IOP Conf. Series: Materials Science and Engineering **426** (2018) 012012 doi:10.1088/1757-899X/426/1/012012

Improving the HAZ toughness of Q+T high strength steels by post weld heat treatment

M Gáspár[1] and R. Sisodia[2]

[1]Assistant professor, University of Miskolc, Institute of Materials Science and Technology, Miskolc-Egyetemváros, Hungary
[2] PhD student, University of Miskolc, Institute of Materials Science and Technology,Miskolc-Egyetemváros, Hungary

E-mail: gasparm@uni-miskolc.hu

Abstract. Steel producers are continuously developing the mechanical properties and improving the weldability of high strength steels. Quenched and tempered steels belong to the one of the highest strength grades of structural steels with outstanding toughness characteristics due to the high temperature tempering. During fusion welding the thermal cycle irreversibly changes the microstructure and the mechanical properties of the base material, therefore an inhomogeneous heat-affected zone (HAZ) forms. In the HAZ hardened and softened zones occur. Due to the thermal cycles experiences during welding, these HAZs can exhibit significant losses in toughness when compared to the base metal. In real welded joints the HAZ properties can be analysed by conventional material tests to a limited degree; therefore physical simulators have been developed for the detailed examination of different HAZ areas. In the present research work the HAZ properties of a 960 MPa yield strength quenched and tempered steel (S960QL according to EN 10025-6) are investigated. Since the toughness reduction can be only partially handled by the adjustment of welding parameters, the possibility of local post-weld heat treatment was examined. Based on preliminary physical simulations and welding experiments a medium heat input gas metal arc welding technology ($t_{8/5}$ = 15 s) was selected for the HAZ simulations. The welding and the post-weld thermal cycles were determined according to the Rykalin 3D model. The effect of post weld heat treatment on the properties of the selected coarse-grained (CGHAZ), intercritical (ICHAZ) and intercritically reheated coarse-grained (ICCGHAZ) zones were investigated by electron microscopic, hardness tests and instrumented Charpy V-notch impact tests. The materials tests showed significant improvement of the toughness properties especially in ICHAZ due to the post-weld tempering, whilst the softening was acceptable.

1. Introduction

Nowadays the application ratio of high strength steels is continuously increasing. Due to their outstanding mechanical properties, especially their strength properties, significant weight reduction can be achieved. Besides decreasing operational costs due to the energy saving in mobile structures, thinner plates and smaller cross sections result in savings in the amount of base and filler materials applied. Because of the above-mentioned advantages the development of strength characteristics of steels is in the research focus of steel and welding consumable producers [1]. Besides the outstanding yield strength the new generations of high strength steels have increased toughness and acceptable ductility properties [2]. When the possible applications of high strength steels are considered their weldability and the

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.
Published under licence by IOP Publishing Ltd

behaviour of welded components during the total lifetime of the welded joint cannot be neglected [3], [4]. Therefore, in parallel to their development as base materials there is extensive research related to their welding. For the demanded intensive spread of high strength steels the possible advantages related to their fatigue resistance should be also exploited; however, the effect of mismatch ratio on the fatigue behaviour, further complicates this goal as the available filler metals are limited in the higher categories [5].

Quenched and tempered (Q+T) high strength steels belong to the highest steel grades of structural steels. They have generally a tempered martensitic microstructure due to the water cooling used in the quenching cycle and to the high temperature tempering applied after quenching. In order to realize the quenching condition in the whole cross section, alloying components (Cr, Mo) are added to the steel, which moves the continuous cooling temperature (CCT) curves to the right. Microalloying elements (Nb, V and Ti) are also used in order to ensure and preserve a fine grain microstructure; however, their amount and ratio can strongly and not always positively affect the toughness properties in the different HAZ areas [6]. The tempered, fine-grained microstructure results in high toughness at negative temperatures (even at -40 ºC); however the welding thermal cycle can be detrimental to this ideal microstructure. The outstanding strength and toughness properties of quenched and tempered high strength steels cannot be adequately preserved during welding due to the irreversible microstructural changes in the HAZ. Cold cracking, softening and the reduction of toughness properties can also happen due to the effect of the welding heat input [7]. Controlled heat input is indispensable during welding; whilst adjustment of welding parameters has little effect on the toughness reduction, however the HAZ width can be minimized. Using advanced welding technologies (e.g. electron beam welding), that minimally damages the special microstructure of the base material in the HAZ and ensure a productive solution for their joining may have wider application in the future [8].

