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Weld HAZ Toughness and Its Improvement in Low Alloy Steel SQV-2A for Pressure Vessels (Report 3)†

— Toughness Improvement by PWHT —

Jinsun LIAO*, Kenji IKEUCHI** and Fukuhisa MATSUDA***

Abstract

The effect of PWHT conditions on the toughness of the weld HAZ of SQV-2A steel was investigated to determine the optimum PHWT condition. The mechanism of toughness improvement was discussed on the basis of TEM observation and fractography. The results showed that the toughness after PWHT was strongly influenced by cooling time $\Delta t_{8/5}$ of weld HAZ and PWHT conditions. Provided that PWHT time was 28.8 ks at about 893 K and $\Delta t_{8/5}$ was shorter than 40 s, the toughness was greatly improved. However, when the PWHT temperature was 723 K or lower, embrittlement occurred. When $\Delta t_{8/5}$ was longer than 80 s, toughness was increased for PWHT temperatures from 523 to 823 K. When the PWHT temperature was about 893 K, toughness was increased considerably, regardless of cooling time $\Delta t_{8/5}$. The toughness was also affected by PWHT time. By increasing the cooling time to 7.2 ks, the toughness was clearly increased. Therefore, a PWHT at 893 K for 7.2 ks could greatly improve the weld HAZ toughness of SQV-2A steel. If the cooling time $\Delta t_{8/5}$ of weld HAZ was shorter than 20 s, the toughness could be improved to the level of as received material.

Metallurgical analysis showed that in the case of $\Delta t_{8/5}$ of 6 s, after PWHT at 893 K for 7.2 ks, recovery phenomenon occurred to martensite laths, and the matrix was significantly softened. For this reason, the toughness was improved. In the case of $\Delta t_{8/5}$ of 150 s, the M-A constituent was decomposed, but there was no obvious change in ferrite lath of upper bainite after a PWHT at 893 K for 7.2 ks. Because the ferrite lath was too coarse, the improvement in toughness was limited.

KEY WORDS: (Toughness Improvement) (PWHT) (Decomposition of M-A Constituent) (Matrix)

1. Introduction

In previous studies, the effect of cooling time $\Delta t_{8/5}$ on the microstructures and toughness was investigated.[1] The results showed that toughness was drastically decreased if the cooling time $\Delta t_{8/5}$ was longer than 20 s, because of the formation of upper bainite (including M-A constituent). Even if $\Delta t_{8/5}$ was short, for example 6 s, the toughness was still lower than that of as-received material, whereas the hardness was so high (about 420 Hv) that the risk of cold cracking was very high. Therefore, Post Weld Heat Treatment (PWHT) is necessary to improve the toughness and lower the hardness.

In practice, low heat-input is generally adopted in building pressure vessels, so the microstructure is often martensitic. However, in order to increase welding productivity, medium or high heat-input welding is preferred. In this case, the microstructure is usually bainite. It has been well known that a martensitic structure, if properly tempered by PWHT, probably contributes to high toughness, whereas the toughness of an upper bainite microstructure is quite difficult to increase by PWHT. However, recent studies showed that weld HAZ toughness with long cooling times $\Delta t_{8/5}$ (i.e. with high heat-input welding) of some low alloy steels is capable of improvement by the proper using of PWHT.[2] For those low alloy steels, in which the M-A constituent was responsible for the decreased HAZ toughness at long cooling times $\Delta t_{8/5}$,[3] the toughness improvement by PWHT was said to be mainly due to the decomposition of

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M-A constituent. For SQV-2A steel, the M-A constituent was one of main reasons for toughness decreasing, but the increment of ferrite lath width of upper bainite with increasing cooling time $\Delta t_{8/5}$ was also responsible for the toughness deterioration of the HAZ.[1) It is reasonable to expect that PWHT will improve the weld HAZ toughness by decomposing M-A constituent also for SQV-2A steel. But because the matrix became brittle as a result of increase in ferrite lath width at slow cooling rates, the improvement of toughness might be limited. Therefore, it was suggested that when cooling time was increased to a certain degree, toughness improvement by PWHT would become difficult.[4) It is therefore important to know the range of cooling time $\Delta t_{8/5}$ within which toughness of weld HAZ can be improved by PWHT, because this will allow the correct choice of welding heat-input in practical engineering.

Moreover, by studying the effect of PWHT on toughness improvement of the weld HAZ for long cooling times, the role of M-A constituent and matrix (including ferrite lath width) in weld HAZ toughness can be understood more thoroughly.

Therefore, the effect of PWHT conditions on the toughness improvement of weld HAZ of SQV-2A steel was investigated in this paper. The optimum PWHT conditions were determined, and corresponding cooling time $\Delta t_{8/5}$ ranges, i.e. welding heat-input ranges, have been suggested. The the mechanism of toughness improvement is also discussed.

2. Experimental details

The chemical composition of SQV-2A steel is shown in Table 1. The as-received material was quenched-and-tempered steel with thickness (t) of 200 mm.

