Simulation of microcrack growth under multiaxial random loading and comparison with experimental results

A. Ahmadi & H. Zenner
Institute for Plant Engineering and Fatigue Analysis,
University of Technology, Clausthal-Zellerfeld, Germany

Abstract

In this paper a model designed to simulate the growth of microcracks under the influence of cyclic loading is presented. Considering fatigue crack growth microstructural barriers as well as the state of stress play an essential role. The crack growth is initially dominated by shear stresses leading to microstructurally short cracks (stage I). As the tip of the microcrack approaches a grain boundary the crack growth rate decreases. The transition from stage I to stage II crack growth is also considered in the model as the crack reaches a specific length and continues to grow under the influence of maximum normal stresses (physically short cracks). The comparison of the simulation results to experimental results of variable amplitude loading for bending, torsion, multiaxial proportional loading and multiaxial non-correlated loading applied to notched specimens of 42CrMo4V reveals a close match with the experimental results.

1 Introduction

The accuracy of life prediction under repetitive loading is still unsatisfactory. Inadequate predictions appear particularly when the loading sequence involves effects with High-Low/Low-High changes, overloads or mixture and changing of mean stresses. If these loading effects are combined with multiaxial stress states, most life prediction concepts fail. To improve the accuracy of lifetime predictions, the algorithm applied for a lifetime calculation has to take into account the microstructural damage process. A microcrack simulation model

Transactions on Engineering Sciences vol 40, © 2003 WIT Press, www.witpress.com, ISSN 1743-3533

bears the opportunity to verify the current hypotheses of the micro structural crack growth mechanism in comparison to experimental results [1-3]. Furthermore, it is possible to study the influencing parameter, such as grain size and orientation, or the influence of multiaxial loading or variable load sequences. As a result, an improvement of lifetime prediction should be possible.

In the following paper a simulation model which describes the microcrack growth is introduced.

2 Simulation

The programm μCrack^{sim} Version 1.0 designed with Visualbasic 6.0, Visual C^{++} and Delphi can be operated with Windows and was developed to simulate the damage process caused by microcrack growth. Our first aim was to predict the microcrack distribution as a function of their orientation as well as the simulated crack growth behaviour up to the final crack length of 500μm during a fatigue test. Therefore, for the verification with experimental data adequate parameter identification is necessary [4].

2.1 Model concept and microcrack simulation

The model must be capable to describe micro crack growth in metallic materials subjected to cyclic loading. The polycrystalline material is modeled as a structure of two-dimensional hexagonal elements. The program μCrack^{sim} offers to simulate also the possibility irregular grains up to real crystalline structures. Individual slip systems are active in each grain with a randomized crystallographic orientation ω.

The stress state in the slip plane of each grain is dependent on its orientation and the externally applied loading. Only the material surface with its plane stress state is considered. The locations of the microcrack nucleation are determined by a random generator. The shape of the microcrack seed is a point with no spatial extension, denoting an initial crack length of zero. It is assumed that the points of crack nucleation are given at the beginning of the simulation and that the crack growth starts with the first load cycle.

The growth of microstructurally short cracks (MSC, stage I) is simulated starting from the points of microcrack nucleation using the equations for crack growth rate developed by Miller [5]. Further assumptions consider the additional effect of the normal stress on the shear crack stage I as well as the coalescence of neighbouring microcracks. Finally after a specific crack length has been attained a diversion of the crack takes place from stage I to Stage II – physically small cracks (PSC). The initiating cause for crack growth is the stress state in the direction of the appropriate slip plane. The shear stress in individual slip plane directions ω is calculated for the plane stress state by using the equation

$$\tau_\omega = \frac{\sigma_x - \sigma_y}{2}\sin(2\omega) + \tau_{xy}\cos(2\omega) \qquad (1)$$

Transactions on Engineering Sciences vol 40, © 2003 WIT Press, www.witpress.com, ISSN 1743-3533

