THRESHOLD OF THE STRESS INTENSITY RANGE AND THE THRESHOLD OF THE EFFECTIVE STRESS INTENSITY RANGE OF ARMCO-IRON: THE INFLUENCE OF MICROSTRUCTURE AND ENVIRONMENT

R. Pippan[1]

The influence of the grain size and cold working on threshold of fatigue crack growth was studied in ARMCO-iron (grain size 3 to 3000 μm and degree of cold working 0 to 90%). Furthermore, the effect of different oxygen pressure was studied. The role of crack tip shielding due to crack closure mechanisms and crack deflection was examined. In air the effective threshold $\Delta K_{eff\ th}$ for all the microstructures is about 2.75 MPa$\sqrt{m}$. The increase of ΔK_{th} with grain size at $R = 0.1$ is attributed to the increase of crack tip shielding due to crack closure. The influence of the environment on $\Delta K_{eff\ th}$ is not very significant.

INTRODUCTION

It is well known that the fatigue threshold and the propagation near the threshold is affected by both, the microstructure of the material and the environment. However it is not clear, how the effective threshold $\Delta K_{eff\ th}$ is influenced by the microstructure and the environment. A few experimental studies show a great dependence of $\Delta K_{eff\ th}$ on the microstructure, which can not completely be explained by the different crack geometries. Examples for such behavior in steels are described by Y. Nakai et al. [1], Yu et al. [2] and Ravichandran et al. [3] which show a variation of $\Delta K_{eff\ th}$ between 0.6–9 MPa$\sqrt{m}$. On the other hand many studies show that $\Delta K_{eff\ th}$ is not significantly influenced by the microstructure (examples for steels are presented by Beevers [4], Beatty et al.[5] and Liaw [6]). A reason for this discrepancy in the literature may be caused by the large uncertainty (Allison [7] and Pippan et al. [8]) for the determination of the crack closure stress intensity. Some investigations show that $\Delta K_{eff\ th}$ is larger than in air (for example, Döker and Peters [9] and Petit [10]) and others indicate a reduction of ΔK_{th} in vacuum ([10] and Stanzl and Ebenberger [11]). In the most cases it is not clear, whether $\Delta K_{eff\ th}$ or the

[1]Erich-Schmid-Institut für Festkörperphysik, Österreichische Akademie der Wissenschaften, A-8700 Leoben, Austria

TABLE 1: The degree of cold rolling, the recrystallization conditions and mechanical properties of different microstructures

Microstructure (grain size)	cold rolled %	$T_{recryst.}$ °C	recryst. time	$\sigma_{0.2}$ MPa	σ_{UTS} MPa
3 mm	5%	850	150^h	96	221
0.5 mm	10%	850	150^h	108	225
70 μm	75%	1000	1^h	150	280
10 μm	75%	580	1^h	240	325
3 μm[2]	90%	470	12^h	530	530
cold rolled	50%			650	655
cold rolled	75%			770	770
cold rolled	90%			780	780
cold rolled TL	75%			830	830

crack closure is changed.

The purpose of the present study is to clarify how $\Delta K_{eff\ th}$ and the crack closure are influenced by the microstructure and the vacuum conditions. To minimize the microstructural parameters which must be taken into account, we performed the experiments on a material with a simple microstructure (ARMCO-iron). The variation of both the grain size and the degree of cold working was very large to point out clearly their influence on ΔK_{th} and $\Delta K_{eff\ th}$. In order to determine $\Delta K_{eff\ th}$ with a sufficient accuracy, direct and indirect methods to study the effect of crack closure were performed.

EXPERIMENTAL PROCEDURE

ARMCO-iron (analylsis in wt.% C 0.007, Mn 0.08, P 0.015, the balance is iron) with grain size of $\approx 60\mu$m was cold rolled to plates of different thickness. To obtain different grain sizes, few of the cold rolled plates were recrystallized for different times at different temperatures as listed in table 1. The experiments were performed on CT-specimens in the LT-orientation; only one of the cold rolled microstructures was also tested in the TL-orientation. The pre-crack was produced in cyclic compression ($R = 20$), where the load amplitude corresponded to a $\Delta K_{th} \approx 12$ MPa$\sqrt{m}$ for the recrystallized specimens and to a $\Delta K_{th} \approx 20$ MPa$\sqrt{m}$ for the cold rolled specimens. About 70000 cycles were used for the production of the pre-crack with a length of about 0.4 mm measured from the notch root.