The experimental process is shown in Fig.1. Firstly, the weld HAZs with cooling times $\Delta t_{8/5}$ from 6 to 500 s were simulated by using thermal/ mechanical simulator Gleeble 1500. The samples (10x10x55 mm^3) used for thermal simulation were cut from SQV-2A steel plate at positions of 1/4t or 3/4t. Then PWHT was performed by the use of an electrical furnace. The furnace was preheated to the selected PWHT temperatures, then those thermally simulated samples were put inside the furnace. After the PWHT was finished, the samples were taken from the furnace and cooled in air. After that, the samples were machined into standard V notch Charpy impact test specimens, and impact testing was performed at room temperature to evaluate the toughness.

Table 1 Chemical composition of experimental steel used

Material	Chemical composition (mass%)						
	C	Si	Mn	P	S	Ni	Mo
SQV-2A	0.19	0.24	1.48	<0.01	<0.01	0.62	0.56

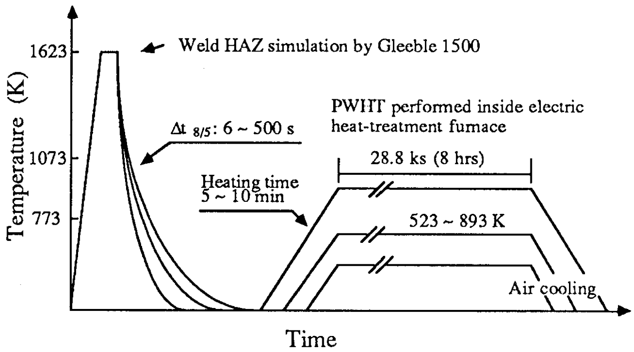

Fig. 1 Thermal cycles for weld HAZ simulation and PWHT

PWHT time was firstly chosen as 28.8 ks from the view of stress-relief, and PWHT temperatures were varied from 523 to 893 K to investigate the influence of temperature on toughness. After an optimum PWHT temperature, at which toughness was improved obviously, was identified, the PWHT time was varied from 3.6 to 28.8 ks, and its effect on toughness was investigated to discover the optimum PWHT time.

To investigate the mechanism of toughness improvement by PWHT, metallurgical analysis was carried out using SEM and TEM. Fracture surfaces were checked by SEM.

3. Experimental results and discussion

3.1 Effect of PWHT conditions on toughness

3.1.1 Effect of PWHT temperature

When the PWHT time is 28.8 ks, the absorbed energies of Charpy impact tests at room temperature are shown in Fig. 2, as a function of cooling time $\Delta t_{8/5}$. It can be seen that the effect of PWHT on toughness is strongly influenced by both PWHT temperature and cooling time $\Delta t_{8/5}$. For cooling times $\Delta t_{8/5}$ shorter than 40 s, the absorbed energy increased after PWHT at above 823 K. When PWHT temperature was 893 K, the absorbed energy was improved significantly. However, when PWHT temperature was at or below 723 K, the absorbed energy became lower than that of the as-welded HAZ. This phenomenon implies that tempering embrittlement (or tempering martensite embrittlement) will occur if the PWHT temperature is not properly chosen. The absorbed energy was the lowest when the temperature was about 623 K. For cooling times $\Delta t_{8/5}$ longer than 80 s, however, the absorbed energies were

