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EFFECTS OF HOT ROLLING REDUCTION ON MICROSTRUCTURAL EVOLUTION AND MECHANICAL PROPERTIES OF 1.25Cr-1Mo-0.5V-0.3C STEEL FOR HIGH-SPEED RAIL BRAKE DISCS

In this study, the effect of rolling of 1.25Cr-1Mo-0.5V-0.3C American Iron and Steel Institute 4340 modified steel for high-speed railway brake discs on the microstructure and mechanical properties was investigated. The materials were hot-rolled at 0%, 51%, and 66% reduction ratios, and then analyzed by optical microscopy, scanning electron microscopy, and electron backscattering diffraction (EBSD). needle-shaped ferrite block morphology in bainite varied with the rolling ratio. EBSD analysis reveals dynamic recovery and dynamic recrystallization, affected ferrite block boundaries and dislocation densities during rolling. Mechanical tests showed that hardness, toughness and elongation increase at higher rolling reduction ratio, while strength remained relatively constant. In particular, the impact toughness increased almost twice from the level of 70 J in S1 (0% reduction) to the level of 130 J in S3 (66% reduction). These results showed that the hot rolling can significantly improve the strength and toughness combination of cast brake discs material.

Keywords: Hot rolling; Rolling reduction; Toughness; Medium carbon steel; EBSD

1. Introduction

As global travel has become achievable within a day, there is progress in the development of various high-speed vehicles, including supersonic airliners and high-speed railways. In terms of land transportation, trains, automobiles, and motorcycles are commonly used. Furthermore, there is rapid advancement in the development and commercialization of next-generation trains, such as high-speed trains, maglev levitation trains, and hyperloop trains. Consequently, research is being conducted on the development of train components and material enhancement. Among components, brake discs for high-speed trains must possess excellent mechanical properties, including strength, toughness, and wear resistance, to handle the demands of high-speed operation [1]. Various methods can be employed to enhance mechanical properties. One accessible approach for cast steels disc is to apply plastic work, such as forging and rolling. Wrought steels are known to have fewer defects while exhibiting higher strength and toughness compared to cast steels [2,3]. That also offer superior resistance to fatigue cracking and a longer service life. In particular, hot rolling induces uniform deformation to form a homogeneous microstructure. Mechanical properties are further improved due to the occurrence of dynamic recovery (DRV) and dynamic recrystallization (DRX) during the thermal mechanical process of hot rolling [3,4]. However, few studies on the effect of hot rolling on high-speed rail brake disc steel have been conducted. In this paper, a study was conducted on the microstructure development and mechanical properties changes depending on rolling ratio in high-speed railway brake disc materials. The analysis results will be used to determine the optimal manufacturing process for the maximizing the physical properties of the brake disc material.

2. Experimental

The material used in this study was 1.25Cr-1Mo-0.5V-0.3C steel for high-speed rail brake discs manufactured by vacuum induction melting furnace (INDUTHERM, VTC800V). As shown in TABLE 1, the materials were hot-rolled at 1250°C by 4Hi HotCold Rolling System (MilaeCS, LDF 10000-100). The reduction ratio per pass was set to 30%, thereby the rolling pass

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TABLE 1

The hot rolling process variables of the test samples

Specimen	Number of rolling passes	One-pass reduction rate (%)	Total reduction rate (%)	Initial height (mm)	Final height (mm)
S1	0	0	0	25.0	25.0
S2	2	30.0	51.0	50.0	24.5
S3	3	30.0	66.0	65.0	22.3

was performed 2 to 3 times to change the overall reduction ratio to 51% and 66%. The hot-rolled materials denoted as S2 and S3 depending on the reduction ratio, meanwhile the materials for as casted denoted as S1. As shown in Fig. 1, the materials were subjected to quenching-tempering to generate homogeneous bainite structure in rolled block. Afterwards, the specimens for microstructure and mechanical properties were manufactured. All specimens were taken in the direction of the rolling direction (RD).