The threshold tests were performed by increasing the load amplitude in steps until ΔK_{th} is reached. This technique was proposed by Suresh [12], Pippan [13,14] and Nowack and Marissen [15]. The fatigue crack propagation tests were conducted at room temperature in air, in ultra high vacuum (total

[2]only 50% recrystallized

pressure was between $2 \cdot 10^{-8}$ and $5 \cdot 10^{-9}$ torr) and in oxygen environment at pressures between 1 and 10^{-5} torr. The load frequency in air was 150 Hz and in vacuum 70 Hz. The crack tip strain technique was performed to detect the closure of the crack. The crack length was measured with a travelling microscope, and in the case of very short extension of the crack with a stationary optical microscope.

RESULTS AND DISCUSSION

Figs. 1–4 show the typical results of crack growth tests, where the load amplitude was increased in steps.

- Below a certain load amplitude we observed no extension of the crack (more precisely Δa was after 10^7 cycles below the detection limit, about 2μm). Since the pre-crack was produced in cyclic compression at the beginning of the fatigue crack growth test the crack should not close in tension [12,13,14]. Therefore, these ΔK values are below $\Delta K_{eff\ th}$ [14].
- At higher load amplitudes ($\Delta K > \Delta K_{eff\ th}$) the crack starts to grow. When crack closure occurs, the growth rate decreases and when ΔK is smaller than ΔK_{th}, growth stops after a certain extension of the crack.
- With the load amplitude, which correspond to a ΔK value greater than ΔK_{th}, the whole da/dN vs. ΔK curve can be measured.

With other words, $\Delta K_{eff\ th}$ should be between the last load step where no extension of the crack is observed and the first step where an increase of the crack occurs, and ΔK_{th} lies between the load steps where the last arrest of the crack and where no arrest occurs. From such a test it is easy to estimate the influence of crack closure effect [14]. It should be noted that these $\Delta K_{eff\ th}$ values agree with the measured $\Delta K_{eff\ th}$ values (K_{max}–K_{cl} at the threshold), if we take into account the inaccuracy of the used closure measurement technique (crack tip strain technique).

The results of the different tests are summarized in Figs. 5 and 6. Fig. 5 shows the influence of the grain size on ΔK_{th} and $\Delta K_{eff\ th}$. One can see that $\Delta K_{eff\ th}$ is not affected by the grain size. At the $R = 0.7$ tests in the fine grain material the influence of the crack closure is insignificant, therefore is $\Delta K_{eff\ th} = \Delta K_{th}$. In the coarse grain material sliding contacts and "hooks" [8] cause an increase of the ΔK_{th} values at $R = 0.7$. The increase of ΔK_{th} with the grain size in the fine grain material is mainly caused by the roughness induced crack closure, which seems to be controlled by the increase of the mean deflection length. This was also observed by Wasen et al. [16]. In the coarse grain material "hooks" and sliding contacts increase the effect of crack closure. Fig. 2 shows the crack growth results of the $R = 0.7$ tests of the different cold rolled specimen. In this case the effect of crack closure is also insignificant.

This ΔK_{th} value ($=\Delta K_{eff\ th}$) is independent of the degree of cold rolling and is equal to the $\Delta K_{eff\ th}$ value of the recrystallized specimens.

This result was surprising, because a great difference between the crack profiles of the cold rolled and recrystallized specimens was observed (see Fig. 7). This difference should cause a different shielding of the crack tip (Ritchie [17]) due to deflection. However it seems that this effect is not significant.

Fig. 6 presents the influence of the vacuum conditions on ΔK_{th} and $\Delta K_{eff\ th}$. $\Delta K_{eff\ th}$ is not significantly affected by the environment, only at $p = 10^{-5}$ torr O_2 and in ultra high vacuum $\Delta K_{eff\ th}$ is somewhat larger than in air. The ΔK_{th} value in ultra high vacuum is a bit smaller than in air, which is caused by a decrease of the crack closure effect. But it should be noted that this is not only caused by the disappearence of the oxid closure. The roughness of the fracture surface in vacuum is smaller than in air, therefore the roughness induced closure should also decrease.

CONCLUSION

In air the effective threshold $\Delta K_{eff\ th}$ for all the investigated grain sizes and the different cold rolled conditions was about 2.75 MPa$\sqrt{m}$. The increase of ΔK_{th} with grain size is caused by an increase of the crack closure effect (in the fine grain material by the roughness induced closure and in the coarse grain material additional by hooks and sliding contacts). The influence of the environment on $\Delta K_{eff\ th}$ is not very significant. However, the crack growth rate is affected by the vacuum condition especially near ΔK_{th} (see Fig. 4).

