ADVANCED TECHNOLOGIES AND MATERIALS VOL. 47, NO.2 (2022), 9 – 16
DOI: 10.24867/ATM-2022-2-002

Received: 15 October 2022
Revised: 25 October 2022
Accepted: 04 November 2022

Advanced Technologies & Materials

http://journal-atm.org
ISSN: 2620-0325 (print), ISSN: 2620-147X (online)

Original article

# Different ways for HAZ microstructure preparation and testing on high alloy steel

***Tomaž Vuherer**

*University of Maribor, Faculty of Mechanical Engineering, Maribor, Slovenia*

## ABSTRACT

*The heat-affected zone (HAZ) is the part of the weld that is affected by the heat generated by the welding process during welding. The microstructure of the HAZ is very heterogeneous and consists of different zones such as the coarse-grained HAZ, the fine-grained HAZ, the intercritical HAZ, and the over-tempred HAZ [1]. All these zones are very narrow and their properties are slightly different. These properties affect the integrity of the entire weld, so in many cases the HAZ may be the worst part of the weld. Another challenge is determining the properties of the individual HAZ regions, since the entire HAZ is very narrow and inhomogeneous. For this reason, many properties cannot be determined accurately, with the exception of a few, such as hardness, for which only a small region is sufficient for measurement. Therefore, it is important to know how to produce the individual microstructure of a HAZ in a wider range of the material in order to determine the actual properties of such a HAZ. One of the ways is to measure the welding parameters during welding to determine the actual influence of the thermal cycle on the formation of the invidual microstructure of HAZ in the weld. Moreover, it is crucial to repeat this weld thermal cycle in an unaffected base metal on a thermal welding simulator to obtain a suitable microstructure of the HAZ [1,2]. The second option is to prepare the microstructure in the furnace by slow heating which is followed by rapid cooling [1,3]. Both processes must be precise and accurate to obtain suitable HAZ microstructures. This article addresses the challenges of producing HAZ microstructures on the high-alloy steel CT781, which is widely used in the automotive industry for parts subjected to high dynamic loads.*

Key words *Fatigue growth test, Heat Affected Zone, Mechanical testing, Welds;*

## 1. INTRODUCTION

Welded joints made by fusion welding consist of weld metal, heat-affected zone and base material. The heat-affected zone (HAZ) is very narrow and has very different microstructures. There are different zones such as the coarse-grained grain HAZ (CG HAZ), the fine-grained grain HAZ (FG HAZ), the inter-critical HAZ (IC HAZ) and over-tempered HAZ (OT HAZ). Fig. 1 shows the individual zones of the HAZ as a function of the maximum temperature reached during welding. Since the distance of each HAZ from the fusion line is different, the weld thermal cycle affects each HAZ differently. Fig. 2 and Fig. 3 show the effects of the weld thermal cycle on the individual HAZs to which they are exposed during welding and how this affects the process of microstructure formation of the HAZs.

* Corresponding author's.e-mail: tomaz.vuherer@um.si

*Published by the University of Novi Sad, Faculty of Technical Sciences, Novi Sad, Serbia.*

