

Comparison of microstructure and mechanical behavior of lower bainite and tempered martensite in JIS SK5 steel

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Abstract

This study investigated the microstructures and mechanical properties of lower bainite and tempered martensite in JIS SK5 steel. At equivalent hardness, the toughness and ductility of lower bainite are superior to those of tempered martensite. However, the lower bainite has a lower yield strength owing to that the bainite sheaf is larger than the tempered martensite plate. The fracture surface of lower bainite exhibits transgranular cleavage and differs considerably from that of tempered martensite. Tempered martensite embrittlement (TME) occurred in the tempered martensite, which is dominated by intergranular failure. It is caused by grain boundary segregation of phosphorus and grain boundary precipitation of carbide during tempering. Additionally, the size of the cleavage facet of lower bainite was demonstrated to be correlated with the width of the bainite sheaf. The results of electron back-scatter diffraction (EBSD) analysis indicates not only that the sheaf boundary is a high-angle boundary, but also that the cleavage crack travels along the $\{001\}$ ferrite plane, whose surface energy is low.

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1. Introduction

JIS SK5, a high-carbon tool steel, is often used as a commercial material for making hose clamps in the auto industry. The toughness and ductility of this steel can be improved by replacing conventional quenching and tempering with austempering, which transforms the structure of the material into a bainitic structure instead of a martensitic structure.

A question arises regarding whether the bainitic structure is necessarily tougher than the martensitic structure at the same hardness. The presence of internal twins in martensite may reduce its ductility [1,2] and causes the toughness to be inferior to that of bainite at the same strength [3]. Comparing untwinned martensite with bainite reveals the opposite result [4–6]. Internal twins herein always supply interfaces for the precipitation of carbide. These carbide precipitates act as strong barriers to the motion of dislocations, subsequently causing high stress concentrations where cracks are nucleated.

Tempered martensite embrittlement (TME), which reduces toughness at tempering temperatures of 250–400 °C is also taken

into account in this work. Horn and Ritchie [7] classified the fracture mechanisms of TME into transgranular cleavage, interlath cleavage and intergranular cracking, according to fracture morphologies. The fracture mode of steels that contain a small amount of impurities and retained austenite will be transgranular cleavage. Steels that contain larger volume fractions of austenite fracture by interlath cleavage due to the mechanical instability of the retained interlath austenite, which transform into interlath carbide and an interlath layer of martensite. When the grain boundary of the prior austenite includes sufficient segregated impurities and carbide precipitates, the resulting fracture mode will be intergranular cracking.

This study compares the mechanical properties of tempered martensite with lower bainite at a given hardness in SK5 steel. It focuses on explaining why lower bainite is tougher than tempered martensite. Moreover, the fracture behaviors of two structures are discussed.

2. Experimental

Table 1 presents the chemical composition of JIS SK5 steel used in this study. The standard sub-size Charpy V-notch specimens with a thickness of 2.5 mm and tensile specimens with gauge dimensions of 25 mm × 5 mm × 3 mm were machined from the as-received steel plates. All test specimens were heated in salt bath furnaces using three heat treatments to yield lower bainite and tempered

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Table 1

Chemical composition of JIS SK5 steel (wt.%)

C	Si	Mn	P	S	Ni	Cr	Mo	Fe
0.78	0.21	0.45	0.015	0.002	0.007	0.16	0.002	Bal.

martensite with equivalent hardness. The first treatment involved austempering, the second was conventional quenching and tempering, and the third was marquenching and tempering. Fig. 1 schematically depicts the heat treatment procedures. Herein, two sets of treatment of tempered martensite were applied to distinguish their fracture behaviors.

Mechanical impact tests were conducted using a 50-J Charpy machine at room temperature. Tensile tests were performed using a MTS testing machine at a strain rate of $1 \times 10^{-4} \text{ sec}^{-1}$. Hardness was measured using a Rockwell (C scale) hardness test machine. The microstructure was observed after polishing and etching with a 2% nital solution, and the metallographic samples were observed using an optical microscope (OM). Thin foils were prepared for transmission electron microscope (TEM) using double-jet electropolishing at 0°C and 80 V with a 5% perchloric acid–25% glycerol–70% ethanol electrolyte. They were investigated using JEOL2000EX TEM at 200 kV.

Following impact testing, the fracture surfaces of specimens were investigated using scanning electron microscope (SEM, Philip XL30) at 20 kV. Furthermore, the crystallographic information regarding the fracture surface was obtained using electron back-scatter diffraction (EBSD) technology within SEM (JEOL 6500F). The microchemistry characteristic of the fracture surface was also analyzed using a PHI 660 scanning electron spectroscopy (AES) at 5 keV.

