CRACK EMANATION FROM DEFECTS MODELLED BY EXTREMELY SMALL DRILLED HOLES IN TWO CONDITIONS

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Abstract Fatigue is the primary reason for the failure of structural components. Resistivity of a coarse grain heat affected zone against fatigue crack initiation in presence of micro-defects is discussed in the present article. Samples of material with a martensitic coarse grain heat affected zone microstructure were prepared by proper thermal treatments. Microstructurally small holes were used as artificial micro-defects. They were created by drilling. Compressive residual stresses appear in the material due to the irreversibility of plastic deformation. Moment of hole drilling enables to prepare samples with and without effects of residual stresses. Critical stress level for fatigue crack initiation depends on the actual size of the hole. The location and the way of crack initiation is affected by the presence and character of residual stresses.

Introduction

Welds consist of base material, heat affected zone (HAZ) and weld metal. Figure 1 shows the weld microstructure. The filler material and part of the base material melt down during welding and form solidified weld metal while the base material in the close vicinity undergoes transformation to HAZ.

The HAZ formation is result of an applied thermal cycle caused by the heat source movement, which is necessary to melt material during welding. The effects of the thermal cycle diminish with the distance from the fusion line. The material close to the weld metal is exposed almost to the melting point. High temperatures give rise to grain growth. The result is formation of a coarse-grain microstructure in the so-called coarse-grain heat-affected zone (CGHAZ) found adjacent to the fusion line. The coarse grain microstructure influences the mechanical properties, such as impact toughness and fatigue limit.

Table 1: Chemical composition of the steel CT781

Elem.	C	Si	Mn	P	S	Cr	Ni	Mo	Cu	Al
wt. [%]	0.18	0.22	0.43	0.012	0.028	1.56	1.48	0.28	0.15	0.023

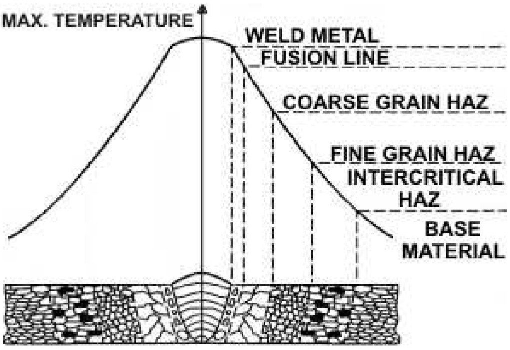


Figure 1: The microstructure across the weld

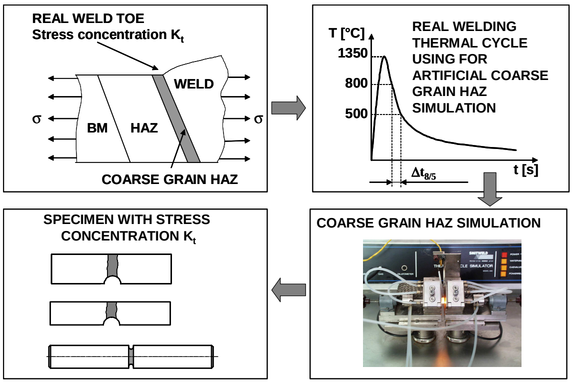


Figure 2: The simulation of HAZ microstructure using a thermal-cycle simulator

Concentration of the stress appears at the weld toes of loaded welds, due to the shape of the solidified weld metal. The location of stress concentration in Figure 2 is marked as K_t

(left, above). In order to avoid stress concentration at the weld toes fine grinding of weld reinforcement is sometimes performed, but it is economically hardly acceptable. If grinding of welds is not carried out, the fatigue strength is certainly reduced.

Weld defects in the weld metal and HAZ appear mainly due to insufficiently controlled process of welding. Non-destructive examination methods are successfully used to assure regular soundness of welds. Defects, smaller than the threshold sensitivity of the method, cannot be detected. Presence of those small defects in welds caused either by welding or base metal production can promote crack initiation during cyclic loading. The final consequence of defects is lower fatigue strength of welds.

The effect of defect on the fatigue limit of polycrystalline metals ceases to exist when its size is smaller than the biggest microstructural units [1]. Such microstructurally small defects are micro-defects. Grains are usually the biggest microstructural units of a CGHAZ.