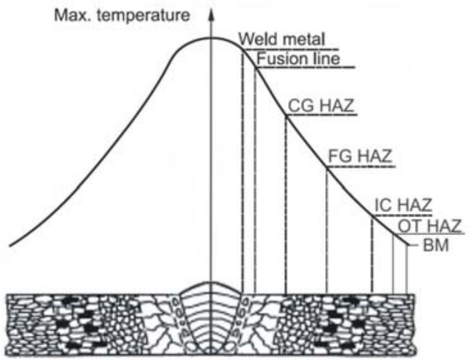



Fig.1 *Weld joint and its different regions*

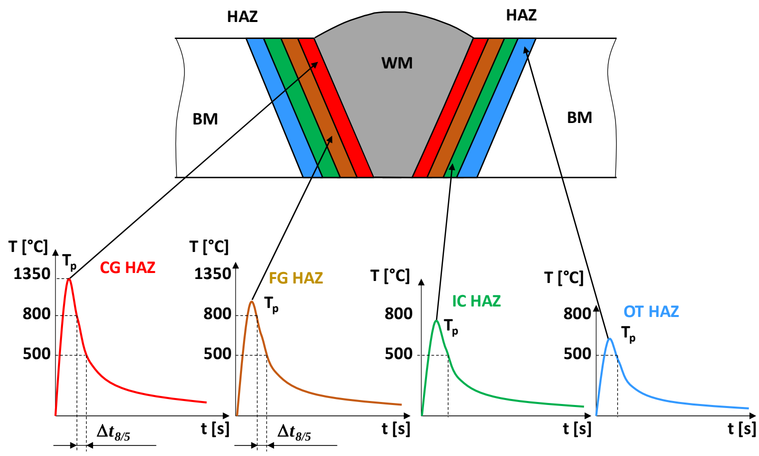



Fig.2 *Influence of the weld thermal cycle to individual HAZ*

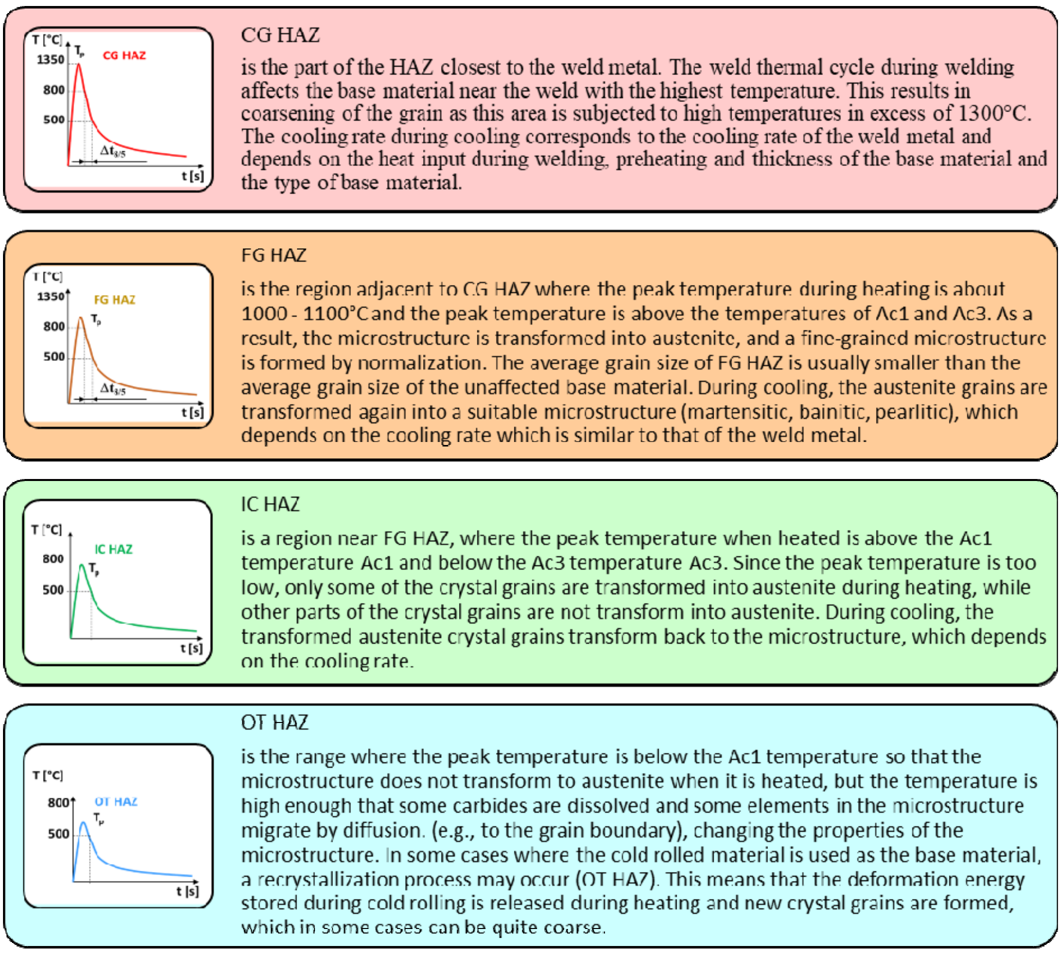



Fig.3 *Different HAZ in the welded joint*

Table 1. Chemical composition of the 17CrNiMo7 steel (weight %)

| C | Si | Mn | Cr | Ni | Cu | Mo | Al | P | S |
|---|---|---|---|---|---|---|---|---|---|
| 0.18 | 0.22 | 0.43 | 1.56 | 1.48 | 0.15 | 0.28 | 0.023 | 0.012 | 0.028 |

For the integrity of the entire welded joint, it is important that each part of the welded joint has the appropriate properties that exceed the minimum requirements. This also applies to individual HAZs, where in some cases high hardness and low impact toughness can be a problem due to rapid cooling after welding [1-4].

## 2. MATERIAL

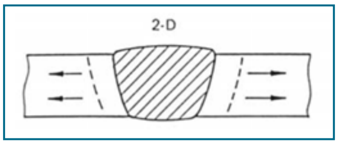
The 17CrNiMo7 steel was used for this investigation. This steel has good weldability and is suitable for various heat treatments. For this reason, it is suitable for parts and components subjected to high dynamic loads in the construction and automotive industries. The chemical composition of 17CrNiMo7 steel is shown in Table 1 and its mechanical properties are shown in Table 2.