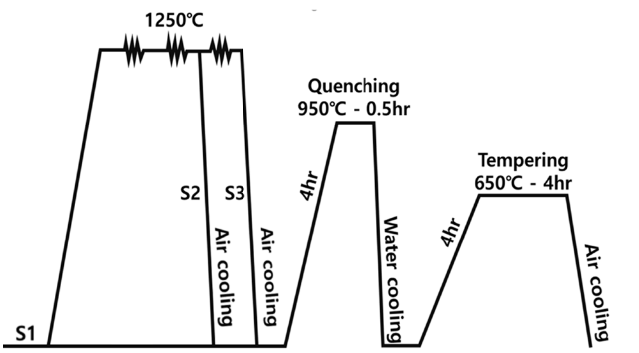

Fig. 1. Schematic illustration of hot rolling and heat treatment process

The specimens were polished until one micrometer, and etched with a 3% Nital solution (97 mL of ethanol + 3 mL of nitric acid). Microstructures were observed using an optical microscope (OM; Leica DM 2700M) and a field emission-scanning electron microscope (FE-SEM; JEOL JSM-7200F). After micro-polishing and stress relief polishing with colloidal silica, electron backscatter diffraction (EBSD; JEOL JSM-7200F) and orientation imaging microscopy (OIM) software analysis were performed. In addition, for mechanical property analysis, hardness, tensile, and Charpy impact test were conducted in accordance with American Society for Testing and Materials E8 and A370.

3. Results and discussion

Fig. 2 shows the microstructure after heat treatment of 1.25Cr-1Mo-0.5V-0.3C steel hot-rolled at 1250°C observed by OM and FE-SEM. In all specimens, needle-shaped ferrite blocks representing bainite microstructure were observed. From the OM observation, for the Fig. 2a (without rolling), the ferrite blocks were observed coarse and distinct. In Fig. 2b, in which hot rolling with 50% reduction was performed, the ferrite block boundaries were blurred and needle ferrite block directions scattered. The vague grain boundary was a result of the dynamic recovery (DRV) during rolling, while dynamic recrystallization (DRX) was not fully achieved. For the Fig. 2c, in which hot rolling was performed with 67% reduction, the microstructure exhibited elongation along the rolling direction (RD), despite undergoing austenizing heat treatment. Meanwhile, both DRX and DRV occurred, leading to grain refinement.

Needle-shaped ferrite blocks were observed through FE-SEM analysis (Fig. 2d). Fig. 2e exhibited highly refined grains, indicating by DRV and partial DRX during multi-pass rolling. In Fig. 2f, grain boundaries were clearly observed, and the ferrite blocks within the grains were distinctly visible. Equiaxed grains were observed due to the growth of recrystallized ferrite blocks. This phenomenon can be attributed to the insertion of an excessive amount of additional shear strain into the material during the rolling process, resulting in a significant dislocations accumulation required for DRX [3-5].

Fig. 3 shows the results of EBSD analysis. In Fig. 3a and 3d, prior austenite grain (PAG) boundaries with were observed. As a result, the ferrite block textures displayed regular orientation arrangements. However, in Fig. 3b and 3e, the PAG boundaries were hardly visible, leading to a random arrangement of ferrite block orientations. This can be attributed to the presence of

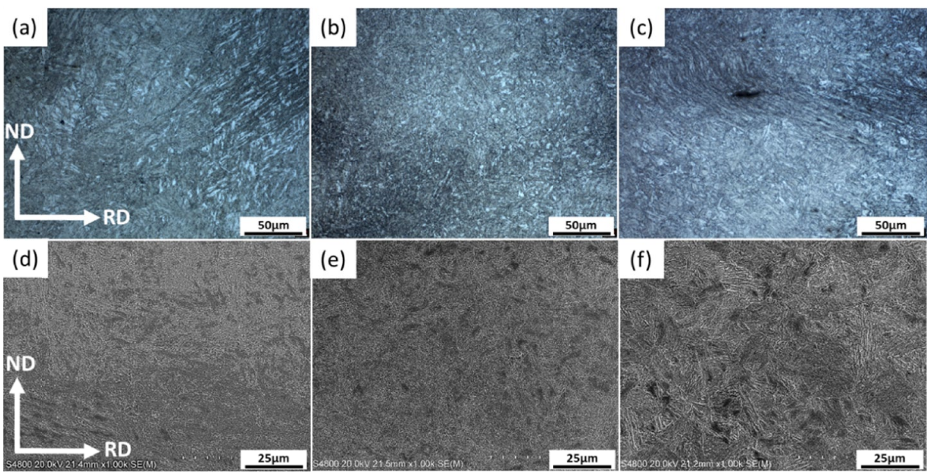

Fig. 2. Microstructure depending on rolling ratio observed from OM (a-c) and FE-SEM (d-f): (a), (d) S1, (b), (e) S2, (c), (f) S3

