POST WELD HEAT TREATMENT OF A HIGH-TEMPERATURE STEEL

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Abstract: After welding, heat treatment of weld joints on components made of high-temperature steels is usually necessary. In this work, several microstructures occurring in the heat affected zone (HAZ) in X10CrMoVNb9-1 high-temperature steel were simulated: Coarse grained HAZ (CGHAZ), two different fine grained HAZ (FGHAZ) and intercritical HAZ (ICHAZ). Test pieces were mechanically tested at room temperature in as welded condition and after post weld heat treatments at 760 °C and 780 °C. At both temperatures, already after 0.5 h even the hardness of CGHAZ met the requirements of EN ISO 15614-1, and also the impact toughness was significantly above the required minimum. However, to decrease the hardness of all HAZ subzones close to 250 HV, which is within the hardness range of as delivered normalized and tempered material, it took 4 h at 280 °C and 8 h at 760 °C.

1 INTRODUCTION

Components that operate at elevated temperatures must not only exhibit appropriate mechanical properties at the operating temperature but also sustain cooling down to room temperature (e.g. for maintenance or repair). Weld joints should have similar properties as base materials.

Nowadays, one of often used steels for such components is X10CrMoVNb9-1. Before welding, it must be preheated [1], and the heat inputs must not be too high to ensure appropriate interpass temperatures. After welding, the welds must cool down slowly at controlled cooling rates.

Usually, the most critical areas of a weld joint are heat-affected zones (HAZs), where undesired microstructures are most likely to develop. Consequently, most of the weld joints need to be post weld heat treated (PWHT).

The creep strength of X10CrMoVNb9-1 welds is most often limited due to cracking [2, 3]. It was found out that cracks usually occur in HAZ [4, 5–8], especially often in fine grained HAZ (FGHAZ) adjacent to intercritical HAZ (ICHAZ) [6], and in ICHAZ [9, 10]. To prevent formation of martensite after PWHT, temperature of PWHT must be below A_1 [11, 12]. According to the CCT diagram, A_1 is about 810 °C [13]. Consequently, the maximum recommended temperature reported in the literature was up to 800 °C [14], but numerous researchers recommended much lower temperatures, not exceeding 780 °C [11, 15-18]. The majority of researchers applied 760 °C [17, 18, 21-24], in duration up to 3 h. Mechanical testing of a real-weld HAZ is difficult [4, 25, 26], because the HAZ is to narrow [25]. Consequently, results cannot be linked to only one certain type of microstructure and the scattering of results is often enormous. In order to obtain reliable data on mechanical properties in relation to microstructure, a larger volume of homogeneous microstructure is inevitable. The most suitable way to produce sufficiently large volumes of material exhibiting a homogeneous microstructure of a certain type is the simulation of microstructures [4, 25–27]. In spite of that simulated material for the study of HAZ subzones was used less frequently than expected and no publications reporting the influences of different PWHT time–temperature combinations on impact toughness of different HAZ subzones could be found in the open literature. Therefore, this work focuses on the hardness and impact toughness of simulated HAZ subzones after PWHT at several different time-temperature combinations.

2 MATERIALS AND METHODS

The X10CrMoVNb9-1 creep resistant steel was used in this research. The mechanical properties according to the material’s certificate are presented in Table 1. Specimens measuring 11 mm × 11 mm × 56 mm were prepared.

Table 1. Mechanical properties of the X10CrMoVNb9-1 steel

R_{p02} / MPa	R_m / MPa	A_5 / %	*HV* 10	*KV* (ISO-V) at 20 °C/J
450	620	19	211	192

Four different HAZ sub zones were simulated; CGHAZ ($T_{peak} >>> A_{C3}$) and FGHAZ-1 ($T_{peak} >> A_{C3}$), FGHAZ-2 ($T_{peak} > A_{C3}$) and ICHAZ. A weld thermal cycle simulator Smitweld 1405 was used for simulations. Heating rates and cooling times from 800 °C to 500 °C ($\Delta t_{8\text{–}5}$) in different regions of HAZs were measured during real-welding and the determined heating and cooling rates were applied for the simulations, Table 2. The transformation temperatures A_{C1}, A_{C3}, M_s, and M_f were determined from the T-ΔL curves, recorded on a weld thermal cycle simulator during preliminary tests. The peak temperatures for the simulation of ICHAZ were selected on the basis of the determined A_{C1} and A_{C3}. The preheating temperature 200°C before the start of the simulation was selected according to recommendations for real welding [13, 28, 29].

Table 2. Parameters for HAZs material preparation in a weld thermal cycle simulator.

