HIGH CYCLE FATIGUE AND THRESHOLD BEHAVIOUR OF POLYCRYSTALLINE COPPER

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ABSTRACT

Specimens of polycrystalline recrystallized copper in various conditions (purity, grain size, oxygen contamination) were selected in order to study the fatigue behaviour in the range of high numbers of loading cycles ($10^6 < N < 10^{10}$). A high frequency resonance tension-compression test method was used which permitted cyclic loading from $\varepsilon_t = 1 \times 10^{-4}$ up to $\varepsilon_t = 10 \times 10^{-4}$ (test conditions: room temperature, 20 kHz, ε_t = const., R = -1). Fatigue failure, PSB-accumulation, crack initiation, and slow crack growth near threshold was investigated to provide supporting information on the existence of a fatigue limit in fcc copper. A statistical evaluation of the fatigue data reveals the existence of threshold stress values for fatigue failure (58 MPa < σ_f < 88 MPa, depending on material condition) and for PSB-formation (38 MPa < σ_{PSB} < 44 MPa). The ratio of these values is strongly affected by the grain size. The threshold stress intensity value ΔK_{th} determined at the same test frequency indicates that the microcracks observed in specimens cycled below the stress fatigue limit are non-propagating cracks.

KEYWORDS

Endurance limit; fatigue microcrack initiation; fatigue limit; persistent slip band formation; fatigue microcrack propagation; fatigue failure; high cycle fatigue; fatigue threshold stress; statistical evaluation.

INTRODUCTION

The existence of a fatigue limit, defined as the stress amplitude below which failure never occurs in smooth specimens is well established for bcc metals. The evidence of the occurrence of such a fatigue limit in fcc metals is still a matter of controversy.

Based on literature data of polycrystalline Cu (Lukas and others, 1974) and in particular based on unpublished results of Cu-single crystals by Mughrabi (1978), Laird (1976) inferred the existence of a fatigue limit in fcc metals. A well defined fatigue limit of Cu-single crystals is equated with a threshold value of the plastic strain amplitude below which no persistent slip bands (PSBs) are formed. Similarly, experiments with polycrystalline Cu revealed the existence of a threshold of the plastic strain amplitude, "below which fatigue failure did not occur, either not at all or not up to 10^7 cycles" (Lukas and others, 1974). In view of the close similarity of these threshold values it has been concluded by Laird(1976) and Mughrabi (1978) that the formation of PSBs is the governing factor for the occurrence of a fatigue limit in polycrystalline metals and alloys. However, to our knowledge there exists a lack of sufficient systematic data to provide experimental support for this assumption. Notable are experimental findings of Hempel (1967) that in Al and stainless steel PSBs and even microcracks are formed well below the endurance limit.

Under the assumption that the fatigue limit exists in fcc metals it may be speculated that such a fatigue limit is not characterized by a pronounced inflection in the S-N curve as exhibited by the bcc metals. In fcc metals the fatigue limit may be approached assymptotically at high N, say $N > 10^8$. In most published investigations, the tests only rarely exceeded 10^7 cycles and even then remained limited to a small number of specimens. This may be one of the reasons why a fatigue limit has not been identified unambiguously for fcc metals. Only a few publications by Anderson and others (1941, 1946) and Awatani and others (1975) contain data of extended fatigue cycling ($N > 10^9$).

The objective of the present investigation was to perform fatigue experiments in the low stress amplitude regime with a fatigue exposure between $10^6 < N < 10^{10}$. For a statistical evaluation of the test results a sufficiently large number of specimens should be examined. In particular, the formation of PSBs in the stress range below the S-N curve and the effects of trace elements, microstructure and annealing treatments were to be determined. Measurements of the slow crack growth near threshold should provide additional information on the contribution of microcracks to the phenomena of the fatigue limit.

EXPERIMENTAL PROCEDURES

A summary of chemical composition, microstructure, annealing treatments and mechanical properties of the material investigated is given in Table 1.