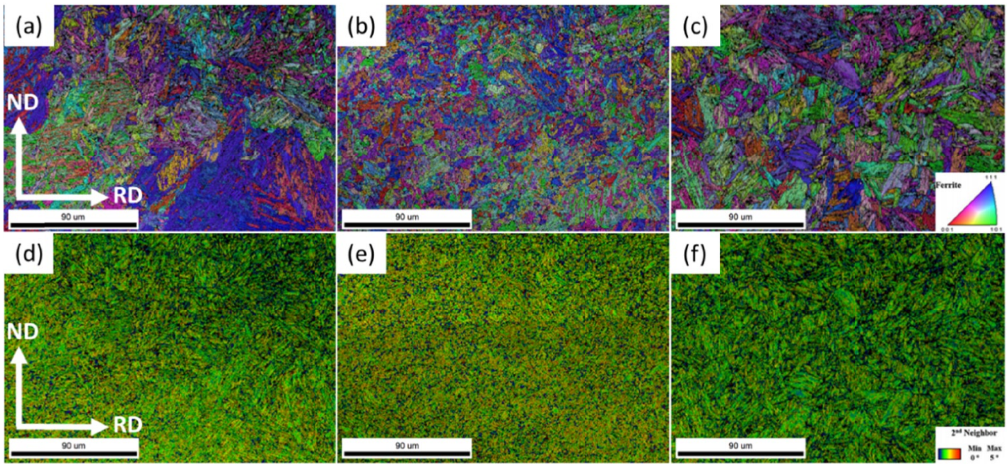

Fig. 3. Inverse pole figure (IPF) maps (a-c) and kernel average misorientation (KAM) maps (d-f) from EBSD: (a), (d) S1, (b), (e) S2, (c), (f) S3x

dynamic recrystallization (DRV) and discontinuous dynamic recrystallization (DDRX) in the ferrite blocks [5]. DDRX is associated with the high density of dislocation observed in KAM images (Fig. 3d-f). In S2, the dislocation network formed during hot rolling did not accumulate enough energy to develop low-angle grain boundaries (LAGB) with misorientation of 2-15°. Consequently, dislocation networks with a high density of dislocation were maintained. In this DDRX state, the network did not fully integrate into the matrix, resulting in irregular directional arrangement of textures and high dislocation density [6].

In Fig. 3c and 3f, locally arranged grains were observed, which had regular orientation. This was because of the ongoing process of dynamic recrystallization (DRV) and continuous dynamic recrystallization (CDRX) that occurred during repeated hot rolling [3,5]. In addition, as a result of observing the KAM image, it was evident that the dislocation density was remarkably low. This was because the energy present in the dislocation network created during the rolling process allowed LAGB to form and grow into the surrounding matrix [5,6]. Consequently, ferrite blocks with regular arrangement and reduced dislocation density could be observed.

Fig. 4 presents mechanical properties' results based on the rolling reduction ratio. Increasing the rolling reduction led to higher hardness, toughness, and elongation. However, there was little variation in strength. In S2, a 75% improvement in impact toughness compared to S1 was measured. S3 exhibited an 89% increase in impact toughness compared to S1 and a 15% increase compared to S2. Elongation also showed an increase. Essentially, increasing the rolling reduction through hot rolling resulted in a material with comparable strength and hardness but improved ductility. This enhancement in toughness could be attributed to grain refinement achieved through dynamic recrystallization (DRX) and dynamic recovery (DRV), in contrast to casting steels [7]. While the toughness benefits from grain refinement [8], there was no increase in strength. This could be attributed to the presence of high dislocation density leading to internal stress in S2, while S3 exhibited a lower dislocation density resulting in reduced internal stress and consequently decreased strength. This finding was demonstrated by Thirathipviwat et al. [9]. The lower dislocation density in S3, as compared to S2, could be attributed to the formation of low-angle grain boundaries (LAGB) through the development of a high-density dislocation network. Sakai et al. confirmed these results, indicating that the sliding of the high-density dislocation network promoted the rotation of sub-grains, leading to the propagation of grain boundary cracks [5]. Grain textures were analyzed using Euler spaces, as depicted in Fig. 5.