During cyclic loading at a sufficient high level fatigue cracks appear due to the interactive effect of micro-defects and applied remote stress. The first stage of the fatigue crack appearance is crack initiation. Crack initiation in the specimens with micro-defects of the size of microstructural units is made easier because of the locally enhanced stress/strain field.

Crack initiation from micro-defects is followed by unusual fast crack growth [2]. Grain boundaries are strong barriers for the crack growth in this early sequence of fatigue crack propagation. However, growth rate of cracks smaller than grains decreases when crack tip approaches grain boundary. If the level of cyclic stress is not enough high to overcome such obstacles, crack growth will stop. Stable cracks are non-propagating cracks.

Welding residual stresses are present in the welds in the as-welded condition [3]. Tensile welding residual stresses promote crack emanation from micro-defects, while compressive ones have an opposite effect.

For all above described reasons CGHAZ often represents the weakest link of cyclically loaded high quality welds because of

- coarse grain microstructure
- changed mechanical properties
- welding residual stresses
- stress concentration due to weld shape
- existence of defects

Only if fatigue tests are executed on actual welds and after that specimens with an initiated fatigue crack examined in details the most critical HAZ microstructure will be located. Fatigue limit prediction of welds with or without micro-defects is therefore a thankless task.

Artificial HAZ microstructures can be used to study behaviour of different areas of welds during fatigue [4-8]. The advantages of such an approach are:

- identical microstructure in an extensive volume of the sample
- homogeneity of material, i.e. without present weld defects
- absence of the welding residual stresses
- possibility to simulate effects of defects by preparing artificial micro-defects

The fact that preparation of artificial micro-defects in mechanical way results in appearance of residual stresses is crucial for the behaviour of polycrystalline metals with such defects. Residual stresses can be tensile or compressive and sometimes even at the yield point of the material. The main reason of residual stress appearance due to micro-defects preparation is irreversibility of material plastic deformation.

All residual stresses have effect on the fatigue crack initiation from micro-defects. Local very high residual stresses can even change the actual shape of prepared micro-defect.

To evaluate the effects of defect size to the fatigue limit alone, effects of residual stresses due to artificial defects preparation should be omitted. Electro-etching is usually used. Part of material with the highest stress is removed without plastic deformation. In this way the residual stress level is substantially lowered. Unfortunately, removing of residual stresses by etching is accompanied with change of shape and size of the micro-defects.

The aim of this article is to discuss about the influence of residual stresses caused by drilling small holes to the fatigue strength of coarse grain steel.

Material, specimens and experimental procedure

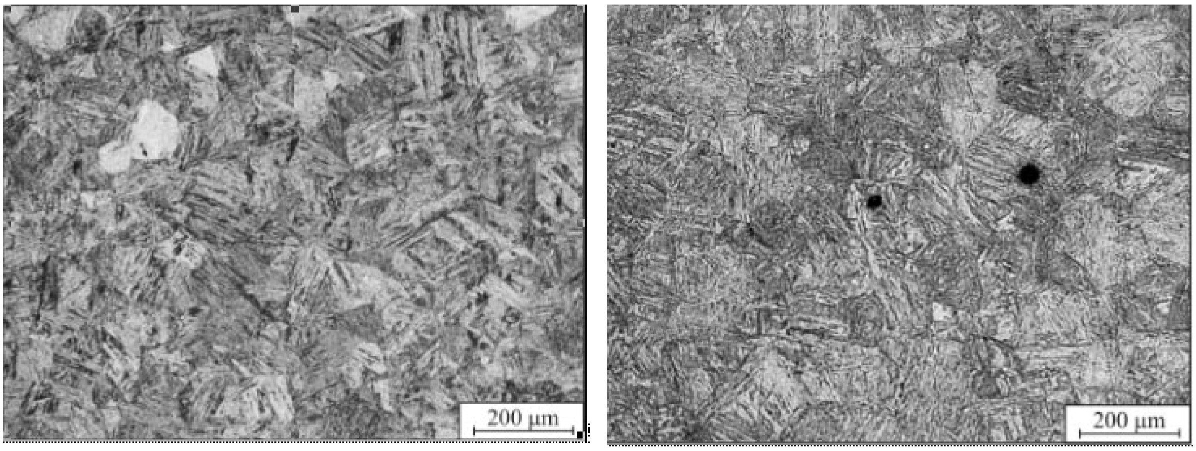
Testing which is impossible with samples of materials from the real welds, as the tensile test, the impact test, the fatigue test etc, is easily performed using specimens with artificial HAZ microstructure. Microstructure is prepared by simulation using either a weld thermal cycle simulator or a furnace.