TABLE 1 Composition, Heat Treatment and Mechanical Properties of Specimen Material

Material Condition	Purity wt.%	Heat Treatment	Average Grain Size, μm	Yield Stress, MPa	Dynamic Young's Modulus in MPa recrystallized/	cycl. hardened (ε_t=5x10^{-4}, N= 10^7)
I	99,98[a)]	650°C/4h in vac. (p=2,7x10^{-3}Pa)	20-30	27	130 200	126 400
II	99,98[a)]	650°C/2,5h vac. (p=2,7x10^{-3}Pa + 1,5h at p=5,3x10^{-2}Pa,O_2)	20-30	27	130 200	126 400
III	99,98[a)]	1000°C/2 h in vac. (p=2,7x10^{-3}Pa)	200-300[c)] 2000	17	142 000	137 900
IV	99,999[b)]	650°C/4h in vac. (p=2,7x10^{-3}Pa)	150-200	19	130 400	126 600

a) trace impurities in ppm: 14 O_2, 32 Ag, 35 S, 10 Pb, 12 Ni, 8 Fe, 9 Zn
b) trace impurities in ppm: 2 Si, 1 Ag, < 1 Cd, < 1 Fe, < 1 Mg
c) duplex structure, equal amount of fine and coarse grains

The specimen dimensions and geometries are shown in Fig. 1.

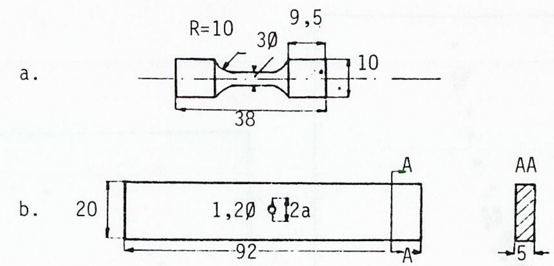

Fig. 1 Specimen geometry (dimensions in mm)
a. dumbbell specimen for fatigue test
b. center-notched specimen for crack growth measurements

Dumbbell shaped specimens were used for the determination of S-N curves. For the measurements of the fatigue crack growth bar-shaped center-notched specimens were prepared from the same material. After machining all specimens were electropolished in the gauge section using a (H_3PO_4-H_2O)-electrolyte.

All fatigue experiments were carried out at ambient temperature. A 20 kHz resonance testing equipment was used to excite the specimens to longitudinal push-pull vibrations under zero mean load (R = -1) as described previously by Weiss and others (1976). Under these particular experimental conditions the specimens are subjected to cyclic loading under controlled total strain (ε_t=const.; $1\times10^{-4} < \varepsilon_t < 10\times10^{-4}$). However, due to the peculiarities of the resonance system a ramp of approximately 10^5 cycles was necessary to reach the preselected strain amplitude. For the small ε_t-values applied during this investigation the plastic strain ε_p can be assumed not to exceed several percent of ε_t. Because of this almost elastic deformation it appeared justified to compute the stress amplitudes from ε_t by multiplication with the experimentally determined values of the dynamic Young's modulus (Table 1).

To obtain S-N curves at least ten specimens were tested at each strain (stress) level. The experimental data were evaluated by statistical procedures reported by Maennig (1976) to compute a correlation between failure probability p and stress amplitude or cycles to failure by following relations:

$$p = \frac{r}{n+1}$$

r ... number of failed specimens
n ... number of tested specimens

$$p = \frac{i}{n+1}$$

i ... ranking number of specimens related to increasing cycles to failure

Plotting these data in a probability diagram the 1 % failure probability ($p_{1\%}$) could be obtained by extrapolation, in our case assuming a gaussian distribution of the test results.

The formation of PSBs with increasing N was recorded micrographically for various strain levels. The increase in PSB density was estimated from the area fraction of the specimen surface covered by PSBs. Intermittent SEM-examinations of the specimen surfaces in the gauge section were carried out to determine the first appearance and the sizes of microcracks. Slow crack growth rates (da/dN) and threshold stress intensity values for crack growth (ΔK_{th}) were determined as described by Weiss and others (1979).

RESULTS AND DISCUSSION

The dependence of the number of cycles to failure on ε_t and σ_t, respectively, is shown in Fig. 2 for commercially pure Cu vacuum heat treated at 650°C (Condition I, Table 1). In addition to the scatterband containing the experimental data probability curves for 50 % and 1 % failure probability ($p_{50\%}$, $p_{1\%}$) are plotted. Characteristic for both probability curves is their constant value for loading cycles $N > 10^8$. The 50 %-curve may be assumed to resemble the conventional S-N (Wöhler) curve. The stress value corresponding to the horizontal branch of the $p_{1\%}$-curve may correspond to the stress fatigue limit below which failure would not occur.