Parameter	CGHAZ	FGHAZ-1	FGHAZ-2	ICHAZ
Preheat T / °C	200	200	200	200
Heating rate / °C s^{-1}	150	150	150	150
T_{peak} / °C	1350	1100	940	875
T_{hold} / °C	1350	1100	940	875
t_{hold} / s	0.5	0.5	0.5	0.5
Δt_{8-5} / s	10	10	10	10
T_{finish} / °C	220	220	220	220

All PWHTs were performed in the laboratory chamber furnace Bosio EUP-K. PWHT temperatures were 760 °C and 780 °C, and soaking times at each temperature were 0.5, 1, 2, 4, and 8 h. The heating and cooling rates were 150 °C h^{-1}, which was consistent with recommendations found in the literature [4, 29, 30]. Below 200 °C, the cooling rate was not controlled.

After HAZ-simulation and PWHT, the test pieces were machined to ISO-V specimens according to EN ISO 148-1. Hardness *HV* 10 was measured with a hardness tester Shimadzu HMV-2000. Impact tests followed. An instrumented Charpy pendulum Amsler RPK300 was used for the impact toughness tests. The impact energy *KV* was divided into energy for crack initiation E_i and energy for crack propagation E_p.

3 RESULTS AND DISCUSSION

The hardness and impact energies of simulated HAZ zones before PWHT are summarized in Table 3.

Table 3. Hardness and impact energies of simulated HAZ subzones.

HAZ subzone	T_{peak} / °C	*HV* 10	*KV*/J	E_i/J	E_p/J	% of Ductile Fracture
CHHAZ	1350	462	73	70	3	3.9
FGHAZ-1	1100	466	121	79	42	44.1
FGHAZ-2	940	390	172	70	102	74.3
ICHAZ	875	235	246	74	172	100

ASTM recommends a maximum hardness of 265 *HV* for a very similar steel, while Li et al. [31], established 189 *HV* as the minimum value for safe operation. Therefore, the goal was to achieve a hardness between 190 and 250 HV. The aimed impact toughness was to be close to the base metal (192 J) and the portion of ductile fraction 100 %.

Hardness and impact toughness of different HAZ-subzones after different PWHTs is shown in Figures 1-4. Annealing time t = 0 denotes as-weld condition. In all four figures, hardness is represented by red (760 °C) and black (780 °C) curves, and impact energies are represented by blue (760 °C) and green (780 °C) curves.

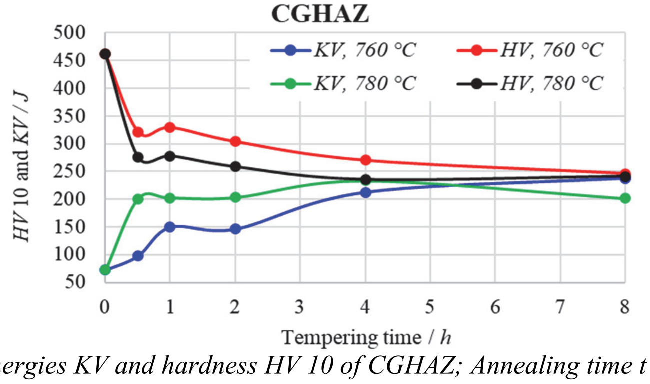

Figure 1. The impact energies KV and hardness HV 10 of CGHAZ; Annealing time t = 0 denotes as-welded condition.

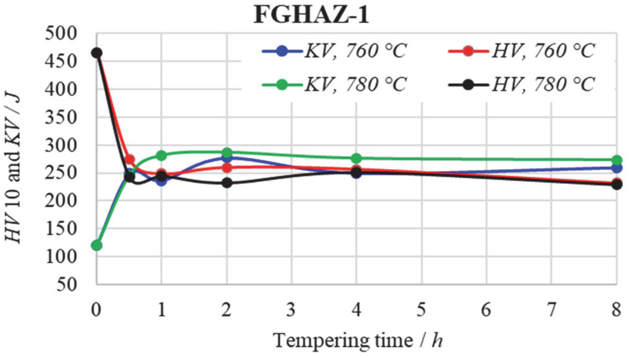

Figure 2. The impact energies KV and hardness HV 10 of FGHAZ-1; Annealing time t = 0 denotes as-welded condition.

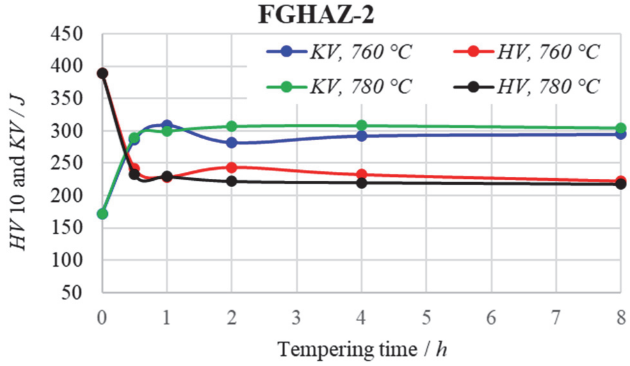

Figure 3. The impact energies KV and hardness HV 10 of FGHAZ-2; Annealing time t = 0 denotes as-welded condition.