Data on heating rate ($\dot{T}$), peak temperature (T_{max}) and cooling time ($\Delta t_{8/5}$) are used for simulation of thermal conditions during welding. Sketch in Figure 2 (right, above) presents a temperature lapse during preparation of CGHAZ microstructure using a weld thermal cycle simulator. Actual simulation is shown in the photograph (right, below). Few shapes of specimens with the limited volume of simulated CGHAZ microstructure located in the middle of the specimen’s length (shaded areas) are shown in the drawing (left, below).

If CGHAZ microstructure is prepared in a furnace an appropriate heat treatment should be applied to the pieces of base material in order to obtain as coarse grain microstructure as relevant microstructural constituents. In the first part of the heat treatment a coarse grain annealing should be performed to obtain right grain size, in the second one, suitable quenching medium should be used to assure formation of the expected microstructural constituents. The main advantage of HAZ microstructure simulation in furnace is homogeneous microstructure in the whole specimen not only in a limited volume.

Nickel-molybdenum steel CT781 (W. Nr. 1.6587) is used in the research. Its chemical composition is presented in Table 1. The steel is used in the automotive industry.

In order to form CGHAZ microstructure using weld thermal cycle simulator a thermal cycle with $\dot{T}$ = 200°C/s, T_{max} =1350°C, $\Delta t_{8/5}$ = 5 s is simulated. Simulation parameters define “cold” welding, resulting in martensitic microstructure with the grain size of approx. 200 μm (Figure 3a) and hardness 460 HV10.



a) b)

Figure 3: Microstructure of the simulated CGHAZ: a) preparation using the welding thermal simulator, b) preparation in the furnace

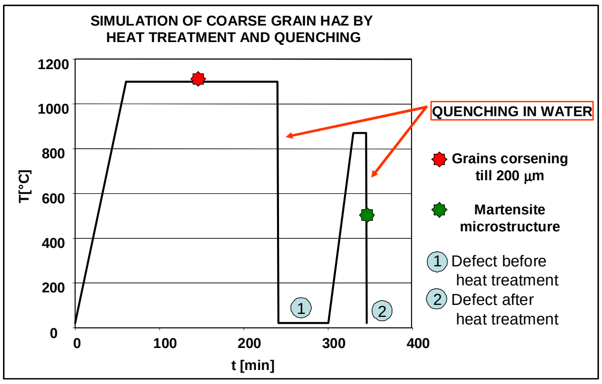


Figure 4: The heat treatment for CGHAZ formation in the furnace

The aim of the CGHAZ microstructure simulation in furnace was to prepare the same microstructure in the whole sample (Figure 4). At the first step suitably shaped samples of steel are heated in the furnace to 1100°C and held for 3 hours. Grains grow to the size of approx. 200 μm. The coarse grain annealing, is followed by cooling in water. The next step is heating to 870°C and water quenching. The result of combined thermal treatment is martensitic microstructure. The grain size and the hardness of this microstructure is the same as that prepared with the thermal cycle simulator; only the martensitic needles are somewhat finer (Figure 3b).

In order to determine the fatigue limit of CGHAZ material rotary bending fatigue test was used. Dimensions of the circumferentially notched bend specimen are shown in Figure 5. Stress at the bottom of the notch is concentrated (theoretical stress concentration factor K_t = 1.74 [9]). Stress due to cyclic bend-loading during the test is alternating (stress rate $R = -1$). Microstructurally small defects (micro-defects) at the bottom of the notch are prepared by drilling holes with diameter approximately 90 μm and depth 50 μm. It is obviously that the prepared holes belong to micro-defect because they are smaller than the biggest microstructural unit, i.e. average grain.

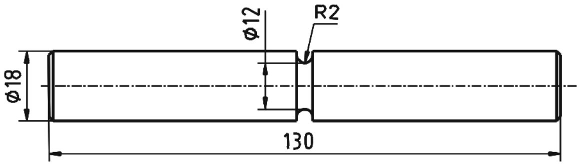


Figure 5: Rotary bending specimen

During the cyclic loading at a specified level fatigue cracks appear due to the interactive effect small hole and applied stress. The moment of crack initiation was detected, testing stopped and specimen analysed using optical and scanning microscopes.

