FATIGUE STRENGTH OF MATERIAL AT THE WELD TOE IN THE PRESENCE OF SURFACE MICRO-DEFECTS

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Experimental results of bending fatigue strength measured on specimens made of material that is similar to the material at the weld toe were analysed.

Specimens were grooved to cause stress concentration in the simulated material of heat affected zone. Surface at the bottom of the groove was smooth or with artificial micro-defects. Micro-defects used were single and series of Vickers indentations. Their influence on the coarse grained material near the weld fusion line by fatigue is assessed in the scale of equivalent geometrical parameter.

Fatigue strength of material at the weld toe depends on several variables that is on gamma grain size, ultimate tensile strength and micro-defect size.

INTRODUCTION

Weld joints that are dynamically loaded beyond their load carrying capacity use to fail by fatigue. In the case of high quality butt-weld joints fatigue crack always originates at the weld toe. The reason is characteristic weld joint profile causing stress concentration. The resistance of material at the weld toe to fatigue crack initiation that is its fatigue strength is decisive factor in the dynamic load carrying capacity of weld joints.

Welding process affects material properties at the weld toe. Numerous of micro-defects are present there and previous fine grain micro-structure of base metal (BM) is drastically changed. Weld toe material is one part of the heat affected zone (HAZ) where grains are coarser than grains of BM. The interaction between stress and existing micro-defects may cause micro-crack nucleation, propagation and formation of fatigue macro-crack. Grain boundaries use to be micro-structural barriers for micro-crack propagation.

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The aim of this experimental work was to study the effects of welding parameters and weld build-up on the fatigue strength of HAZ at the weld toe in the presence of surface micro-defects.

EXPERIMENTAL WORK

Samples of HAZ material were made by welding simulation on high strength quenched and tempered structural steel nionicral 70 (R_p=690 MPa). A computer controlled thermal cycle simulator was used. Stress concentration existing at the weld toe was modeled by machined groove. Single and series of Vickers indentations were used as artificial surface micro-defects.

As regards weld joint build-up the material at the weld toe is mostly either single cycle coarse grain (CG) HAZ or double cycle HAZ. CGHAZ has been significantly affected by heat once. The highest temperature of this thermal cycle is very close to the melting point of steel. Double cycle HAZ near to the fusion line has been significantly affected by heat twice. The highest temperature of the first thermal cycle caused by the nearest weld run is very close to the melting point of steel, while the second one caused by the subsequent run reheats existing CGHAZ beyond the Ac_1 temperature. Previous coarse grained micro-structure is changed during the second thermal cycle partially or completely.

For determination of weld thermal cycle linear heat input with constant power is supposed by welding. In the case of thick plate welding cooling sequence of thermal cycle at the distance R from the welding line depends on specific heat input q and thermodynamic properties of steel. This expression was given by Rosenthal (1):

$$T(R,t) = \frac{q}{2\pi\lambda \cdot t} \cdot e^{-\frac{R^2}{4D \cdot t}} \qquad (1)$$

Constants λ and D are thermal conductivity and diffusivity of steel. Eq. 1 is used for computation of thermal profile during the particular weld run execution. R and q have to be specified and relevant data of material known.

According to Easterling (2) cooling time through the range 800-500 °C ($\Delta t_{8/5}$) and peak temperature (T_p) are the main HAZ micro-structure controlling parameters if heating rate and dwell time at T_p are held constant. $\Delta t_{8/5}$ and T_p for simulation have been derived from the temperature field of the moving heat source:

$$\Delta t_{8/5} = \frac{q}{2\pi\lambda}\left(\frac{1}{500 - T_0} - \frac{1}{800 - T_0}\right) \quad ; \quad T_p = T_0 + \frac{2q}{\pi e \rho c_p} \cdot \frac{1}{R^2} \qquad (2)$$

ρ and c_p are density and specific heat capacity of steel. T_0 is temperature of steel before the weld run execution. R and q can be specified by Eq. 2 and used in Eq. 1.

Three types of material near the fusion line were used in this work:

a) BM heated to the temperature over 1350 °C and then cooled with chosen $\Delta t_{8/5}$ (~5, 9, 25, 100 s). The result is synthetic micro-structure of CGHAZ.
b) CGHAZ material heated over Ac_1 temperature and then cooled with the same $\Delta t_{8/5}$ as previously (~9, 25 s). The result is synthetic micro-structure of double cycle HAZ near the fusion line when equal heat inputs are used by weld build-up.
c) CGHAZ material obtained by high heat input welding reheated over Ac_1 temperature and then cooled with much shorter $\Delta t_{8/5}$ as previously (the first thermal cycle ~100 s while the second one ~9 s). The result is synthetic micro-structure of double cycle HAZ near the fusion line when different heat inputs are used by weld build-up on the weld joint cap.