It is assumed, that the microcrack growth can be divided into the phases of stage I and stage II crack growth. During the stage-I crack growth, the cracks are driven by the cyclic shear stress with occur in the slip planes of the polycrystalline material. The crack growth rate depends on the magnitude of shear stress amplitude and on the distance (d-a) between the crack tips and the dominant microstructural barriers, in this case the grain boundary. The microcrack growth equation is

$$\left(\frac{da}{dN}\right)_{\omega} = A\left(\Delta\tau_{\omega}\right)^{\alpha} \cdot \left(d - a\right) \qquad \mu\text{m / cycle} \tag{2}$$

where $\Delta\tau_{\omega}$ is the shear stress amplitude, d is the grain size and a the length of the microcrack. (d-a) is the crack tip distance to the next barrier, and A and a are material parameters. This relationship states that the crack growth rate decreases with increasing crack length (decreasing distance between crack tip and barrier). Equation 2 assumes that the shear cracks propagate (stage I). In the current model the grain boundary is regarded to be the dominant material barrier. When the stage I-crack is sufficiently long to permit an opening of the crack front, the development of stage II (tensile) crack occurs. At this point, the influence of the microstructure is limited, and crack growth can be described by continuum mechanics. The equation of stage II crack growth proposed by Hobson, Brown and de los Rios [6] can be described by the following equation:

$$\left(\frac{da}{dN}\right)_{\omega} = B\left(\Delta\sigma_{\omega}\right)^{\beta} a^{\chi} - C \qquad \mu\text{m / cycle} \tag{3}$$

where $\Delta\sigma_{\omega}$ represents the tensile stress perpendicular to the crack plane, and β, χ, B and C are experimentally determined material parameters. Taylor and Knott [7] suggest a value of about three grain diameters for the transition. In the transition zone the crack growth is calculated by using the higher value between equation 2 and equation 3.

In addition to this continuous crack growth there is a sudden discontinuous crack growth through crack coalescence. The crack coalescence is described by assuming that the linking of cracks appears when the length of the cracks reaches 75 percent of the grain size, and the distance r between their tips is less then a critical distance r_c. Socie and Furman [8] proposed a critical distance of 25 percent of the grain diameter.

The simulation ends when the a predetermined number of load cycles is reached, or the microcrack reaches the predetermined crack length. The crack length is defined by the direct line between both crack tips. If a crack was formed by linking of several microcracks, the crack length is always represented by the crack tips with the longest distance. In the following simulations the final crack length is 500μm.

Transactions on Engineering Sciences vol 40, © 2003 WIT Press, www.witpress.com, ISSN 1743-3533

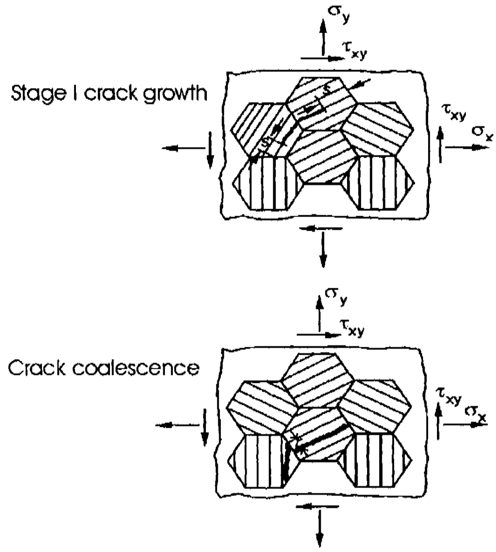

Figure 1: Microstructure, stress state and crack growth of simulation.

The simulation does not yet consider the crack growth in the depth direction of the material. Furthermore, the deformation behavior of microstructure, the cyclic hardening and softening of the material and the crack opening effects have to be taken into account in further improvement steps.

2.2 The parameter identification tool in μCrack^{sim}

The parameter identification tool is capable of identifying material parameters for the simulation of microcracks to predict the number of cycles to failure (final crack length of a_i=500μm). As a result of the parameter identification the simulated S-N curves performed for uniaxial loading show a close match with the experimental results [4].