Table 2. Mechanical properties of the steel in as delivered condition

| $R_{P0.2}$ (MPa) | $R_m$ (MPa) | $A_5$ (%) |
|---|---|---|
| 1. 484 | 2. 634 | 3. 26 |

## 3. CG HAZ MICROSTRUCTURE PREPARATION USING WELDING SIMULATOR

The artificial HAZ microstructure can be prepared by various methods, e.g. by preparing the microstructure using a welding simulator or by producing the microstructure in a furnace with appropriate quenching. For the formation of the HAZ microstructure, it is important to know the welding process, the heat input during welding (welding parameters) and the thickness of the base material. All these parameters affect the width of HAZ. Since most of the transformations in this steel take place between 800 °C and 500 °C, the cooling time Δt8/5 is crucial for the microstructure formation.




$$T(R,t) = T_0 + \frac{q/v}{2\cdot\pi\cdot\lambda\cdot t}\cdot e^{-\frac{R^2}{4\cdot a\cdot t}}$$

$$T_m(R) = T_0 + \frac{2}{\pi\cdot e}\cdot\frac{q/v}{\rho\cdot c\cdot R^2}$$

$$\Delta t_{8/5} = \frac{q/v}{2\pi\lambda}\left[\frac{1}{500-T_0}-\frac{1}{800-T_0}\right]$$

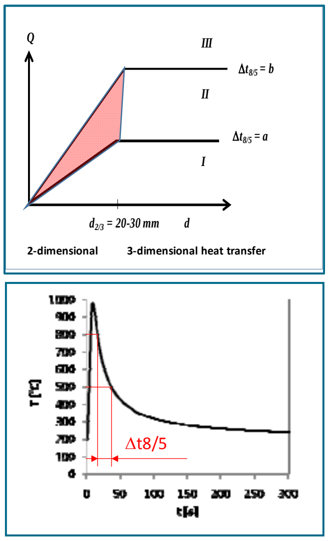
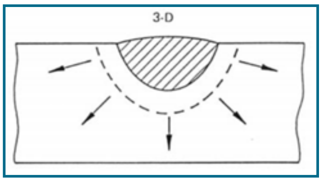



Fig.4 *Determination of welding diagram and the influence of weld thermal cycle for 2-D heat transfer during welding*




$$T(R,t) = T_0 + \frac{q/v}{d\cdot\sqrt{4\cdot\pi\cdot\lambda\cdot\rho\cdot c\cdot t}}\cdot e^{-\frac{R^2}{4\cdot a\cdot t}}$$

$$T_m(R) = T_0 + \frac{1}{\sqrt{2\cdot\pi\cdot e}}\cdot\frac{q/v}{d\cdot\rho\cdot c\cdot R}$$

$$\Delta t_{8/5} = \frac{(q/v)^2}{4\pi\lambda\rho c d^2}\left[\frac{1}{(500-T_0)^2}-\frac{1}{(800-T_0)^2}\right]$$

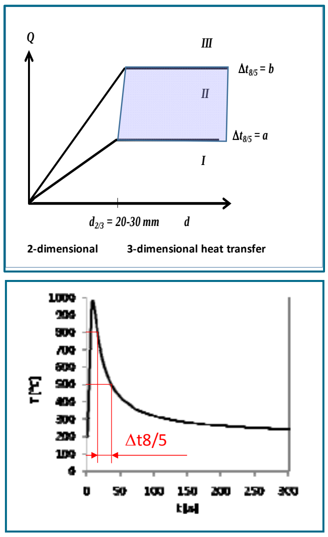



Fig.5 *Determination of welding diagram and the influence of weld thermal cycle for 3-D heat transfer during welding*

The cooling time Δt8/5 can be easily measured or it can be calculated from the welding parameters using the standard procedure EN ISO 1011-2. The other important parameters for simulating the specific part of the HAZ on the welding simulator are: the peak temperature reached in the HAZ during welding, the preheating temperature, the holding time at the peak temperature, and the final temperature at the end of the simulation. All these parameters can be measured during welding or calculated using the standard procedure EN ISO 1011-2. The procedures for determining the welding diagram and the influence of the weld thermal cycle are shown schematically in Fig. 4 and Fig. 5 for the 2D and 3D heat transfer during welding, while Fig. 6 shows the procedure for evaluating the limiting thickness of both heat transfers. In these cases, the Rycalin equations of the moving heat source are used to construct the influence of the weld thermal cycle during welding on the material CG HAZ. These data are used for the simulation performed on the unaffected base material (upper parts on the left side of Fig. 7. In the case of CGHAZ made of 17CrNiMo7 steel, the parameters were measured during real welding, where the cooling time Δt8/5 was 5 s and the peak temperature was 1300°C. All parameters required for the simulation are listed in Table 3, and the overall influence of weld thermal cycle used to formation of the CG HAZ microstructure is shown on the right side of Fig. 7.

