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Effects of the thermomechanical treatment on the microstructure and mechanical properties of ferrite–martensite dual phase steel

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ABSTRACT

Purpose: The study aims to investigate the effects of thermomechanical treatment, including tempering and hot–rolling, on the microstructure and mechanical properties of ferrite–martensite dual phase steel.

Design/methodology/approach: The initial steel billet was a hypoeutectoid steel, which was annealed at 1000°C, then hot–rolled at 920°C, followed by austenitisation at various temperatures (730, 770, 800, and 830°C), and finally quenched to obtain ferrite–martensite dual phase steel. X-ray diffractometer and optical microscopy investigated the microstructure and grain size of the dual-phase steel. Mechanical properties such as hardness, elongation, and tensile strength were also examined.

Findings: The grain size decreased with increasing elongation percentage and remained constant after an elongation of 30%. The martensite/ferrite phase ratio increased with higher tempering temperatures. The hardness, elongation, and tensile strength reached a maximum when the tempering temperature was 800°C.

Research limitations/implications: Future studies could consider the effect of hot–rolling temperature or cold-rolling.

Practical implications: The study proposes a straightforward and efficient thermomechanical treatment process to transform hypereutectoid steel into ferrite-martensite dual-phase dual-phase steel with improved mechanical properties.

Originality/value: The study reveals the contributions of grain size and the martensite/ferrite ratio to the mechanical properties of ferrite–martensite dual steel through thermomechanical treatment.

Keywords: Dual-phase steel, Ferrite, Austenite, Martensite, Thermomechanical treatment, Mechanical properties

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MATERIALS

1. Introduction

High-strength low-alloy (HSLA) steels, including dual phase (DP) steels such as ferrite-martensite, ferrite-bainite, and ferrite-martensite-bainite, have been extensively studied. The steels typically consist of the continuous ferrite phase with another phase uniformly distributed within it. The major alloying elements in DP steels are C, Mn, Si, and Cr. The DP steels exhibit a wide range of ultimate tensile strength, ranging from 450 to 1200 MPa, and elongation percentages ranging from 10% to 40% [1-3]. When the primary phases are ferrite and martensite, the mechanical properties of DP steels can be controlled by adjusting the phase ratio [4].

Various techniques are employed to manufacture DP steels. One approach involves annealing the steels at a temperature where two phases, α and γ, coexist, followed by quenching in water to achieve a ferrite–martensite microstructure. Another technique is isothermal quenching, which leads to a ferrite–bainite microstructure. The ratio between the discrete and continuous phases depends on the annealing temperature and duration.

In order to elucidate the origin of superior mechanical properties of DP steels, effects of grain size [5,6], martensite/ferrite strain ratio [7], volume fraction of martensite [5], and constituent phases morphology [6,8] have been investigated. The yield-strength/tensile-strength ratio decreases as the grain size of the ferrite phase increases, reaching a constant value after a certain ferrite grain size of approximately 60 μm [5]. However, the tensile strength of DP steels exhibits a nonlinear relationship with the martensite volume fraction [9]. Therefore, the strength of DP steels mainly depends on the nanohardness of the martensite phase and the difference in hardness between the martensite and ferrite phases [10]. Tempering can reduce the nanohardness of the ferrite and martensite phases [11,12].

Additionally, reducing the nanohardness difference between the martensite and ferrite phases effectively mitigates void formation in the martensite phase [13]. Furthermore, the carbon concentration in martensite and its morphology also influences the strength of DP steels [14]. Increasing the carbon concentration in the martensite phase while maintaining a constant martensite/ferrite phase ratio improves the ductility of the steel [15-17].

In the article, we investigate the effects of thermo-mechanical treatment on the microstructure and mechanical properties of DP ferrite-martensite steels. By controlling the hot-rolling process, we manipulate the grain size to analyse its impact on the mechanical properties of DP steel. Furthermore, we explore the influence of annealing temperature on the martensite/ferrite phase ratio, which subsequently affects the mechanical properties. Thus, we can achieve dual-phase ferrite-martensite steels with high strength and ductility by precisely controlling the thermomechanical treatment.

2. Materials and experiments

The given section shows the preparation of the steel billet, which was compositionally confirmed by Optical Emission Spectrometry (OES). The prepared steel was annealed, hot–rolled, and quenched to final samples. The samples were investigated by Optical Microscopy, X-ray diffractometer, and mechanical testing to obtain microstructure and mechanical properties.