In the case of multiaxial loading material parameters must be determined for tension/compression loading as well as for torsional loading. A successful identification of parameters allow for a good comparability between the simulations and the experiments.

The cyclic material parameters, uniaxial S-N curve data of the investigated material and synthetic S-N curve data applied by using artificial neural networks (ANN) [9] can be used as entry data for the identification tool.

3 Comparison between simulation and experimental results

Experiments were carried out with notched specimens of 42CrMo4V (743 MPa yield stress, 920 MPa tensile stress) under combined bending, torsion, proportional and non-proportional (non-correlated) loading. A Gauss-standard

Transactions on Engineering Sciences vol 40, © 2003 WIT Press, www.witpress.com, ISSN 1743-3533

load spectrum (normal distribution) [10] with the irregularity factor I=0.99 and a sequence length of $H_0=1\cdot 10^6$ cycles was used for the fatigue tests [11-12]. In the following a comparison between the results of the load-controlled tests and the simulated fatigue life will be shown. The failure criterion was defined to be the failure of the specimens and the crack initiation.

3.1 Results of uniaxial random loading

Figure 2 shows an example of the simulated crack growth behaviour for variable amplitude loading. The microcracks occur in the maximum shear stress direction and change their growth direction at a specific size in the direction perpendicular to the surface of the material, as it can be seen in the experiments. The simulated crack length a [μm] versus the number of load cycles is plotted in Figure 2.

Generally the microstructural damage is not a linear process, in the case of crack coalescence (joining of closely neighboring cracks) it can even be unsteady.

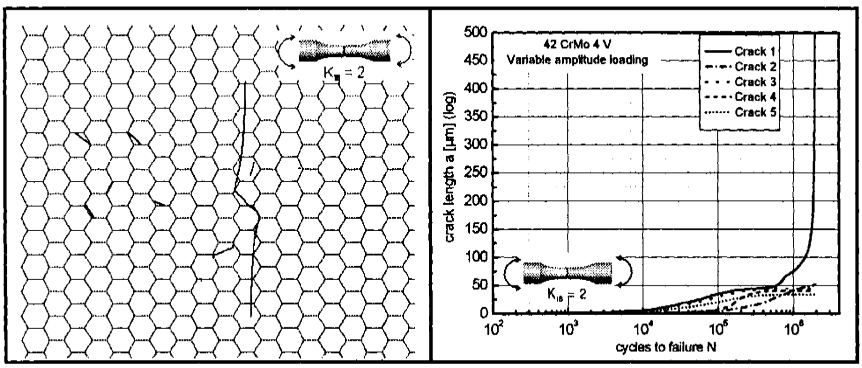

Figure 2: Simulated crack growth for variable amplitude loading, bending, s_a=650 MPa, grain size d=60 μm.

The determination of the effective damage sums is given by the following equation evaluated by [13]:

$$D_{eff} = \frac{N_{experiment,50\%}}{N_{simulation,50\%}} \tag{4}$$

The scatter band T (log. normal distribution) were determined:

$$T_D = \frac{D_{90\%}}{D_{10\%}} \tag{5}$$

According to eqn(4) the effective damage sum for bending is $D_{eff,b}$=0.96 with a scatter band of $T_{D,b}$=1.9, for torsion the effective damage sum is $D_{eff,t}$=0.57 with a scatter band of $T_{D,t}$=3.3. Figures 3 and 4 show the simulated fatigue-life curves obtained under uniaxial random bending and uniaxial random torsion. The nominal stress amplitude presented is the maximum value of the spectrum.

