Effects of Austenite Conditioning and Hardenability on Mechanical Properties of B-Containing High Strength Steels

Chang-Sun LEE, Wung-Yong CHOO

Plate, Rod & Welding Research Group, Technical Research Laboratories, POSCO

Direct quenching(DQ) has become widespread instead of conventional reheat quenching in order to obtain good mechanical balance of high strength steels in addition to productivity, energy savings, alloy savings, and weldability. It is well known that mechanical properties of DQ steel can be changed by varying slab reheating temperature, finish rolling temperature, and cooling rate in addition to alloy composition. The effect of pancaking by controlled rolling at low temperatures on mechanical properties was investigated. The effect of pancaking depends on hardenability determined by alloy contents. Pancaking increased strength or toughness when alloy-determined hardenability is high. But pancaking decreased strength when alloy-determined hardenability is low.

KEY WORDS: direct quenching, B-containing steel, high strength steel, austenite conditioning, hardenability, pancaking.

1. Introduction

In direct quenching and tempering (DQT) process, which is a kind of thermomechanical process, plates are direct quenched after rolling and tempered to obtain good mechanical balance of high strength steels. Before the advent of DQT process, high strength steels were manufactured by reheat quenching and tempering (RQT) process, in which plates are air cooled after rolling, austenitized, quenched, and tempered.

DQT process has higher productivity and energy efficiency than RQT process due to omission of austenitizing after rolling, and also higher alloy efficiency and weldability due to higher hardenability at the same composition. High hardenability of DQT process can be explained by austenite grain size, non-equilibrium segregation of alloying elements to grain boundaries, and sufficient solid-solutioning of carbide-forming and nitride-forming elements due to high heating temperature(1)

DQT process has more degree of freedom than RQT process in controlling austenite condition before quenching. Austenite condition can be controlled by changing slab reheating temperature and rolling schedule in DQT process, and by changing austenitizing temperature only in RQT process. Consequently, the mechanical properties can be changed widely by austenite conditioning in DQT process.

This study investigated the effect of pancaking before direct quenching on mechanical properties of high strength steels with various alloy-determined hardenabilities.

2. Experimental Procedure

5 heats with the compositions of various hardenability, shown in Table 1, were vacuum induction melted and cast

as 50kg ingot. Each ingot was heated to 1260°C, rolled to a cross section of about 125*102mm (width * thickness), and air cooled for sizing. Fig. 1 shows one example of rolling history. After dividing the slab, the first divided slab for direct quenching after hot rolling (HR/DQ) was finish rolled at 954°C to 13mm of thickness with 7 rolling passes and water quenched. The second divided slab for direct quenching after controlled rolling (CR/DQ) was finish rolled at 843°C and water quenched. In CR/DQ process, the thickness was reduced to 20mm from 102mm by 7 passes at austenite recrystallization region and then reduced to 13mm by 2 passes at non-recrystallization region of 871°C and 843°C for pancaking. The quenched plates were tempered at 204 and 371°C, respectively.

Table 1. Chemical compositions of steels(mass%).

Heat	A3	A4	E1	F1	G1
C	0.131	0.127	0.147	0.147	0.145
Si	0.51	0.49	0.25	0.24	0.25
Mn	1.34	1.32	0.87	0.89	0.089
Cr	-	-	-	0.58	0.59
Mo	-	-	0.252	-	0.233
Ti	0.016	0.030	0.017	0.017	0.017
Sol-Al	0.030	0.039	0.019	0.027	0.038
B(ppm)	70	8	21	18	10
N(ppm)	20	130	40	90	70

In order to evaluate the hardenabilities of each steels and the effect of pancaking on hardenability, continuous cooling transformation(CCT) tests were carried out using Gleeble 1500. Table 2 shows the CCT schedules to simulate HR/DQ and CR/DQ processes. CCT specimens were

finally deformed at 950°C for HR/DQ and 800°C for CR/DQ.

Tensile test was carried out with subsize specimen of ASTM E8-81 and toughness test with Charpy V-notch specimen of ASTM E23-82 at -40°C.

Fig. 1. Rolling history of G1 steel.