In industrial applications gas metal arc welding (GMAW) is the most commonly used welding technology; however, the heat input cannot be significantly minimized, since sufficient penetration and productivity are important requirements in the industry [9]. The present research aims to investigate a possible local post-weld heat treatment solution for the improvement of HAZ properties. In real welded joints the HAZ toughness can be analysed by conventional material tests only to a limited extent due to the complex microstructure, and thus physical simulators (i.e. Gleeble) were developed for the examination of different HAZ areas [10], [11]. The present paper examines the effect of post-weld heat treatment on the critical HAZ areas of the quenched and tempered steels.

2. Structure of heat-affected zone during fusion welding

The special structure of HAZ in single and multipass welded joints, including the formation of subzones is presented in [12]. In quenched and tempered high strength steels the toughness can significantly decrease in the coarse-grained (CGHAZ) and the intercritical zones (ICHAZ) compared to the base material. 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.

Next to the fusion line the material will be heated far above A_{c3} temperature and therefore homogeneous austenite forms. During grain coarsening the peak temperature is above 1100 °C where the grains start to exponentially grow in the function of presence of different microalloying elements [13]. There are two reasons for the decreased toughness of this zone in quenched and tempered high strength steels. First, the grain size can be more than 10 times higher than of the base material (>100 μm). The reason originates from the alloying elements resulting in a hard, lath martensitic microstructure. 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.

Further from the fusion line in ICHAZ, where the peak temperature during the thermal cycle is between A_{c1} and A_{c3}, the austenitic transformation just partially take place and 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-dissolving ability in this temperature range. In Q+T high strength steels the austenitic parts transform to a more brittle microstructure than the base metal, which is mostly martensite. Retained austenite can be often observed near the brittle martensitic islands, so these areas are called together M-A constituents. The transformed parts between the relatively softened microstructure mean local brittle zones in the welded joint [1] [13].

In the case of multipass welded joints a combination of CGHAZ and ICHAZ can evolve, when the second heat cycle reheats the primer coarse grains between A_{c1} and A_{c3}. In Q+T steels this local zone can have 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 unfavourable properties of ICCGHAZ are less harmful, since this zone just forms locally whilst ICHAZ can be found in the whole plate thickness [12].

3. Investigated material and the experimental program

In the present study the highest steel grade of EN 10025-6 standard, S960QL is investigated in the aspect of the microstructural changes in the HAZ of GMAW joints. It is important to note that higher steel grades are already available on the market, although they have not been included in the governing standard yet [2], [8]. The chemical composition of the investigated base material is shown in Table 1 and the mechanical properties are summarized in Table 2.

Table 1. Chemical composition of the investigated S960QL (m%)

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

Table 2. Mechanical properties of the investigated S960QL base material

$R_{p0.2}$ (MPa)	R_m (MPa)	A_5 (%)	$CVE_{-40\,°C}$ (J)
1014	1053	14	75

Applying the 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 [10]. Although several welding thermal cycle models are available in the 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 [14]. 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.