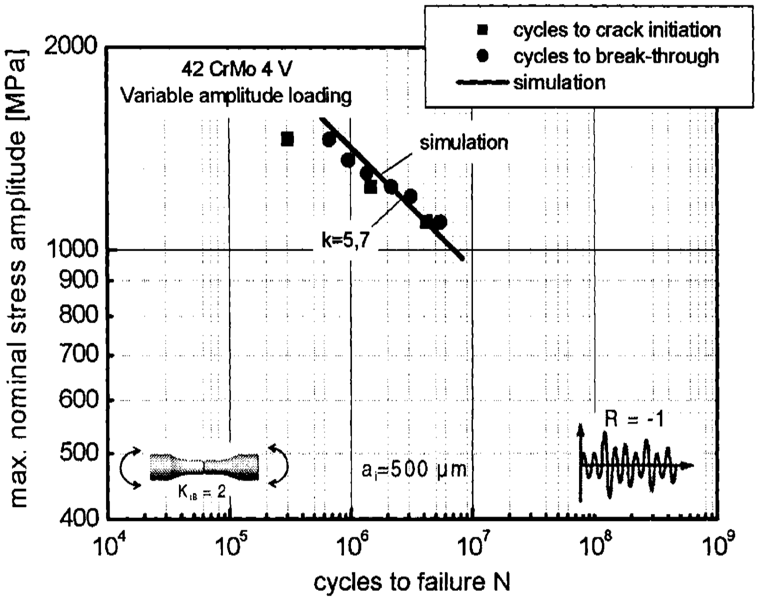

Figure 3: Fatigue test results under pure bending, simulation and experiment.

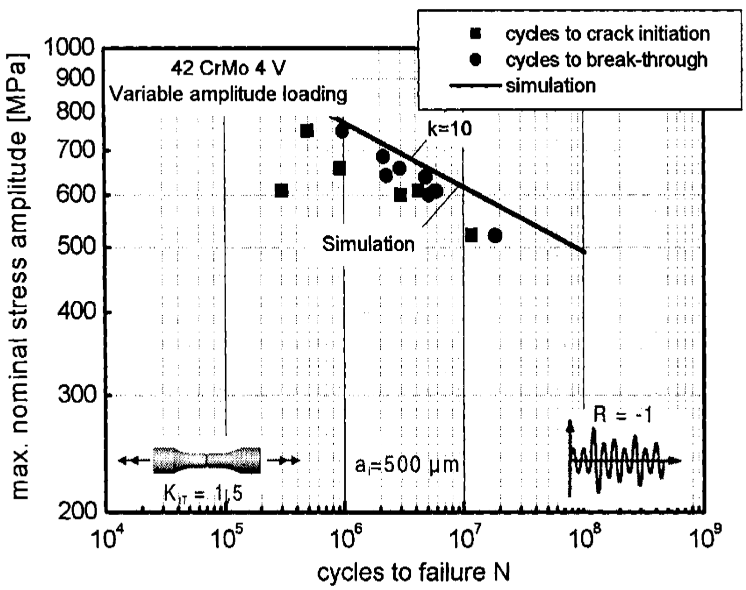

Figure 4: Fatigue test results under pure torsion, simulation and experiment.

Transactions on Engineering Sciences vol 40, © 2003 WIT Press, www.witpress.com, ISSN 1743-3533

3.2 Results of multiaxial random loading

Figure 5 shows the results of the simulation at R=-1 for combined bending and torsion with $\delta=0°$ (proportional loading).

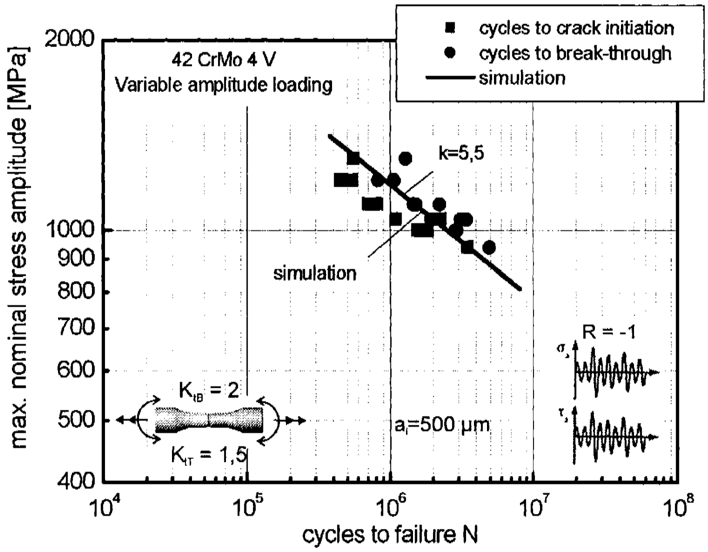

Figure 5: Fatigue test results under combined variable amplitude loading (proportional loading), simulation and experiment.

