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Development of multilayered steels consisting of medium-high carbon steels for improved strength-ductility combinations

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Abstract: Multilayered steels consisting of medium-high carbon steels were developed to achieve more improved strength and ductility combinations. Medium-high carbon martensitic steels (0.4-0.6wt%C) and a high carbon TRIP steel (0.6wt%C) were prepared. The mechanical properties of these steels were investigated to design the geometry of multilayered steels. Then, these steels were stacked and hot-rolled to achieve enough interfacial toughness between layers. Based on the fracture toughness of martensitic steels obtained from three-point bending fracture toughness test, multilayered steels with 3-7 layers were fabricated. The total thickness and layer thicknesses were controlled by cold rolling process. After various heat treatments including tempering, the extraordinary strength and ductility combinations such as 1.6 GPa and 25% can be obtained.

1. INTRODUCTION

Because of lightweight of structural materials for automobile and suppression of CO_2 gas emission as well as the collision safety, multilayered steels have been developed in order to improve the combination of strength and ductility in our group. In the past, many studies have utilised multilayered metals to better understand crack propagation behavior in brittle/ductile multilayered composites, as well as to investigate enhanced properties such as fracture toughness, fatigue behavior and impact behavior. Regarding the ductility of the multilayered composites, however, it is well known that the total elongation of composites is lower than that obtained by rule of mixture [1]. To overcome this problem, the concepts to improve the ductility for the multilayered composites were proposed such as the interfacial toughness between components [2], the fracture toughness of more brittle component as well as the layer thickness [3] and so on. Based on the concepts, the authors developed multilayered steels, consisting of martensitic steels as a high strength layer and austenitic stainless steels or TRIP steels as a high ductile layer using commercial steels with low carbon contents, and achieved improved strength and ductility combinations as well as good formability [4]. In this study, our recent study for multilayered steels consisting of medium-high carbon steels to achieve more improved strength and ductility combinations is reported.

2. EXPERIMETAL PROCEDURES

The multilayered steels employed in this study consisted of medium-high carbon martensitic steels (Fe-0.4~0.6wt%C-Si-Mn-Cr-Ni-Mo) for strength layer and a high carbon TRIP steel (Fe-0.6wt%C-Si-Mn) or a high carbon TWIP steel (Fe-0.6wt%C-Si-22Mn-Al) for ductile layer. In order to design the multilayered structure, the transformation temperature and the mechanical properties of these constituent steels were investigated. Regarding the mechanical properties, a tensile test and a three-point bending fracture toughness test were conducted after several heat treatments. The geometry of tensile test specimen is 12.5 mm in width with a uniform gauge length of 60 mm. The tensile test was conducted at an engineering strain rate of 10^{-3} s^{-1}, and the length of the extension meter was 50 mm. the geometry of fracture toughness test is 5 mm in width, 10 mm in height and 40 mm in lower span length with a pre-crack of half length in height. Microstructures were observed by using an optical microscopy and a FE-SEM combining EBSD analysis.

To fabricate the multilayered steels, the constituent steels were bonded together using a hot-rolled

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process and then the stack was cold-rolled to 1.0~1.2 mm in thickness. The complete multilayered steels consisted of the constituents alternately arranged into three to seven layers according to the fracture toughness of martensitic steels. In the case of martensite/TRIP steels, the heat treatment condition should be considered to obtain the desired microstructures.

3. RESULTS AND DISCUSSION

Fracture toughness of martensitic steel was evaluated by a three-point bending test. Figure 1 shows the fracture toughness of steels with 0.4~0.6 wt%C after a heat-treatment at 1000ºC for 300 s followed by water-quenching (WQ) or air-cooling (AC) to room temperature. In the case of WQ, the obtained fracture toughness was very low and independent of carbon content in steels. On the other hand, the obtained fracture toughness becomes higher by decreasing the carbon content but was independent of holding time in the case of AC. Based on the obtained fracture toughness of martensite, the transition layer thickness from ductile to brittle fracture was evaluated using the elastic and elasto-plastic solutions [4, 5], and the calculation results are plotted in Fig. 2 in which the solid line shows the result of elastic solution and the dashed line shows the results of elasto-plastic solution. In the case of 40 MPam$^{1/2}$, that is after the heat-treatment of 1000ºC for 300 s and AC, the lower limit of transition layer thickness was obtained as about 150 μm. In order to reduce the number of layer thickness, the fracture toughness should be improved, so the additional heat-treatment, tempering at 200ºC for 3600 s, was conducted. After the tempering, the fracture toughness was improved and the transition layer thickness was also evaluated, as shown in Figs. 1 and 2. The result indicated that the number of layer in multilayered steels can be reduced as five layers in the case of total thickness of 1.0~1.2 mm and volume fraction of martensite of about 50% to achieve the good elongation as well as high strength.

