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The effect of single and double quenching heat treatments on the mechanical properties of low alloy steel

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1. Introduction

The disposal of spent nuclear fuel is a long-standing issue in nuclear technology because the capacity of spent fuel pool was exceeded by spent nuclear fuel or high level waste [1, 2]. Dry cask storage is a method of storing high-level radioactive waste, such as spent nuclear fuel that has already been cooled in the spent fuel pool for at least one year [3, 4]. For spent fuel storage, low alloy steel is widely used for shielding materials for dry storage cask of spent fuel because of their excellent mechanical properties, weldability and low price [5]. However, they may suffer embrittlement by high levels of radiation and heat for a long period. Therefore, it is important to improve mechanical properties of low alloy steel for the integrity of structure materials.

Generally, conventional single quenching and tempering (CQT) heat treatment process is used to improve the mechanical properties by controlling the temperature and time of heat treatment. Recently, it showed that a double quenching heat treatment (DQT) process resulted in a significant improvement of strength and toughness by austenite grain refinement [6, 7, 8]. In this study, the microstructure and mechanical properties of DQT heat treated specimens were investigated to improve the mechanical properties of low alloy steels comparing the CQT heat treated specimen.

2. Experiments

The material used in the present study was low alloy steels which have a chemical composition: Fe-0.1C-0.3Si-0.8Mn-3.5Ni. The conditions of heat treatment which is used in this work are shown in Fig.1. A plate of low alloy steels was CQT and DQT heat treatment processes to compare the mechanical properties by heat treatment conditions.

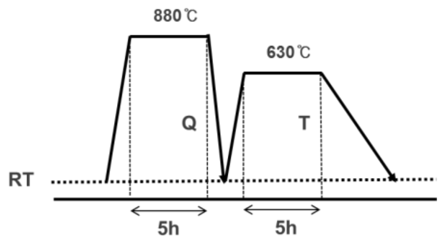
Tensile tests were carried out on a ZWICK tensile machine at room temperature. The dimension of round type specimen was gauge length of 25mm and diameter of 6.25mm. Hardness tests are conducted at 5 N during 10sec by vickers hardness tester of SHIMADU HMV-2T and calculated average value to hardness vickers value of 10 points.

Charpy impact tests using a standard Charpy V-notch (CVN) specimens (10 mm x 10 mm x 25 mm) were performed to evaluate the ductile to brittle transition temperature (DBTT) and upper shelf energy (USE) at temperatures from 20 ℃ to -140 ℃. A specimen was set up in a cold bath filled with isopentane, which was cooled by liquid nitrogen for low temperature testing. The data were curve fit using a hyperbolic tangent function of the form:

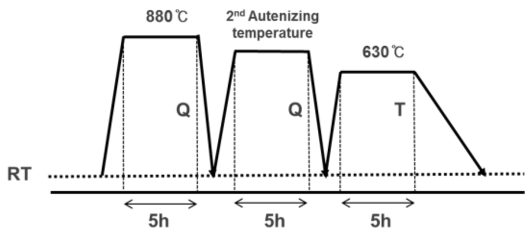
$$E = a + b \tanh [c (T - d)]$$

where E is the absorbed energy (J), a, b, c and d are constants where d = DBTT and a + b = USE, and T is testing temperature (℃).

Microstructures were observed with optical microscope (OM) and scanning electron microscope (SEM).



(a)



(b)

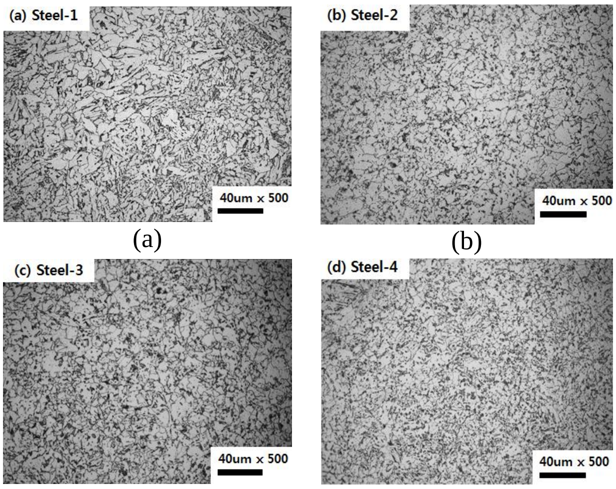
Specimens ID	Process	Quenching	Quenching	Tempering
Steel-1	CQT	880℃, 5Hr	-	630℃, 5Hr
Steel-2	DQT	880℃, 5Hr	860℃, 5Hr	630℃, 5Hr
Steel-3		880℃, 5Hr	820℃, 5Hr	630℃, 5Hr
Steel-4		880℃, 5Hr	780℃, 5Hr	630℃, 5Hr