In the case of proportional loading the effective damage sum is $D_{eff,prop}=1.18$ with a scatter band of $T_{D,prop}=2.6$. The load amplitude ratio is $\tau_a/\sigma_a=0.5$ for a given number of endurable load cycles. The comparison with the test results for proportional random loading confirms the results of the simulation.

The effective damage sum for a non-correlated random loading is $D_{eff,non}=0.34$ with a scatter band of $T_{D,non}=6.4$. Compared to the experimental data for a non-correlated multiaxial loading and a load ratio of $\tau_a/\sigma_a=0.5$ leads to an increase of the fatigue life in the microcrack simulation. The simulated fatigue life for a non-correlated loading is given in Figure 6. The simulated results correspond to a large extent with the experimental data.

For the prediction of fatigue life in the case of multiaxial stress, a number of hypotheses depending on the type of material and failure mechanism have been developed. They can be subdivided into integral multiaxial damage hypothesis (IMSH) and critical plane damage hypothesis (CPSH) [14,11,12,15]. The results of the fatigue life estimation for pure bending, pure torsion and combined bending and torsion with $\delta=0°$ show that the IMSH, CPSH and the microcrack simulation concept predict similar results achieved in the experiments. For the uncorrelated load case all concepts lead to an overestimation of the fatigue life.

Transactions on Engineering Sciences vol 40, © 2003 WIT Press, www.witpress.com, ISSN 1743-3533

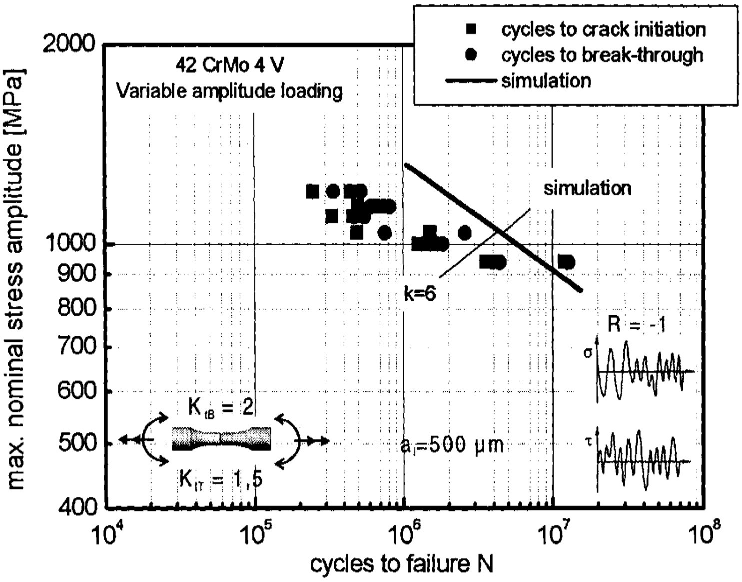

Figure 6: Fatigue test results under non-correlated loading (non-proportional loading), simulation and experiment.