In our earlier physical simulation tests [15] we found that the toughness in the HAZ decreased sharply (almost independently from the applied welding parameters) in the $t_{8/5}$ cooling time (cooling time between 850 and 500 ºC) interval (5-30 s) of conventional arc welding processes. Therefore $t_{8/5}$ = 15 s (the middle value of the previously tested interval) cooling time was selected for simulating the effect of post-weld heat treatment on CGHAZ, ICHAZ and ICCGHAZ. Regarding the selection of the peak temperatures 1350 ºC (safely under the nil-strength temperature (NST) of the investigated steel where the material can not bear any mechanical loading [16]) was set for the CGHAZ simulation in order to allow the largest possible grains to form in the HAZ. Related to ICHAZ, 775 ºC was selected based data in the literature [10] and previous experiments [15]. In all cases a T_{max} = 650 ºC tempering thermal cycle, similarly to the high temperature tempering during the base material production, was applied for investigating the effect of post-weld heat treatment (PWHT). In industrial practice the arc of GTAW (gas tungsten arc welding) equipment can be used for the improvement of fatigue properties of welded joints by remelting (or just reheating) the weld-base material transition [17]. The idea was to analyse whether local and relatively short PWHT by arc can have a positive effect on the toughness of the heat-affected zone. In Figs. 1-3. the determined thermal cycles applied during the HAZ and PWHT physical simulations are presented.

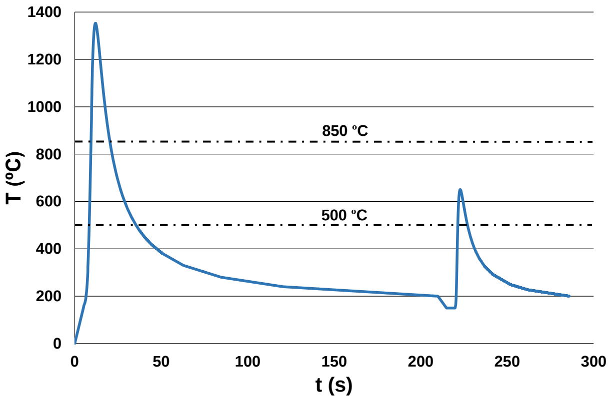

Figure 1. Thermal cycle for PWHT of CGHAZ

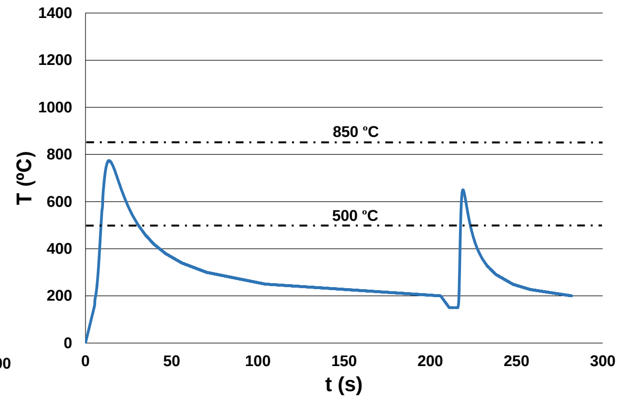

Figure 2. Thermal cycle for PWHT of ICHAZ

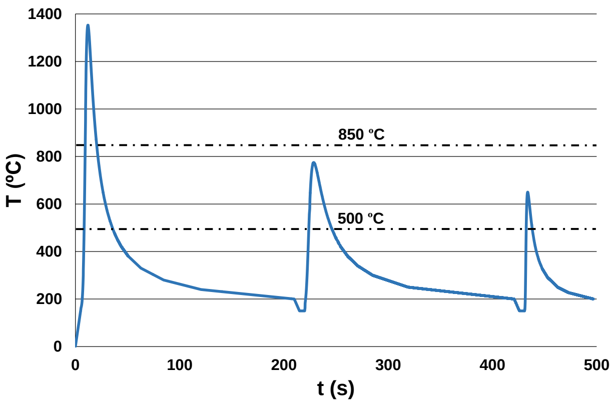

Figure 3. Thermal cycle for PWHT of ICCGHAZ

The thermal cycles were realized in the centre of 10×10×70 mm specimens, manufactured from the 15 mm thick 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 cycle was simulated on six specimens each. From each series five samples were used for the instrumented Charpy V-notch impact test and the rest for hardness testing.

4. Results and discussion

4.1. Scanning electron microscopy (SEM) tests

A ZEISS EVO MA10 scanning electron microscope was used for the examination; results are illustrated in Figs. 4-9. Samples were coated with a thin gold layer in order to increase picture quality due to the resin surrounding the specimen. All microscopic tests verified that the desired heat-affected zones were simulated. Regarding the CGHAZ, a martensitic microstructure with large (>100 μm) prior austenite grain size were measured. In ICHAZ fine M-A islands formed as the result of partial austenitic transformation, while the middle of the original grains was tempered. In ICCGHAZ similar microstructural changes can be identified with essentially ten-time-larger grains. The tempering of lath martensite is shown in Fig 6, while tempered M-A islands can be identified in Figs 8. and 10.