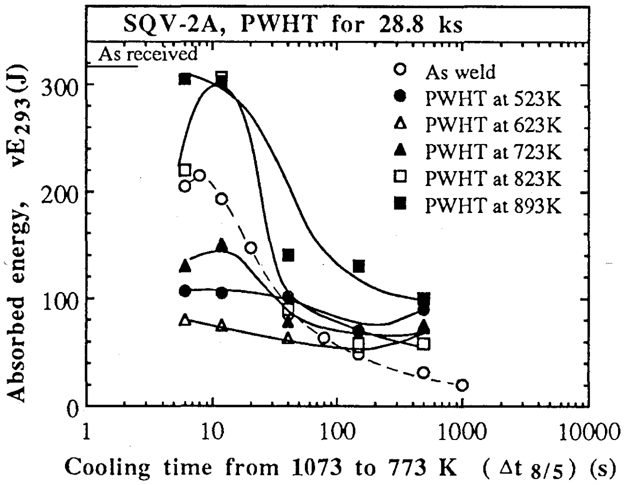

Fig. 2 Absorbed energy after PWHT as a function of cooling time $\Delta t8/5$

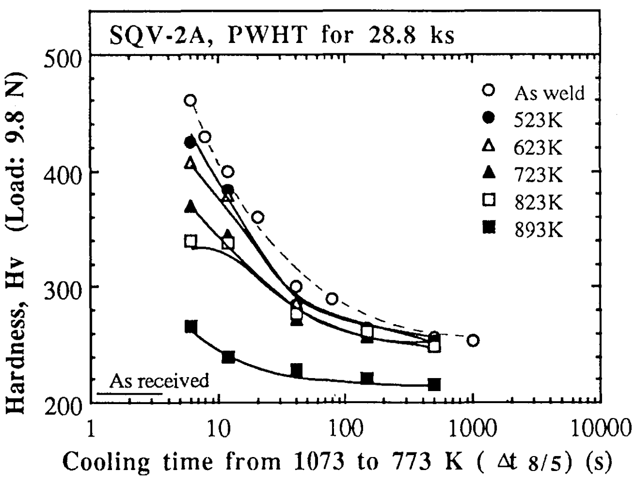

Fig. 3 Hardness after PWHT as a function of cooling time $\Delta t_{8/5}$

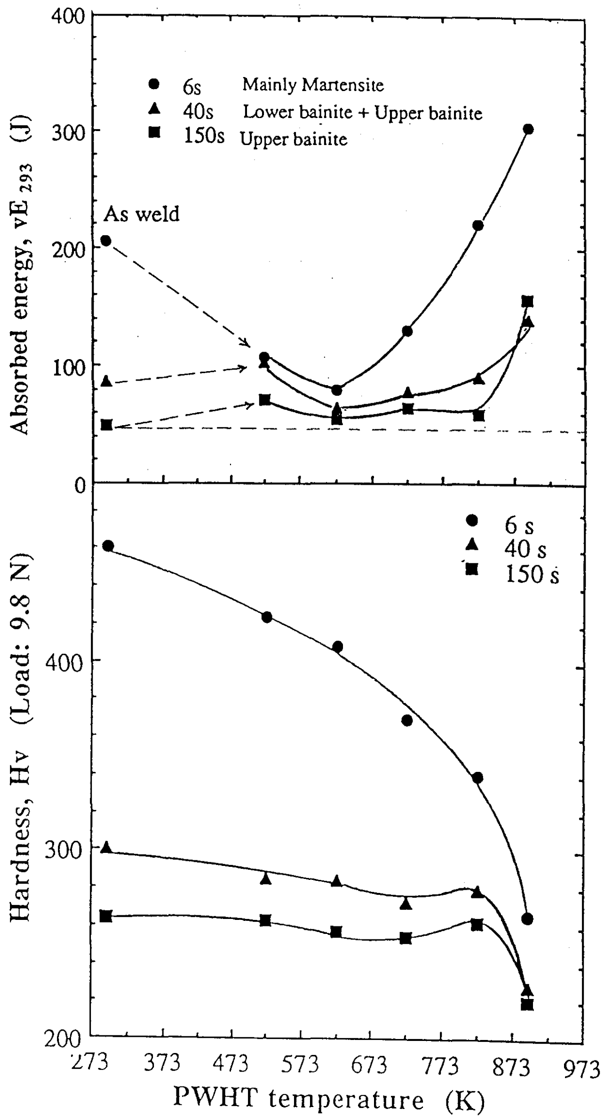

Fig. 4 Effect of PWHT temperature on absorbed energy and hardness (for PWHT time of 28.8 ks)

always slightly higher than that of as-welded HAZ for the PWHT temperatures from 523 to 823 K. When PWHT temperature was about 893 K, the absorbed energy was obviously improved. Regardless of cooling time $\Delta t_{8/5}$, the absorbed energy was greatly increased after PWHT at 893 K. However, when $\Delta t_{8/5}$ was 40 s or longer, although the absorbed energy was increased after PWHT at 893 K, it was still low, even lower than that of as-weld HAZ for $\Delta t_{8/5}$ of 6 s. Only when $\Delta t_{8/5}$ was shorter than 20 s, could the absorbed energy be improved to the level of as received material. Therefore, in order to obtain a superior toughness at a similar level to that of as-received material, both a high PWHT temperature and a short cooling time (i.e. low heat-input welding) are necessary.

The hardness after PWHT is shown in **Fig. 3**. With increasing PWHT temperature, the hardness decreased. When PWHT temperature was about 893 K, the hardness was reduced to the level of as received material.

The absorbed energy of Charpy impact tests and hardness as a function of PWHT temperature are shown in **Fig. 4**. Relationships of absorbed energy and hardness with PWHT temperature were dependent on the cooling time $\Delta t_{8/5}$ of the weld HAZ, or in other words, on the microstructure of the weld HAZ. For cooling time $\Delta t_{8/5}$ of 6 s, (microstructure was martensite), absorbed energy decreased at a PWHT temperature of 523 K, and further decreased with increasing PWHT temperature to 623 K. The absorbed energy was lower than that of the as-welded HAZ when the PWHT temperature was 723 K or lower, which means that the temperature range of embrittlement is from 523 to 723 K. For PWHT temperatures higher than 823 K, the toughness was improved. For cooling time $\Delta t_{8/5}$ of 40 s, (microstructure was lower bainite + upper bainite), the change of absorbed energy with PWHT temperature was somewhat similar to that for $\Delta t_{8/5}$ of 6 s, except that the absorbed energy was slightly higher than that of the as-welded HAZ at a PWHT temperature of 523 K. For $\Delta t_{8/5}$ of 150 s, however, the toughness variation was different. At all PWHT temperatures in our experiments, the absorbed energies were higher than that of the as-welded HAZ. When the PWHT temperature is between 523 and 823 K, the absorbed energies are about 20 ~ 30 J higher than that of the as-welded HAZ. This could be considered to be the result of the M-A constituent decomposition, because no other microstructural change was observed and a hardness decrease was also not obvious. When PWHT temperature was 893 K, absorbed energy was increased considerably. This is due to the M-A constituent decomposition and matrix softening, as discussed later.

