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Materials

Microstructure and mechanical properties of automobile beam steels produced by EAF-CSP process

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Abstract: The microstructure, mechanical properties, and misorientation of automobile beam steels produced by EAF-CSP process were studied using optical microscopy (OM) and electron back-scattered diffraction (EBSD). It is shown that the microstructure of strips is mainly polygonal ferrite, and the average grain size is about 5-8 μm. The electron back-scattered diffraction results show that grain boundaries in ferrite are basically high-angle grain boundaries without remarkable preferred orientation. Hot strips of automobile beam steels possess a good combination of strength and plasticity because of their fine microstructures and low quantity of impurities.

Key words: steel; CSP; microstructure; mechanical property; electron back-scattered diffraction

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1. Introduction

Compact strip production (CSP) is an advanced manufacturing technology that is currently employed in the production of steels in steel industry, and this technique is used to produce hot strips using a short product line, involving the principles of science, technology, and engineering. Since the first CSP steel plant was commissioned at Nucor in 1989, 39 production mills with 54 strands have been established worldwide. There are distinct differences between CSP and conventional processes with respect to slab casting, reheat schedule, rolling process, delivery speed on the runout table, and so on [1], especially with respect to thermal history; the CSP technology exhibits $\gamma\rightarrow\alpha$ thermal history, whereas the conventional technology exhibits $\gamma\rightarrow\alpha\rightarrow\gamma^*$ thermal history [2]. The manufacture of hot strips by the CSP technology faces numerous metallurgical problems, which have to be reconsidered. Considerable attention has been paid to microstructure features and its evolution, precipitation behavior *etc.* [3-6].

In view of the issues of global concern that need immediate attention, namely, conserving natural resource and environment and saving energy, lightweight automobile bodies are required from the viewpoint of saving energy, which contributes to amelioration of the ecological problem. A commonly used method to alleviate this problem is through the use of high-strength steel sheets for manufacturing automobile bodies. Automobile beam steel is mainly made into cross beam, longitudinal beam, and other structures. With the rapid development of automobile industry, there is a wide foreground for high-strength automobile beam steel sheets with high elongation, excellent formability, impact toughness, weldability, and so on.

Guangzhou Zhujiang Iron and Steel Co. Ltd (Zhujiang Steel) is the first CSP plant in China. Up to now, Zhujiang Steel has made much more technical achievements than expected. The plant always focuses on constantly increasing the range of products with continual improvement, as well as improving the strip quality. In this article, the microstructure, mechanical properties, and misorientation of automobile beam steels developed and produced in Zhujiang Steel were investigated using optical microscope and electron back-scattered diffraction.

2. Materials and experimental procedure

The chemical composition of an automobile beam steel produced by the CSP process is (wt%): C, 0.172; Si, 0.33; Mn, 1.19; P, 0.015; S, 0.003; Cu, 0.11; Al_t, 0.034; remaining iron. Table 1 gives a summary of the processing conditions for CSP to produce hot strips.

Tensile tests were performed using a universal mate-

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rial testing machine at room temperature. In this study, an optical microscopy and LEO-1450 scanning electron microscope were used for the microstructural analysis. The specimens were cut parallel to the rolling direction for optical metallography using a nital solution for etching. The samples for electron backscattered diffraction (EBSD) were mechanically polished and then electropolished in an electrolyte (electrolyte of ethanol : perchloric acid : glycerol, 7:2:1 (*v/v*)), operated at room temperature and at 15 V dc for 10-15 s. The EBSD data were obtained using LEO-1450 SEM equipped with HKL-CHANNEL4 unit.

Table 1. Processing parameters of automobile beam steels produced by CSP

Thin slab thickness / mm	Casting speed / $(m\cdot min^{-1})$	Soaking temperature / °C	Final rolling temperature / °C	Coiling temperature / °C
50, 60	4.5-5.0	~1150	790-840	560-610

3. Results and discussion

3.1. Mechanical properties

The mechanical properties of automobile beam steels produced by the EAF-CSP process in Zhujiang Steel are shown in Table 2.

It can be seen from Table 2 that the yield strength of hot-rolled strips ranges from 420 to 455 MPa, the tensile strength is 565-595 MPa, and the elongation is 27.9%-33.0%. There are no differences in mechanical properties of an automobile beam steel sheet between the rolling direction and normal direction. The comparative result of the mechanical properties indicates that the anisotropic property of ZJ510L steel is not obvious.