Specimens for fatigue strength measurement were either smooth or with surface micro-defects. Artificial micro-defects which size is comparable with the grain size of HAZ at the weld toe were single and series of Vickers indentations shown in Fig. 1a. They were placed at the bottom of the groove perpendicular to the highest stress. According to Peterson (3) such a groove is producing stress concentration of 1,74. Micro-defect sizes used were $d \approx 110$ and ≈ 220 μm (d-diameter of single indentation) and $l \approx 680$ μm (l-length of series indentations, $d \approx 220$ μm). The specimens were fatigued in the load control in pulsating bending. Loading was progressively increasing up to the fatigue crack initiation when the specimen compliance is changed.

RESULTS AND DISCUSSION

As the result of fatigue testing nominal bending fatigue strength $\Delta\sigma_{eBn}$ was obtained. Local stress at the bottom of the groove σ is higher than nominal bending stress σ_{Bn}. The reason is stress concentration caused by the groove. Depending on the type of specimen (with or without micro-defect) local fatigue strength $\Delta\sigma_e$ is expressed as:

$$\Delta\sigma_e = K_t \cdot \Delta\sigma_{eBn} \quad ; \quad \Delta\sigma_e = K_f \cdot \Delta\sigma_{eBn} \qquad (3)$$

Theoretical stress concentration factor K_t depends only on the groove geometry that is on its shape and relative size. Fatigue notch factor K_f depends on the groove geometry and material (notch sensitivity). Whenever surface micro-defects were present the left equation is used otherwise the right one.

Fatigue strength of treated materials depending on cooling time $\Delta t_{8/5}$ are shown in Fig. 2. They correspond to the smooth specimens and specimens with three different surface micro-defects. These results are compared with the primary gamma grain size of HAZ near the fusion line. Grain growth during the welding occurs at the very high temperatures (>1200 °C). Thus, grain size of single cycle CGHAZ is influenced by T_p and $\Delta t_{8/5}$ while of double cycle HAZ near the weld fusion line practically only by T_{p1} and $\Delta t_{8/5}$ of the first thermal cycle. Thermal cycle of the distant weld run can not be significant in respect of grain growth due to the lower temperatures. So, fatigue strength of double cycle HAZ is shown according to $\Delta t_{8/5}$ of the first thermal cycle. Observing data in Fig. 2 it is obvious the following: while primary gamma grain size is increasing with the increasing cooling time (heat input) fatigue strength is decreasing.

Fatigue strength $\Delta\sigma_e$ was then compared with the ultimate tensile strength of material R_m. Taking into account all specimens with micro-defect the following relation was found in our previous work (4):

$$\Delta\sigma_e = 0{,}5 \cdot R_m + 220 \quad ; \quad \Delta\sigma_e, R_m \text{ - [MPa]} \tag{4}$$

Finally, fatigue strength was compared with the size of artificial micro-defects. Parameter $\sqrt{area}$ introduced by Murakami (5) was not found to be suitable for both types of micro-defects treated in this work. The influence of series of indentations was namely overestimated as shown in reference (4). So, equivalent geometrical parameter (EGP) was introduced. It was assumed that micro-defects cause the same stress intensity at the point A as the equivalent elliptical crack shown in Fig. 1a if bending stress level is the same. The longer axis of equivalent crack coincides with the defect length (d or l) and shorter one with the defect depth (b). Then EGP is defined to be the depth of elliptical crack that causes at the same stress level the same stress intensity at the points A and B as previous crack (Fig. 1b). Newman and Raju solution for bend loading was used as in the Murakami's handbook (6).

$$K_I(\sigma_{Bn}, \text{EGP}) \equiv K_I(\sigma_{Bn}, \text{equivalent crack})_{max} \tag{5}$$

Experimentally obtained dependence of $\Delta\sigma_{eBn}$ on EGP is shown in Fig. 3 as Kitagawa-Takahashi plots (7). It is obvious that EGP is quite convenient measure of artificial surface micro-defects influence as regards fatigue strength lowering. Therefore, each single value of $\Delta\sigma_e$ was normalised with regression parameters from Eq. 4 and compared with EGP size as shown in Fig. 4. It is clear that fatigue strength of HAZ can be treated to be linearly dependent on its tensile strength and hyperbolically on the micro-defect size in scale of EGP:

$$\Delta\sigma_e = \left(0{,}92 \cdot R_m + 370\right) \cdot \text{EGP}^{-0{,}15} \quad ; \quad \Delta\sigma_e, R_m \text{ - [MPa]} \quad \text{EGP - [}\mu\text{m]} \tag{6}$$