For a cooling time $\Delta t_{8/5}$ of 6 s, hardness continuously decreased with increasing PHWT temperature. However, for $\Delta t_{8/5}$ of 40 and 150 s, a hardness decrease was not obvious at PWHT temperatures between 523 and 823 K. Only when PWHT temperature was about 893 K, was hardness decreased. It can be seen from Fig. 4 that when PWHT temperature is about 823 K, the hardness is slightly higher than that for PWHT temperature at 723 K, which implies that secondary hardening has probably occurred.

3.1.2 Effect of PWHT time

When the PWHT temperature is 893 K, the relationships of absorbed energy and hardness to PWHT time are shown in **Fig. 5**. For cooling times $\Delta t_{8/5}$ of 6, 40 and 150 s, the trends of absorbed energy and hardness variance with PWHT time were almost the same. Namely, the toughness was increased with increasing PWHT time to 7.2 ks, then it fell when PWHT time was about 14.4 ks. The toughness increased again with further increasing PWHT time to 28.8 ks.

On the other hand, the hardness was markedly decreased with increasing PWHT time to 7.2 ks for $\Delta t_{8/5}$ of 6 s. However, hardness decrease was not so great for $\Delta t_{8/5}$ of 40 s, and even less for 150 s. When the PWHT time was 14.4 ks, a slight increase in hardness was observed compared with the case at 7.2 ks, which implies that secondary hardening probably occurred.

From above results, it can be seen that 893 K - 7.2 ks is the optimum PWHT condition from the view of toughness improvement. In practice, considering the

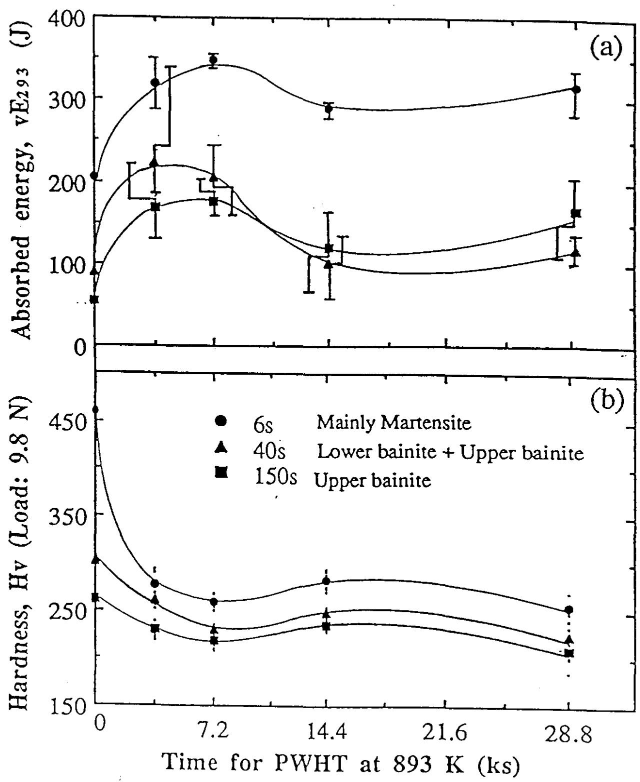

Fig. 5 Effect of PWHT time on absorbed energy and hardness (for PWHT temperature at 893 K)

stress relief, PWHT time is usually chosen as 28.8 ks. In this case, the toughness can also be increased greatly, especially when low heat-input welding is adopted.

3.2 Fractographic analysis

As mentioned above, when $\Delta t_{8/5}$ was shorter than 40 s and PWHT temperature was 723 K or lower, the absorbed energy was even lower than that of the as-welded HAZ. To investigate the reason, the surface of fractured samples at room temperature was checked by SEM. For $\Delta t_{8/5}$ of 6 s, as an example, the fractographs at different PWHT temperatures are shown in **Fig. 6**.

The fractography of the as-welded HAZ was characterized as cleavage and dimple. When the PWHT temperature was 523 K, cleavage was dominant. Intergranular fracture was observed when the PWHT temperature was from 623 to 723 K. With increasing PWHT temperature to 823 K or higher, intergranular fracture was almost absent, and instead, dimple and cleavage were confirmed. The average area fractions of intergranular fracture, cleavage and dimple can be summarized as in **Fig. 7**.