2.1. Materials

The initial steel billet is cast in a vacuum furnace. The composition of the billet is confirmed by OES and listed in Table 1.

Table 1.
Composition of the steel billet, wt.%

Elements	C	Si	P	S	Cr
wt.%	0.2200	1.6007	0.0212	0.0089	0.0101
Elements	Mo	Ni	Mn	Al	Cu
wt.%	0.0062	0.0456	1.3978	0.0605	0.0399

The critical temperature $Ac1$, $Ac3$, Bs, and Ms are calculated by:

$$Ac1 = 723 - 10.7 \times \mathrm{Mn} - 16.9 \times \mathrm{Ni} + 29.1 \times \mathrm{Si} + 16.9 \times \mathrm{Cr} \quad (1)$$

$$Ac3 = 910 - 203 \times \sqrt{C} - 15 \times \mathrm{Ni} + 44.7 \times \mathrm{Si} + 104 \times \mathrm{V} + 31.5 \times \mathrm{Mo} \quad (2)$$

$$Bs = 830 - 270 \times \mathrm{C} - 90 \times \mathrm{Mn} - 37 \times \mathrm{Ni} - 70 \times \mathrm{Cr} - 83 \times \mathrm{Mo} \quad (3)$$

$$Ms = 539 - 423 \times \mathrm{C} - 30.4 \times \mathrm{Mn} - 7.5 \times \mathrm{Si} + 30 \times \mathrm{Al} \quad (4)$$

where $Ac1$ and $Ac3$ are critical temperatures for austenite transformation, Bs and Ms are bainite and martensite start temperatures. Mn, Ni, Si, and so on are the composition (wt.%) of the steel. Hence, the critical temperatures $Ac1$ and $Ac3$ are 728 and 832°C, respectively.

Thermal expansion of the steel was measured by a dilatometry (ZRP-1, Beijing Jingyi Gaoke Instrument) and illustrated in Figure 1. According to Figure 1, the actual critical temperatures $Ac1$ and $Ac3$ were 716 and 872°C. Hence, the heat treatment would be conducted in two phases region, from 730 °C to 830 °C.

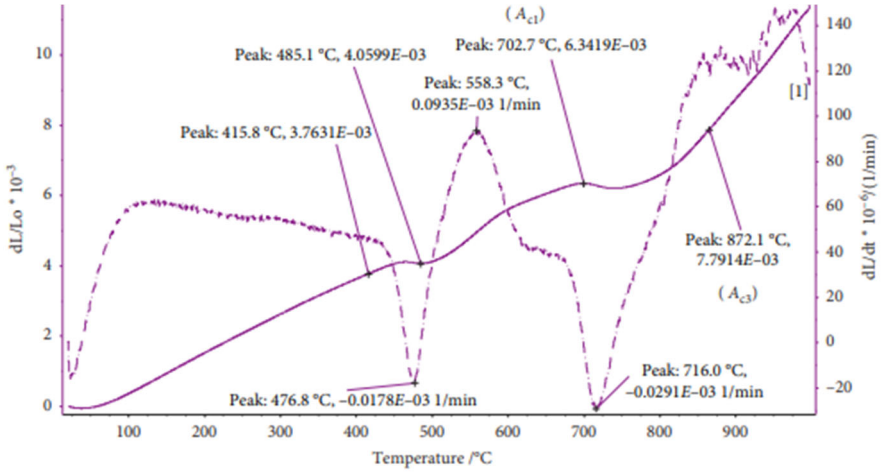

Fig. 1. Thermal expansion of the steel

2.2. Experiments

The billet underwent a four-step thermomechanical treatment process. In the first step, the billet was annealed at 1000°C for 3 hours to dissolve and redistribute any segregation within the steel.

In the second step, the billet was hot rolled at 920°C, equivalent to $Ac3$ + 30°C. Following the step, the billet thickness was reduced by 30%, 40%, and 50%.

In the third step, the as-rolled steels were partially austenitised at a temperature between $Ac1$ and $Ac3$, which are critical temperatures for austenitisation. Four different austenitisation temperatures were investigated in this study: 730, 770, 800, and 830°C.

Finally, the steels were quenched using water to obtain the desired ferrite–martensite DP alloys. The steel samples were assigned names as listed in Table 2.