Welding parameters and weld build-up have strong influence on the material near the fusion line that is at the weld toe. Grains are coarser (especially primary gamma grains). The reason is the most intensive thermal cycle that is applied during the weld joint execution. In the case of single significant thermal cycle (CGHAZ) hardness at the weld toe is dependent on $\Delta t_{8/5}$. In the case of two or more significant thermal cycles applied to the material near the weld fusion line

HAZ hardness is dependent on $\Delta t_{8/5}$ and on T_p of the second (or the last) thermal cycle what can be seen in references (5,8). Initial micro-defect sizes are dependent on the weld method used and the welding parameters.

CONCLUSIONS

Fatigue strength of material at the weld toe is decreasing with the increasing cooling time while primary gamma grain size is increasing. At the same time fatigue strength is a linearly increasing function of ultimate tensile strength of material that is of its hardness and a hyperbolically decreasing function of micro-defect size measured by EGP. Hardness of HAZ near the fusion line is usually a decreasing function of cooling time due to softer micro-structure formed at slower cooling. It is not clear yet what is prevailing whether the effect of grain size or the effect of micro-constituents.

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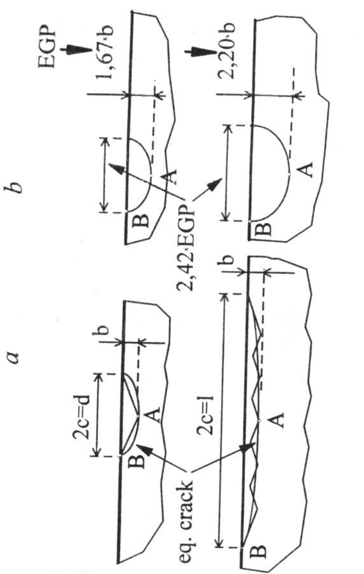

Figure 1 Shape and size of: a) micro-defects and equivalent cracks, b) EGP

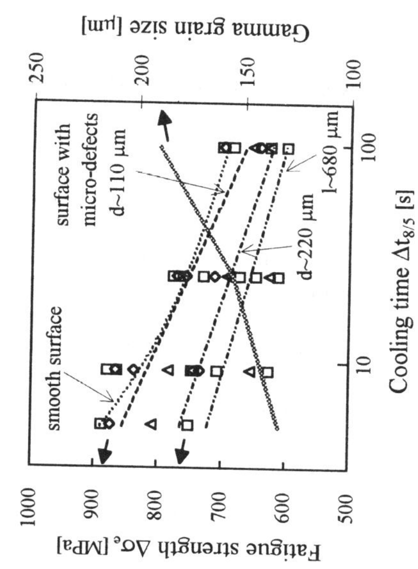

Figure 2 Fatigue strength and gamma grain size dependence on cooling time

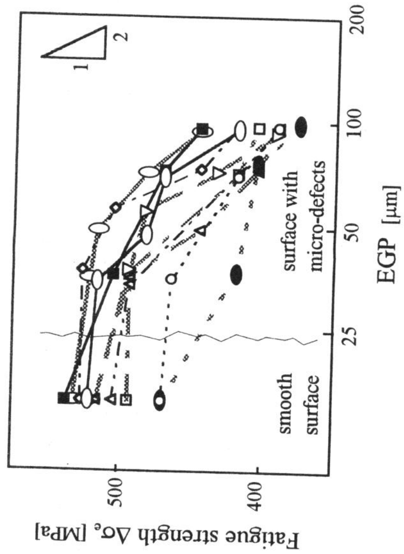

Figure 3 Fatigue strength dependence on EGP size for various materials of HAZ

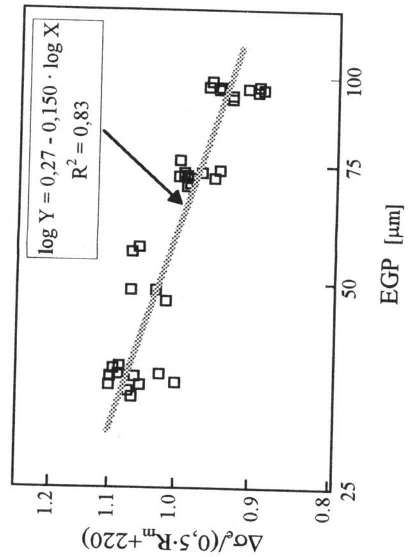

Figure 4 Relation between normalized fatigue strength and EGP size