It should be noted that the area fraction was obtained by measuring the whole surfaces of fractured samples. The intergranular fracture fraction near the V-notch was much higher than the average, as shown in **Fig.8**, and

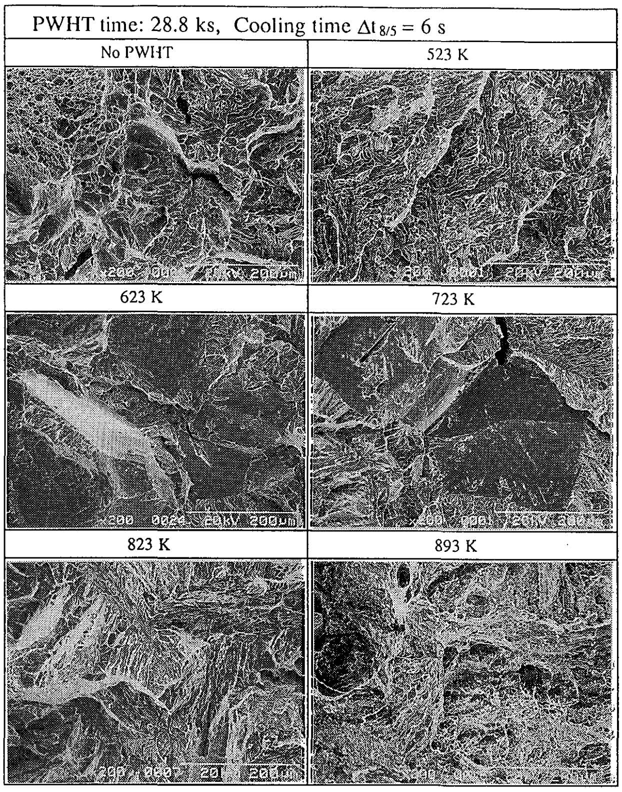

Fig. 6 Fractography after PWHT for 28.8 ks ($\Delta t_{8/5}$ = 6 s)

fracture initiation site was always observed at the intergranular fracture surface.

It was suggested that phosphorous segregation at grain boundary was responsible for intergranular fracture in the weld metal of SQV-2B steel with lower P content.[5] Therefore, the interganular fracture may also be due to the P segregation at grain boundaries for SQV-2A steel.

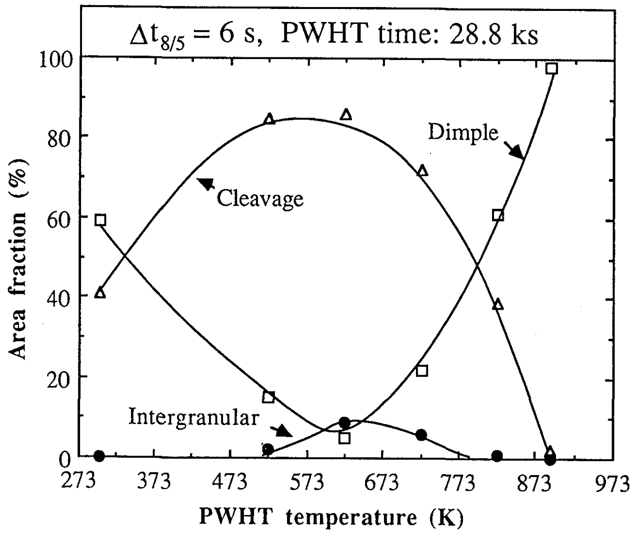

Fig. 7 Relationship of area fractions of cleavage, dimple and intergranular fracture to PWHT temperature

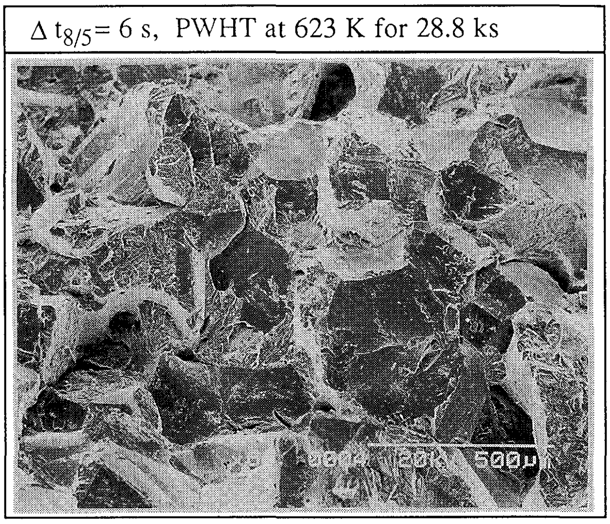

Fig. 8 Fractography near V-notch

3.3 Microstructural change after PWHT

The microstructures after PWHT were characterized by SEM observation after specimens were etched in 3% Nital. The microstructural changes with PWHT temperature are shown in **Fig. 9** and **10**, respectively for martensite and upper bainite structures.

For the martensite structure, inter-lath carbide was precipitated when the PWHT temperature was about 523 K, as shown in Fig. 9. With increasing temperature, this phenomenon became more obvious. However, when PWHT temperatures were very high, for example 893 K, the carbide seems to be spheroidized.