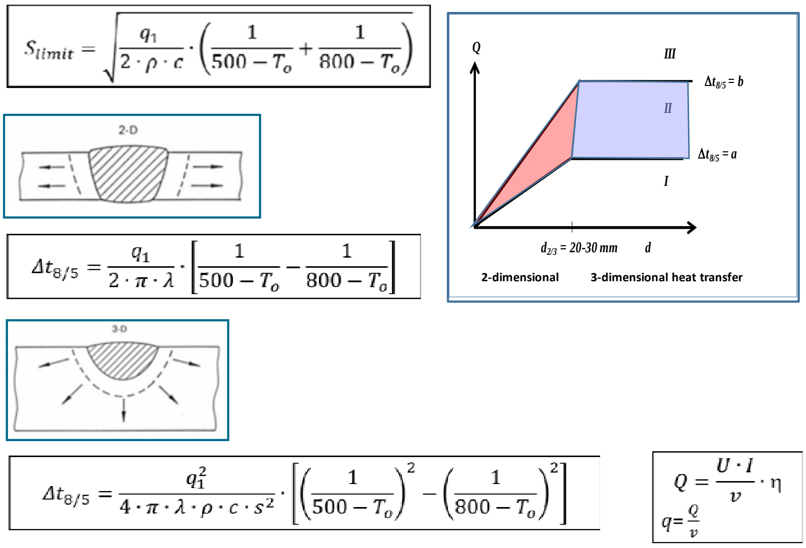



Fig.6. *Determination of the limiting thickness between 2-D and 3-D heat transfer during welding*

Table 3. Parameters for CGHAZ simulation by using weld thermal simulator

| Preheating temp. (°C) | Heating rate (°C/s) | Peak temperature (°C) | Holding time at peak temperature (s) | Cooling time $\Delta t_{8/5}$ (s) | Finish time (s) |
|---|---|---|---|---|---|
| 4. 50 | 5. 200 | 6. 1300 | 7. 3 | 8. 5 | 9. 70 |

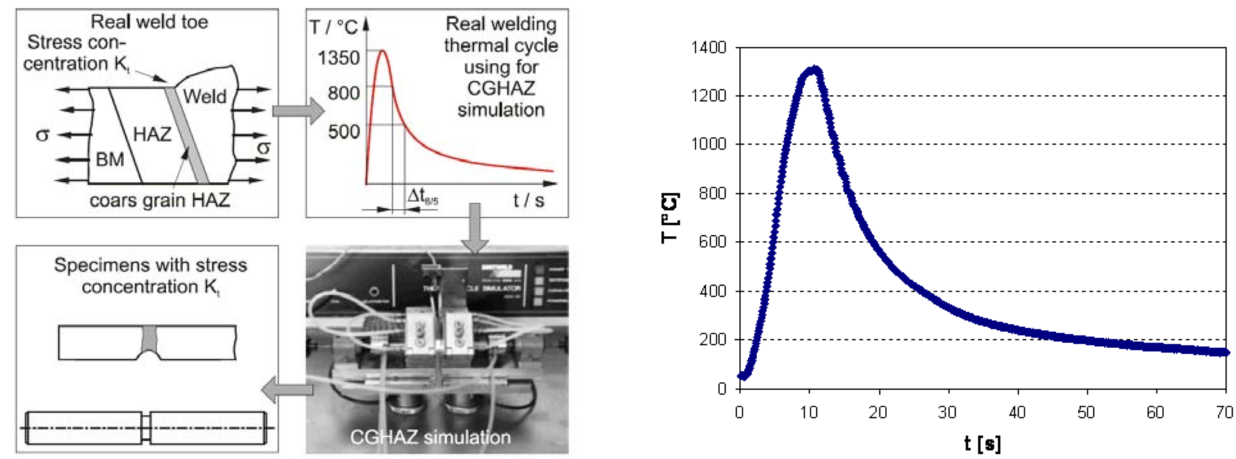



Fig.7 *HAZ preparation by using weld thermal simulator with influence of weld thermal cycle of the CG HAZ*

## 4. CG HAZ MICROSTRUCTURE PREPARATION IN FURNACE

The preparation of CG HAZ in the furnace is more complicated than by using a welding simulator, but it has the advantage that the whole sample has the CG HAZ microstructure and not only a part of the sample as in the HAZ preparation on the welding simulator. Therefore, the preparation of the microstructure in the furnace must be precise and accurate to obtain a suitable CG HAZ microstructure.