REFERENCES

[1] Nakai, Y., Tanaka, K. and Nakanishi, *Engng. Fracture Mech.*, **Vol.15**, 1981, pp.291–302.

[2] Yu, W., Esaklul, K. and Gerberich, W. W., *Metall. Trans.*, **Vol.15A**, 1984, pp.889–900.

[3] Ravichandran, K. S., Rao, V. H. C., Dwarakadasa, E. S. and Krishnadas Nair, C. G., *Metall. Trans.*, **Vol.18A**, 1987, 865–876.

[4] Beevers, C. J., *"Some Aspects of the Influence of Microstructure and Environment on ΔK Thresholds"*, Proc. "Fatigue Threshold", Edited by J. Bäcklund et al., **EMAS**, Warley, UK, 1981, pp.257–276.

[5] Beatty, J. H., Shiflet, G. J. und Jata K. V., *Metall. Trans.*, **Vol.19A**, 1988, pp.973–986.

[6] Liaw, P. K., *Acta metall.*, **Vol.33**, 1985, pp.1489–1502.

[7] Allison, J.E., *"The Measurement of Crack Closure During Fatigue Crack Growth"*, Proc. "Fracture Mechanics: 18th Symp.", Edited by D. T. Read and R. P. Reed, **ASTM STP 945**, 1988, pp.913–933.

[8] Pippan, R., Haas, G. and Stüwe, H. P., *Engng. Fracture Mech.*, **Vol.34**, 1989, pp. 1074–1084.

[9] Döker, H. and Peters, M., *"Fatigue Threshold Dependence on Material, Environment and Microstructure"*, Edited by C. J. Beevers, **EMAS**, Warley, UK, 1984, p.275.

[10] Petit, J., *"Some Aspects of Near-Threshold Crack Growth: Microstructure and Environment Effects"*, Proc. "Fatigue Crack Growth Threshold Concepts", Edited by D. L. Davidson and S. Suresh, **AIME**, Warrendale, PL, 1984, pp.3–42.

[11] Stanzl, S. E. and Ebenberger, H. M., *"Concepts of Fatigue Crack Growth Threshold Gained by the Ultrasound Method"*, Proc. "Fatigue Crack Growth Threshold Concepts", Edited by D. L. Davidson and S. Suresh, **AIME**, Warrendale, PL, 1984, pp.399–416.

[12] Suresh, S., *Engng. Fracture Mech.*, **Vol.21**, 1985, pp.453–463.

[13] Pippan, R., *Fatigue Fract. Eng. Mater. Struct.*, **Vol.9**, 1987, pp.319–328.

[14] Pippan, R., *"Threshold and Crack-Growth Tests on Pre-Cracked Specimens Produced in Cyclic Compression"*, Proc. "Fatigue 87", Edited by R. O. Ritchie and E. A. Starke, **EMAS**, Warley, UK, 1987, pp.933–940.

[15] Nowack, H. and Marissen, R., *"Fatigue Crack Progagation of Short and..."*,Proc. "Fatigue 87", Edited by R. O. Ritchie and E. A. Starke, **EMAS**, Warley, UK, 1987, pp.207–230.

[16] Wasen, J., Hamberg, K. and Karlsson, B., *Materials Science and Engineering*, **Vol.102**, 1988, pp.217–226.

[17] Ritchie, R. O., *Materials Science and Engineering*, **Vol.103**, 1988, pp.15–28.

---

[1]This work was supported by the "Fonds zur Förderung der wissenschaftlichen Forschung" Projekt P6675.

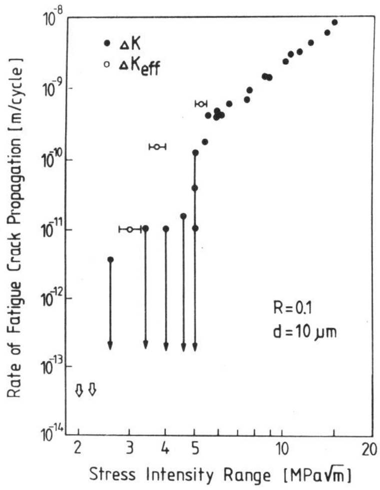

Figure 1: Fatigue crack growth behavior in air, grain size 10 μm

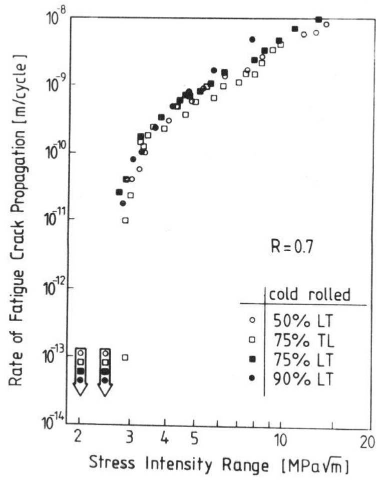

Figure 2: Fatigue crack growth behavior of different cold rolled specimens in air