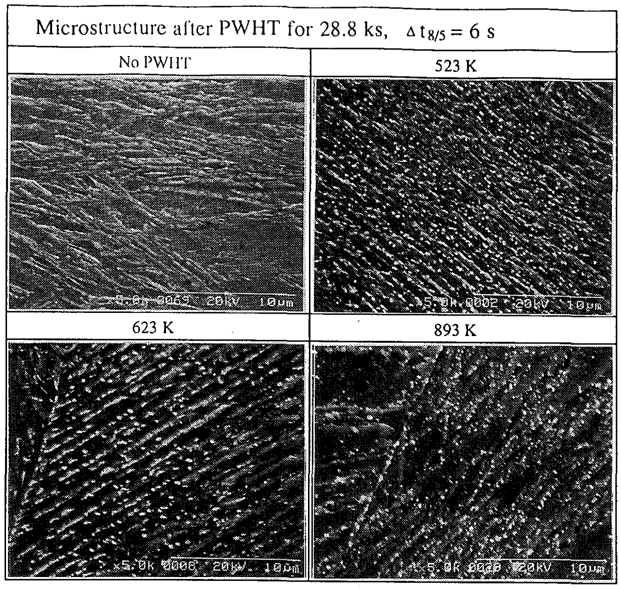

Fig. 9 Effect of PWHT temperature on martensitic microstructure

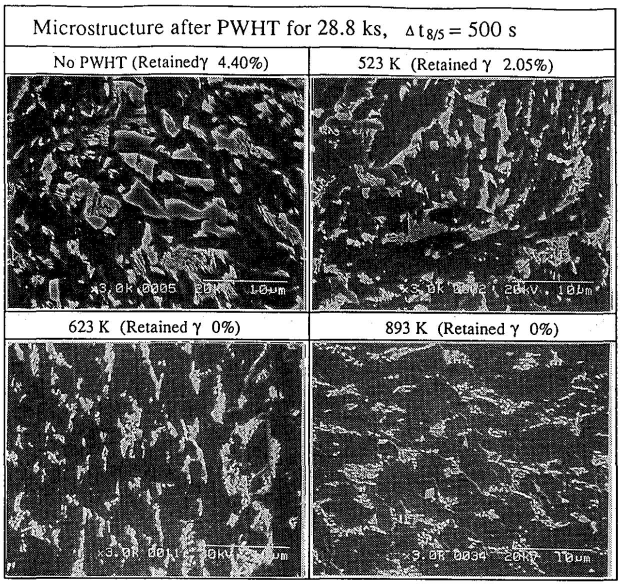

Fig. 10 Effect of PWHT temperature on upper bainite microstructure

It has been suggested that film-like inter-lath carbide is a main reason for toughness decreasing.[6-8] The drop in toughness after PWHT at 523 K for 28.8 ks is probably due to the film-like inter-lath carbide precipitation. This precipitated inter-lath carbide was also observed with TEM, as shown in **Fig. 11**.

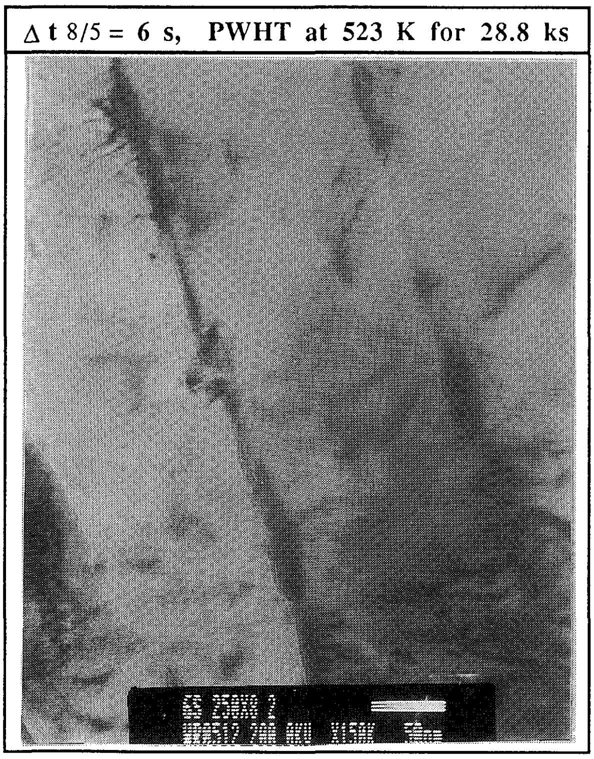

Fig. 11 Precipitated inter-lath carbide

For Upper bainite structures, decomposition of M-A constituent was observed, as shown in Fig. 10. When the PWHT temperature was 523 K, the M-A constituent was partially decomposed. With increasing temperatures above 623 K, M-A constituents were completely decomposed. After PWHT at 523 ~ 623 K for 28.8 ks, a decrease in hardness was not obvious in the case of $\Delta t_{8/5}$ of 150 and 500 s, but the absorbed energy was increased, as shown in Fig. 2 and 3. This can be thought as a result of M-A constituent decomposition.

3.4 Discussion on toughness improvement by PWHT

From above experimental results, it has been shown that a high PWHT temperature (about 893 K) is necessary to improve the weld HAZ toughness. To improve the toughness to the level of as-received material, low heat-input, i.e. cooling time $\Delta t_{8/5}$ less than 20 s, is also required. When PWHT time is about 7.2 ks, the toughness is increased to the highest level.

