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The Dependency of Mechanical Properties on the Microstructure Anisotropy Index of Some Alloyed Steels

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Abstract. The microstructure banding of the 4340, 42CrMo4 and 20NC11 alloyed steels is estimated using the approach of the ASTM E 1268 standard. The values of the anisotropy index and microhardness are obtained on the longitudinal specimens at various distances from the center of round steel bars with various diameters. Impact strength values in the transversal and longitudinal directions of the bars are obtained. The correlation of the anisotropy index values and the mechanical properties (microhardness and impact strength) of the steels under consideration is derived.

INTRODUCTION

A banded microstructure is generally observed in hot-rolled carbon and alloyed steel products [1-5]. The main cause of its formation is chemical inhomogeneity, which occurs during the dendritic solidification of a steel ingot or a billet [6-10]. The subsequent hot deformation (rolling or forging) and heat treatment reveal bands with various microstructures – ferrite and pearlite bands, martensite and ferrite or bainite bands, etc. [7-14]. The microstructure banding causes the anisotropy of mechanical properties (since crack movement is facilitated along the direction of the bands [15]) and decreases corrosion resistance [16]. Although some progress was achieved in understanding the nature of the microstructure banding, the existing technological routes designed to avoid banding [4, 17, 18] or to eliminate the initial cause of banding [19, 20] are still not effective [3] and even thermodynamically impossible [21].

Nowadays, some standards are implemented to estimate microstructure banding; however, most of them are based on the comparison of observed and reference microstructures [22-24]. This results in only a qualitative estimation of banding. The quantitative estimation of microstructure banding [14, 25, 26] is a key factor for deriving correlations of the mechanical or physical properties of steel and its microstructure characteristics, and further production of steel with low microstructure inhomogeneity.

EXPERIMENTAL

The chemical composition of the hot-rolled commercially-produced steels under study is present in Table 1. Round steel bars with a diameter of 110 to 190 mm were annealed after the hot rolling. The steel specimens were heat-treated using an electrical chamber furnace and a quenching tank with industrial oil. The austenitization temperature was 850 °C and the hold time was 60 min. The tempering temperature was 200 °C for the 20NC11 steel and 525 °C for the 4340 and 42CrMo4 steels, and the hold time was 3 h.

Specimens of the 4340 steel (10×10×10 mm) were cut from different positions of the cross section, namely, near the surface, at the half of the radius and at the center of the bars with diameters 110, 140 and 190 mm. The quantitative estimation of microstructure banding was conducted in accordance with ASTM E1268 [14] using SIAMS 800 image analyzer. The studied area of each specimen was approx. 70 mm^2. The anisotropy indexes (AI) were obtained at different cross section positions of the bars with various diameters.

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TABLE 1. Chemical composition of the steels, wt%

Steel	C	Si	Mn	Cr	Ni	Mo	Cu	S	P
4340	0.42	0.29	0.73	0.77	1.45	0.33	0.03	0.003	0.012
42CrMo4	0.35	0.24	0.74	0.90	0.08	0.18	0.21	0.006	0.010
20NC11	0.22	0.32	0.40	0.66	2.88	0.07	0.17	0.001	0.001

The microstructure of the steels was estimated using optical microscopy (Meiji IM7200). The microprobe analysis was conducted using a Jeol JSM 6490 scanning electron microscope. The microhardness of the specimens was estimated using a HVS-1000A tester with the loads in ranging between 300 and 1000 g. At least 30 measurements were implemented for each type of the microstructure bands.

Specimens for Charpy impact tests were cut from the steel bars in the longitudinal and transversal directions so that the notch was in the same bar cross section area (half of the radius) for both specimens. The impact tests were conducted according to ASTM E23 at room temperature.

RESULTS AND DISCUSSION

The microstructure banding of the 4340 steel bars was revealed after heat treatment. The bands were tempered martensite (light bands) and secondary sorbite (dark bands). The width of the alternating bands was approx. 100 μm. The content of Cr, Ni, Mo and Mn in the dark microstructure bands was lesser (Mn 0.60, Ni 1.33, Mo 0.19 wt%, respectively), than the average content of these elements in the steel (Table 1). This was due to the dendritic origin of these microstructure bands, as demonstrated in [6]. Various contents of the alloying elements led to the local inhomogeneity of the austenite, formed martensite and its stability during tempering.

The decrease of the bar diameter (i.e. the increase of the degree of hot deformation) led to the increase of the steel anisotropy index in all of the cross section positions (Fig. 1). The lesser increase of AI was obtained near the surface area of the steel bars (1.6 for 190 mm bar and 2.6 for 110 mm bar). It is evident that the surface of the steel bars was extremely deformed during the hot rolling. That is why the microstructure banding caused by chemical inhomogeneity at this area decreased to greater values than in the bulk metal.

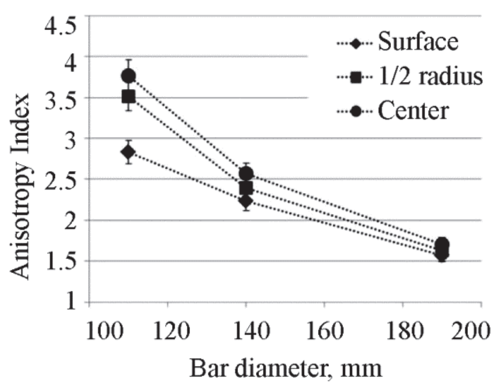

FIGURE 1. The anisotropy index versus the diameter of the 4340 steel bar at various positions

At the central area of the steel bars, the microstructure banding was more evident than at the surface area. The bands had sharp contrast and a width of approx. 225 μm. The anisotropy index (AI) was 1.7 at the central area of the 190 mm bar and 3.8 at the central area of the 110 mm bar. The possible reason for the microstructure banding increase with the increase of the degree of hot deformation was higher deformation rate of the alloying elements versus their diffusion rate. As a result, the interdendritic areas of the steel were shrunk and extended without sufficient redistribution of the alloying elements. This led to the formation of explicit microstructure band boundaries in the bar of a smaller diameter.