Table 2. Mechanical properties of automobile beam steels produced by CSP

No.	Gauge / mm	Normal direction			Rolling direction		
		σ_s / MPa	σ_b / MPa	δ / %	σ_s / MPa	σ_b / MPa	δ / %
1	5.0	450	595	30.5	435	570	33.0
2	6.0	430	585	28.0	420	565	31.0
3	6.0	455	590	27.9	445	590	29.7
4	8.0	435	580	28.0	425	580	30.5
Average	—	442.5	587.5	28.6	431.3	576.3	31.1

Note: σ_s—yield strength; σ_b—tensile strength; δ—elongation.

3.2. Microstructure

To understand the relationships among techniques, microstructure evolution, and mechanical properties, the microstructures of automobile beam steels were studied.

Fig. 1 shows the microstructures of two gauge strips along the rolling direction. The microstructure consists of polygonal ferrite and some pearlite. The ferrite grain of two strips is fine and uniform. Using the mean linear intercept method, the average ferrite grain size of the gauge strip in 6.0 mm is about 5.8 μm, whereas about 7.7 μm for the gauge strip in 10.0 mm.

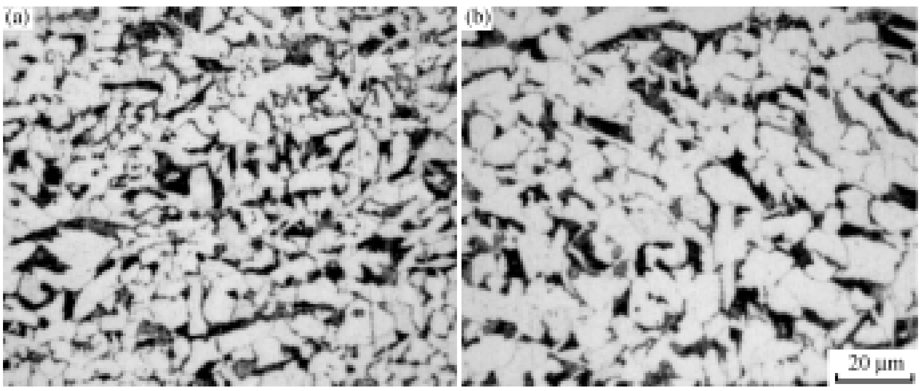

Fig. 1. Optical micrographs of automobile beam steels: (a) 6.0 mm; (b) 10.0 mm.

Hot strip production by CSP technology used a 50-mm near-net shape thin slab with uniform fine dendrites that is liable to recrystallize under certain strain conditions, which provides preconditions for microstructure refinement [7]. Heavy deformation increases the free energy of austenite especially nucleation densities during $\gamma\rightarrow\alpha$ phase transformation, which is the main reason for refining the microstructure. The total plastic deformation for CSP technology is not heavy, but the deformation in each stand is relatively heavy, which leads to well-developed dislocation structures, subgrain boundaries, and deformation bands. Subsequently, the supercooling rate of laminar region of hot worked austenite reduces the phase transformation temperature and increases the driving force of $\gamma\rightarrow\alpha$ phase transformation, which results in high nucleation densities and fine particles [8-9].

There is small amount of impurities in this low-carbon steel strip produced by CSP process. The impurity dimension ranges from 1 to 5 μm, and most dimensions are below 3 μm. By means of X-ray energy dispersive spectroscopy (XEDS), it is observed that these impurities are mainly complex oxides and brittle mixtures with round and elliptical shape. Under CSP conditions, liquid steel is cleaner, and therefore the majority of inclusions in steel strips are fine endogenetic structures, whereas large ones are rare and mainly extraneous structures.

3.3. Analysis of electron back-scattered diffraction (EBSD) microstructures

EBSD technology as a valid method to research microstructure is developing rapidly in recent years, and can provide more details and information than the metallographic examination. Direct relationship between microstructures and misorientations offers a means to analyze the microstructure evolution from the point of view of texture.

Fig. 2 shows the EBSD image and misorientation-angle distribution of an automobile beam steel. High-angle grain boundaries (HAGBs) are homophase interfaces with a misorientation angle of $\theta\geq 15°$. Lower values of the local misorientation ($2°\leq\theta<15°$) represent low-angle grain boundaries (LAGBs).