Table 2. CCT test schedule to simulate HR/DQ and CR/DQ process.

HR/DQ	10°C/s → 1200°C/5min → 1°C/s → 1000°C/20% → 1°C/s → 950°C/20% → 20sec → Cool
CR/DQ	10°C/s → 1200°C/5min → 1°C/s → 1000°C/20% → 1°C/s → 800°C/20% → 20sec → Cool

3. Result

Fig. 2, in which open mark stands for HR/DQ and solid mark for CR/DQ, shows the effect of pancaking before direct quenching on mechanical properties of steel A3. Tensile strength increased by 360MPa from 950MPa to 1310MPa in as-quenched state with little change of Charpy impact energy at -40°C by applying pancaking. Tensile strength increased by 230MPa and 210MPa after tempering

Fig. 2. Effect of pancaking before direct quenching on mechanical balance of A3 steel

Fig. 3. Effect of pancaking before direct quenching on mechanical balance of A4 and F1 steel.

Fig. 4. Effect of pancaking before direct quenching on mechanical properties of E1 and G1 steel.

at 204 and 371°C, respectively by pancaking

Fig. 3 shows the effect of pancaking before direct quenching on mechanical properties of steel A4 and F1. Tensile strength decreased by 65, 175, and 185MPa after as-quenching or tempering at 204 and 371°C, respectively, with little change of impact energy in steel A4. And decreases of strength were 329, 230, 455MPa in steel F1.

Fig. 4 shows the change of mechanical balance by pancaking E1 and G1 steels. Charpy impact energy increased by about 20joules with little change in strength in both steels.

Fig. 5. shows change of microstructure with processes in A3 steel. Austenite grain was equi-axed in HR/DQ and elongated in CR/DQ while there were no ferrite grains at the austenite grain boundaries. Fig. 6 shows micro-structures of F1 steel. Austenite grain was equi-axed in HR/DQ and elongated in CR/DQ while there were ferrite grains at the austenite grain boundaries in CR/DQ and no ferrites in HR/DQ.

Fig. 7 shows microstructures of G1 steel. Austenite grain was equi-axed in HR/DQ and elongated in CR/DQ while there were no ferrite grains at the austenite grain boundaries.

Fig. 5. Microstructures of A3 steel.
(a)HR/DQ, (b) CR/DQ

Fig. 6. Microstructures of F1 steel.
(a)HR/DQ, (b) CR/DQ

Fig. 7. Microstructures of G1 steel.
(a) HR/DQ, (b) CR/DQ

Fig. 8, in which open mark stands for HR/DQ and solid mark for CR/DQ, shows change of hardenability by pancaking A3, A4 and F1 steels. Hardenability is evaluated by the temperature of 50% transformation (TT50%) during cooling. TT50% decreases as hardenability increases. And pancaking decreased hardenability, i.e. increased TT50% by about 47°C from 493°C to 540°C at the cooling rate of 50°C/sec in A3 steel containing 70ppm B and 20ppm N. TT50% was lower than 550°C at the cooling rates higher than 10°C/sec even after pancaking in A3 steel. TT50% of A4 steel containing 8ppm B and 130ppm N was between 600 and 650°C while that of F1 steel containing 0.58% Cr-18ppm B-90ppm N was between 550 and 600°C. And pancaking also increased TT50% of both A4 and F1 steels. Fig. 9 shows change of hardenability by pancaking E1 and G1 steels. TT50% was lower than 550°C at the cooling rates higher than 10°C/sec even after pancaking E1 steel containing 0.252% Mo. TT50% was lower than 520°C at the cooling rates higher than 10°C/sec even after pancaking G1 steel containing highest alloying contents such as 0.233% Mo and 0.59% Cr.

4. Discussion

The effect of pancaking on mechanical balance can be classified into three groups. Pancaking increased strength without a change in impact toughness, as shown in Fig. 2, in the first group to which A3 steel belongs. Pancaking decreased strength without a change in toughness, as shown in Fig. 3, in the second group to which A4 and F1 steels

Fig. 8. Effect of Pancaking on temperature of 50 transformation in A3, A4, and F1 steel.