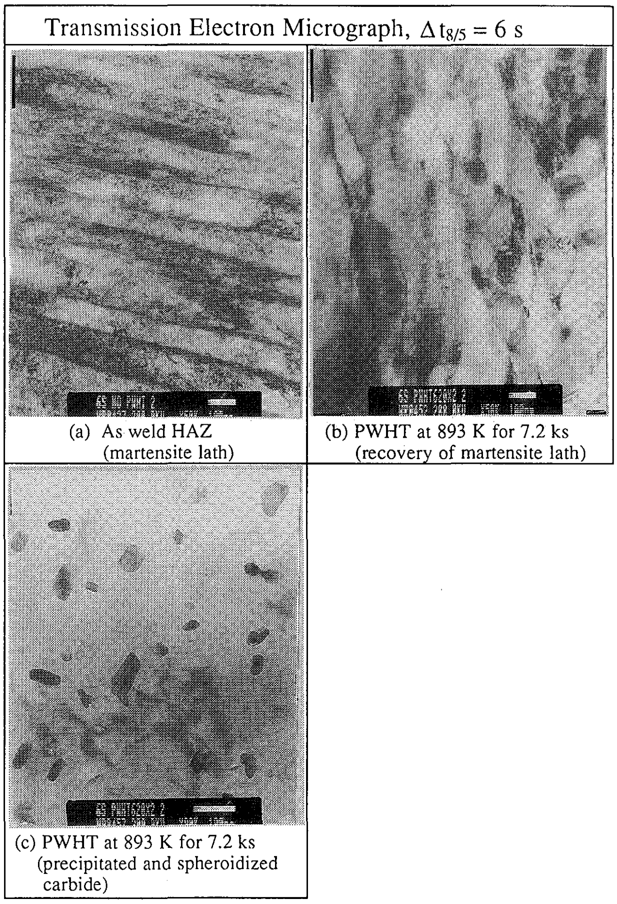

Fig. 12 Effect of PWHT at 893 K for 7.2 ks on the microstructure for $\Delta t_{8/5}$ of 6 s

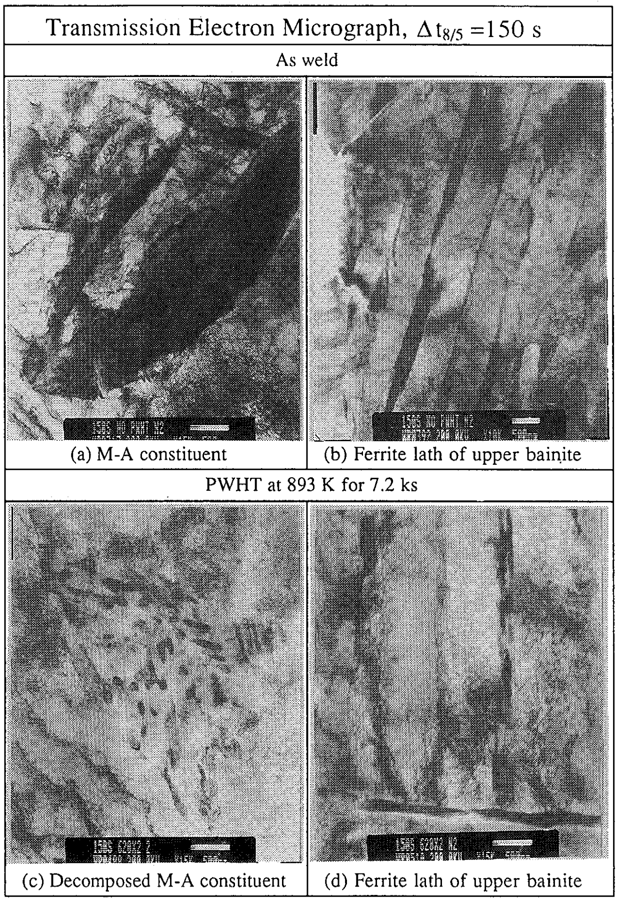

Fig. 13 Effect of PWHT at 893 K for 7.2 ks on the microstructure for $\Delta t_{8/5}$ of 150 s

To understand the mechanism of toughness improvement by PWHT, the microstructural change after PWHT at 893 K for 7.2 ks was observed with TEM by the use of thin foil techniques. The results are shown in **Fig. 12** and **13**, respectively for $\Delta t_{8/5}$ of 6 and 150 s.

When $\Delta t_{8/5}$ was 6 s, the microstructure of the as-welded HAZ was massive martensite, made up of packets of parallel laths, as shown in Fig. 12 (a). After PWHT at 893 K for 7.2 ks, sub-lath boundary was observed, and carbide was precipitated near the sub-lath boundaries or lath boundaries. Within a plane of martensite, carbide was precipitated and spheroidized, as shown in Fig. 12 (c). This implied that recovery occurred and the matrix became softened. Because of this, toughness was increased.