The first step is to coarsen the austenite grains, and the coarsening of the grain can be achieved by high temperatures over a short period of time or by lower temperatures over a longer period of time. In our case, the target size of the crystal grains that occur during real welding of the CG HAZ was 200μm. The temperature of 1100°C was chosen to achieve the size of the grains. The duration of the holding time at this temperature was determined experimentally. Different samples of the base material were heated and held in the furnace at a temperature of 1100°C for different periods of time and cooled by quenching in water. During this process, martensite microstructures with grains of different sizes were formed. The results of the experiments are shown in Fig. 8. The target holding time at 1100°C for the formation of the martensite microstructure with an average size of 200μm is 3 hours. This holding time was chosen for the further investigations.

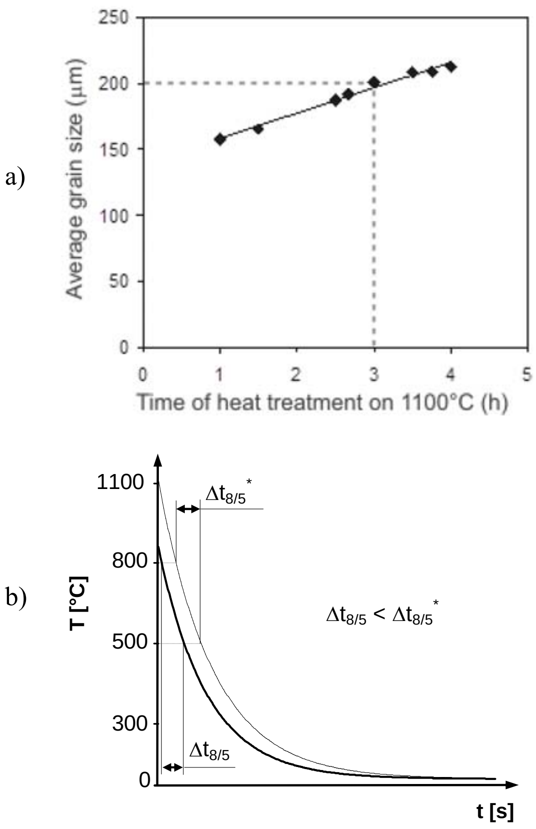



Fig.8 *Average size of crystals grain versus holding time in furnace at 1100°C (a) and Δt8/5 measurements at quenching in water (b)*

In for proper CG HAZ microstructure formation, the cooling rate during quenching should be the same as during welding. This means that the cooling time Δt8/5 must also be the same. The cooling time during quenching was measured experimentally. It was found that when quenching in water at a temperature of 870°C, a cooling time Δt8/5 of 5s can be achieved, while this time is longer when quenching in water at a temperature of 1100°C. The reason for this is the accumulation of heat in the sample, which does not allow such a fast cooling of the sample in contact with the water. See results in Fig. 8.

The final heat treatment to produce the microstructure CG HAZ in the furnace is shown in Fig. 9. The first part is held at a temperature of 1100°C for three hours to achieve grain coarsening. Then the temperature is lowered to 870°C, followed by water quenching to achieve an appropriate cooling rate and the correct CG HAZ microstructure.

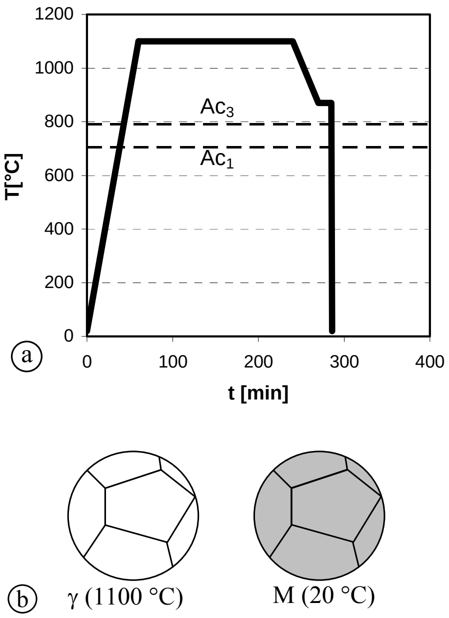



Fig.9 *CG HAZ microstructure preparation regime in furnace*

## 5 RESULTS AND DISCUSSION

The microstructure of CG HAZ, produced with the Smitweld 1405 weld thermal simulator, was imaged with the Epiphot300 optical microscope at two different magnifications. Fig. 10 (left) shows the CGHAZ microstructure (100x) and Fig. 10 (right) shows the CGHAZ microstructure at (200x). The average grain size is 200μm. The microstructure consists of lath martensite.in water at a temperature of 870°C.

The furnace-produced CG HAZ microstructure was photographed with the same Nikkon Ephiphot 300 light microscope at two different magnifications. Fig. 11 (left) shows the microstructure of CG HAZ (100x) and (200x). The average size of the crystal grains is 200μm, and the microstructure consists of lath martensite.