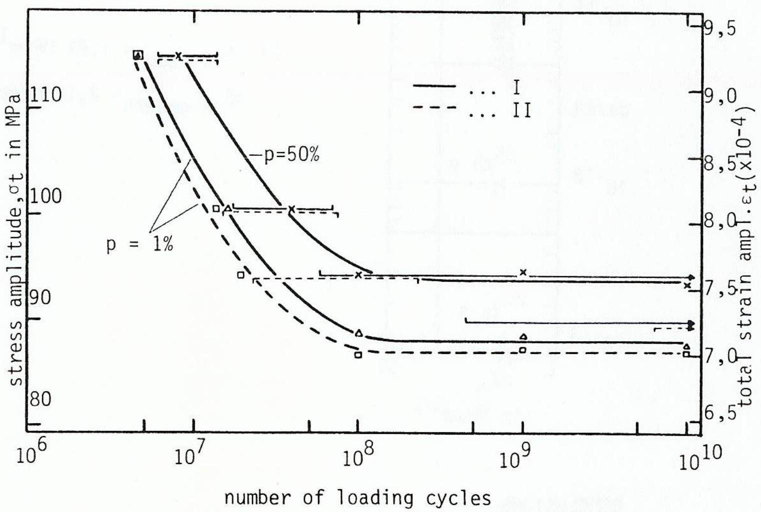

Fig.2. Results of fatigue tests and fracture probability curves of polycrystalline Cu (material conditions I,II)

Heat treatment of specimens at the same temperature of 650°C, but in a weakly oxidizing atmosphere (Condition II, Table 1) resulted in a minor shift of the S-N curves to lower values, e.g. as shown for $p_{1\%}$ in Fig. 2. The scatterband of experimental data of specimens in the condition II is narrower than that of specimens in condition I. It is notable that the shape of the S-N failure curve is similar to that of bcc metals.

Similar measurements were also carried out with specimens in conditions III and IV (Table 1). All results are plotted for the failure probability of p= 1% in the logσ_t-log N diagrams of Figs. 3a - 3c. This presentation shows that for polycrystalline Cu the endurance limit for $N = 10^8$ is equivalent to the stress fatigue limit independent of specimen condition. However, the stress amplitude decreases with increasing grain size contradictory to findings of Thompson and others (1971).

Fatigue exposure even well below the failure curve causes the formation of PSBs in the gauge length, increasing in density with N and stress amplitude. The estimated surface coverage of specimens in all three conditions is presented in Figs. 4a-4c as function of N for various stress amplitudes. Based on these results a boundary curve for the first appearance of PSBs could be drawn as shown by the 0 %-PSB-curves in Fig. 3a - 3c.

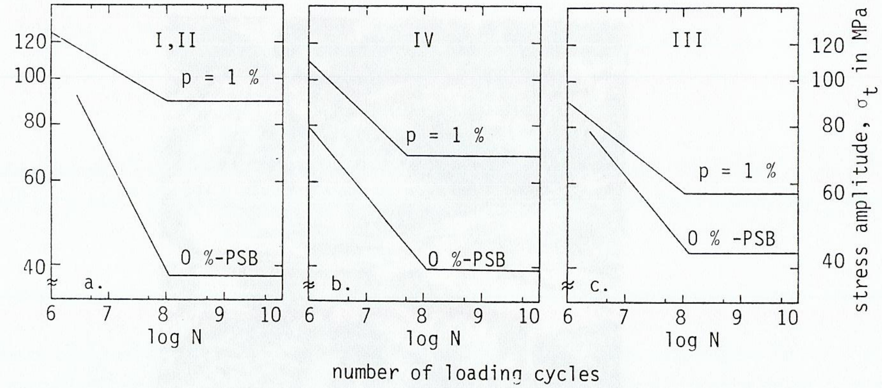

Fig.3. log σ_t-log N plot of fracture probability (p = 1%) and "0%-PSB"-curves of polycrystalline copper for various conditions

