Compromise between environmental burdens and performance in strengthening steels

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In order to develop the steels bearing low environmental burdens as well as high performances, the present situation in Japan has been analyzed from several points of view. The issues related with steel production include 1) potentiality of the domestic contribution to reducing the global amount of CO₂ emission and 2) possible recipes in practical process to lower the environmental load with high performance. A sector occupying a huge share in the industry field can reduce the CO₂ emission effectively and the steel industry is such the sector. A sophisticated use of thermo-mechanical process in steel production can improve both the environmental and the service performance. By lowering the heating temperature in the thermo-mechanical process, the CO₂ emission can be decreased and the yield strength can be increased by ultrafine-grain strengthening.

Keywords: Yield strength, CO₂ emission, Ultrafine grain strengthening, Solid solution hardening, Precipitation hardening

I. INTRODUCTION

Steel has been manufactured approximately 100 Mt in Japan every year which occupies about 46 % in the total amount of materials manufactured in Japan. The amount of CO₂ emission in Japan occupies about 5 % of the global amount.¹ In Japan the CO₂ emission in the steel industry occupies about 34 % in the category of industry.^{2, 3}

That is about 13 % of the domestic total amount. Figure 1. shows a change in curtailment rate of CO₂ emission in Japan for the steel industry, chemical industry and construction industry, respectively. Hence, 10 % curtailment in the steel industry can reduce about 1 % of the total CO₂ emission in Japan. By considering steel scrap increasing and steel recycling, the future role of steel in the

resources-circulating society will become more important.

In this study, a balance between the amount of CO₂ emission during the production and the yield strength is investigated for several strengthening mechanisms to propose the steels showing both low environmental burdens and high performances. Here, solid solution hardening, precipitation hardening and ultrafine grain strengthening are selected as the strengthening mechanisms.

Fig. 1. Effects of the category of industry on curtailment rate of CO₂ emission in Japan.

II. PROCEDURE

The MLCA database developed by Halada *et al.*⁴ is used to evaluate the environmental loads in terms of CO₂ emission in the production of hot strip slab.

The database including unit requirements of fuel and electric power for furnace and hot strip mill is referred to the data from Japanese steel industries.^{5,6} Here, based on the variations of unit requirements of fuel and electric power from 1970's and 1980's and the relationship between unit requirement of fuel and inserting temperature of slab, their unit requirements in thermo-mechanical process were determined according to heating temperatures and deforming temperatures. Figures 2 and 3 show unit requirement of fuel for furnace and hot strip mill as

a function of inserting temperature of slab, respectively. The unit requirement of fuel at heating and deforming temperatures can be estimated for calculations of CO₂ emission.

Fig. 2. Unit requirement of fuel for heating furnace as a function of inserting temperature of slab.⁵

Fig. 3. Unit requirement of fuel for rolling as a function of inserting temperature of slab.⁵

The following equation summarized by Pickering⁷ is used to calculate the yield strength (YS) of ferrite-pearlite steels for various alloying elements and ferrite grain sizes.

YS [MPa]
 $=15.4[3.5+2.1(\text{Mn})+5.4(\text{Si})+23(\text{N}_f)+1.13D_\alpha^{-0.5}](1)$
 where Mn, Si, N_f and D_α refer to Mn concentration in mass percent, Si one, free nitrogen one and ferrite grain size, respectively.

III. RESULTS AND DISCUSSIONS

Figure 4 shows the relationship between CO₂ emission in the production and the yield strength for three strengthening mechanisms.

Fig. 4. Yield strength vs. CO₂ emission in the production for three strengthening mechanisms.

Reference material

JIS-SM490 steel with a ferrite-pearlite structure is selected as reference material to compare three strengthening mechanisms. The CO₂ emission and the yield strength of the reference material are as follows;

CO₂ emission: 1542.7 kg/t,

Yield strength: 235 MPa.

Solid solution hardening

Figure 5 shows changes of CO₂ emission by

alloying elements. The MLCA database considers effects of alloying elements as the environmental load discharged in the productions of ferro-alloys. Figure 6 shows changes of yield strength by alloying elements. The yield strength increases with increasing the alloying elements except Cr. Solid solution hardening thereby increases both the yield strength and the CO₂ emission with increasing the alloying elements in most cases.

Fig. 5. Change of CO₂ emission as a function of alloying elements.⁴

Fig. 6. Change of the yield strength as a function of concentrations of alloying elements.⁷

Precipitation hardening

The balances for a tempered martensite steel and

JIS-SUS630 are estimated. Figure 2 is used in order to estimate the change in the amount of CO₂ emission by tempering while the yield strength is determined by experiments. The yield strength is decreased while the amount of CO₂ emission is increased with increasing of tempering temperature.

Ultrafine grain strengthening

Ohmori *et al.*⁸ reported that ultrafine-grained steels with ferrite grain size between 0.5 and 2 μm were obtained by changing the deforming temperature between 673 and 923 K. In this experiment, rods were subjected to the multi-pass warm rolling with an accumulated area reduction of 93 %.

The yield strength increases with lowering the processing temperature by ultrafine grain strengthening.⁸ The unit requirement of fuel for furnace decreases with lowering heating temperature but that for hot strip mill increases with lowering deforming temperature as seen in Figs. 2 and 3. The CO₂ emission increases with lowering those temperatures in the case of ultrafine grain strengthening.

The heating temperature of furnace and the deforming temperature of hot strip mill are major factors to affect the amount of CO₂ emission in the thermo-mechanical process. The emission is suppressed by lowering those temperatures compared with that of reference material. Accordingly, the low temperature may decrease the CO₂ emission and increase the strength.

IV. SUMMARY

A balance between CO₂ emission in the production and yield strength are estimated for three strengthening mechanisms. Low temperature process like ultrafine grain strengthening has a possibility to improve both the environmental loads and performance compared with the conventional process.

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