Hardness measurements were carried out by Vickers method, by using diamond pyramid with angle 136° and load 10kg. Average hardness in both CG HAZ microstructures was approximately 388 HV. Scatter of the measurements was around 18HV in both cases.

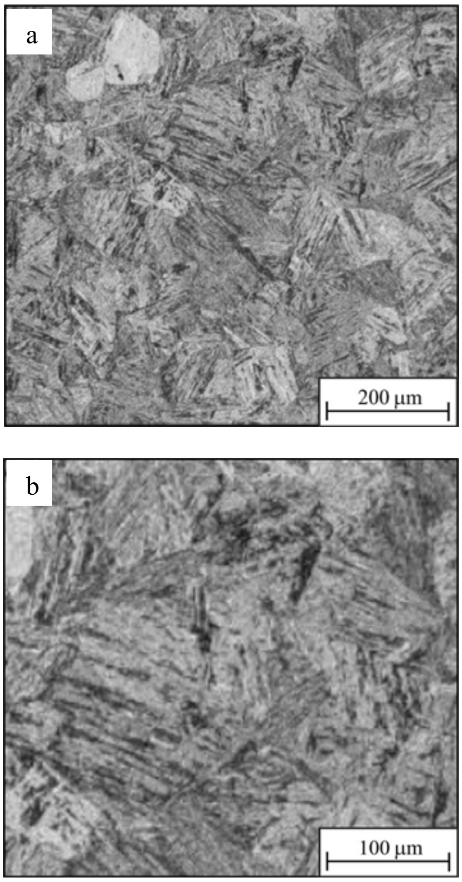



Fig.10 *CG HAZ prepared by weld thermal cycle simulator at different magnification 100 x (a) and 200 x (b)*

The tensile test from the CG HAZ, which was prepared using weld thermal simulator, could not be performed because this area is too narrow to machine the tensile specimens. However, there are the following correlations according to BSI 7448 part 2 to predict the estimated values for the yield strength at room temperature and the tensile strength.

$Rp_{02}$= 3.28 HV – 221 valid for 165 < HV < 495 (1)

Rm = 3.15 HV + 93 valid for 250 < HV < 400 (2)

The tensile test was performed only on the microstructure CG HAZ, which was produced in the furnace. A cylindrical specimen was milled from the material. Table 4 shows the results of the tensile test, which was carried out on a servo-hydraulic 200 kN AMSLER machine.

Standardised Charpy specimens with ISO -V notch were prepared from CG HAZ in an oven. Specimens were tested at various temperatures (-40, -20, 0, +20, and +50°C) on an instrumented Charpy pendulum AMSLER RPK 300. During the test, plots of force versus time and energy versus time were recorded. The results of the Charpy test at room temperature are shown in Figure 12 (left). The fracture surface of the specimen is shown in the same figure (right) and was photographed using a microscope SEM.

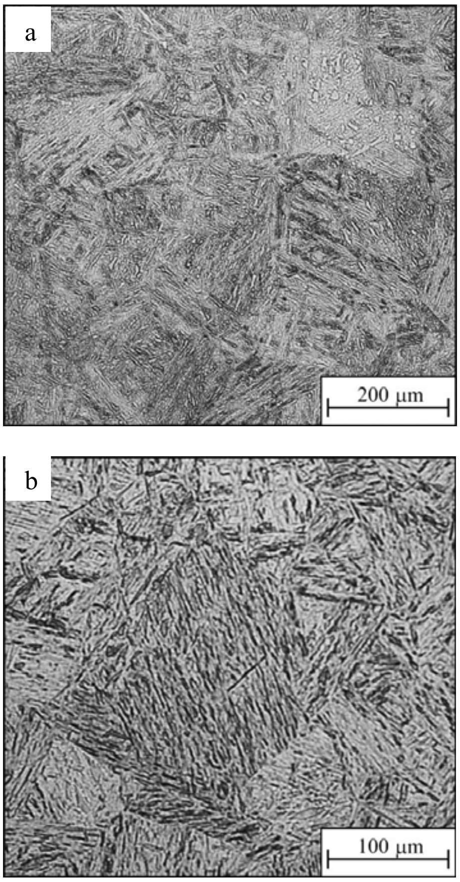



Fig.11. *CG HAZ prepared in furnace at different magnification 100x (a) and 200 x (b)*

Standardized Charpy specimens with ISO -V notch were prepared from CG HAZ in an oven. Specimens were tested at various temperatures (-40, -20, 0, +20, and +50°C) on an instrumented Charpy pendulum AMSLER RPK 300. During the test, plots of force versus time and energy versus time were recorded. The results of the Charpy test at room temperature are shown in Fig.12a. The fracture surface of the specimen is shown in Fig.12b and was photographed using a microscope SEM.
Other results are shown in Fig.13.