A volume of material is plastically deformed when drilling hole. Level of generated residual stresses depends on material properties, their expansion on the volume of deformed material. The effects of those residual stresses are crucial for the fatigue crack initiation stage and early growth of micro-cracks.

A new approach to remove residual stresses was necessary in the experimental work with drilled holes. Re-crystallisation during transformation in the last stage of CGHAZ simulation using furnace seems a convenient way to remove residual stresses without significant change of defect’s geometry.

Therefore, two stress conditions of the specimen with small holes were prepared:

1. as-drilled condition, i.e. with residual stresses (drilling is executed after the complete heat treatment for CGHAZ simulation – point 2 in Figure 4)
2. residual stress-free condition, i.e. without residual stresses (drilling is executed before heating for water quenching – point 1 in Figure 4)

Results and discussion

Unification of effects of small defects, small cracks, small inclusions etc on the fatigue strength of metals was studied by Murakami and Endo more than twenty years ago [10]. They did not approach it as a notch problem. The fatigue limit of polycrystalline metals was interpreted as the condition for non-propagation of cracks emanating from defects. They introduced geometrical parameter of small defects $\sqrt{\text{area}}$ with which the transition from the non-propagating crack to the propagating crack condition is defined. It is the square root of an orthogonal projection of micro-defect to the plane of applied stress. This defect size parameter was used with great success as quantitative measure of detrimental effect of small defects to the fatigue strength of metals [11-18]. The greatest portion of published results is dealing with the effects of drilled small holes, though other kind of small defects were used, too.

Geometrical concept of area of a drilled hole is shown in Figure 6 (the shaded area). Residual stresses caused by hole-drilling of strain-hardening elastic-plastic steel are compressive in the surrounding area of the hole. It is possible that prepared hole even slightly changes shape due to elastic stress relaxation after drilling.

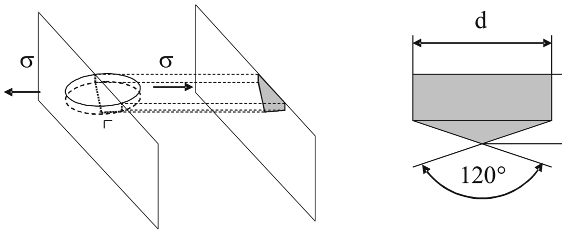


Figure 6: Orthogonal projection of the hole to the plane of applied stress

According to Murakami, fatigue limit and threshold stress intensity factor of polycrystalline metals are calculated from parameter $\sqrt{\text{area}}$ and hardness [11,12] as:

$$\sigma_w = \frac{1.43\,(\text{HV}+120)}{\left(\sqrt{\text{area}}\right)^{\frac{1}{6}}}; \qquad \Delta K_{th} = 3.3\cdot 10^{-3}\left(\text{HV}+120\right)\cdot\left(\sqrt{\text{area}}\right)^{\frac{1}{3}} \qquad (1)$$

σ_W is fatigue limit in MPa, ΔK_{th} threshold stress intensity factor in MPa $m^{1/2}$, while HV is Vickers hardness number and $\sqrt{\text{area}}$ defect's size parameter in μm. For the used holes it is equal to approximately 58 μm.

The dimensions of drilled hole used as a micro-defect in the present research are: length and depth, d and h (Fig. 6). Stress intensity at the deepest point of the outlined ellipse is lower than that at the surface [19]. Therefore, crack from drilled hole is expected to initiate at the surface. Different crack grow rate due to different stress intensity range in different directions gradually fulfils necessary crack shape condition (aspect ratio approximately 0.4).

In the material treated as continuum the highest stress concentration caused by such hole exists at the surface. This is the next reason to expect crack initiation at the surface.

In the case of polycrystalline metals with micro-defects stress intensity along the crack periphery cannot be defined. Stress/strain field depends on the orientation of grains, too. Nevertheless, crack initiation from the used micro-defect is most likely at the surfaces. Cracks will then continue its propagation and finally will comprise the whole drilled hole as schematically shown in Fig. 7.