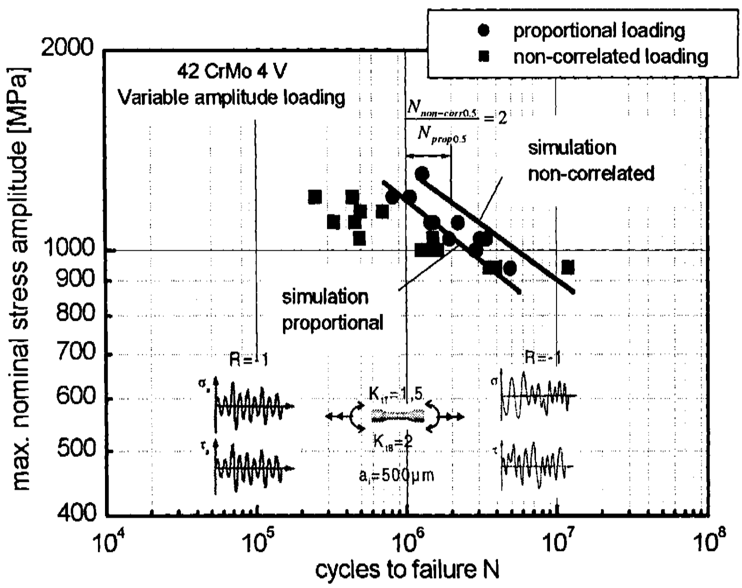

Figure 7: Fatigue test results of variable amplitude loading, proportional and non-correlated, simulation and experiment.

Figure 7 shows a comparison of experimentally determined and simulated results for tests with proportional and non-correlated loads. The non-correlated

Transactions on Engineering Sciences vol 40, © 2003 WIT Press, www.witpress.com, ISSN 1743-3533

tests with a load ratio of τ_a/σ_a=0.5 lead to a reduced lifetime compared with the proportional loading. A significantly increased lifetime (factor of 2 compared with proportional loads) was found in the simulation under non-correlated loads. This is due to the rotating principal stress direction during one load cycles in case of the uncorrelated load case. As a result, initial crack growth takes place in the simulation in every grain containing a crack seed. On the other hand, the effective shear stress amplitude τ_ω in the slip planes is reduced compared to the in phase loading. In addition to that, the normal- and shear stress cycles in a specific slip direction do not appear at the same time. As a result, a microcrack experiences two stress cycles during one load cycle. The results of the simulation for all test series are plotted in Figure 8 and compared with the experimental data.

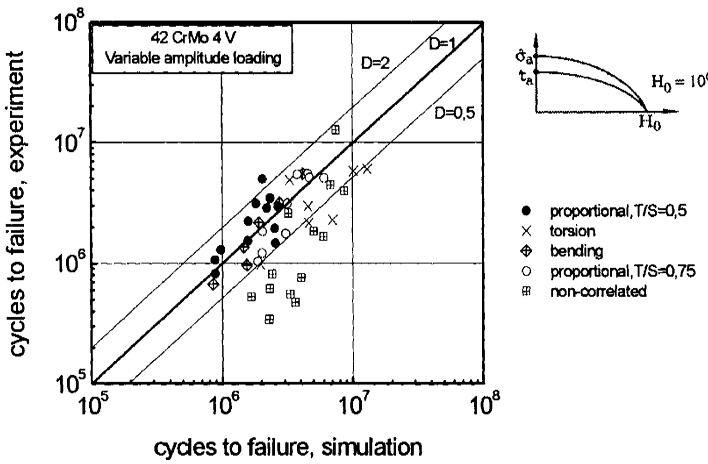

Figure 8: Comparison of fatigue test results of variable amplitude loading, simulation and experiment.

The effective damage sum D_{eff} for pure bending, torsion and proportional loading is D_{eff}=0.86 with a scatter band of T_D=2.2. For all test series is the damage sum D_{eff}=0.71 with a scatter range of T_D=3.6. A comparison between test results and the simulation shows a qualitatively good agreement in the case of variable amplitude loading.

4 Conclusions

A two dimensional microcrack simulation model is presented. The model takes into account the rate and direction of microcrack growth, the interaction between the crack and the material barriers, as well as the crack coalescence. A useful feature of the model is the ability to determine the material parameters for the simulation of microcracks and to qualitatively predict the results of experimental tests subjected to multiaxial random loading with a reasonable accuracy. In the future the development of the program is focused on a simulation of the uncorrelated load case.

Acknowledgements

The Authors would like to thank the German Research Council "Deutsche Forschungsgemeinschaft DFG" for the financial support of the research program.

