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BEHAVIOUR OF COARSE GRAIN HEAT AFFECTED ZONE (HAZ) DURING CYCLE LOADING

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This paper presents results of a study on martensitic coarse grain heat affected zone that can appear in welded joints. Mechanical properties of martensitic coarse grain heat affected zone and its microstructure were investigated. Special attention was given to its behaviour during the cycle loading under stress concentration. Stress concentration was similar to the one in real welds. The S-N curve and the fatigue limit were determined. The Paris curve and the threshold for crack propagating were also determined.

Key words: Weld, coarse grain HAZ, microstructure, mechanical properties, fatigue limit, Paris curve

Ponašanje grubozrne zone utjecaja topline (ZUT) zavara tijekom cikličkog opterećenja. U radu se istražuje martenzitna grubozrnata zona utjecaja topline koja se može pojaviti pri zavarivanju. Istražena su mehanička svojstva i mikrostruktura ove zone. Posebna je pažnja posvećena njenom ponašanju tijekom cikličkog opterećenja kada je prisutna koncentracija naprezanja. Koncentracija naprezanja je slična onoj kod realnog zavarivanja. Određena je S-N krivulja i granica umaranja. Također je određena i Parisova krivulja i prag propagacije pukotine.

Ključne riječi: Zavar, grubozrnata ZUT, struktura, mehanička svojstva, granica umaranja, Parisova krivulja

INTRODUCTION

A material is heated locally during an arc welding. Consumable material and a part of a base material are melted and solidified into weld metal during the cooling. The heat input needed for welding increases material temperature in the vicinity of the weld metal. Some microstructure changes appear in high heated area which is not melted. This region is called the heat affected zone (HAZ).

Part of the HAZ that is heated the most is found nearby the weld metal, therefore crystal grains are coarsening during the heating. The coarse grain microstructure, called the coarse grain heat affected zone (CG HAZ), results from this process; see Figure 1.

In some cases, martensitic microstructure can appear in the HAZ, if material contains enough carbon or other elements which increase hardness. The martensitic microstructure is usually hard and brittle with low impact toughness, and is therefore not always convenient for welded joints.

In order to achieve better microstructure, preheating is used before welding and higher heat input is used during welding to reduce cooling speed of heated material. Result of such process is less hard and less brittle microstructure. Heat input does not need to be too high because of grain coarsening and reduce of the HAZ impact toughness. Post weld heat treatment is also used to improve the microstructure, but some types of material do not allow post weld heat treatment like micro-alloyed steels. This is the reason why in some cases martensitic microstructure stays in the HAZ. Taking this into account, stress concentration can appear in welds due to weld toe's shape where inconvenient coarse grain microstructure exists. This region could cause problems especially when welded joint is loaded by cycle loading.

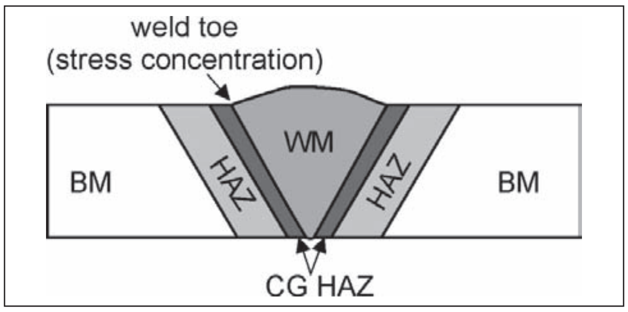

Figure 1 Welded joint; BM (base material), HAZ (heat affected zone), WM (weld material)

The aim of this study was to assess the 17CrNiMo7 CG HAZ microstructure and properties, and to determine its behaviour during the cycle loading under stress concentration.

MATERIAL

The steel 17CrNiMo7 was used to prepare samples of CG HAZ microstructure. Chemical composition and

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Table 1 **Chemical composition of the steel (weight / %)**

C	Si	Mn	P	S
0,18	0,22	0,43	0,012	0,028
Cr	Ni	Cu	Mo	Al
1,56	1,48	0,15	0,28	0,023

Table 2 **Mechanical properties of the steel**

$R_{p0.2}$ / MPa	R_m / MPa	A_5 / %	Z / %	Hardness / HV 10
489	633	26	72	217

mechanical properties of the steel are shown in Tables 1 and 2.

EXPERIMENTAL PROCEDURE

GMAW welding process with low heat input was simulated. The CG HAZ microstructure was investigated. It was prepared by using a weld thermal cycle simulator. The applied weld thermal cycle is shown in Figure 2.

