

## EFFECT OF POSTWELD HEAT TREATMENT ON HAZ TOUGHNESS OF Q+T HIGH STRENGTH STEELS

*Marcell Gáspár<sup>1</sup>, András Balogh<sup>2</sup>, Ádám Dobosy<sup>3</sup>*

<sup>1</sup>assistant lecturer, <sup>2</sup>associate professor, <sup>3</sup>assistant lecturer

<sup>1</sup>[gasparm@uni-miskolc.hu](mailto:gasparm@uni-miskolc.hu), <sup>2</sup>[metweld@uni-miskolc.hu](mailto:metweld@uni-miskolc.hu), <sup>3</sup>[metda@uni-miskolc.hu](mailto:metda@uni-miskolc.hu)

*University of Miskolc, Institute of Materials Science and Technology*

### INTRODUCTION

Nowadays the application ratio of high strength steels is continuously increasing. Due to their outstanding mechanical, especially strength properties significant weight reduction can be achieved. Besides the decreasing operational costs due to the energy saving in mobile structures, the thinner plates and smaller cross sections result savings in the amount of applied base and filler materials. Because of the abovementioned advantages the development of strength properties of these structural steels is in the research focus of steel and welding consumable producers [4].

In the present paper the highest steel grade of EN 10025-6, S960QL is investigated in the aspect of the microstructural changes in the heat affected zone of gas metal arc welded (GMAW) joints. Quenched and tempered (Q+T) high strength steels have a non-equilibrium tempered martensitic microstructure due to the water cooling used in the quenching cycle and to the high temperature tempering. In order to realize the quenching condition in the whole cross section, alloying components (Cr, Mo) are added to the steel, which move the CCT curves to the right. Microalloying elements (Nb, V and Ti) are also used in order to ensure and preserve a fine grain microstructure. The tempered, fine-grained microstructure results high toughness at negative temperature (even at -40 °C). The chemical composition of the investigated base material is shown in Table 1, the mechanical properties are presented in Table 2.

Table 1 Chemical composition of the investigated S960QL in mass percent

<b>S960QL</b>	<b>C</b>	<b>Si</b>	<b>Mn</b>	<b>P</b>	<b>S</b>	<b>Cr</b>	<b>Ni</b>
	0.16	0.23	1.25	0.009	0.001	0.20	0.05
<b>Mo</b>	<b>V</b>	<b>Ti</b>	<b>Cu</b>	<b>Al</b>	<b>Nb</b>	<b>B</b>	<b>N</b>
0.592	0.042	0.003	0.01	0.056	0.015	0.001	0.0036

The outstanding strength and toughness properties of quenched and tempered high strength steels cannot be adequately preserved during the welding due to the irreversible microstructural changes in the heat-affected zone (HAZ). Cold cracking, softening and the reduction of toughness properties can also happen due to the effect of the welding heat input. HAZ properties can be limitedly analysed by conventional material tests, therefore physical simulators (i.e. Gleeble) were developed for the examination of different HAZ areas [7]. In the present paper the effect of postweld heat treatment (PWHT) on HAZ is analysed.

Table 2 Mechanical properties of the investigated S960QL base material

$R_{p0.2}$ , MPa	$R_m$ , MPa	$A_5$ , %	KV <sub>-40 °C</sub> , J
1014	1053	14	75

It should be important to note that 166 J average impact energy was measured at -40 °C on this material during our own Charpy V-notch impact tests.

### CRITICAL HAZ AREAS

The special structure of HAZ of single and multipass welded joints is presented in Figure 1 [3]. In quenched and tempered high strength steels the toughness significantly decreases in the coarse grained (CGHAZ) and the intercritical zones (ICHAZ). In multipass welded joints the intercritically reheated coarse grained zone (ICCGHAZ) may have even a lower toughness than the abovementioned zones. These three areas are considered critical in terms of HAZ toughness [1].