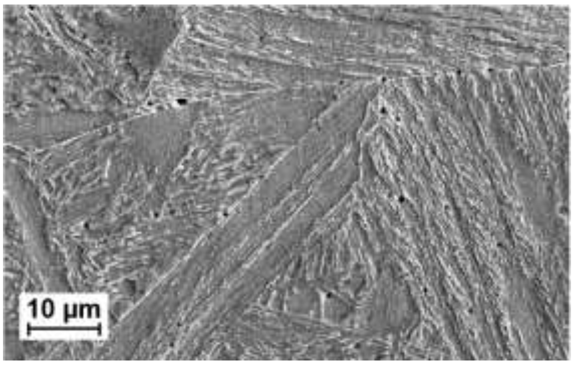

Figure 4. CGHAZ (2% Nital)

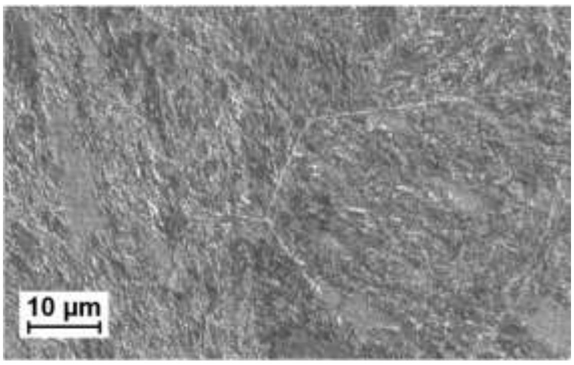

Figure 5. CGHAZ with PWHT (2% Nital)

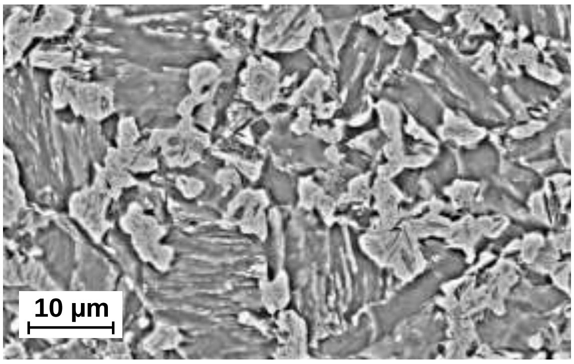

Figure 6. ICHAZ (2% Nital)

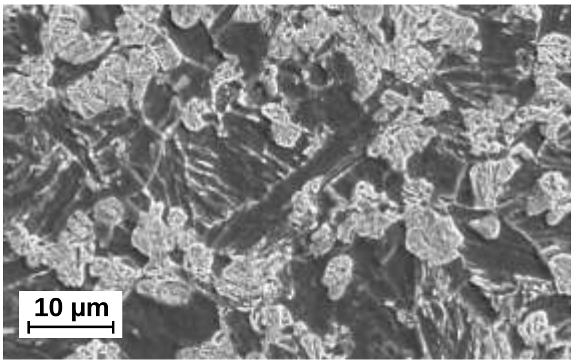

Figure 7. ICHAZ with PWHT (2% Nital)

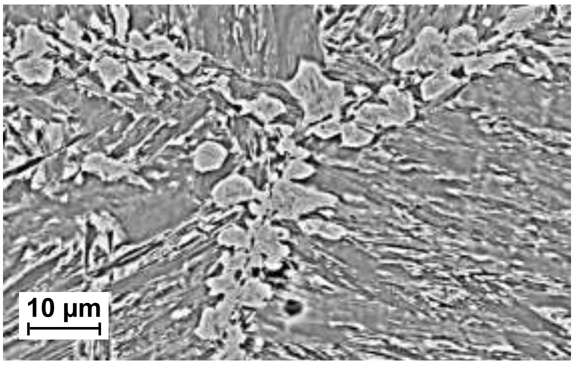

Figure 8. ICCGHAZ (2% Nital)