Table 2.
Sample names according to austenitisation temperatures and elongation percentages

Austenitisation temperatures, °C	Elongation percentage, %			
	0	30	40	50
730	M01	M02	M03	M04
770	M05	M06	M07	M08
800	M09	M10	M11	M12
830	M13	M14	M15	M16

2.3. Characterization

The samples underwent two etching processes. In the first etching, a 4% Nital solution was used to make the grain boundaries visible. In the second etching, a 10% $Na_2S_2O_5$ aqueous solution was used to reveal the phase contrast. The etched samples were then observed by optical microscopy (Axiovert – 25CA) to analyse the microstructure. The phase ratio and gran size were further analysed by the ImagePlus software. The grain size was calculated by determining the average size of grains.

The phases in the samples were characterised using an X-ray diffractometer (Aeris – Malvern Panalytical). The crystallographic structure of the samples was examined by electron backscatter diffraction (Aztec EBSD – Oxford Instruments).

3. Results and discussion

3.1. Microstructure

Figure 2 illustrates the microstructure of samples with varying elongation percentages and tempering temperatures. When comparing the rolled samples to the unrolled ones, it can be observed that the rolled samples exhibit elongated grains ranging in size from 20 to 40 μm. At the tempering temperature of 730°C, it is difficult to observe the presence of martensite, indicating that the conversion of austenite to martensite was minimal. However, at the other temperatures examined, the presence of the martensite phase is observable in the samples.

The crystal orientation is depicted in Figure 3. It is highly evident that the (111) system, known for its high sensitivity to slipping, is likely to be prominently observed in this steel system.

Figure 4 depicts the relationship between grain size and elongation percentage. As observed in the figure, the grain size decreases following hot rolling. Specifically, the average

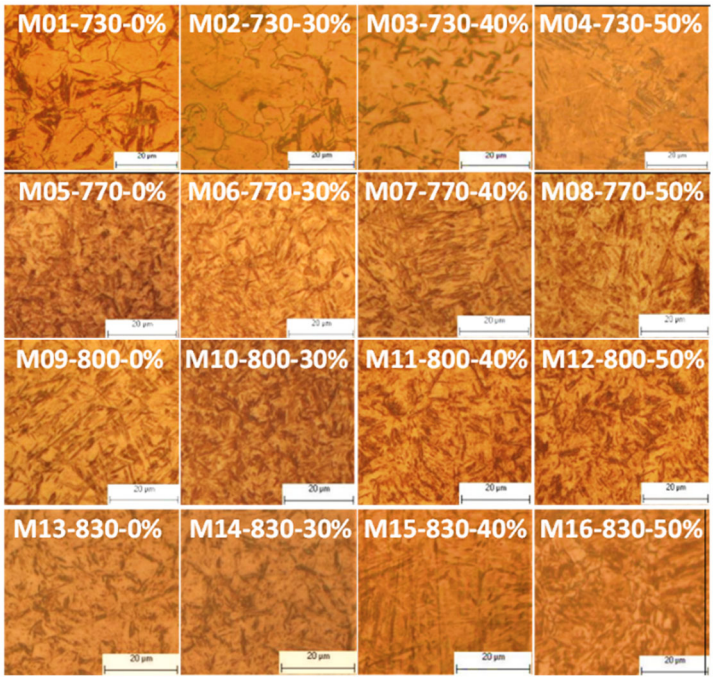

Fig. 2. Optical images of samples with different elongation percentages and tempering temperatures. Scale bar 20 µm

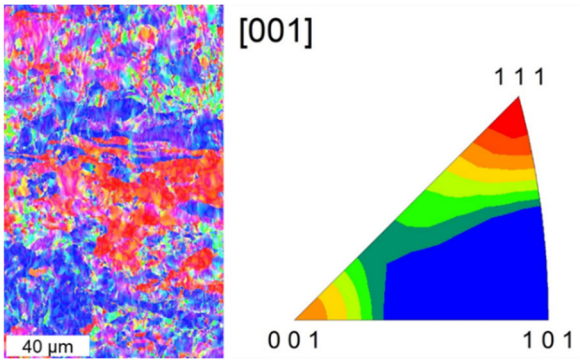

Fig. 3. Local crystal structure and crystal orientation at the surface of the sample M10

