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The effect of precipitation state on strength and toughness of precipitation hardened hot rolled steel sheet

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Abstract: In this study, to clarify the influence of carbide precipitation state on strength-toughness balance, Ti- and/or V- added ferrite single phase steels with different carbide precipitation temperature were investigated. The steels were cooled by the following processes after hot rolling: (A) cooling to 873K by 1 step (for fine precipitation), (B) air cooling from 1053K for 20sec while cooling to 873K (for coarse precipitation). The experimental results were following. The balance of tensile strength and Charpy absorbed energy was better in process B. (Ti,V)C were observed in both processes, but the size of (Ti,V)C were larger in process B. From the above, it was suggested that as the carbide size become larger, the decrease in toughness per strengthening amount becomes smaller.

1. INTRODUCTION

For the purpose of weight reduction and improvement of collision safety for automobile, increasing the strength of steel sheet for automobile has been accelerating more and more in recent years. Precipitation hardening is an effective strengthening mechanism for hot-rolled steel sheet, since the amount of strengthening per alloy addition is large, and it can strengthen microstructure uniformly so it is possible to achieve both high strength and high local deformability [1,2]. Regarding the influence of precipitated particles on mechanical properties of steel, Ashby-Orowan model [3] is well known, which formulated the increment of yield strength by inter-particle spacing. Furthermore, in recent years, influence of precipitated particles on work hardening behavior has been studied [4-6]. However, the influence of precipitated particles on toughness has not been understood enough yet. It is reported that the amount of decrease in toughness is proportional to the amount of precipitation hardening [7]. On the other hand, some reports[8,9] suggested that the amount of decrease in toughness depends on the carbide precipitation state. Kunishige[8] investigated the relationship between the amount of precipitation hardening and the amount of decrease in toughness about Nb and/or V added precipitation hardened steel sheets. It showed that under the condition presumed that the carbide precipitated at high temperature, the deterioration of the toughness per amount of precipitation strengthening was smaller, as compared with the condition presumed to precipitate at low temperature. However, since other microstructure factor (grain size of matrix, size and dispersion state of cementite) also changed with change of hot rolling condition in previous study, it was difficult to discuss only the influence of carbide precipitation state. Therefore, the relationship between carbide precipitation state and toughness is unclear yet. In this study, to clarify the influence of carbide precipitation state on strength-toughness balance, some Ti- and/or V- added ferrite single phase steel sheets with different carbide precipitation temperature were investigated.

2. EXPERIMENTAL PROCEDURE

Ingots with chemical composition shown in Table 1 were casted in the laboratory. In order to change the volume fraction of carbide, the V contents were changed. Furthermore, in order to ignore the influence of cementite, the C contents were changed so that the excess C amount was zero or less. The ingots were subjected to hot-rolling under the conditions shown in Fig. 1. The ingots were homogenized for 60minutes at 1553K and then hot rolled from 20mm to 3mm thickness at finishing temperature 1123K. After hot rolling, in order to change the precipitation states of carbides, cooling

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was carried out under the following two conditions. In process A, water spray cooling was carried out to 873K in one step. In process B, the water spray cooling was stopped at 1053 K, then air-cooled for 20 sec, and water spray cooling was carried out again to 873 K. After cooling, the steel sheets were kept in the furnace for 30min in both processes.

After the hot rolling, in order to remove the scale, mechanical grinding was carried out from 3mm to 2mm thickness. After that, the steels were subjected to tensile test (JIS No.5 specimen, GL 50 mm, crosshead speed 2mm/min) and Charpy impact test (full size specimen (2mmt, 5 pieces piled) with 2mm V-notch, at room temperature). Observation of the microstructure was carried out by optical microscope (nital etching) and EBSD. Observation of carbides was carried out by transmission electron microscope (TEM). In TEM observation, acceleration voltage was 200kV and beam direction was parallel to [100] of ferrite.