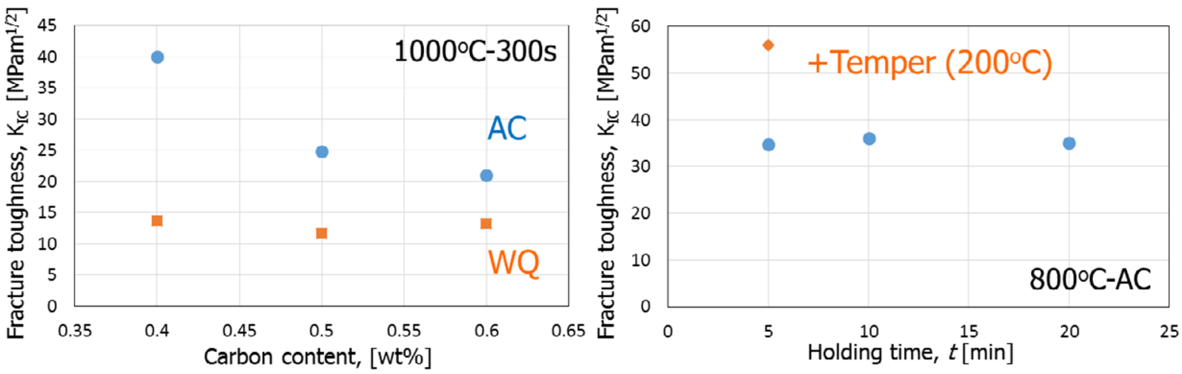

Fig. 1 Fracture toughness of martensite after various heat-treatments. The samples were heat-treated at 1000ºC for 300 s, followed by air-cooling (AC) or water-quenching (WQ). The effect of holding time and tempering at 200ºC for 3600 s on fracture toughness of 0.4 wt%C samples that were heat-treated at 800ºC followed by AC.

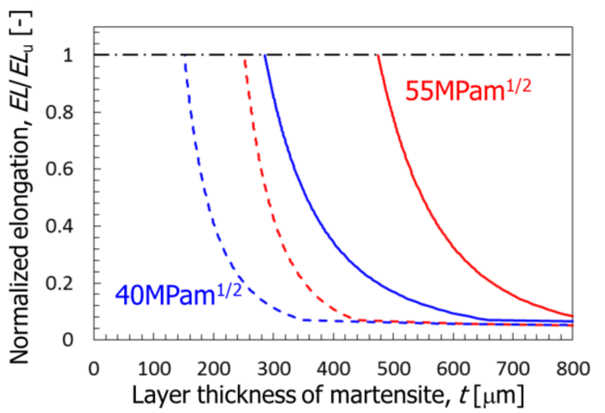

Fig. 2 Transition layer thickness of martensite from brittle to ductile fracture in the cases of 40 and 55 MPam$^{1/2}$ of fracture toughness.

Tensile properties of TRIP and TWIP steels were investigated after various heat-treatments. The temperatures and holding times for austenitization and bainite transformation were varied to obtain better strength and ductility combinations in TRIP steel, and the relatively good tensile properties were obtained as show in Fig. 3. Regarding TWIP steel, the strength and ductility can be controlled mainly by the grain size, so the strength becomes low and the elongation becomes large by increasing temperature and holding time.

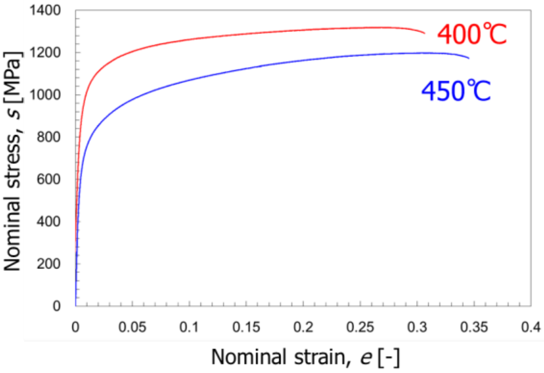

Fig. 3 Stress-strain curves for TRIP steel for the bainite transformation temperature at 400ºC for 300 s and 450ºC for 120 s after austenitizing at 850ºC.