Fig.1. Diagram of heat treatment processes in this study: (a) CQT process, (b) DQT process

3. Results and discussion

3.1 Microstructure

The microstructure of four steels is shown in Fig. 2. Steel-1 with CQT heat treatment process was observed tempered bainite and a little of pearlite in ferrite matrix. However, the others specimens with DQT process were observed pearlite in ferrite matrix. In terms of grain size, the grain size of DQT process has a fine average grain size comparing the CQT process. Especially, in the case of the DQT process, grain size is decreased by decreasing the temperature of heat treatment in Fig. 2.



(a) (b) (c) (d)

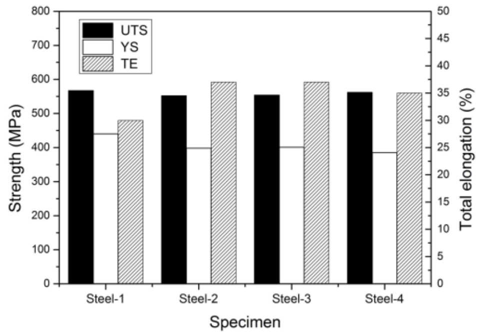
	Steel-1	Steel-2	Steel-3	Steel-4
ASTM grain size number(G)	9.23	11.01	11.07	11.32
Average of Grain size(um)	16.54	8.92	8.74	8.02

Fig. 2. Metallography of the microstructure of the steels: (a)Steel-1, (b)Steel-2, (c)Steel-3 and (d)Steel-4

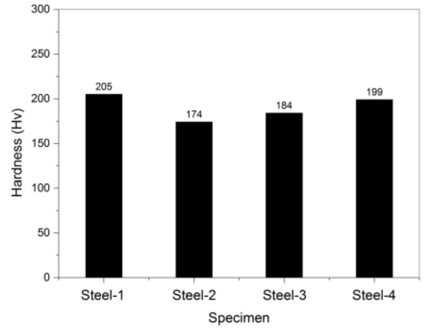
3.2. Tensile and hardness properties

Yield strength (YS; 0.2% offset) and ultimate tensile strength (UTS) of all steels are shown in Fig. 3(a). In this DQT process, total elongation has about 7% higher than that of the CQT process, indicating that the toughness is increased by a fine-graind structure with DQT process. However, UTS of DQT specimens is alomost same as that of CQT specimens (Steel-1).

Hardness of all steels was shown in Fig. 3(b). The hardness of CQT process has higher than that of the DQT process. Generally, hardness of bainite phase is higher than that of pealite phase, while elongation of of bainite phase is smaller than that of pealite phase. Therefore, the change of microstructure which has a fine-graind structure and pealite phase after DQT process affects the reduction of hardness and increase of elongation. The mechanical properties for low alloy steels in this study are summarized in Table 1.



(a)



(b)

Fig.3. The mechanical properties of low alloy steels: (a)Tensile properties and (b) Hardness properties

3.3 Charpy impact properties

The absorbed energy vs temperature curves for steels with four different types of heat treatment process are shown in Fig. 4. The DBTT of steel-1, steel-2, steel-3 and steel-4 was obtained -85 ℃, -115 ℃, -120 ℃ and -125 ℃, respectively. The highest fracture toughness specimen is steel-3 which has a DQT process at the temperature (780 ℃) of heat treatment and the lowest fracture toughness specimen is steel-1 which has CQT process, as shown in Fig. 4. It was found that the DBTT after DQT process is shifted to lower temperatures. Especially, the DBTT of steel-3 is shifted to lower temperature about -40 ℃ in Table 1. In the case of DQT process, the shift of the DBTT increases with increasing the temperature of heat treatment. The highest USE was observed in steel-1 for all specimens. The reason for the reduction of DBTT and USE after the DQT process is related to change of microstructure which is transformed from bainite to pearlite phase and the reduction of grain size with decreasing the temperature of heat treatmnet. Therefore, the DQT process has an influence to increase the toughness of steels.