Table 1 Chemical compositions of the steels (mass%)

	C	Si	Mn	P	S	Ti	V	N	excess C
0V	0.059	0.05	0.49	0.001	0.001	0.21	-	0.0009	0.007
25V	0.093	0.06	0.48	0.001	0.001	0.20	0.26	0.0012	-0.002
50V	0.13	0.05	0.50	0.001	0.001	0.21	0.52	0.0012	-0.014

excess C=C-12.01･(Ti/47.88+0.75･V/50.94-N/14.01)

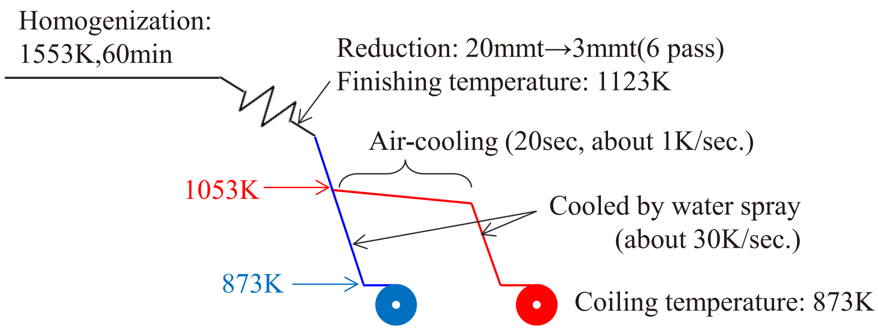

Fig.1 Schematic illustration of hot rolling and cooling conditions (A) 1-step cooling to 873K , (B) air-cooling from 1053K

3. EXPERIMENTAL RESULTS

The optical micrographs of the steels were shown in Fig.2. The microstructures of all steels were single phase of polygonal ferrite. Grain boundary map of 25V steels by EBSD were shown in Fig.3. The grain diameters were 4.7μm in both processes. From the above, it was confirmed that the macroscopic microstructure and crystal grain size did not change depending on the cooling process after hot rolling.

The balance between the tensile strength (TS) and the Charpy absorbed energy (AE) at room temperature of the steel sheets was shown in Fig.4. As the amount of V increased, TS increased and AE decreased in both processes. However, the balance of TS and AE was better in process B than in process A.

TEM micrographs of 25V steels were shown in Fig.5. Aligned (Ti,V)C were observed in both processes. These carbides were presumed to precipitate on the α/γ interface with ferrite transformation during cooling after hot rolling. Also, these carbides had Baker-Nutting relationship with the ferrite matrix in both processes. On the other hand, the size of carbides was different in both processes, carbides in process B was coarser than carbides in process A.

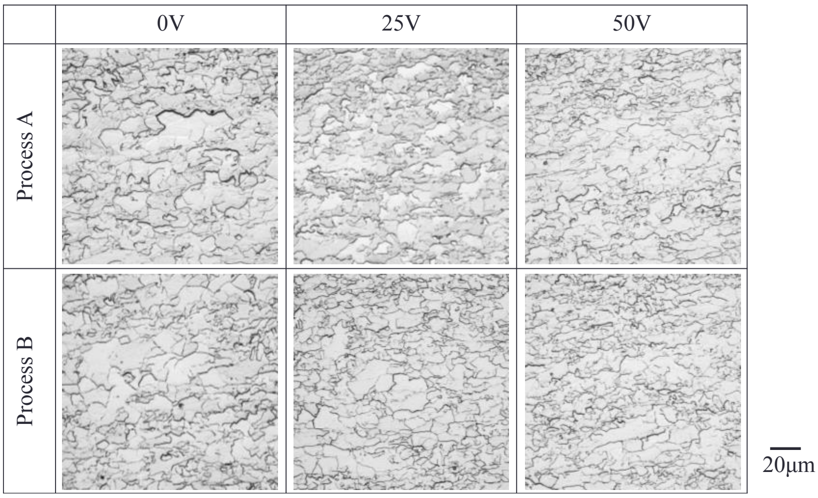

Fig.2 Optical Micrographs of the steels

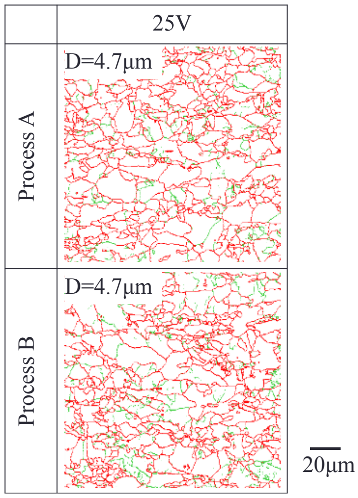

Fig.3 Grain boundary map of 25V steels by EBSD (misorientation angle: green line 5-15deg., red line >15deg.)