The peek temperature was 1300 °C, the holding time was 3 s on the 1300 °C and cooling time between 800 °C to 500 °C was 5 s. The crystal grains coarsened till 200 μm during simulation. Short cooling time ensured the martensitic transformation.

Fifteen cylindrical specimens with a groove were prepared for rotation bending fatigue tests. The groove in the middle of the specimen causes the stress concentration during loading like a weld toe at real weld [1]. Other authors reported that the stress concentration due to the weld toe was approximately 1,74 [1,2,3] for gas metal arc welding. In order to obtain the same stress concentration in the specimens, the specific geometry of the groove was used.

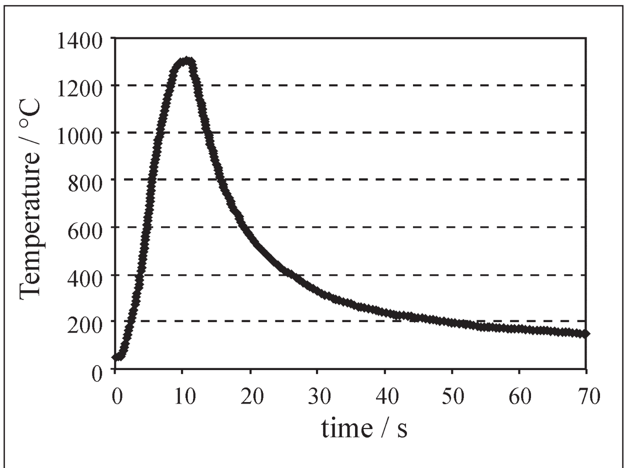

Figure 2 Influence of weld thermal cycle on CG HAZ material

The groove was designed according to equations suggested by Peterson and Young [4,5]; in that way the theoretical stress concentration factor was calculated by using the equations 1 and 2, when the specimen was loaded by bending.

$$K_t = K_1 + K_2 \cdot \left(\frac{2 \cdot h}{D}\right) + K_3 \cdot \left(\frac{2 \cdot h}{D}\right)^2 + K_4 \cdot \left(\frac{2 \cdot h}{D}\right)^3 \quad (1)$$

The factors K_1, K_2, K_3 and K_4 depend on the type of loading (tension, bending, torsion, etc.), h is depth of the groove $(D - d)/2$, D is specimen diameter, d is inside diameter of the groove. In the case of bending loading K_1, K_2, K_3 and K_4 are calculated by equation 2 [5].

$$\begin{aligned} K_1 &= 0{,}455 + 3{,}354 \cdot \sqrt{(h/r)} - 0{,}769 \cdot (h/r) \\ K_2 &= 0{,}891 - 12{,}721 \cdot \sqrt{(h/r)} + 4{,}593 \cdot (h/r) \\ K_3 &= 0{,}286 + 15{,}481 \cdot \sqrt{(h/r)} - 6{,}392 \cdot (h/r) \\ K_4 &= -0{,}632 - 6{,}115 \cdot \sqrt{(h/r)} + 2{,}568 \cdot (h/r) \end{aligned} \quad (2)$$

Geometry of the grooved specimens used for this investigation is shown in Figure 3. The groove causes the stress concentration of 1,74 during bending loading.

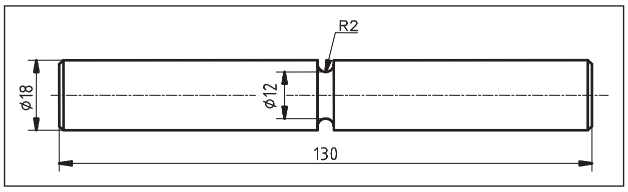

Figure 3 Specimen for rotation bending fatigue testing

Fatigue tests were done on the rotation bending machine (Amsler UBM 200) in order to obtain a fatigue limit and behaviour of CG HAZ material during cycle loading. Fatigue crack growth tests were done on the Amsler cracktronic machine in order to obtain threshold for crack propagation and Paris curve, and finally, analysis of the microstructure was performed on light and TEM microscopes. Preparation of the samples for TEM microscope is shown schematically in Figure 4. The