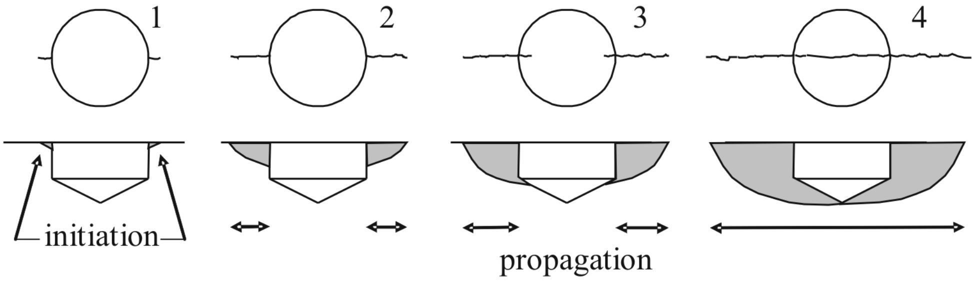


Figure 7: Four stages of crack initiation and early growth from drilled hole in the residual stress-free condition

Fatigue limit of smooth specimens with the studied simulated CGHAZ material, i.e. without drilled holes, is 751 MPa. First non-propagating cracks of size smaller or equal to grain size were perceived at the stress level 733 MPa.

Un-designedly created compressive residual stresses due to material cutting during drilling are limited to nearby surroundings of the hole. They act as an additional obstruction to crack initiation. This can be illustrated as follows:

a) Residual stress-free condition
   As shown in Fig. 8 numerous cracks initiated from the hole at the stress level of 410 MPa. All of them are at this stage non-propagating cracks because their lengths are constant during the last few million cycles.
b) As-drilled condition

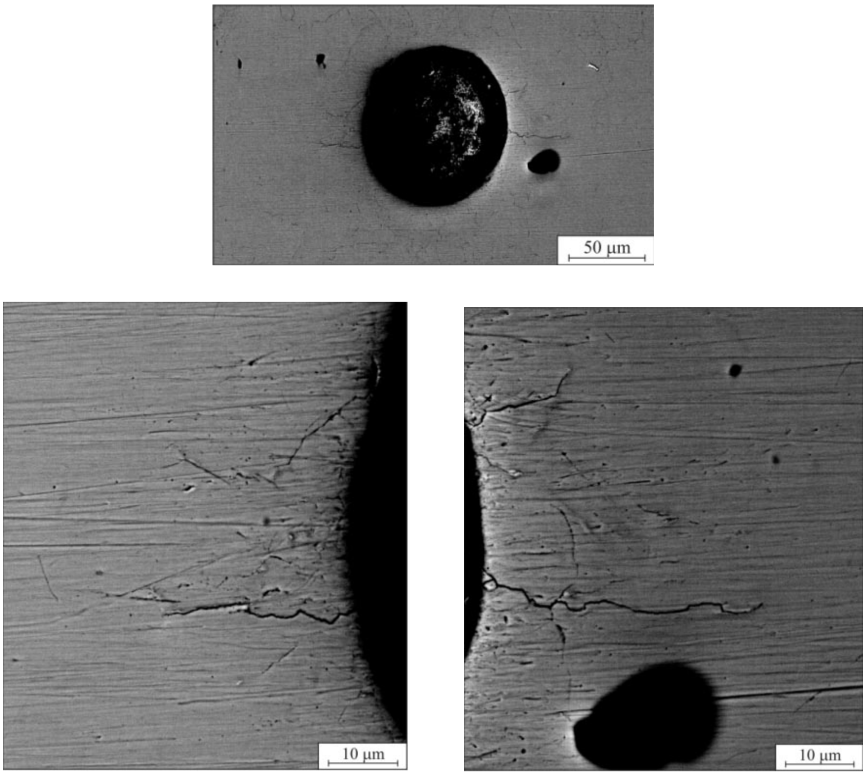


Figure 8: Non-propagating cracks initiated at the edge of the hole perpendicular to the applied cyclic stress in the residual stress-free condition

As shown in Fig. 9 only one crack initiated at each side of the hole at the stress level of 694 MPa. All of them are non-propagating cracks at this stage because their lengths are constant during the last million cycles.

If stress level is higher than 410 and 694 MPa, respectively, initiated cracks (stage 1 in Fig. 7) continue to propagate further at the specimen’s surface and towards the bottom of the hole (stages 2 and 3 in Fig. 7). The effect of cracks depends on the sum of crack lengths and lengths of the defect, d. When both cracks approach the deepest point of the hole, cracks become a single crack (stage 4 in Fig. 7). After that crack continue to propagate without influence of the hole.