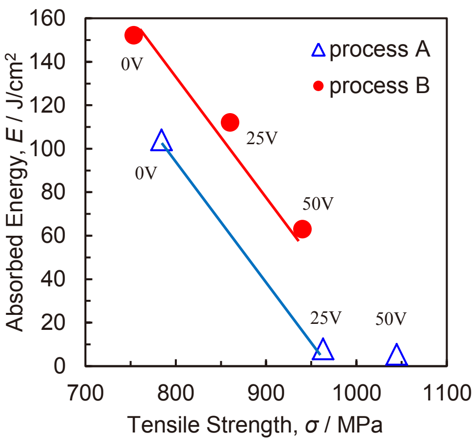

Fig.4 The balance of tensile strength and Charpy absorbed energy of the steels

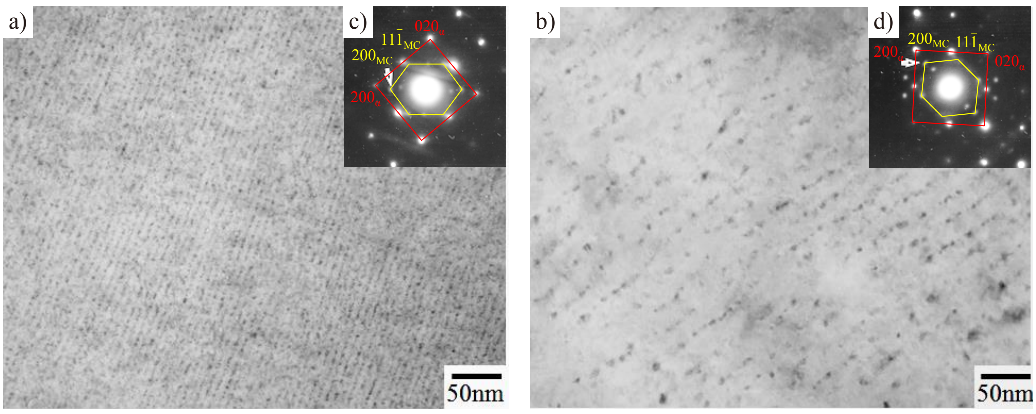

Fig.5 TEM micrographs of 25V steels (beam direction is parallel to $[100]_{\alpha}$) a) bright field image of process A, b) bright field image of process B, c) diffraction pattern of process A, d) diffraction pattern of process B

4. DISCUSSION

The reason why TS-AE balance varied with cooling process was discussed following. First of all, grain size is a factor that dominates the toughness of steel. But grain size did not change with the cooling process in this study. Next, there is a possibility that coarse hard phase such as cementite and inclusions may affected on the destruction. However, excess C of the steels become zero or less in this study, so it is difficult to think of cementite formation. Also, it is unlikely that the state of the inclusions will change with the cooling process after hot rolling. From the above, it is highly possible that the balance of TS-AE balance changed depending on the cooling process, as a result of the change in the precipitation state of (Ti,V)C.

The mechanism of the precipitation state of carbides affecting the TS-AE balance was discussed. As the first mechanism, as suggested by Kunishige et al.[2], there is a possibility that the coherent strain generated around the carbides affects the toughness. In the region where the coherent strain exists, the interatomic distance of the iron lattice deviates from the steady state which iron binding energy becomes minimum. In such a state, it is considered that cutting of iron atom bonds (i.e., cleavage breakage) occurs by smaller stress, compared with the steady state. Another mechanism is discussed following. Since the precipitates were fine in process A, there is a possibility that the interaction mechanism between dislocations and precipitates changed from Orowan to cutting mechanism. In the case of cutting mechanism is working, it is considered that the slip deformation likely localized to the slip plane which cutting have already occurred. In such a situation, stress concentration on the grain boundary is likely to occur, as compared with Orowan mechanism in which more slip system work. As a result, it is considered that deterioration of toughness was caused.

5. SUMMARY

In this study, to clarify the influence of carbides precipitation state on strength-toughness balance, some ferrite single-phase steel sheets with different carbide precipitation state were investigated. As a result, it was suggested that the strength-toughness balance of precipitation hardened steel sheet is affected by carbide precipitation state, furthermore, the smaller the carbide size, the larger the decrease in toughness per strengthening amount.

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