Table 4. Results of tensile tests

| Material | $R_{p02}$ (MPa) | $R_m$ (MPa) | $\sigma_u$ (MPa) | $A_g$ (%) | $A_5$ (%) | $Z$ (%) | $n$ (-) |
|---|---|---|---|---|---|---|---|
| CG HAZ simulator | 1090* | 1315* | - | - | - | - | - |
| CG HAZ furnace | 1021 | 1366 | 1089 | 3.6 | 11.4 | 45.4 | 0.23 |

*Calculated from hardness by using BS 7448 part 2.

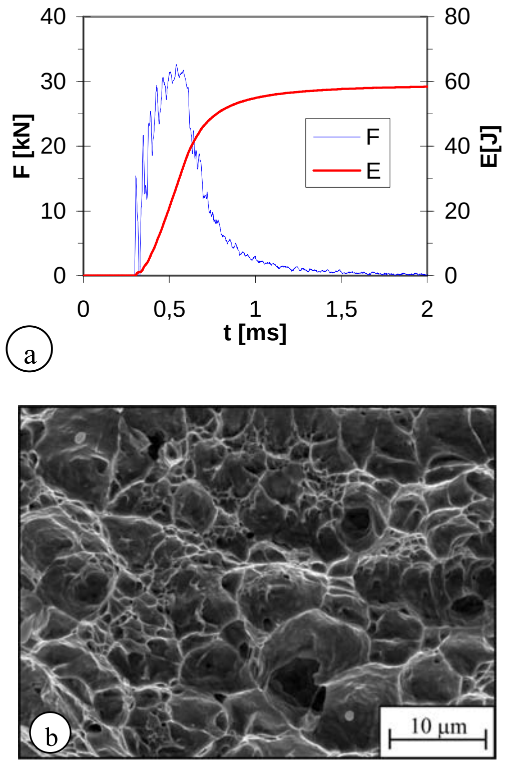



Fig.12 *Results of instrumented Charpy test at +20°C (a), fractured surface-SEM (b)*

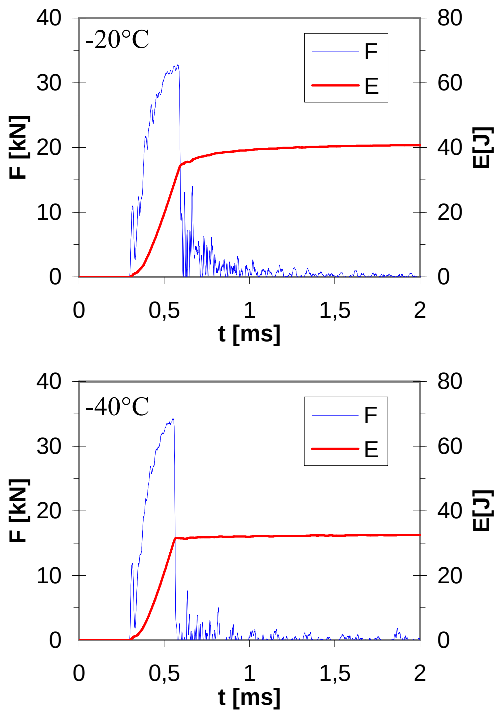



Fig.13 *Results of instrumented Charpy tests at -20°C and at -40°C*

The total energy for fracture decreases with test temperatures. In instrumented Charpy testing, the total energy for fracture can be divided into energy for crack initiation and energy for fracture propagation. The results described above are shown in Fig.14, where the energy for crack initiation remains almost independent of the test temperature, but the energy for crack propagation increases with test temperature.

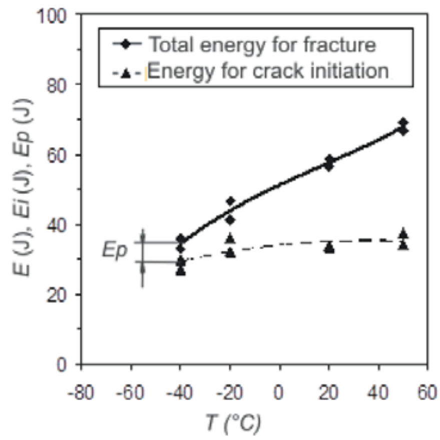



Fig.14 *Total energy for fracture, and split energy for initiation and energy for propagation*

The crack growth tests and fracture mechanics tests were performed on unilaterally notched flexural specimens. Details of the tests and the geometry of the specimens are shown in Fig. 15 and their results are in Fig. 16.