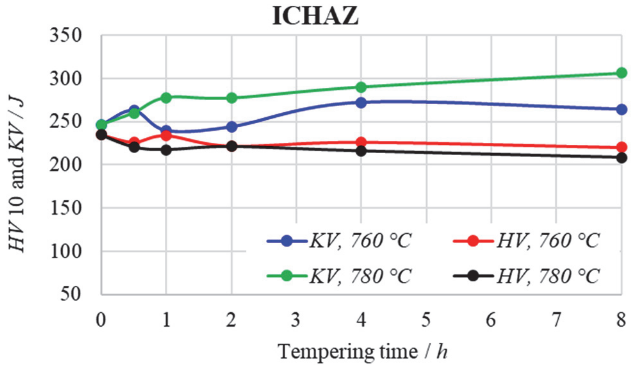

Figure 4. The impact energies KV and hardness HV 10 of ICHAZ-1; Annealing time t = 0 denotes as-welded condition.

Optimum time-temperature combinations depend on actual wall thickness. In our research, specimens having 11 mm × 11 mm cross-sections were used. Therefore, it must be taken into account that at thicker cross-sections longer heating and cooling times will be necessary.

In the CGHAZ, the hardness dropped below 265 *HV* 10 after less than 2 h at 780 °C. At 760 °C, 8 h were necessary, Figure 1. In the FGHAZ-1, the hardness dropped below 265 *HV* after 1 h at 760 °C, and after 0.5 h at 780 °C (Figure 2).

At both temperatures, already after 0.5 h the hardness was below 260 *HV* 10 in the ICHAZ and FGHAZ-2 (Figures 3 and 4). Nevertheless, after 8 h at 780 °C, the hardness was still over 200 *HV* 10. This indicates that even at higher temperatures there was no danger of overtempering,

In industrial practice, time is valuable. Consequently, higher PWHT temperatures can be of advantage. In this regard, the optimum temperature and duration would be 780 °C and less than 2 h, respectively. The exact minimum time at 780 °C has still to be determined with further experiments.

The impact energy *KV* exceeded 190 J (the BM) in all HAZ subzones already after 0.5 h at 780 °C, and the fracture was 100 °ductile, even in the most brittle HAZ-subzone, CGHAZ, Figure 1. Our results of Charpy tests herewith disagree with often recommended PWHT up to 3 h at 760 °C. To obtain good toughness in 3 h or less, the temperature must be higher than 760 °C.

4 CONCLUSIONS

HAZ subzones were simulated with X10CrMoVNb9-1 steel: CGHAZ (T_{peak} = 1350 °C), FGHAZ-1 (T_{peak} = 1100 °C), FGHAZ-2 (T_{peak} = 940 °C), and ICHAZ (T_{peak} = 875 °C). PWHT temperatures were 760 and 780 °C, while the soaking times were 0.5, 1, 2, 4, and 8 h. The goal was a hardness of 200–265 *HV* and impact energies *KV* ≥ 190 J in all HAZ subzones.

Results can be summarized as follows:

1. The PWHTs recommended in the literature were insufficient to obtain the desired combination of properties in all HAZ subzones in the X10CrMoVNb9-1 steel.
2. At 760 °C, the desired properties were obtained in less than 4 hours, while 2 h was insufficient. The exact minimum duration is still to be determined, because no experiments with soaking times between 2 and 4 h were performed in this research.

3. At 780 °C, the desired impact energy of at least 190 J was reached in 0.5 h, while the desired hardness below 250 *HV* was measured after 2 h. The necessary soaking time at 780 °C was in fact shorter, however, as durations between 1 h and 2 h were not tested, the necessary minimum time remains to be determined with additional experiments.
4. Prolongation of soaking time over the necessary minimum did not deteriorate the properties. Even after 8 h the hardness and impact toughness remained in the target range.
5. At both temperatures, in all subzones, impact toughness reached the desired level sooner than the hardness.
6. At 780 °C 1–2 h are appropriate, and at 760 °C 3–4 h. As time is valuable, 780 °C should be preferred to 760 °C.
7. Optimum time-temperature combinations depend on actual wall thickness. In this research, specimens having 11 mm × 11 mm cross-sections were used. Therefore, it must be taken into account that at thicker cross-sections longer heating and cooling times will be necessary.

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