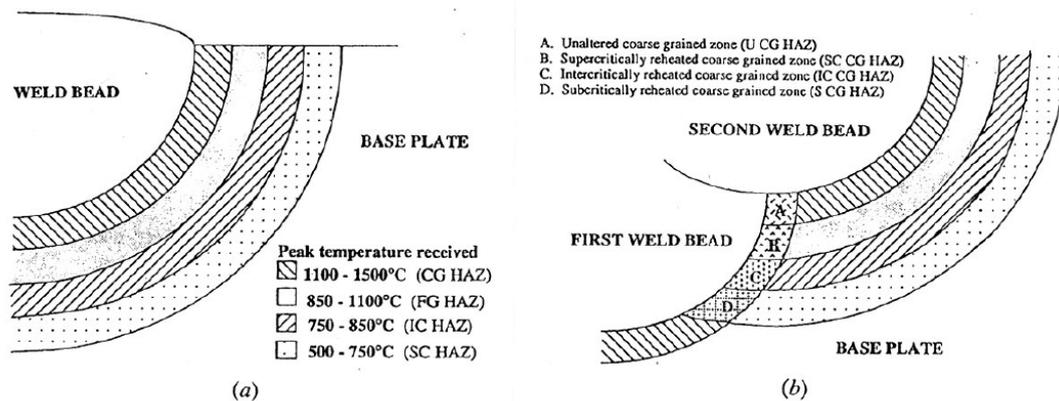


Fig. 1

Schematic presentation of microstructures in single (a) or multipass (b) weld [3]

Next to the fusion line the material will be heated much above  $A_{c3}$  temperature therefore homogeneous austenite forms. When coarse grained zone forms the peak temperature is above 1100 °C where the grains start to exponentially grow in the function of presence of different microalloying elements [2]. The decreased toughness of this zone has two reasons in quenched and tempered high strength steels. On the one hand the grain size can be more than 10 times higher than of the base material (>100  $\mu\text{m}$ ). Another reason is originated from the alloying elements resulting hard, lath martensitic microstructure in short cooling times. Therefore in many cases this area has the lowest toughness within the welded joint. Besides the weld metal CGHAZ has the highest risk of cold cracking since the hydrogen can diffuse from the fusion line to the brittle, coarse grained microstructure. This can cause cold cracks due to the residual tensile stress of the welded joint. Microalloying elements (in present case Nb and V) can form small, disperse precipitates at the grain boundaries restraining excessive grain growth [2].

If preheating is neglected and the heat input is too low, hydrogen cannot leave the weld and the high cooling rate will increase the amount and hardness of brittle martensitic microstructure. This microstructure has an extremely low crack arrest ability even if its' impact energy is acceptable (fulfils the 27 J requirement). In the case of quenched and tempered high strength steels long cooling times can result coarse, upper-bainitic microstructure where M-A constituents can occasionally form, resulting extremely low impact energy values.

Further from the fusion line, next to the fine grained zone (FGHAZ) where the peak temperature of HAZ thermal cycle is between  $A_{c1}$  and  $A_{c3}$ , the austenitic transformation just partially happens, thus an exceptionally heterogeneous microstructure forms. Transformed parts at the boundaries of original grains generally have a higher carbon content, since austenite has higher carbon solvability in this temperature range. In Q+T high strength steels the austenitic parts transform to a more brittle microstructure than base metal which is mostly martensite. Retained austenite can be often observed near the brittle martensitic islands, therefore these areas are called together as M-A constituents. The transformed parts between the relatively softened microstructure mean local brittle zones in the welded joint [2, 4].

In the case of multipass welded joints the combination of CGHAZ and ICHAZ can evolve (as presented in Figure 1.), when the second heat cycle reheats the primer coarse grains between  $A_{c1}$  and  $A_{c3}$ . In Q+T steels this local zone has the lowest toughness in the welded joint, since the disadvantageous properties of CGHAZ and ICHAZ meet here. The toughness of ICCGHAZ is determined by the tempered coarse grained martensite and the amount, distribution, type and hardness of austenitized parts. In real welded joints the abovementioned unfavourable properties of ICCGHAZ are less harmful, since this zone just locally forms whilst ICHAZ can be found in the whole plate thickness [2].

## EXPERIMENTS ON THE GLEEBLE PHYSICAL SIMULATOR

Physical simulation opened a wide range of examination possibility for the precise analysis of materials processing. First simulators were developed primarily for the analysis of HAZ properties in the Soviet Union, China and the United States. On the presented quenched and tempered high strength steel heat affected zone tests were performed on a new generation of simulators, called Gleeble 3500, installed at the Institute of Materials Science and Technology of the University of Miskolc, which is capable for the reproduction of real material processing (e. g. welding, heat treating and metal forming) under laboratory circumstances. Due to its direct resistance heating system the achievable heating rate can be as high as 10 000 °C/s, whilst the cooling rate can be similarly high due to the copper grips and water-cooled jaws (together with external cooling if needed). Although it must be remarked that the heating and cooling rate are always the function of specimen size and shape, and in many cases external cooling is needed for the desired cooling rate.

