, and desirable mechanical properties could be obtained. For steel plates with higher requirements on low-temperature toughness, microstructure, and texture were controlled through the finish rolling temperature to increase the low-temperature toughness of the steel plates. The pancake-shaped grains with RD||<110> texture achieved excellent low-temperature impact toughness even in the tempered martensite embrittlement region, addressing issues of poor low-temperature toughness in abrasion-resistant steel plates and susceptibility to martensite temper embrittlement. This advancement expands the potential applications of future steel plates.

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