Differences of crack/cracks initiation in both stress conditions illustrate the stress level, the number of initiated cracks and the mode of early crack growth:

- Stress level to perceive crack initiation in the residual stress-free condition is 400 MPa while it is 525 MPa in the as-drilled condition. The difference is 125 MPa, i.e. 25%. The compressive residual stresses nearby hole obstruct crack initiation. It is quite likely that crack in the as-drilled condition actually does not initiate just at the edge of the hole where residual stresses are the highest.
- Numerous of cracks are initiated in the same time in the residual stress-free condition. Stress/strain conditions for crack initiations are almost the same in wider zone just at the edge where stress is concentrated when obstruction does not exist.
- Crack propagation is relatively straight in the as-drilled conditions while it propagates in a zigzag in the residual stress-free condition

The reason for described crack behaviour during initiation and early crack/cracks growth are residual stresses arisen as a result of drilling. They are compressive. The highest level of those stresses exists just at the edge of the hole where cracks tend to initiated due to free surface which is the most favourable site for slip and later for crack initiation. When initiated cracks are spread far enough, they join and spread further as a single crack.

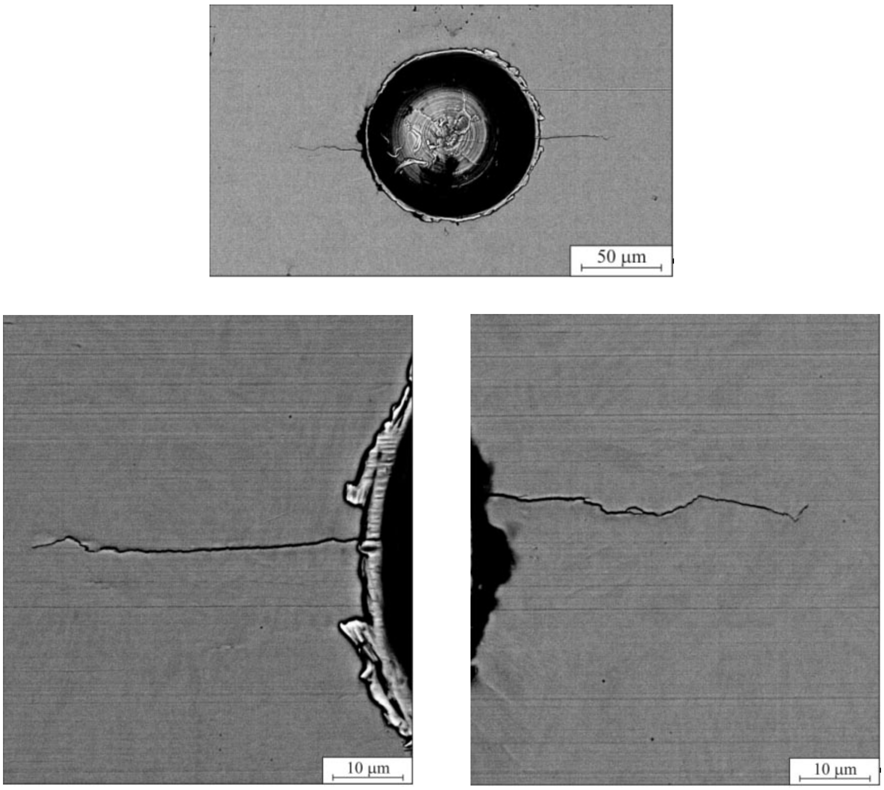


Figure 9: Non-propagating cracks initiated at the edge of the hole perpendicular to the applied cyclic stress in the as-drilled stress condition

Conclusion

Artificially defected specimens with simulated microstructure of CGHAZ were fatigue tested. Crack initiation and its early growth was followed and analysed. The effects of residual stresses caused by drilling were discussed.

Actual shape of a hole is needed to calculate defect size parameter $\sqrt{\text{area}}$ which enables assessment of the fatigue limit, σ_w, and the threshold stress intensity factor, ΔK_{th}, of materials with micro-defects.

Residual stresses in the nearest surroundings of an artificial micro-defect have decisive effect on the stress level sufficient to cause initiation of the crack from small hole. Cracks initiation depends on the residual stresses. If residual stresses exist, only one crack will initiate at the edge of the hole at higher stress level, but, if residual stresses do not exist there are more initiated cracks at 25% lower stress level.