When $\Delta t_{8/5}$ was 150 s, the microstructure was upper bainite coexisting with M-A constituent, as shown in Fig.13 (a) and (b). After PWHT, M-A constituents were decomposed to ferrite and carbide, as shown in Fig. 13 (c). The dislocation density also became lower, so that the hardness was decreased slightly, (see Fig. 4), and the

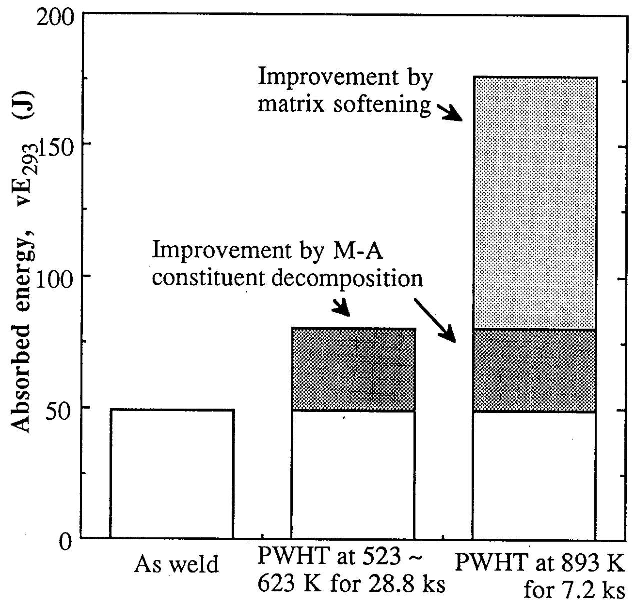

Fig. 14 The roles of M-A constituent decomposition and matrix softening in toughness improving

matrix became somewhat softened. Considerable toughness improvement is probably due to both M-A constituent decomposition and matrix softening, as suggested by Okada et al..[9] If we consider that the toughness improvement was only due to the decomposition of M-A constituents because of no decrease in hardness when PWHT condition is about 523 - 623 K and 28.8 ks, the roles of M-A constituent decomposition and matrix softening in toughness improving after PWHT at 893 K for 7.2 ks can be illustrated as in **Fig. 14**.

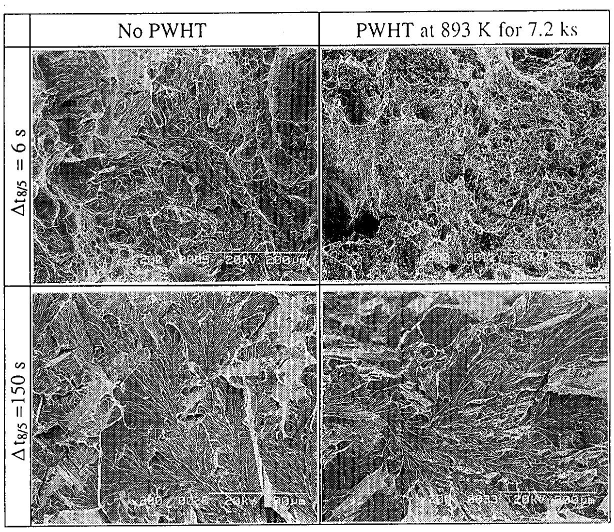

Fig. 15 Fractography with and without PWHT for $\Delta t_{8/5}$ of 6 and 150 s

The fractographs with and without PWHT are shown in **Fig. 15**. When $\Delta t_{8/5}$ was 150 s, no obvious change in fractography was observed after PWHT, except that the initiation sites seem to be fewer. However, when $\Delta t_{8/5}$ was 6 s, the fracture surface was full of fine dimples after PWHT.

When $\Delta t_{8/5}$ was 150 s, although the toughness increased after PWHT at 893 K for 7.2 ks, the value was still lower than that when $\Delta t_{8/5}$ was 6 s. From Fig. 12 and 13, it can be seen that the ferrite lath width is much larger compared with the case of $\Delta t_{8/5}$ of 6 s. After PWHT, no change such as recovery in ferrite lath of upper bainite was observed, and the carbide was almost not spheroidized. It can also be seen from fractographs that the cleavage pattern for $\Delta t_{8/5}$ of 150 s, even after PWHT at 893 K for 7.2 ks, is much coarser than that for $\Delta t_{8/5}$ of 6 s. Therefore, for the weld HAZ of SQV-2A steel, if the ferrite lath becomes too large as a result of increasing cooling time $\Delta t_{8/5}$, the improvement in toughness will be limited.

4. Conclusion

The effect of PWHT conditions on weld HAZ toughness of SQV-2A steel was investigated to determine the optimum PWHT condition; and the mechanism of toughness improvement by PWHT was discussed based on the TEM observation and fractography. The main conclusions are as follows:

(1) For SQV-2A steel, PWHT at 893 K for 7.2 ks can improve the weld HAZ toughness significantly. To obtain a superior toughness of weld HAZ by PWHT, low heat-input welding is also required to confine the cooling time $\Delta t_{8/5}$ within 20 s.

(2) When the PWHT temperature is 723 K or lower, embrittlement occurs for cooling times $\Delta t_{8/5}$ shorter than 40 s.

(3) After PWHT at 893 K for 7.2 ks, the recovery of martensite lath is observed and matrix becomes softened for $\Delta t_{8/5}$ of 6 s. For $\Delta t_{8/5}$ of 150 s, however, no change in ferrite lath is observed, while the M-A constituents are decomposed and the matrix becomes somewhat softened.

(4) When $\Delta t_{8/5}$ is 150 s, although the toughness is increased by PWHT as a result of M-A constituent decomposition and matrix softening, the improving extent of toughness is limited by the coarsened ferrite lath.

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