The Charpy impact strength of the transversal specimens was lower than that of the longitudinal ones in all the cases (Fig. 2a). The lowest impact strength of the transversal specimens was obtained in the case of the 42CrMo4 steel (0.17 MJ/m^2), while the longitudinal specimens of the steels under consideration exhibited an impact strength of 0.8 to 1.0 MJ/m^2. The impact strength ratios (the value obtained for longitudinal versus transversal specimens) were 1.6 for the 4340 steel, 2.0 for the 20NC11 steel and 5.5 in case of the 42CrMo4 steel. The microstructure of the Charpy specimens revealed that the 42CrMo4 steel consisted of contrast light and dark bands with sharp boundaries, whereas the 4340 and 20NC11 steels consisted of smooth bands. The difference in the microhardness values for the light and dark bands was 35 HV for the 4340 and 20NC11 steels and 55 HV for the 42CrMo4 steel. The anisotropy indexes were 3.7 for the 4340 and 20NC11 steels and 4.6 for the 42CrMo4 steel. It was evident that the sufficient decrease of the impact strength of the transversal specimens of the 42CrMo4 steel was attributed to the microstructure banding value.

The correlation between the impact strength ratio and the scatter of the microhardness values (characterized by means of the variation coefficient) is plotted in Fig. 2b. The point with a zero variation coefficient corresponds to the ideal isotropic material with the same impact strength values in the longitudinal and transversal directions. The correlation between the impact strength ratio and the anisotropy index (i.e. microstructure banding) was also experimentally obtained. The 25% increase in the anisotropy index from 3.7 to 4.6 led to a more than three times increase in the impact strength ratio (from 1.6 to 5.5).

The obtained dependences have made it possible, on the one hand, to estimate the microstructure banding value by means of the values of the mechanical properties (microhardness and impact strength) and, on the other hand, to predict the variation of the mechanical properties (microhardness and impact strength) using the banded structure anisotropy index. The present study outlines the further trend of investigations, which would correlate the microstructure banding and anisotropy of the mechanical properties of steels. This problem is urgent in case of the quality control at various stages of steel production. For the subsequent commissioning of the proposed methods, it is necessary to accumulate and analyze a considerable amount of experimental data for various steel grades.

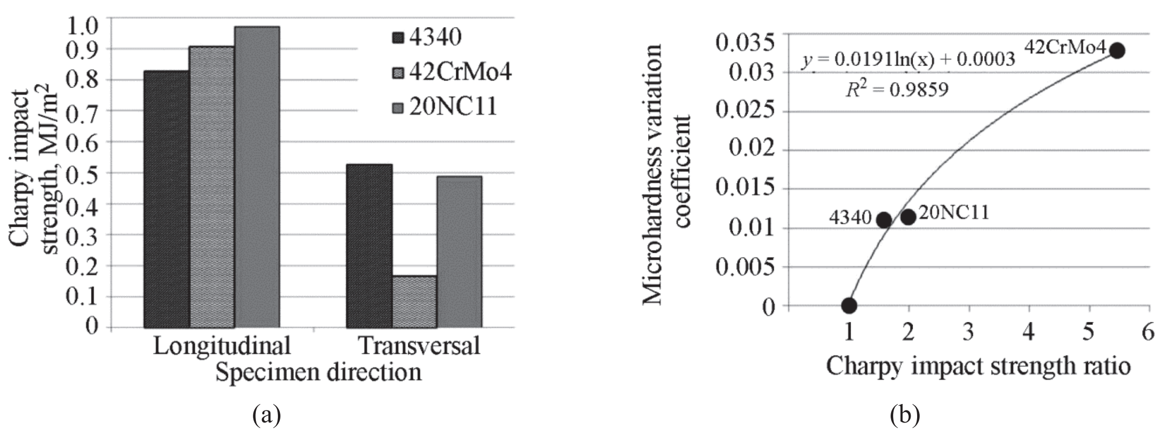

FIGURE 2. The variation of Charpy impact strength for longitudinal and transversal specimens (a) and the correlation between the microhardness variation coefficient and the Charpy impact strength ratio (b) for the steels under consideration

CONCLUSIONS

1. The values of the anisotropy index have been obtained for 4340 steel specimens at various distances from the center of round steel bars with diameters of 110 to 190 mm. The decrease in the bar diameter from 190 to 110 mm leads to an increase in the anisotropy index from 1.6 to 2.6 for the surface area and from 1.7 to 3.8 for the central area of the bar cross section.
2. The Charpy impact strength of the steels 4340, 20NC11 and 42CrMo4 varies with the specimen direction. The maximum value of the Charpy impact strength ratio (the value obtained for longitudinal versus transversal specimens) was obtained in the case of the 42CrMo4 steel (5.5). The 42CrMo4 steel is also characterized by the highest difference in the microhardness values (55 HV) and the highest anisotropy index (4.6).
3. A correlation of the Charpy impact strength ratio, microhardness scatter (the variation coefficient of the microhardness values) and the anisotropy index has been derived.

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