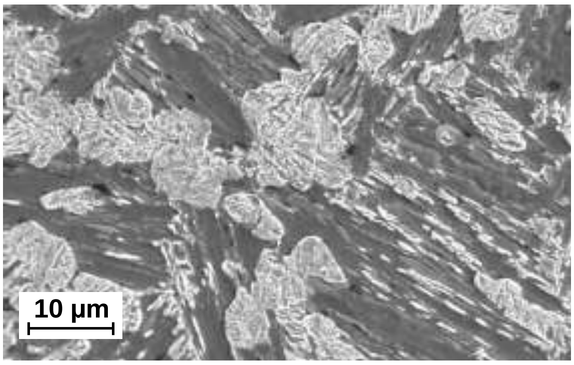

Figure 9. ICCGHAZ with PWHT (2% Nital)

4.2. Hardness tests

Five hardness measurements were made on the surface of the medium cross section of the samples by a Reicherter UH 250 universal hardness tester. The average values and the standard deviations values of hardness tests are summarized in Table 3. It may be important to note that the hardness of the base material was 335±5 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 average hardness

	Hardness (HV10)		
	CGHAZ	**ICHAZ**	**ICCGHAZ**
without PWHT	409±6.8	323±5.4	344±7.6
T_{PWHT} = 650 ºC	346±6.4	298±4.3	328±9.2

From Table 3 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 than 400 HV10 hardness was measured. 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.

4.3. Instrumented Charpy V-notch impact tests

Instrumented Charpy V-notch impact tests (according to EN ISO 14556) were performed for analysing the supposed positive effect on toughness of PWHT. Standardized 10×10×55 mm specimens with a V-notch were manufactured from the Gleeble samples. Measurements were done by a PSD 300 instrumented impact testing equipment. The absorbed energy values (CVE) with the standard deviations (D) are presented in Fig. 10.

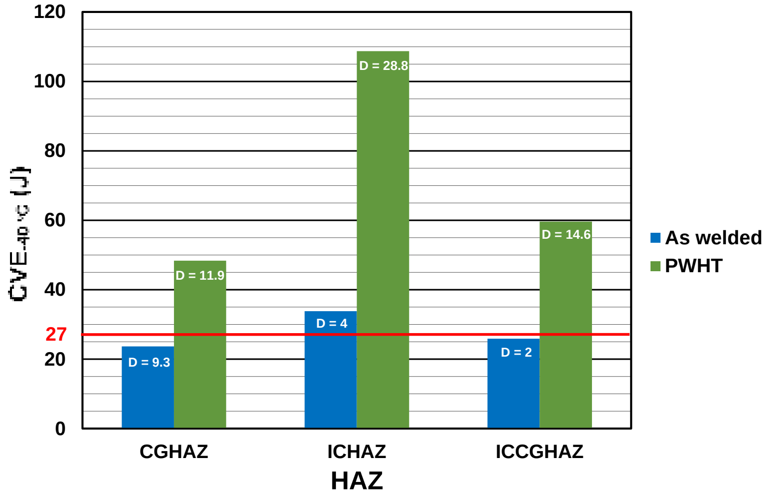

Figure 10. Results of Charpy V-notch impact test in the different HAZ's

According to EN 10025-6 and EN 15614-1 standards the toughness of the heat-affected zone of S960QL should be higher than 27 J at -40 ºC. Due to the 650 ºC tempering cycle the impact energy was doubled in CGHAZ despite the large grain size and tripled in ICHAZ. In the case of ICCGHAZ the improvement was also significant. By the application of instrumented impact testing the force – displacement (F-s) diagrams (Figs. 12 and 14) can be determined, and based on the measured maximum force value the impact energy can be divided according to the absorbed energy needed for crack initiation (W_i) and crack propagation (W_t) [18]. The reduction of the ratio of W_i compared to the Charpy-V energy (CVE) means that more energy is absorbed for crack propagation, therefore the toughness improves. In the base material crack initiation (W_i) was 25.9%, indicating the high toughness of the quenched and tempered microstructure; however, in the investigated HAZ areas this value was systematically higher. The average percentage of the absorbed energy for W_i compared to CVE in the investigated HAZ areas is summarized in Table 4.