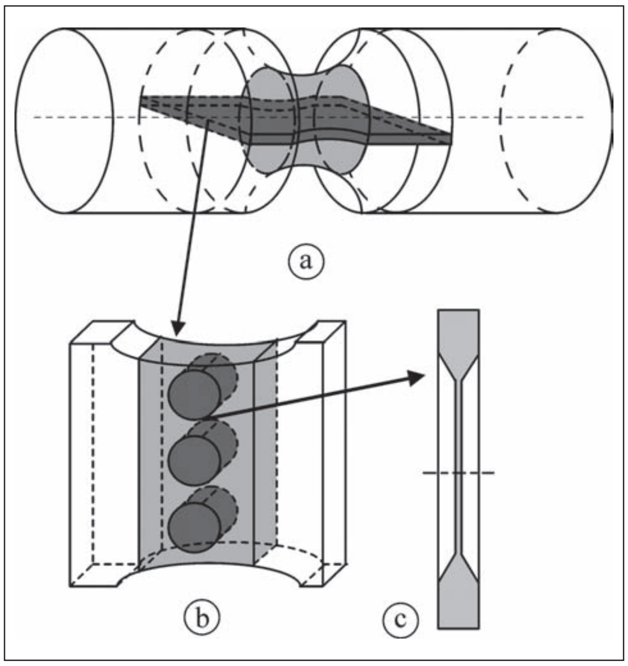

Figure 4 Preparation of the samples for TEM microscope

CG HAZ material is only in grey region of the specimen (see Figure 4). The samples for the TEM microscope were prepared from this region of the specimen.

RESULTS AND DISCUSSION

Microstructure was analysed by the light microscope at magnification of 100×. The microstructure consists of laths martensite, as shown in Figure 5. The size of crystal grains is approximately 200 μm.

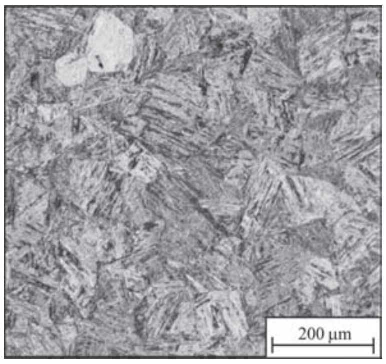

Figure 5 Microstructure of CG HAZ material; light microscope 100 ×

Details of the CG HAZ microstructure were analysed by the TEM microscope. Builds-up are of long martensitic laths. Their thickness is from 0,25 to 2,5 μm. Laths being 0,6 to 1,1 μm thick predominate, but some small regions of thicker or thinner laths also exist. The martensitic laths are shown in Figure 6a, and the boundary between them is shown in Figure 6b. Dislocation density was measured by a secant method and by using diffraction images from the TEM microscope. Dislocation density is high especially in the vicinity of grain boundary, where $8{,}5\ 10^{14} \pm 2{,}5\ 10^{14}$ m/m^3.

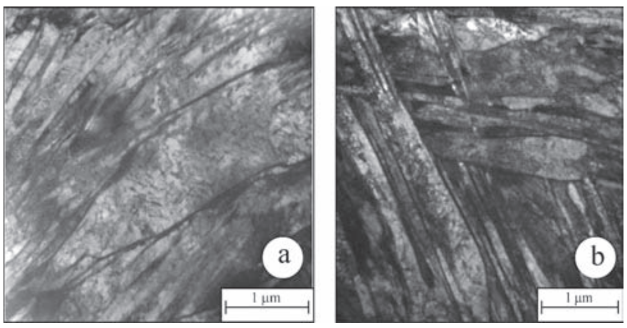

Figure 6 Martensitic laths microstructure; martensitic laths (a) and grain boundary (b)

Mechanical properties

Vickers' hardness was measured by using load of 98,1 N on instrumented Zwick machine. Hardness was 455 HV10. Results are shown in Figure 7, presenting the curve force versus depth.

It was not possible to measure the tensile strength and a yield stress by mechanical testing, because simulated HAZ region was too small. They were calculated

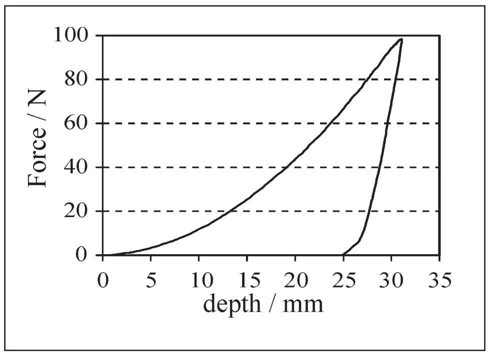

Figure 7 Curve force versus depth during Vickers indentation

approximately from the hardness by applying equations from the BS 7448-2 [6] and equations proposed by Pavlina and Tyne [7], but in such cases error occurs up to 10%. Equations 3 and 4 refer to the BSI standard and equations 5 and 6 were proposed by Pavlina and Tyne.

$$R_{p0.2} = 3{,}8 \cdot \mathrm{HV} - 221 \qquad (3)$$

$$R_m = 3{,}15 \cdot \mathrm{HV} + 93 \qquad (4)$$

$$R_{p0.2} = 2{,}876 \cdot \mathrm{HV} - 90.7 \qquad (5)$$

$$R_m = 3{,}734 \cdot \mathrm{HV} - 99.8 \qquad (6)$$

(HV is the Vickers hardness number)

The yield stress and the tensile stress are presented in Table 3.