Fig. 5 shows Euler spaces which can confirm the grain orientations. In S1, the solidification textures were arranged by the {111} <123>, {113} <130>, and Cube {001} <100>. In S2, arrangements of G/B {110} <111> (grain boundaries), Brass {110} <112>, Cu {112} <111>, and {001} <120> were observed. In S3, ND//<111> (γ-fiber), {001} <230>, and {111} <123> arrangements were confirmed. S1 material with Cube {001} <100> texture changed to G/B {110} <111> (grain boundaries) and Brass {110} <112> textures in S2 as rolling progressed [10]. Finally, for S3 had ND//<111> (γ-fiber) texture with the highest toughness. It is known that the development of ND//<111> (γ-fiber) texture improves formability. It is considered that

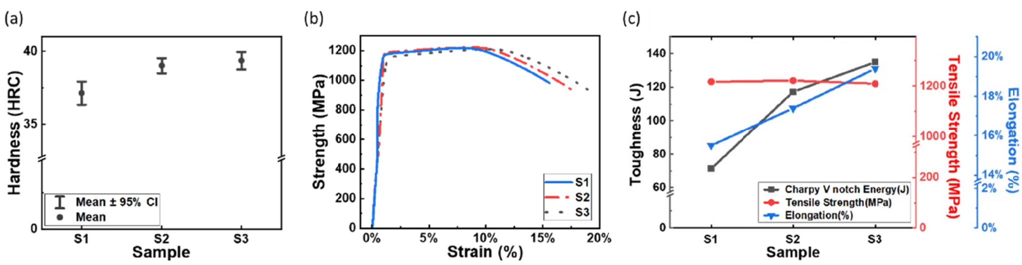

Fig. 4. Mechanical properties depending on rolling reduction: (a) hardness, (b) stress-strain curve, (c) toughness, tensile strength, elongation

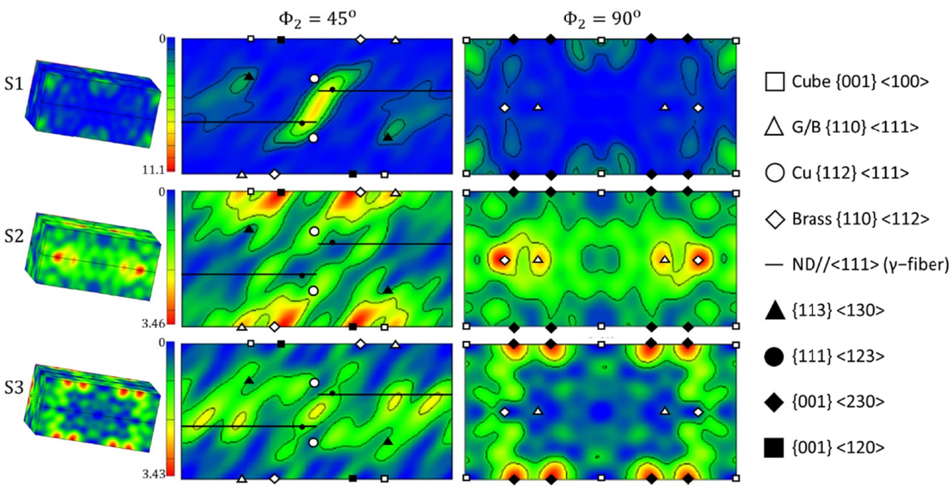

Fig. 5. EBSD Texture in Euler space confirmed at $\Phi_2 = 45°$ and 90°

ND//<111> texture arranged through a high plastic deformation ratio (r-value) simultaneously increased the elongation owing to the high formability [11]. For this reason, in Fig. 4, the result was consistent with that of S3 having the highest toughness.

4. Conclusions

In this paper, mechanical properties and microstructure were observed depending on rolling reduction ratio during hot rolling:

1. DRV and DDRX occurred when the rolling reduction was 50%, meanwhile DRV and CDRX occurred when the rolling reduction progressed to 67%;
2. As the rolling reduction increased, the hardness, toughness, and elongation tended to increase in a similar strength range;
3. When the rolling reduction was 67%, ND//<111> (γ-fiber) texture was most developed, which led to an increase in elongation;

From these experiments, the material with a rolling reduction of 67% had the best impact toughness. The optimal combination of strength and toughness could be selected through heat treatment of the material and used as a brake disc material.

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Conflicts of Interest

The authors declare no conflict of interest

Author Contributions

Hyo-Seong Kim: Investigation, Methodology, Writing – original draft & review & editing, preparation. **Moonseok Kang**: Investigation, Methodology, Writing – original draft, preparation. **Minha Park**: Investigation, Methodology. **Byung Jun Kim**: Investigation. **Yong-Shin Kim**: Resources. **Tae Young Lee**: Resources. **Byoungkoo Kim**: Conceptualization, Investigation, Funding acquisition, Supervision, Writing – original draft, preparation. **Yong-Sik Ahn**: Conceptualization, Supervision, Writing – review & editing.

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