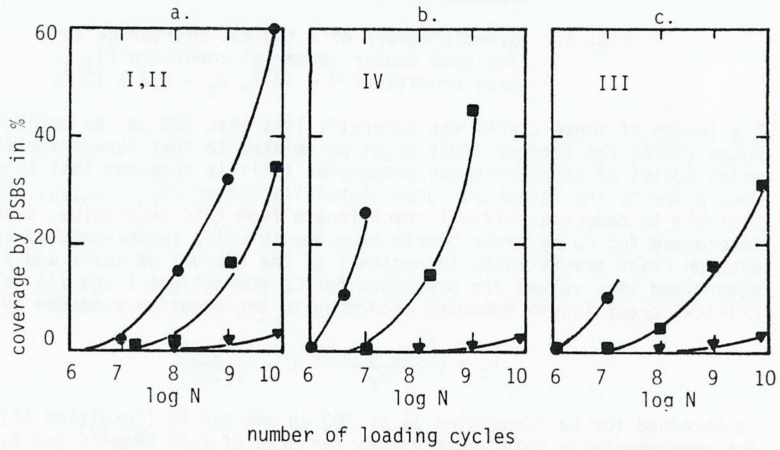

Fig.4. Effect of loading cycles on formation of PSBs in polycrystalline copper for various material conditions
●—● $\varepsilon_t = 6{,}0 \times 10^{-4}$ ■—■ $\varepsilon_t = 5{,}0 \times 10^{-4}$
▼—▼ $\varepsilon_t = 3{,}2 \times 10^{-4}$

A marked threshold in the stress amplitude for the formation of PSBs can be recognized for $N > 10^8$. This threshold may coincide with the "true stress fatigue limit" proposed by Laird (1976). The magnitude of the threshold stress value depends slightly on the microstructure and increases with increasing grain size.

SEM-observations indicate that the shape and topography of PSBs is strongly affected by the grain size. In coarse grained material (Conditions III and IV) a smaller number of more pronounced PSBs developed. This may explain the reduction of the stress fatigue limit relative to the 0 %-PSB-limit in this material.

In areas of high PSB concentration occasionally isolated microcracks could be detected even in specimens which had survived fatigue loading up to $N = 10^{10}$ (Fig.5).

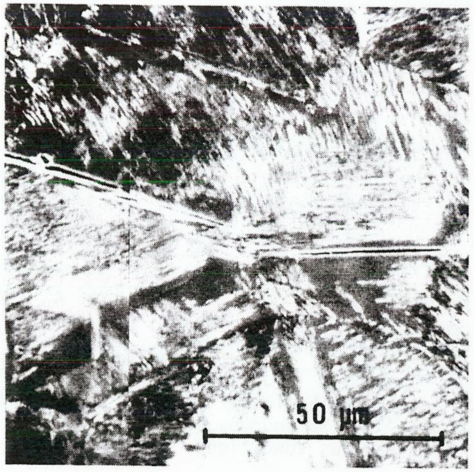

Fig. 5. SEM-micrograph of a typical microcrack in fatigued copper (material condition I); test condition: $N = 10^{10}$, $\varepsilon_t = 7{,}2 \times 10^{-4}$.

The length of these cracks was generally less than 100 µm. As pointed out by Lukas (1978) the fatigue limit might be related to that stress amplitude above which nuclei of microcracks can propagate. If it is accepted that this process is controlled by the threshold stress intensity factor ΔK_{th} (growth), it appears feasible to deduce a critical crack length from this ΔK_{th}-value. Such values were determined for Cu by crack growth experiments using center-notched specimens (Fig.1). Data on crack growth rates in region I of the (da/dN)-ΔK curve and experimentally determined ΔK_{th} values are presented for Cu (Conditions I and II) in Fig. 6. A critical crack length computed according to the equation proposed by Lukas (1978)

$$l_c = \left(\frac{\Delta K_{th\ growth}}{\sigma_f}\right)^2 \cdot \frac{1}{1{,}122\pi}$$

is obtained for Cu (Condition I) of 200 µm and for Cu (Condition II) of 180 µm if the experimentally determined values for ΔK_{th} of 2,35 MPam$^{1/2}$ and 2,19 MPam$^{1/2}$, and for the stress fatigue limit (σ_f) of 88 MPa and 87 MPa, respectively, are used.

It should be pointed out, however, that the computed critical crack length may be considered only as an upper limit. Furthermore, shape and orientation of the microcracks may affect the magnitude of this value.

If the critical crack length is estimated from the plastic zone size $l_c \sim 0{,}3\ r_p$, as proposed by Kitagawa (1976) and Usami (1979), a value of comparable magnitude is obtained.

The critical crack length estimated on the basis of fracture mechanics assumptions is considerably larger than the length of the isolated microcracks actually observed in the fatigue experiments.