References

[1] Zenner, H., Pötter, K., Schram, A & Suhartono, H.A., *Simulation of fatigue microcrack growth*, Part 1 and Part 2, Mat.-wiss. U. Werkstofftech. 32/33, 2001-2002.

[2] Ahmadi, A., Zenner, H., Düwel, V. & Schram, A., *Microcrack initiation and microcrack growth in Aluminium alloys subjected to cyclic loading*, Mat.-wiss. U. Werkstofftech. 33, pp. 265-274, 2002.

[3] Ahmadi, A. & Zenner, H., *Simulation of microcrack propagation for different load sequences*, Fatigue 2002, Eighth International Fatigue Congress, Stockholm, Sweden, eds. EMAS, pp. 1997–2004, 2002.

[4] Ahmadi, A. & Zenner, H., *Erstellung eines Parameteridentifikation-Tools zur Simulation des Mikrorisswachstums bei zyklischer Beanspruchung*, Carl Hanser Verlag, MP Materialprüfung, accepted January 2003.

[5] Miller, K. J., *Metal-Fatigue – Past, Current and Future*, Proceedings of the Institution of Mechanical Engineers, 1991.

[6] Hobson, P. D., M. W. Brown & E. R. de los Rios., "Two Phases of Short Crack Growth in Medium Carbon Steel", *The Behaviour of Short Fatigue Cracks*, EGF Pub. 1, K. J. Miller and E. R. de los Rios, Ed., London, pp. 441-459, 1986.

[7] Taylor, D. & Knott, J. F., *Fatigue Crack Propagation Behaviour of Short cracks*, The Effect of Microstructure, Fatigue Fracture Engineering Materials Structures 4, pp. 147. 1981.

[8] Socie, D. & Furman, S., *Fatigue Damage Simulation Models for Multiaxial Loading*, Fatigue 96, Sixth International Fatigue Congress, G. Lütjering and H. Nowack, Ed., Berlin, Germany, pp. 967-976., 1996.

[9] Zenner, H., Bukowski, L., Karkula, M. & Marquardt, C., *Lifetime perdiction with the application of artificial neural networks*, Fatigue 2002, Eighth International Fatigue Congress, Stockholm, Sweden, eds. EMAS, pp. 2697–2704, 2002.

[10] Haibach, E., Fischer, R., Schütz, W, & Hück, M., *A standard random load sequence of Gaussian type recommended for general application in fatigue testing*, In: Bathgae RG, edt. Fatigue testing and design, 1976:29.1-21.

[11] Esderts, A., Pötter, K. & Zenner, H., *Fatigue of smooth and notched specimens under multiaxial random loading – experimental results and prediction*, ICB5MF&F, Fifth International Conference on

Transactions on Engineering Sciences vol 40, © 2003 WIT Press, www.witpress.com, ISSN 1743-3533

Biaxial/Multiaxial Fatigue and Fracture, Cracow, Poland, eds. ESIS, pp. 609–620, 1997.

[12] Pötter, K., *Lebensdauerabschätzung ein- und mehrachsig schwingend beanspruchter Bauteile*, Dissertation, TU Clausthal, Clausthal-Zellerfeld, Germany, 2000.

[13] Haibach, E., *Betriebsfestigkeit*, VDI-Verlag, Düsseldorf, 1989.

[14] Esderts, A., *Betriebsfestigkeit bei mehrachsiger Biege- und Torsionsbeanspruchung*, Dissertation, TU Clausthal, Clausthal-Zellerfeld, Germany, 1995.

[15] Pötter, K., Yousefi, F. & Zenner, H., *Experiences with Lifetime Prediction Under Multiaxial Random Loading,* In: Multiaxial Fatigue and Deformation: Testing and Perdiction, ASTM STP 1387 (Edited by Sreeramesh Kalluri and Peter J. Bonacuse), eds. American Society for Testing and Materials, Seattle, WA, pp. 157-172.

Transactions on Engineering Sciences vol 40, © 2003 WIT Press, www.witpress.com, ISSN 1743-3533