By the application of HAZ test on Gleeble the desired heat affected zone can be precisely and homogeneously created in a volume sufficient for further material tests, e. g. Charpy V-notch impact or CTOD tests. Although more welding heat

cycle models (Hannerz, Rosenthal, Rykalin) are available in QuickSim software developed for the simulator, the GSL programs were manually written in our case, using the time and temperature values determined by Rykalin-3D model [5]. This model describes the temperature field generated by a moving spot-like heat source on the surface of a semi infinite body. In this case 3D thermal conductivity is dominant whilst surface heat transfer (convection) is negligible.

According to our earlier physical simulation tests [1] we had the experience that the toughness of heat-affected zone was extremely decreased (almost independently from the applied welding parameters) in the  $t_{8.5/5}$  cooling time (cooling time between 850 and 500 °C) interval (5-30 s) of conventional arc welding processes (GMAW, SMAW, GTAW). Therefore  $t_{8.5/5} = 15$  s (the middle value of the previously tested interval) cooling time was selected for simulating the CGHAZ, ICHAZ and ICCGHAZ. In all cases a  $T_{max} = 650$  °C tempering heat cycle was applied for investigating the effect of PWHT. In industrial practice the arc of GTAW (Gas Tungsten Arc Welding) equipment is often used for the improvement of fatigue properties of welded joints by reheating (or remelting) the weld-base material transition [9]. The idea was to analyse whether a GTAW postweld heat treatment can have a positive effect on the toughness of the heat-affected zone. In Figure 2-4. the heat cycles, applied during the physical simulation of heat affected zones, are presented.

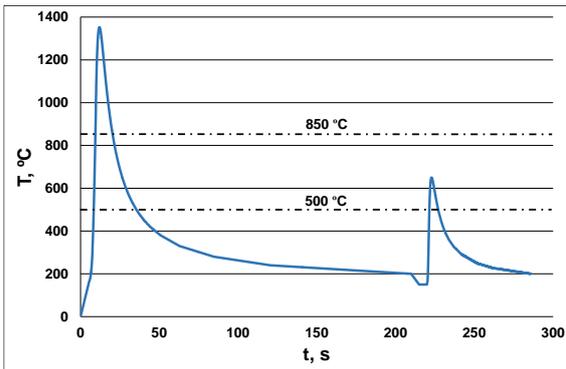


Fig. 2  
CGHAZ heat cycle with PWHT

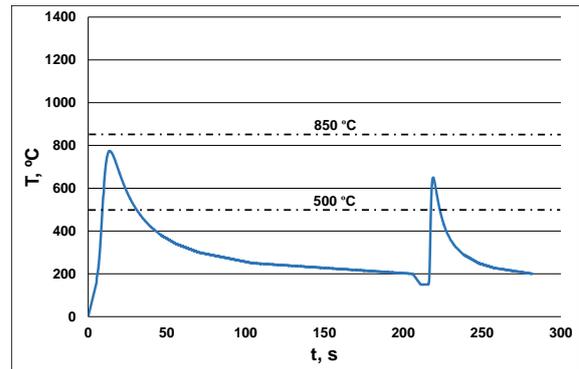


Fig. 3  
ICHAZ heat cycle with PWHT

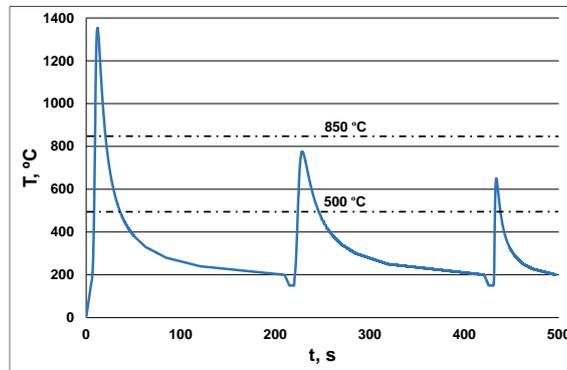


Fig. 4  
ICCGHAZ heat cycle with PWHT

The presented heat cycles were realized in the middle of 10x10x70 mm specimens, manufactured from 15 mm thick S960QL base material. Due to the control process of the simulation, K-type thermocouples were welded to the surface of the samples and joined to the simulator. Each thermal cycles were simulated on 6-6 specimens. From each series five samples were used for instrumented Charpy V-notch impact test and the rest for hardness test.

## MATERIAL TESTS AND THEIR RESULTS

Five hardness measurements were made on the surface of the medium cross section of the samples by an UH 250 universal macro hardness tester. The mean (M) values and the deviations (D) of hardness tests are summarized in Table 3. Before the analysis it may be important to note that the hardness of the base material was 330...340 HV10, whilst the governing EN 15614-1 standard allows maximum 450 HV10 for the welded joints of Q+T high strength steels.