Table 3 **Yield stress and tensile strength CG HAZ and base material**

Material	$R_{p0.2}$ / MPa	R_m / MPa
CG HAZ	1271 (1)	1526 (1)
	1218 (2)	1599 (2)
Steel 17CrNiMo7	474 (1)	761 (1)
	519 (2)	692 (2)

(1) BSI 7448-2 standard (equations 3 and 4)
(2) proposed by Pavlina and Tyne (equations 5 and 6)

Results of fatigue testing

Results of fatigue testing on the rotation bending machine are shown in Figure 8.

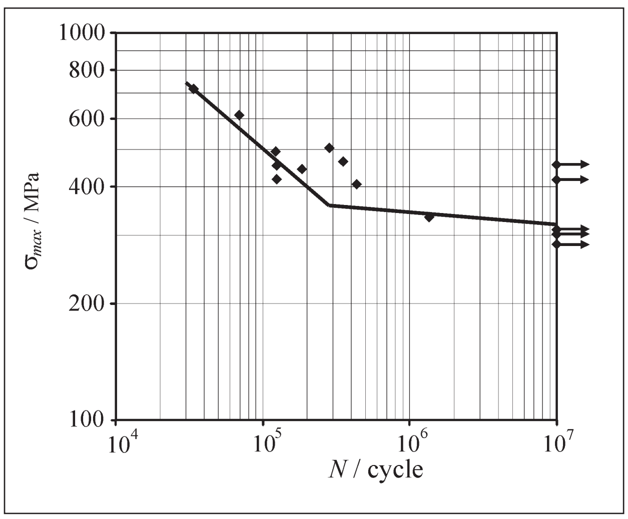

Figure 8 S-N curve of the CG HAZ

Load ratio R was -1 due to rotation bending. The continuing line represented the S-N curve of the CG HAZ microstructure. The fatigue limit was relatively low, only 330 MPa. This was the lowest stress limit beyond which specimen did not break after 10 million cycles.

Results of fatigue crack growth test

Specimens of 10 × 10 × 55 mm were used for the fatigue crack growth test. Before starting the experiment, special thin foil crack gauge was attached on one side of the specimen. It was used for measuring the crack propagation during the loading. The 2 mm-long precrack was prepared with the low ΔK. The crack threshold was obtained step by step by reducing ΔK from ΔK, which was used for precrack creation. Crack threshold was low, only 10,7 $MPam^{0.5}$. Test was continued by increase of ΔK until the breakage of specimens. Results are shown in Figure 9.

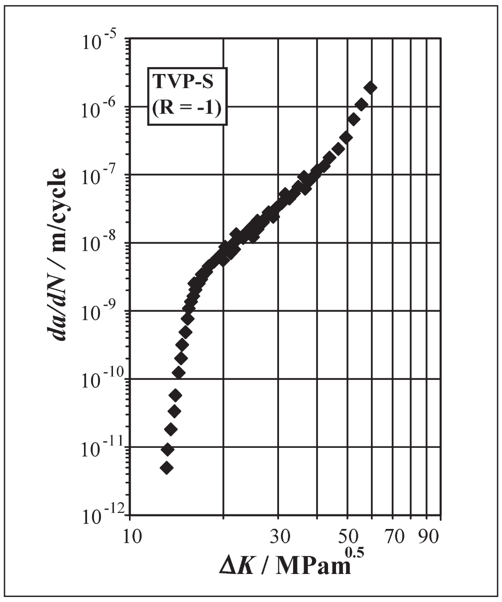

Figure 9 Paris curve of the CG HAZ material

Obtained Paris curve represents CG HAZ material behaviour in case of crack and speed of eventual crack propagation. Paris law is valid in the middle liner part and is explained by equation 7.

$$da/dN = C \cdot \Delta K^{m} \quad (7)$$

The constant C is 1,7 10^{-13} and the constant m is 3,6 for CG HAZ material.

CONCLUSIONS

The CG HAZ microstructure consists of laths matrensite. Its hardness is 455 HV 10. The dislocation density at the boundary of the martensitic laths is 8,5 $10^{14} \pm$ 2,5 10^{14} m/m^3. The fatigue limit of the CG HAZ material is relatively low, according to its yield stress. It is only on one fourth of the yield stress. If compared to the unaffected base material, it is on two third of its yield stress, which is acceptable for welded joints, because base material fatigue limit will be lower. The threshold for crack propagation is low, being only 10,7 $MPam^{0.5}$.

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