The fracture surface of each Charpy specimen broken at lower shelf energy (LSE) region was observed by Scanning Electron Microscope (SEM), and all of the specimens showed a complete transgranular type cleavage fracture, as shown in Fig. 5.

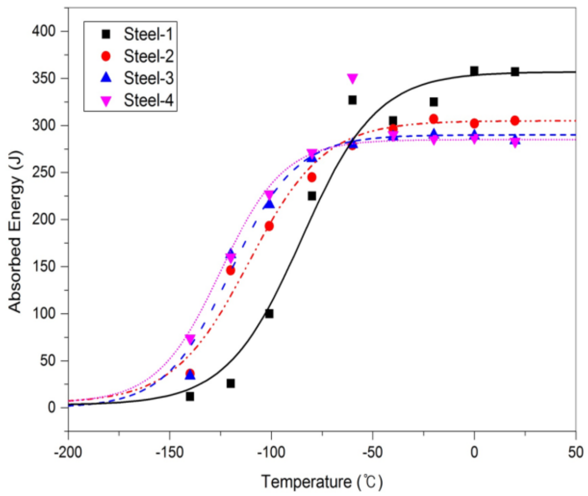


Fig. 4. The energy absorbed vs temperature curves for four steels

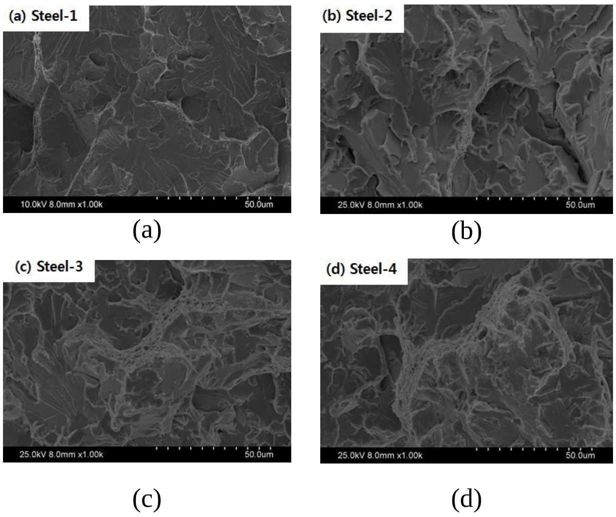


Fig. 5. The fracture surface of each Charpy specimen broken at lower shelf energy (LSE) region (-140℃)

Table.1. The sumarization of mechanical properties for low alloy steels in this study

Specimen ID	YS (MPa)	ΔYS (MPa)	TE (%)	HV	DBTT (℃)	ΔDBTT (℃)	USE (J)
Steel-1	567	-	30	205	-85	-	357
Steel-2	552	-15	37	174	-115	-30	305
Steel-3	554	-13	37	184	-120	-35	290
Steel-4	562	-5	35	199	-125	-40	285

4. Conclusions

In this study, the microstructure and mechanical properties of DQT heat treated specimens were investigated to improve the mechanical properties of low alloy steels comparing the CQT heat treated specimen. The following conclusions were obtained.

(1) The grain size of DQT process has a fine average grain size comparing the CQT process. A fine graind structure with DQT specimen affects the mechanicla properties such as the reduction of hardness and increasement of elongation.
(2) The DBTT after DQT process is shifted to lower temperatures. Especially, the DBTT of steel-3 is shifted to lower temperature about -40 ℃ comparing the CQT specimen(Steel-1).
(3) The reason for the reduction of DBTT and USE after the DQT process is related to the changes of microstructure which are transformed from bainite to pearlite phase and the reduction of grain size with decreasing the temperature of heat treatmnet.

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