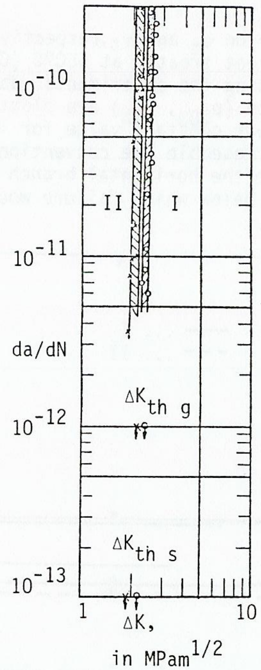

Fig. 6. Slow crack growth near threshold stress intensity in polycrystalline copper (material conditions I and II)

I $\Delta K_{th\ stop} = 2{,}14$ MPam$^{1/2}$ $\pm$ 5 %

$\Delta K_{th\ growth} = 2{,}35$ MPam$^{1/2}$ $\pm$ 6 %

II $\Delta K_{th\ stop} = 1{,}93$ MPam$^{1/2}$ $\pm$ 5 %

$\Delta K_{th\ growth} = 2{,}19$ MPam$^{1/2}$ $\pm$ 6 %

CONCLUSIONS

1. Statistical evaluation of the fatigue data of polycrystalline Cu exhibits a threshold cyclic stress value below which specimens will not fail, at least cycled up to $N = 10^{10}$. This stress amplitude may be considered as the stress fatigue limit. It may be of technological interest that this stress fatigue limit is equivalent to the endurance limit at $N \simeq 10^8$

2. The corresponding stress amplitudes are strongly dependent on grain size. A value of 88 MPa for fine grained Cu was determined decreasing to a value of 58 MPa for coarse grained material.

3. Microscopic examinations revealed the formation of PSBs well below this stress fatigue limit. A clearly defined stress limit for the formation of PSBs could be observed. The stress fatigue limit and the stress amplitude of 0 %-PSB are approaching each other with increasing grain size. It may be speculated that these two values become identical for single crystals.

4. Non-propagating microcracks could occasionally be detected in specimens cyclic exposed at stress amplitudes well below the stress fatigue limit. The dimensions of these microcracks are smaller than a critical length computed on the basis of the corresponding threshold stress intensity values.

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REFERENCES

Anderson, A., and others, (1941), (1946). Proc.Amer. Soc. Testing Mat. 41, 849-857, and 46, 678 - 692.

Awatani, J., K. Katagiri, A. Omura, and T. Shiraishi (1975). A study of the fatigue limit of Cu. Met. Trans. 6A, 1029 - 1034.

Hempel, M., (1967). Die Entstehung von Mikrorissen in metallischen Werkstoffen unter Wechselbeanspruchung. Arch. Eisenhüttenw. 38, 446 - 455.

Hessler, W., H. Müllner, B. Weiss, and R. Stickler (1980). Near threshold behaviour of polycrystalline Cu. Presented at the Conf. on Micromechanism of Crack Extension, Cambridge, UK.

Kitagawa, H., and S. Takahashi (1976). Applicability of fracture mechanics to very small cracks in the early stage. ICM-II,ASM, 627 - 631.

Laird, C. (1976). The fatigue limits of metals. J. Mat. Sci. Eng. 22, 231 - 236

Lukas, P., M. Klesnil, and J. Polak (1974). High cycle fatigue life of metals. J. Mat. Sci. Eng. 15, 239 - 245.

Lukas, P., and M. Klesnil (1978). Fatigue limit of notched bodies. J. Mat. Sci. Eng. 34, 61 - 66.

Maennig, W., and M. Pfender (1976). Zur Problematik der Dauerschwingfestigkeit metallischer Werkstoffe. Eng. Fract. Mech. 8, 39 - 67.

Mughrabi, H. (1978). The cyclic hardening and saturation behaviour of Cu-single crystals. J. Mat. Sci. Eng. 33, 207 - 223.

Polak, J., M. Klesnil, and P. Lukas (1974). High cycle plastic stress - strain response of metals. J. Mat. Sci. Eng. 15, 231 - 237.

Thompson, A. W., and W. A. Backofen (1971). The effect of grain size on fatigue. Acta Met. 19, 597 - 606.

Usami, S., and S. Shida (1979). Elastic-plastic analysis of the fatigue limit for a material with small flaws. Fat. of Eng. Mat. and Struct. 1, 471 - 481.

Weiss, B., and R. Stickler (1976). The high frequency test method. ICM-II, ASM, 1584 - 1588.

Weiss, B., R. Stickler, J. Femböck, and K. Pfaffinger (1979). High cycle fatigue and threshold behaviour of PM Mo and Mo-alloys. Fat. of Eng. Mat. and Struct. 2, 73 - 84.