According to the obtained mechanical properties of constituent steels, the final thickness of martensite layer should be less than 250 μm. By arranging the initial thickness of steel plates, three to seven plates were stacked alternately and then hot-rolled after a heating at 1050ºC. The total thickness was reduced to 1.0~1.2 mm by a subsequent cold-rolling. In the case of martensite/TRIP multilayered steels, both constituents were fully austenitized at 850ºC, and then kept at 400 or 450ºC for bainite transformation in TRIP steel but not in martensitic steel. Finally, TRIP steel consisted of bainite and retained austenite, and the martensitic steel consisted of martensite due to the above heat-treatment. The optical micrograph of obtained multilayered steels is shown in Fig. 4, in which the bright layer is martensite layer and the dark layer is TRIP layer. It is also noted that the volume fraction of constituent steels can be easily controlled by arranging the plate thickness and number of layer.

Fig. 4 Optical micrograph of multilayered steels consisting of martensite/TRIP.

Figure 5a shows the stress-strain curves of martensite/TRIP multilayered steels with the volume fraction of martensite of 40% after different heat-treatments with the tempering process. Although there is a little difference in the tensile properties due to the difference in the tensile properties of TRIP steels, improved combinations above 1.5 GPa of strength and 20% of elongation were obtained. Figure 5b shows the stress-strain curves of martensite/TWIP multilayered steels with the volume fraction of martensite of 40% after different heat-treatments. Both strength and ductility of multilayered steels after the heat-treatment at 800ºC are better than that at 900ºC although the ductility of TWIP steel after the heat-treatment at 800ºC shows lower than that at 900ºC. It is probably due to the work hardening ratio in the strain range around 30%. The strength and ductility combinations from the multilayered steels consisting of medium-high carbon steels were plotted in Fig. 6 with those of conventional steels for automobile and the multilayered steels reported in our previous study [4]. The strength can be improved by applying the medium-high carbon steels while maintaining the good ductility, and the extraordinary strength and ductility combinations such as 1.6 GPa and 25% can be achieved.

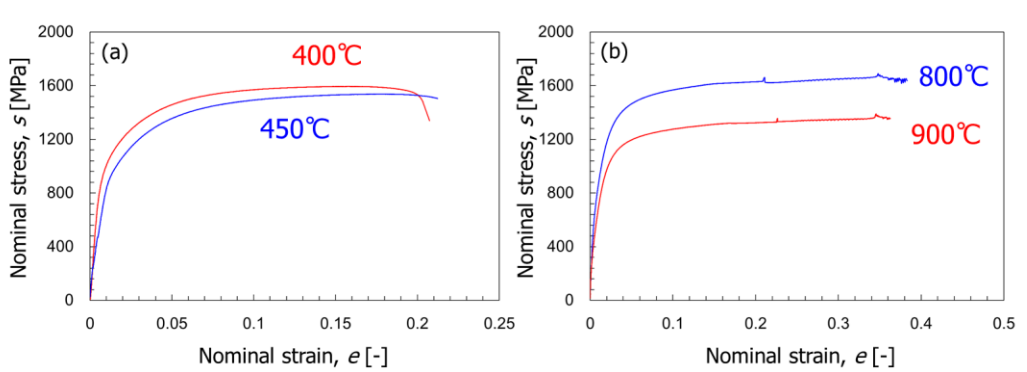

Fig. 5 Stress-strain curves of multilayered steels for (a) martensite/TRIP samples after heat-treatments at 850ºC-120 s of austenitizing and 400ºC-300 s/450ºC-120 s of bainite transformation, and (b) martensite/TWIP samples after heat-treatments at 800ºC-120 s and 900ºC-120 s.

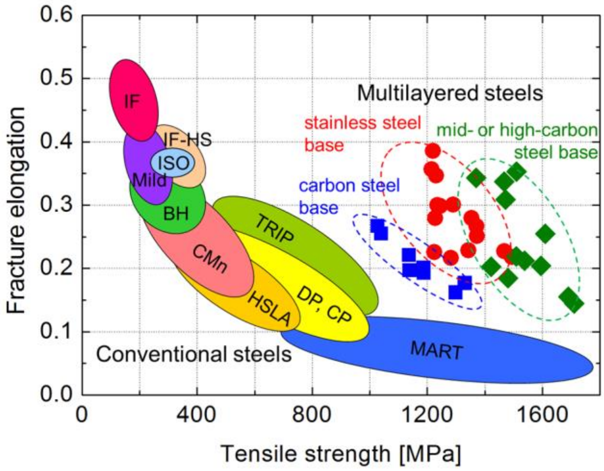

Fig. 6 Strength and ductility plot of multilayered steels with conventional steels and the our previous results [4].

4. CONCLUSIONS

a) Fabrication process for multilayered steels consisting of martensitic steels and TRIP steels was established by considering the transformation temperatures and the mechanical properties of constituent steels with medium-high carbon.
b) Good elongation can be achieved even by five layers of multilayered steels by improving the fracture toughness of martensitic steels.
c) Much more improved strength and ductility combinations can be achieved based on the design concept of multilayered steels with medium-high carbon.

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