Fig. 9. Effect of Pancaking on temperature of 50 transformation in E1 and G1 steel.

belong. Impact toughness increased without a change in strength by pancaking, as shown in Fig. 4, in the last group to which E1 and G1 steels belong.

When strength decreased by pancaking, there were ferrite grains at the austenite grain boundaries as shown in Fig. 6 for F1 steel. And TT50% of A4 steel was higher than 600°C and that of F1 steel was higher than 550°C as shown in Fig. 8. And ferrite grains were observed in CCT specimens of A4 steel in all the cooling rates and process conditions with TT50% higher than 600°C. Meanwhile ferrite grains were observed in almost all CCT specimens of F1 steel except in HR/DQ simulation with cooling rate faster than 20°C/sec showing TT50% lower than 580°C. F1 steel was expected to have a high hardenability due to 0.58% Cr addition. But it had a lower hardenability than expected because of a high N content of 90ppm, resulting in a decrease of effective B. From above results, it can be said that pancaking decreases strength due to formation of ferrite at the austenite grain boundaries when pancaking is applied to the steels of low hardenability with TT50% higher than 550°C.

When TT50% were lower than 550°C, pancaking improved mechanical balance by increasing strength(Group 1) or increasing toughness(Group 3). In Group 1 and 3, there were no ferrite grains at the austenite grain boundaries as shown in Fig. 5 and 7. And there were no ferrite grains in all CCT specimens of A3, E1, and G1 steels with high alloy determined hardenability. Consequently, effective grain size can be decreased by pancaking and fine grain size increases strength or toughness without decreasing strength due to the formation of ferrite at austenite grain boundaries.

There are many reports about increase of toughness with slight increase⁽²⁾ or slight decrease^(3,4,5) of strength by pancaking. And there are also reports about increase⁽⁶⁾ or decrease⁽⁷⁾ of strength without change of toughness by pancaking. It can be said that there are various effects of pancaking on mechanical balance.

H. Yoshinaga et al. reported that strength decreased by decreasing finish rolling temperature from 900°C to 800°C in HT60 and HT80 steels⁽⁷⁾. They explained that the decrease of strength is due to poor hardenability resulted from the strain induced by hot working in the non-recrystallized austenite region, resulting in the formation of ferrite. Their results and explanation are similar with our second group. HT580 and HT780 steels have relatively low alloying contents compared with steels of tensile strength higher than 1000Mpa.

K.A. Taylor reported that strength increased while upper shelf Charpy impact energy and impact transition temperature decreased by pancaking before direct quenching A514 steel of 0.2C-0.6Mn-0.5Mo-B with Ti:N ratio of 4.⁽⁸⁾ In this steel, added B is effective in increasing hardenability due to high Ti:N ratio, resulting in low transformation temperature lower than 520°C.

Some authors^(9,10) reported that the effect of pancaking depends on hardenability indexed by calculated ideal diameter. Vicker's hardness increased by 30 from 360 to 390 in steel with a large diameter, and decreased by 30 from 340 to 310 in steel with a small ideal diameter by applying 30% of strain in non-recrystallized austenite region. But there was no change of hardness by pancaking steel with middle ideal diameter.⁽⁹⁾ When ideal diameter is small, strength decreased and fracture appearance transition temperature(FATT) increased by pancaking. Meanwhile, when ideal diameter is larger than 12cm, strength increased and FATT decreased by pancaking⁽¹⁰⁾.

Hardenabilities of the steels of this investigation depend on B, Ti, and N in addition to C, Si, Mn, Mo and Cr. But B, Ti, and N are not included in the equation to calculate ideal diameter. Consequently, we used an TT50% instead of ideal diameter as an index of hardenability. And the effect of pancaking on mechanical balance can be categorized based on TT50%.

5. Conclusions

(1) Strength decreased due to ferrite formation at austenite grain boundaries by pancaking before direct quenching steels with low alloy-determined hardenability, showing temperature of 50% transformation(TT50%) higher than 550°C.

(2) Strength or toughness increased due to fine effective grain size by pancaking before direct quenching steels with high alloy-determined hardenability, showing TT50% lower than 550°C.

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