Table 4. Average percentage of the absorbed energy for crack initiation (W_i) compared to CVE

	without PWHT	**T_{PWHT} = 650 ºC**
CGHAZ	90%	71%
ICHAZ	78%	38%
ICCGHAZ	88%	68%

These values verify the positive effect of PWHT on the toughness of critical HAZ areas, especially in ICHAZ During the instrumented impact tests the registered force-displacement diagrams at tempered ICHAZ included few instable crack propagation stages (from the five specimens three did not include any at all). As an example, the determined force-displacement diagrams during the instrumented Charpy V-notch impact test of normal and tempered ICHAZ are shown in Figs. 11 and 12.

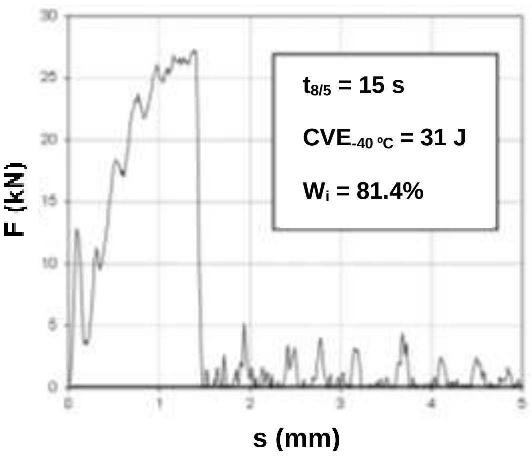

Figure 11. F-s diagram of instrumented Charpy V-notch impact test on ICHAZ

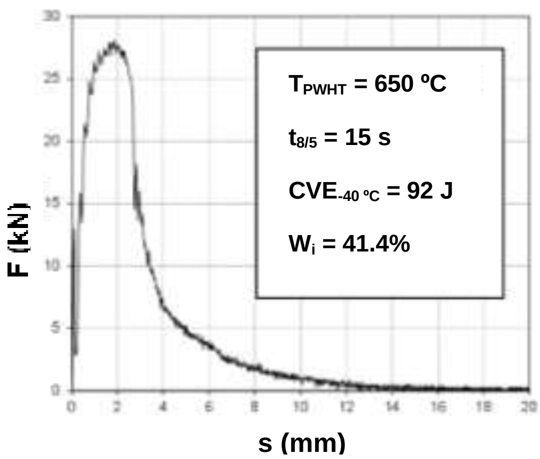

Figure 12. F-s diagram of instrumented Charpy V-notch impact test on ICHAZ with PWHT

Although the presented PWHT only influences the part of the heat-affected zone that 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 HAZ tempering always automatically happens due to the heat input related to the further layers and therefore the tempering effect of filler passes. Because of this, HAZ toughness can be mostly critical at the face side, where the highest hardness values are generally measured. As could be seen above, a local tempering heat cycle can significantly increase the toughness at this crucial part of the HAZ, which can be also combined with the improvement of fatigue properties of the welded joints.

5. Conclusion

By applying post-weld heat treatment the toughness in the heat-affected zone of quenched and tempered high strength steels can be significantly improved. After welding at the HAZ a local and short heat input, which should be strictly kept under A_1 temperature, can effectively increase the toughness of CGHAZ, ICHAZ and ICCGHAZ. The highest improvement can be expected in ICHAZ, where the toughness characteristics approached the properties of the base material during the physical simulation experiments.

Acknowledgement

The presented research work was supported by the European Union and the Hungarian State, co-financed by the European Regional Development Fund in the framework of the GINOP-2.3.4-15-2016-00004 project, aimed to promote the cooperation between the higher education and the industry. The authors are grateful to the Institute of Physical Metallurgy, Metalforming and Nanotechnology at the University of Miskolc for ensuring the scanning electron microscope during the evaluation of HAZ tests.