3. Results and discussion

3.1. Microstructure analysis

Fig. 2 presents the optical microstructures of lower bainite and tempered martensite. After austempering at 300°C for 1 h, a full typical lower bainite structure was obtained, as shown in Fig. 2(a). The sheaf of lower bainite was around $1\text{--}5 \mu\text{m}$ wide and $20\text{--}30 \mu\text{m}$ long. After marquenching and tempering at 330°C for 1 h, almost all of the matrix was transformed into plate-martensite, because of its high carbon content. The

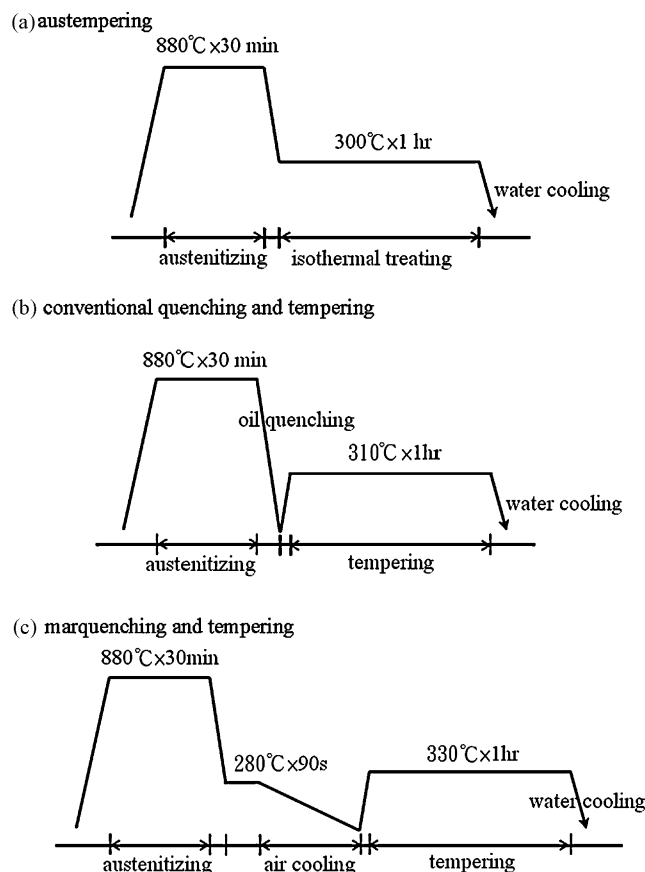


Fig. 1. Schematic illustration of heat treatments.

tempered martensite plate appears to be smaller, being around $0.5\text{--}2 \mu\text{m}$ wide and $10 \mu\text{m}$ long, as presented in Fig. 2(b).

Fig. 3 displays transmission electron micrographs of these two structures. Fig. 3(a) reveals that bainitic ferrite is plate-like, and carbide platelets are embedded in the bainitic ferrite and precipitated unidirectionally at an angle of $55\text{--}60^\circ$ to the long

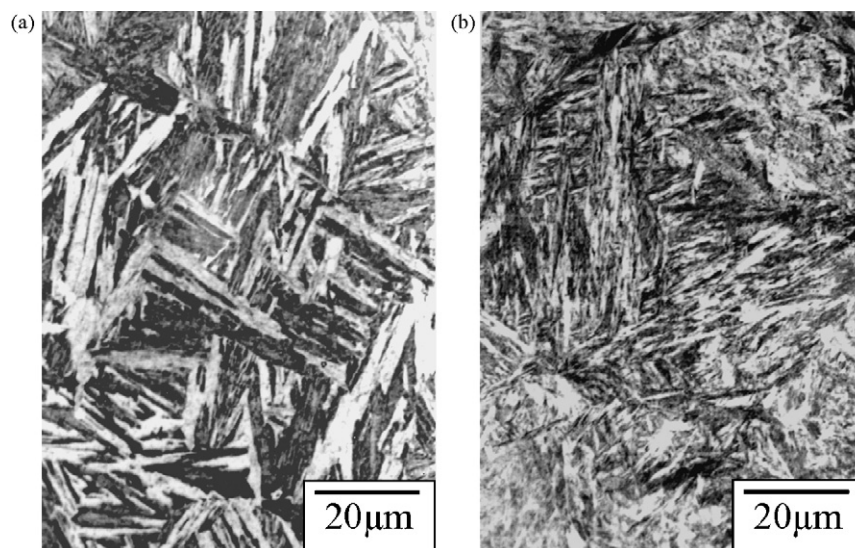


Fig. 2. Optical micrographs of transformation products; (a) austempering at 300°C for 1 h, lower bainite and (b) marquenching and tempering at 330°C for 1 h, tempered martensite.

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