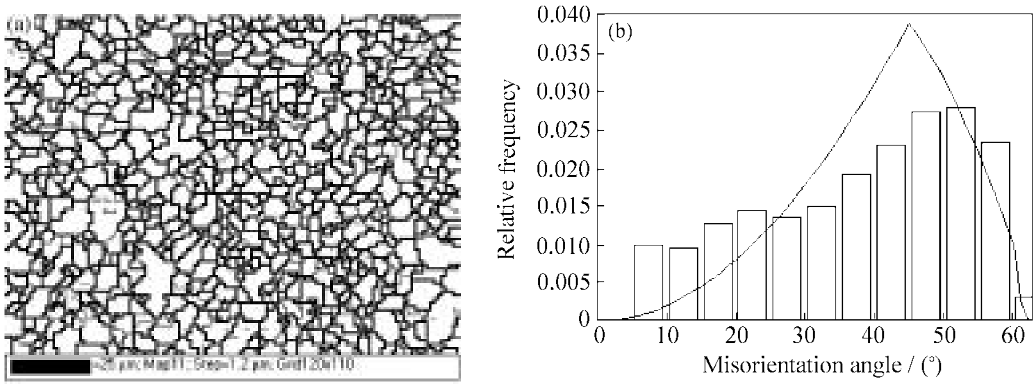

Fig. 2. EBSD image (a) and misorientation angle distribution (b) of an automobile beam steel.

From Fig. 2, it can be seen that the shapes of most grains are polygonal, but not uniform. There are some dislocations and subgrains in the microstructure. The percentage of HAGBs is greater than that of LAGBs, and hence most grains are separated by HAGBs. High-angle misorientations still exist among ferrite grains although some ferrite grains contain subgrains; therefore, some austenite grains recrystallize during the hot rolling process. It can be concluded that the finishing hot-rolled microstructures are the mixture of recrystallized and deformed austenite, and the percentage of recrystallized austenite is greater than that of deformed austenite. The percentage of high-angle misorientations increases with decrease in low-angle misorientations due to subgrains exhibiting similar reductions in misorientations in the process of recrystallization [10]. The possible mechanism for this is the accumulation of geometrically necessary dislocations in the subgrain boundaries, and the increase in the grain boundary misorientation that occurs by merging LAGBs during subgrain coalescence and subgrain growth by the migration of LAGBs *via* dislocation motion.

Compared with LAGBs, HAGBs are more important for strengthening of steels. Also, HAGBs are more efficient in improving the toughness of steels [11]. The reason is that if an intragranular cleavage crack moves across HAGBs, the crack front usually branches according to the change of the preferred fracture. Such branching results in additional fracture. In contrast, when a crack encounters a low-angle grain boundary, the crack can typically penetrate such an interface without a substantial change in the propagation direction and without branching. Therefore, it is necessary to clearly identify and quantitatively characterize the grain boundary character together with the analysis of the grain size. The careful characterization of the average grain size is essential for predicting the mechanical properties of steel based on the Hall-Petch relationship. In this study, the ferrite grain size in product microstructures was measured using EBSD maps in terms of adjacent area (Fig. 3). The ferrite grain size is about 4.91 μm and finer than that based on morphometry. The strength of the automobile beam steel sheet is high because of fine ferrite particles and many subgrains and dislocations in the microstructure. According to Ref. [8], the maximum texture index of the hot strip produced by CSP process is about 2; therefore, texture strengthening can be neglected because of the sundry and weak texture. Owing to mainly high-angle grain boundaries, the refinement strengthening mechanism is actually in effect, whereas the subgrain strengthening mechanism is not.

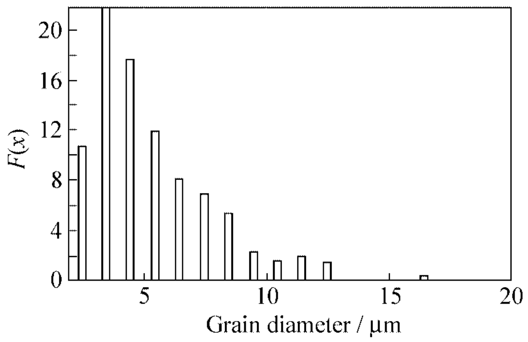

Fig. 3. Grain size distribution of hot strips according to EBSD technique. The values of *F*(*x*) represent the number of measurement in a bin.

4. Conclusions

(1) The microstructure of the automobile beam steel consists of polygonal ferrite and some pearlite. The ferrite grain of two gauges is fine and uniform. By using the mean linear intercept method, the average ferrite grain size of 6.0-mm gauge strips is about 5.8 μm, whereas it is approximately 7.7 μm for the gauge strips in 10.0 mm.

(2) The finishing hot-rolled microstructure is a mixture of recrystallized and deformed austenite. The percentage of recrystallized austenite is greater than that of deformed austenite. Owing to mainly high-angle grain boundaries, the refinement strengthening mechanism is actually in effect, whereas the subgrain strengthening mechanism is not.

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