Table 3 Effect of PWHT on the mean hardness

HV10	CGHAZ		ICHAZ		ICCGHAZ	
	M	D	M	D	M	D
without PWHT	409	6,8	323	5,4	344	7,6
T <sub>PWHT</sub> = 650 °C	346	6,4	298	4,3	328	9,2

From Table 2. it can be seen that the tempering heat cycle reduced the hardness of all zones. The most significant reduction was noticed in CGHAZ, where originally higher hardness was measured than 400 HV10. Due to the PWHT the hardness decreased to the level of base material which can be favourable in terms of cold cracking sensitivity. In the case of ICHAZ and ICCGHAZ the hardness decreased under the level of the base material, although this softening cannot be considered critical, since in multipass welded joints of the same material generally similar hardness values are measured at the root side [1].

In Figure 5-8. the base material and the simulated microstructure of tempered CGHAZ, ICHAZ and ICCGHAZ are shown in M = 500x.

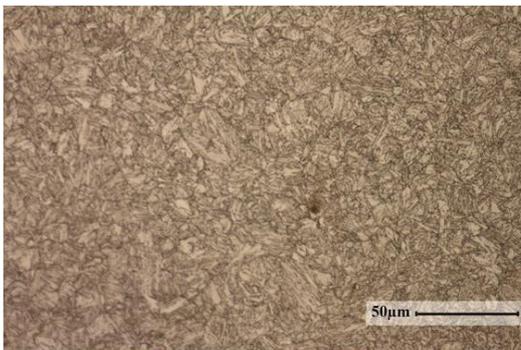


Fig. 5  
Base material (2% HNO<sub>3</sub>)

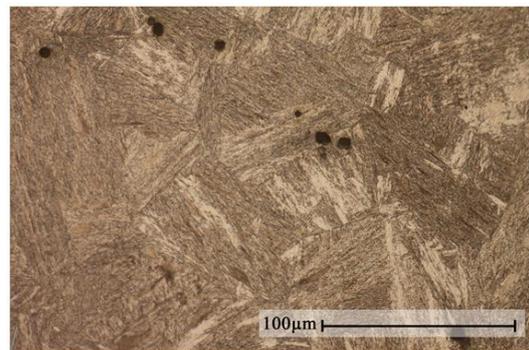


Fig. 6  
Tempered CGHAZ (2% HNO<sub>3</sub>)

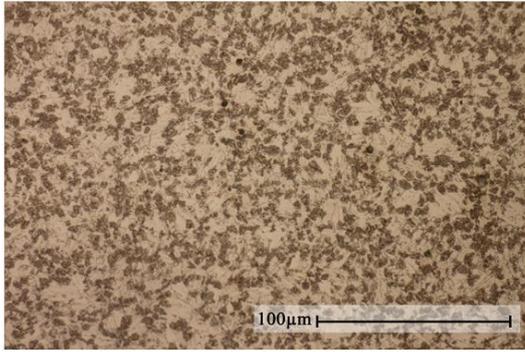


Fig. 7  
Tempered CGHAZ (2% HNO<sub>3</sub>)

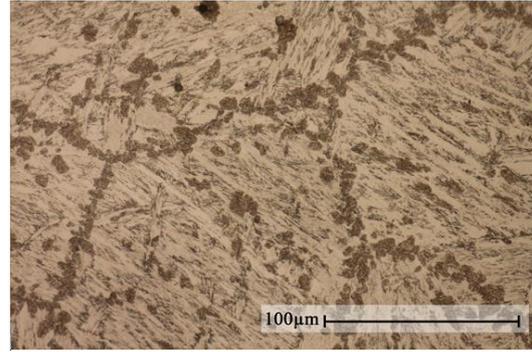


Fig. 8  
Tempered ICHAZ (2% HNO<sub>3</sub>)

Instrumented Charpy V-notch impact tests (according to EN ISO 14556) were performed for analysing the supposed positive effect of PWHT. Standardized 10x10x55 mm specimens with V-notch were manufactured from the Gleeble samples. Measurements were done by a PSD 300 instrumented impact testing equipment. The absorbed energy values (CVE) are presented in Figure 9.