References

1. Kitagawa H., Takahashy S.: “Applicability of fracture mechanics to very small cracks or the cracks in the early stage”, 2nd International Conference on the Behaviour of Materials, Boston, USA, 1976.
2. Miller, K. J.: “The behaviour of short fatigue cracks and their initiation, Part I and Part II”, Fatigue and Fracture of Engineering Materials and Structures, Vol. 10, No. 1, pp 75-91 and No. 2, pp 93-113, 1987.
3. Vuherer T.: Acceptance level for planar flaws in fusion welds depends on the conditions of welds due to residual stresses”, International Conference MATEST '99, Cavtat, Croatia, 1999.
4. Gliha V.: “Fatigue strength of material at the weld toe in the presence of surface macro-defects”, Proceedings of the 12th Biennial Conference on Fracture - ECF 12, Sheffield, UK, 1998.
5. Gliha V., Vuherer T., Ule B., Vojvodič-Tuma J.: “Fracture resistance of simulated areas in HSLA structural steel, Science and Technology of Welding and Joining”, Vol. 9. No. 4, pp 399-406, 2004
6. Vuherer T, Gliha V., Yasniy P., Hutsaylyuk V., Nykyforchyn H.: “Uticaj malih grešaka na zamorno čvrstočo grubozrnatog dela ZUT”, Zavarivanje i zavarene konstrukcije, No. 3, pp 112-116, 2004.
7. Vuherer T., Gliha V., Maver V., Yasniy P., Nykyforchyn H.: “Influence of small artificial defect on the fatigue strength of coarse grain heat affected zone”, Dynamics, Strength and Reliability of agricultural machines, DSR AM –I Conference, Ternopil, Ukraine, 2004.
8. Gliha V.: “The microstructure and properties of materials at the fusion line”, Metalurgija, Vol. 44, No. 1, pp. 13-18, 2005
9. Petterson R. E.: “Stress concentration factors; Charts and relations useful in making strength calculations for machine parts and structural elements”, Westinghouse Laboratories, 1974.
10. Murakami Y, Endo M.: “Quantitative evaluation of fatigue strength of metals containing various small defects or cracks”, Engineering Fracture Mechanics, Vol. 17, No. 1, pp 1-15, 1983.
11. Murakami Y, Endo M.: “Effect of hardness and crack geometries on ΔK_{th} of small cracks emanating from small defects”, The Behaviour of Short Cracks, Mechanical Engineering Publication, pp 275-294, London, 1986.
12. Murakami Y.: “Effect of small defect and inhomogeneities on fatigue strength: experiments, model and application to industry”, 11th Biennial European Conference on Fracture - ECF 11, Poitiers-Futuroscope, France, 1996.
13. Murakami Y., Nomoto T., Ueda T.: “Factors influencing the mechanism of superlong fatigue failure of steels”, Fatigue Fracture and Engineering Structure, Vol. 22, pp 581-590, 1999.
14. Murakami Y., Matsuda K.: “Cause of unsuccessful results of Miner’s rule: Behaviour of small fatigue crack growth under repeated two step loading”, Small fatigue crack: Mechanics Mechanisms and Applications, pp 119-131, Elsevier, 1999.
15. Endo E.: “Effect of small defect on the fatigue strength of steel and ductile iron under combined axial/ torsion loading”, Small fatigue crack: Mechanics Mechanisms and Applications, pp 375-387, Elsevier, 1999.
16. Endo M. and Ishimoto I.: “The fatigue strength of steels containing small holes under out-of-phase combined loading”, International Journal of Fatigue, Vol. 28, No. 5-6, pp 592-597, 2006.
17. Gliha V., Vuherer T.: “Influence of small defects made up by Vickers indentations on the fatigue strenght of steel”, 3rd International Conference Fracture Mechanics of Materials and Structural Integrity, Lviv, Ukraine, 2004.
18. Gliha V., Vuherer T.: “The behaviour of coarse grain HAZ materials with small defects during cyclic loading”, 6th International Conference on Fatigue and Fracture - NT2F6, Brdo pri Kranju, Slovenia, 2006.
19. Murakami Y.: “Stress intensity factors handbook”, Pergamon Press, 1987.