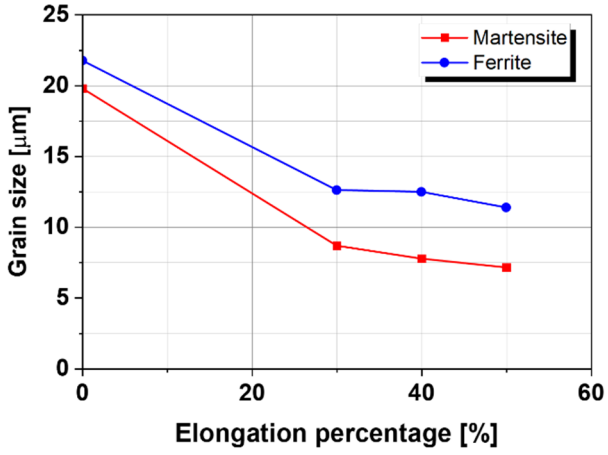

Fig. 4. Dependence of grain size on elongation percentage

grain size of martensite and ferrite notably reduces from 19.8 µm and 21.7 µm (without hot rolling) to 8.5 µm and 12.6 µm, respectively, at an elongation percentage of 30%. However, the grain size decreases slightly when the elongation percentage is further increased.

According to the X-ray diffraction pattern of sample M12 in Figure 5, the microstructure includes ferrite, martensite, and retained austenite. It is important to note that the transformation of austenite to martensite is a diffusionless process, and in many cases, a complete transformation of austenite to martensite does not occur. Hence, both ferrite and austenite become the ductile matrix of the alloys.

Figure 6 displays optical images and phase contrast of sample M16. The martensite phase is highlighted in red, while the remaining phases, primarily ferrite, are represented in grey. In such a case, the ratio of martensite to the remaining phase is approximately 1:4.

Figure 7 depicts the phase ratios of samples M03, M07, M11, and M15, all having an elongation percentage of 40%. It is observed that the martensite/ferrite phase ratio shows a linear increase as the tempering temperature increases. It can be explained by the fact that increasing the tempering

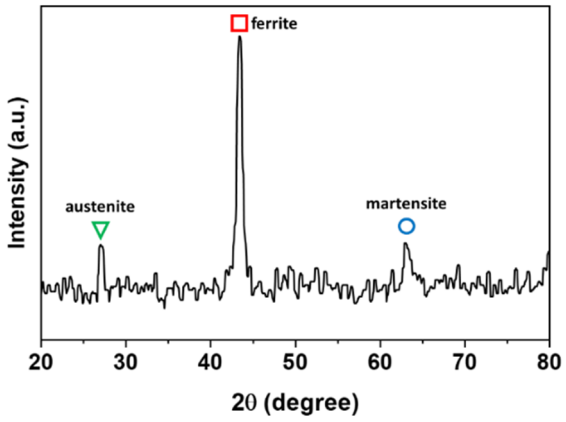

Fig. 5. X-ray diffraction of sample M12

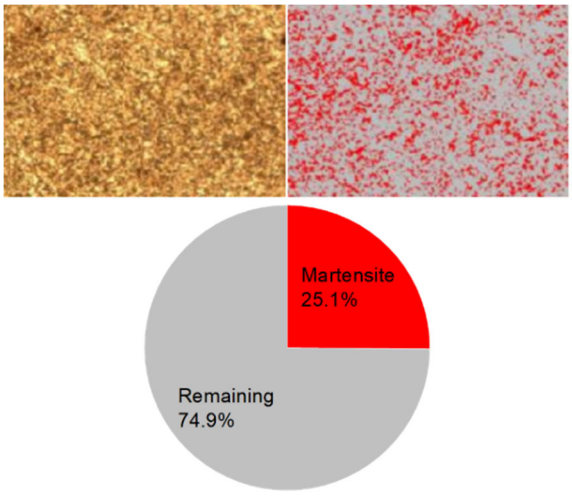

Fig 6. Phase contrast and phase ratio of sample M16

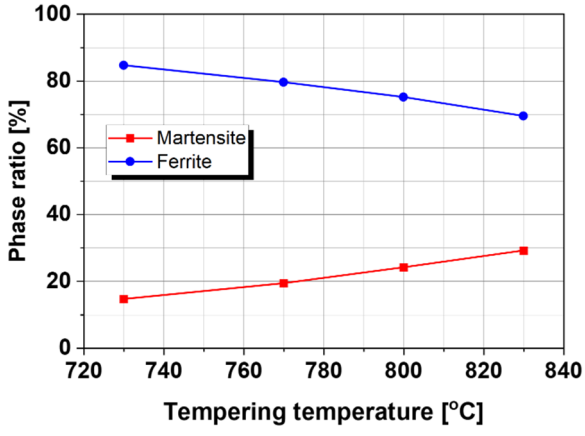

Fig. 7. Dependence of phase ratio on the tempering temperature of 40% elongation percentage samples

temperature leads to decreased carbon content in austenite, thereby increasing the austenite ratio. Consequently, after quenching, the martensite ratio increases. Considering that the initial steel has a carbon content of 0.384%, the maximum martensite ratio reaches 30% at a temperature of 830 °C, which is very close to the critical temperature $Ac3$.