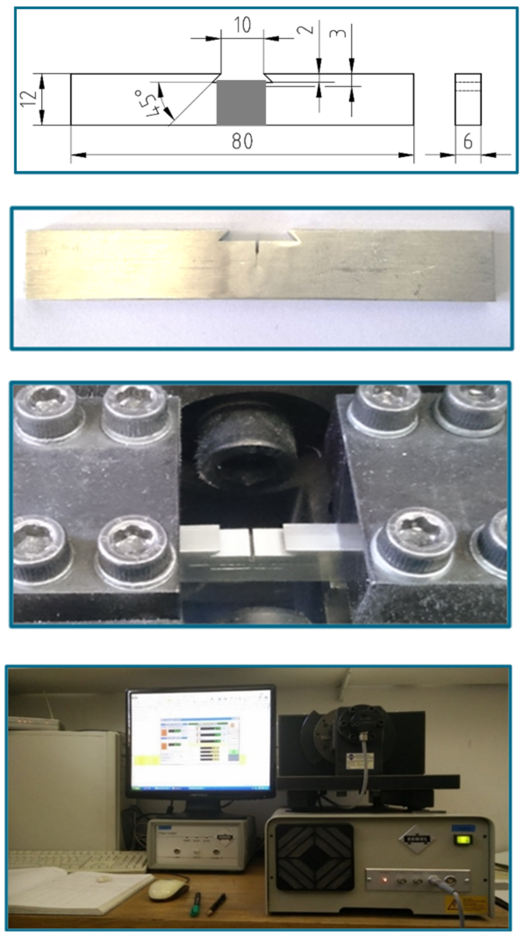



Fig.15 *Details from SENB fracture mechanics tests and fatigue growth tests*

Paris curve

$$da/dN = C\,\Delta K^m$$

| R | C | m |
|---|---|---|
| –1 | 1.7 $10^{-13}$ | 3.6 |

Threshold for crack propagation

| $\Delta K_{th}$ [MPam$^{0.5}$] |
|---|
| 10,7 |

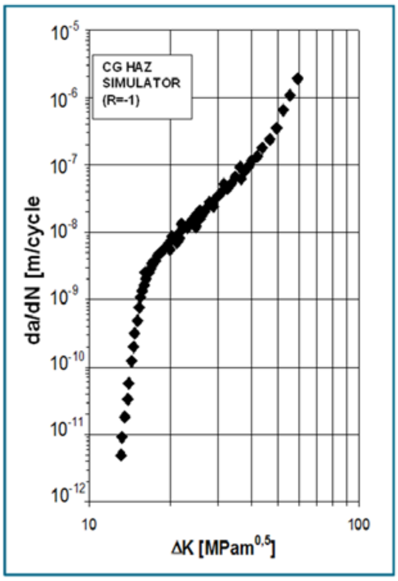



Fig.16 *Results of fracture mechanics tests*

## 6 Conclusion

The HAZ region of the weld is very narrow and therefore does not allow specimens to be processed for testing. Moreover, this region is very heterogeneous, it consists of different types of microstructures and consequently has very different mechanical properties. To determine the properties of such HAZ regions, an artificial preparation of the HAZ macrostructure is required.

In this article, two different methods of producing an artificial CG HAZ structure are presented. It can be produced by using a weld thermal simulator or by using a furnace and water quenching. Such an artificial HAZ microstructure is now present in a larger area (production of HAZ using weld thermal simulator); therefore, it is possible to machine the specimens for testing while the CG HAZ microstructure is distributed over the entire specimen (production of HAZ in a furnace).

Various properties have been successfully tested on artificially produced CG HAZ on steel CT 781, e.g. hardness test, tensile test, Charpy test, fracture mechanics tests and fatigue growth tests.

## References

[1] Vuherer, T. (2008). Analysis of influence of micro defects on fatigue strength of coarse grain HAZ in welds - PhD Thesis, University of Maribor, Faculty of Mechanical Engineering.

[2] Vuherer, T., Maruščak, P.O., Samardžić, I. (2012). Behaviour of coarse grain heat affected zone (HAZ) during cycle loading. Metalurgija 51/3, p.p. 301–304.

[3] Vuherer, T., Dunđer, M., Milović, Lj., Zrilić, M., Samardžić, I. (2013), Microstructural investigation of the heat-affected zone of simulated welded joint of P91 steel. Metalurgija 52/3, p.p. 317–320.

[4] Vuherer, T., Milović, Lj., Gliha, V. (2011). Behaviour of small cracks during their propagation from Vickers indentations in coarse-grain steel: an experimental investigation. International journal of fatigue 33/12, p.p. 1505–1513.

## Note

This paper is based on the paper presented at 6 th International scientific conference ”*Conference on Mechanical Engineering Technologies and Applications*” COMETa 2022, East Sarajevo - Jahorina 2022.