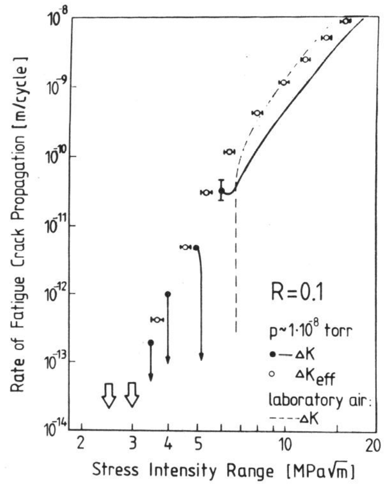

Figure 3: Fatigue crack growth behavior in ultra high vacuum, grain size 70 μm

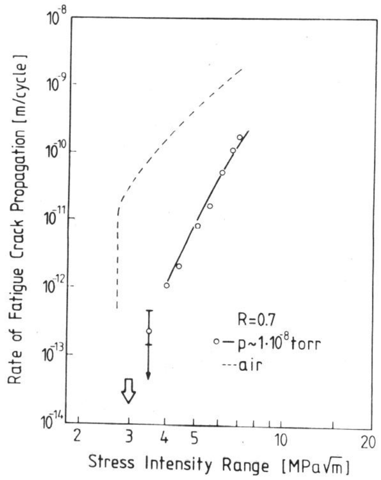

Figure 4: Fatigue crack growth behavior in ultra high vacuum and air, grain size 70 μm

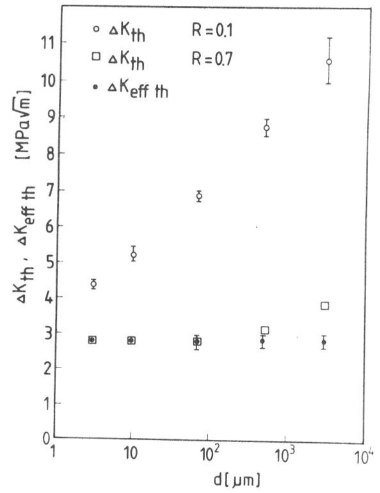

Figure 5: Threshold and effective threshold as a function of the grain size in air

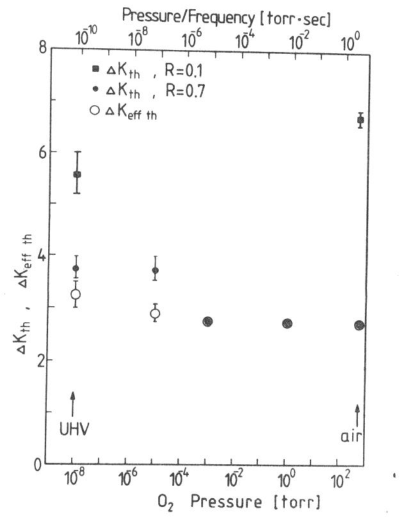

Figure 6: Threshold and effective threshold as a function of O_2 pressure

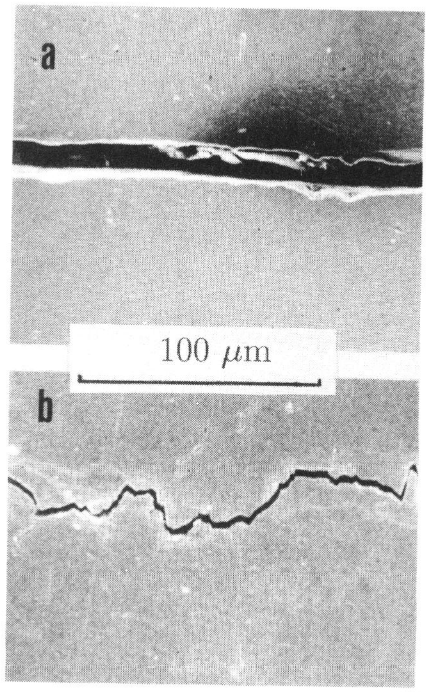

Figure 7: Comparison of crack profiles (a) in cold rolled (90%) and (b) recrystallized specimens, grain size 10 μm