3.2. Mechanical properties

According to Figure 8(a), the ultimate tensile strength shows improvement with increasing tempering temperature, rising from 691 MPa at 730°C to 763 MPa at 800°C. Beyond that temperature, the strength remains relatively constant. Additionally, the strain exhibits only slight variations due to tempering temperature. The strain slightly increases from 20.8% at 730°C to 24% at 800°C, but then abruptly decreases to 17.5% at 830°C, as Figure 8(b) shows. Such behaviours can be explained by considering the carbon content and martensite ratio. According to the Fe-C phase diagram and Figure 7, the saturated carbon content in austenite decreases as the temperature increases while steels the martensite ratio increases. Both effects have opposing

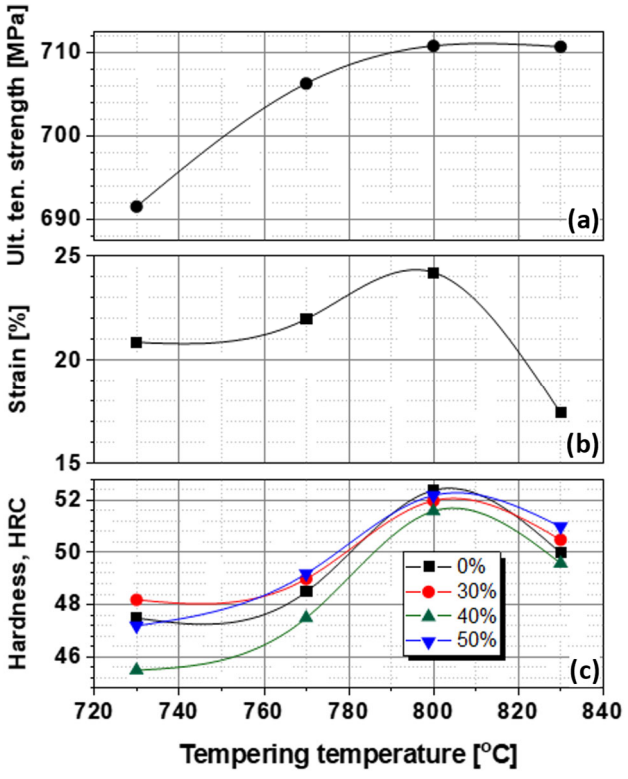

Fig. 8. Dependence of (a) ultimate tensile strength and (b) strain on tempering temperature, (c) hardness (HRC) of the concerning elongation percentage and tempering temperature

impacts on the strength and strain of the steel. A lower carbon content promotes higher strain but diminishes strength, whereas a higher martensite ratio significantly enhances the strength of the steel.

Indeed, the effects of martensite ratio and carbon content on the mechanical properties of the DP steel can be further demonstrated by the macro hardness results presented in Figure 8(c). In general, hardness and ultimate tensile strength exhibit a linear relationship. As depicted in Figure 8(c), the hardness increases with increasing tempering temperature and reaches its peak at 800°C. However, beyond the temperature, the hardness starts to decrease. Such a trend aligns with the observations made for the ultimate tensile strength.

Therefore, it can be concluded that both the martensite ratio and carbon content have a combined contribution to the overall mechanical properties of the dual-phase steel. The martensite ratio significantly influences the hardness and strength, while the carbon content impacts the strain and ductility of the material.

4. Conclusions

The article focuses on investigating the mechanical properties of ferrite-martensite dual-phase steel, particularly emphasising the influence of thermomechanical treatment. The results indicate that the hot-rolling process effectively reduces the grain size, leading to an enhancement in the strength of the steel. Furthermore, tempering at a temperature within the critical two-phase temperature range, particularly at around 800°C, promotes the austenitisation process. As a result, the martensite phase ratio increases after quenching. Such increased martensite content contributes to elevated hardness and ultimate tensile strength in the dual-phase steel, reaching up to 52 HRC and 710 MPa, respectively.

Furthermore, at higher temperatures, the low carbon concentration in the austenite phase has a slight positive effect on the ductility of the dual-phase steel. Overall, the findings highlight the significance of thermomechanical treatment in tailoring the microstructure and mechanical properties of ferrite-martensite dual-phase steel, leading to improved strength and ductility.

Acknowledgements

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