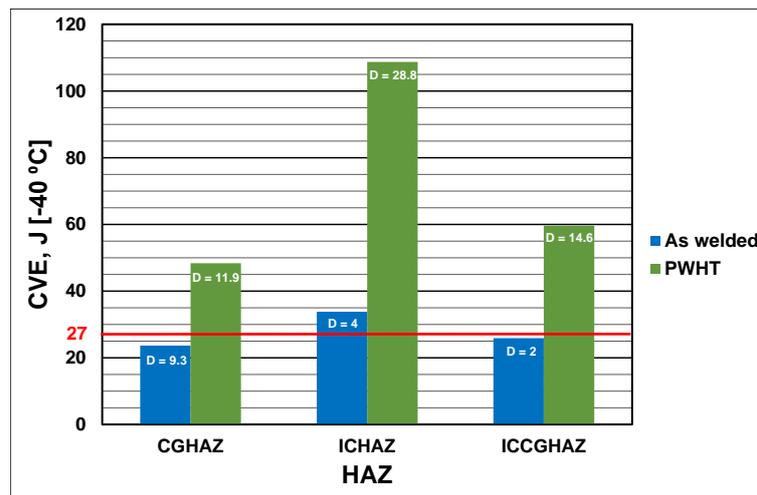


Fig. 9  
Results of Charpy V-notch impact test

According to EN 10025-6 and EN 15614-1 standards the toughness of heat-affected zone of S960QL should be higher than 27 J at -40 °C. Due to the 650 °C tempering cycle the impact energy was doubled in CGHAZ despite of the large grain size and tripled in ICHAZ. In the case of ICCGHAZ the improvement was also significant. If the impact energy is divided according to the absorbed energy needed for crack initiation ( $W_i$ ) and crack propagation ( $W_t$ ) (as in [6]) the following results were obtained. In the case of CGHAZ the ratio of  $W_i$  decreased from 89,9% to 71%, at ICHAZ from 77,7% to 37,6%, whilst at ICCGHAZ from 87,7% to 68,4%. The reduction of the ratio of  $W_i$  means that more energy absorbed for crack propagation, therefore the toughness improved. These values also verifies, especially at ICHAZ, the positive effect of PWHT on the toughness of critical HAZ areas. During the instrumented impact tests the registered force-time diagrams at

ICHAZ hardly included instable crack propagation stages (from the five specimens three did not include at all). As an example, the determined force-shift (F-S) diagrams during the instrumented Charpy V-notch impact test of normal and tempered ICHAZ are shown in Figure 10.

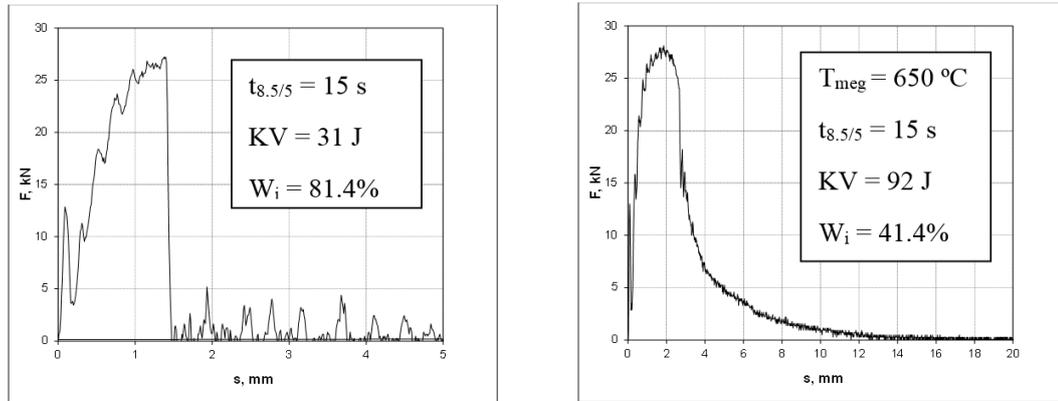


Fig. 10

The effect of PWHT on the toughness of ICHAZ

Although the presented PWHT only influence that part of the heat-affected zone which is close to the surface, the improvement can be still relevant for the total lifetime of the welded joint. At the root side of the multipass welded joints the tempering of the HAZ always happen due to the heat input related to the filler passes. Therefore the HAZ toughness can be mostly critical at the face side, where the highest hardness values are generally measured. As it could be seen above, a local tempering heat cycle can significantly increase the toughness at this crucial part of the HAZ. It can be also combined by the improvement of fatigue properties of the welded joints. Fatigue properties of high strength steels, and especially their welded joints, are in the focus of researchers nowadays, since the advantages of high strength cannot be fully utilized when cyclic loading is applied [8].

## SUMMARY AND CONCLUSIONS

By applying a postweld heat treatment the heat-affected zone of quenched and tempered high strength steels can be significantly improved. After the welding at the HAZ a local heat input, which should be strictly kept under  $A_1$  temperature, can effectively increase the toughness of CGHAZ, ICHAZ and ICCGAZ. The highest improvement is noticed in the case of ICHAZ, where the impact energy values approached the properties of the base material.

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