IOP Conf. Series: Materials Science and Engineering **426** (2018) 012012 doi:10.1088/1757-899X/426/1/012012

References

[1] Porter D A 2015 Weldable high-strength steels: challenges and engineering applications Portevin lecture IIW International Conference on High Strength Steels – Challenges and Applications, Helsinki Finland 0102

[2] Weglowski M 2012 February Modern toughened steels – their properties and advantages, *Biuletyn Instytutu Spawalnictwa* pp 25-36

[3] Lukács, J 2013 Dimensions of Lifetime Management *Mat. Sci. For.* Vols. **473-474** pp 361-368

[4] Alus H Katz Y Maros M B Tóth L: Some insights into the remote strain vs. fatigue life relationship *Journal of Mat. Pro. Tec.* **157-158** pp 16-22

[5] Dobosy Á and Lukács J 2017 The effect of filler material choice on the high cycle fatigue resistance of high strength steel welded joints, *Mat. Sci. For.* Vol. **885** pp 111-116

[6] Spachinger J S Ernst W and Enzinger N 2017 Influence of Ti on the toughness of the FGHAZ and the CGHAZ of high-strength microalloyed S700MC steels *Wel. in the Wor.*, Vol. **61**., Issue 1. pp 1117-1131

[7] Dobosy Á Lukács J 2015 Welding properties and fatigue resistance of S690QL high strength steels, *Mat. Sci. For.* Vol. **812** pp 29-34

[8] Blacha S Weglowski M S Dymek S and Kopyscianski M 2017 Microstructual and Mechanical Characterization of Electron Beam Welded Joints of High Strength S960QL and Weldox 1300 Steel Grades *Arc. of Met. and Mat.* Vol. **62** Issue 2 pp 627-634

[9] Májlinger K Kalácska E Spena P R 2016 Gas metal arc welding of dissimilar AHSS sheets *Mat. and Des.* Vol. **109** pp 615-621

[10] Laitinen R Porter D A Karjalainen L P Leiviskä P and Kömi J 2013 Physical Simulation for Evaluating Heat-Affected Zone Toughness of High and Ultra-High Strength Steels *Mat. Sci. For.* Vol. **762** 711-716

[11] Adonyi Y 2006 Heat-affected zone characterization by physical simulations *Wel. Jou.* Vol. **85** Issue 10 pp 42-27

[12] Davis C and King J 1994 Cleavage initiation in intercritically reheated coarse-grained heat affected zone: Part I. Fractographic evidence *Met. and Mat. Tra. A* **25** 563–573

[13] Bhadesia H K D H and Honeycombe R W K 2006 Steels Microstructure and Properties Third Edition Elsevier Linacre House Hordan Hill Oxford OX2 8DP UK

[14] Rykalin N N 1953 Teplovie processzi pri szvarke Vüpuszk 2 *Izdatelsztvo Akademii Nauk SzSzSzR*, Moscow 56

[15] Gáspár M Balogh A Lukács J 2017 Toughness Examination of Physically Simulated S960QL HAZ by a Special Drilled Specimen *Lecture notes in mechanical engineering* **F12** pp 469-481

[16] Kuzsella L. Lukács J. Szűcs K. 2013 Nil-strength temperature and hot tensile tests on S960QL high-strength low-alloy steel *Pro. Proc. and Sys.* Vol. **6** No. 1. pp 67-78

[17] Sjors H J Van Es H Kolestein R J M Pijpers F S K Bijlaard 2013 TIG-dressing of High Strength Steel Butt Welded Connections – Part 1: Weld Toe Geometry and Local Hardness *Pro. Eng.* **66** pp 216-225

[18] Lenkeyné Bíró Gy Winkler S Tóth L and Blauel J G 1997 Investigations on the brittle to ductile fracture behaviour of base metal, weld metal and HAZ material by instrumented impact testing, 1st Int. Conf. on Welding Technology, Materials and Material Testing, Fracture Mechanics and Quality Mgmt., Wien Austria pp 423-432