Experimental Investigation of Barkhausen Noise Variations During the Fatigue Life of Steel Specimens

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Abstract

Barkhausen noise was measured during pulsating axial fatigue tests on annealed steel specimens in a preliminary investigation of the extent to which marked changes in noise intensity can be related to progressive damage leading to crack nucleation and propagation, and final failure. The results suggest that the amplitude of the noise signal can be used to discriminate initial structural arrangement (softening and hardening), and crack nucleation and propagation. Some explanations of the findings are proposed in the light of recent research in this field.

Riassunto

Vengono presentati i primi risultati di misure del rumore Barkhausen eseguite dall'autore durante prove di fatica assiale con ciclo dallo zero su provette in acciaio. Lo scopo di tali misure era di evidenziare eventuali significative variazioni dell'intensità del rumore Barkhausen nel corso della prova, in grado di segnalare il progressivo danneggiamento che conduce alla nucleazione e propagazione della cricca. I rilievi eseguiti sembrano indicare la possibilità di distinguere le fasi di assestamento iniziale, nucleazione e propagazione della cricca, assumendo quale parametro di controllo l'ampiezza ciclica del segnale. Sulla base di recenti sviluppi della ricerca nel campo, vengono altresì proposte alcune ipotesi interpretative dei fenomeni riscontrati sperimentalmente.

Introduction

Changes in the mechanical, microstructural and physical (e.g. electrical and magnetic) characteristics of a metal component appear during its fatigue life [1]. They reflect progressive and irreversible damage leading from macroscopic crack nucleation and propagation to eventual failure, and their investigation in relation to the progress of damage thus aids in the understanding and forecasting of fatigue. Ways and means for monitoring and checking the reliability of a structure during its use can also be devised.

Barkhausen noise measurement [2, 3] is a nondestructive technique for assessing the magnetic properties of ferromagnetic materials. Its employment in various applications has recently been rendered even more attractive by the introduction of very simple instruments. In the demagnetised state, the domains are randomly oriented, resulting in zero overall magnetisation. When an exciting magnetic field is applied, movements of the domain walls or rotation of the domain magnetisation vectors lead to overall magnetisation [4]. These abrupt, discontinuous movements can be displayed by means of a magnetic coil, in which the noise they produce ("Barkhausen noise") is picked up by electromagnetic induction. Measurements are taken by applying an alternating magnetic field and displaying the cyclic noise thus induced in the coil.

Evaluation of residual stresses is an important application of this method. Magnetorestriction [5], in fact, is also involved in determination of the intensity of these movements and hence that of the noise. A correlation between noise intensity and stress state, however, is still being sought [6-10].

Sensitivity of Barkhausen noise intensity to several other factors, for example, the degree of plastic strain [11, 12] and such microstructural parameters as hardness, grain size, fibre texture, etc. [4, 13-15], makes the technique itself extremely versatile. Against this, however, must be set the complications generated by the difficulty of determining the contribution of each effect when assessing the results.

This drawback, of course, is enhanced when several parameter values change at the same time, as in the measurement of residual stress in the presence of weldments. The best way of avoiding it seems to lie in the concomitant determination of other quantities of the magnetisation cycle, such as coercivity, residual induction and incremental permeability, whose sensitivity to the parameters being investigated is not the same [4, 11, 16].

Another approach considers the noise power spectrum, since this is influenced in different ways by tensional and microstructural parameters [17].

This difficulty in the empiric determination of reliable measurement criteria reflects the absence of an exhaustive physical interpretation of Barkhausen noise, even though several theoretical models have led to a better understanding of the phenomena responsible for movement of the magnetic domains [18, 19].

This paper presents the result of preliminary tests designed to study Barkhausen noise intensity patterns during the fatigue life of steel specimens in uniaxial stress. Since the progress of fatigue damage leads to changes in the tensional and structure state of a material, as well as the generation of an air gap due to the crack, the main aim of the experiment was to see whether significant changes in Barkhausen noise intensity could be used as indicators of initial structural rearrangement, and crack nucleation and propagation. Previous work had shown that the method is sensitive to fatigue damage in iron and steel when noise intensity is serially measured after removal of the load [23-24-25-26]. This, however, was concerned with the first stage of fatigue only, and no correlations with the presence of a crack and its size were established.

Material specifications

Specimens were taken from rolled steel bars whose rough-rolled composition in set out in Table 1.

TABLE 1 - Chemical composition of the material in the rough-rolled state

C	Mn	Si	P	S	Cr	Ni	Mo	Al
0.37	0.72	0.19	0.012	<0.005	0.14	0.13	0.019	0.015

The material was annealed for the tests so as to secure better homogenisation of its structure and reduce residual stresses. Specimens were heated to 600°C, held at this temperature for 3 hours and then slowly cooled. The maximum stress, yield stress and Brinell hardnes of the steel in the rough-rolled state and after annealing are shown in Table 2.

TABLE 2 - Mechanical characteristics of the material in the rough-rolled state and after annealing

	σ_Y [MPa]	σ_M [MPa]	HB
rough-rolled	450	707	223
annealed	387	640	190

Description of the specimens and the instrument used to measure Barkhausen noise

The shape and size of the specimens are illustrated in fig. 1. A Barkhausen noise sensor was placed in a semicircular notch (radius 1 mm) machined in the middle of one of the arcs to ensure crack nucleation just below its coil (fig. 3).

The AST Rollscan 100-2 instrument used to measure the noise (fig. 2) consists of a central energising unit, which also processes and displays the signal, and an AST-S1-138 miniature, uniaxial generalpurpose sensor composed of two magnetising poles on either side of a coil with a 1 × 2 mm sensitive area. The direction of measurement coincides with the line joining the poles and the coil.

Fig. 3 provides a detailed illustration of the area of contact between the Barkhausen sensor and the specimen. It can be seen that an air gap of about 0.1 mm is formed between the notch root and the lower face of the coil owing to the geometry of the notch and the coil, and undoubtedly influences the absolute value of the signal. This point, of course, is irrevelant for the purposes of the present study, whose aim was measure signal variations during the fatigue life of each specimen and make comparisons with the initial value and between specimens subjected to the same cyclic load.

A sinusoidal magnetic field with a frequency of about 7 Hz was applied. The signal was analysed from 3 to 15 Hz. As is well known, the frequency range, together with the permeability and conductivity of the material, influences the measurement depth [20-22], which was approximately 0,1 mm in this study.

Preliminary tests were run on specimens of the same steel to determine the optimum field intensity by applying an increasing uniaxial longitudinal load and measuring the corresponding noise level as the rms value: this parameter is directly displayed by the instrument and also called the "magnetoelastic parameter (MP).

This procedure was repeated with a variety of field intensities. The intensity value giving the maximum signal and sensivity was chosen as the optimum field intensity, namely 20 units on the instrument selector switch. Saturation and a gradual fall in sensitivity appear when a slightly higher value is used. A detailed description of the procedure can be found in [10].

Description of the tests

A 500 kN INSTRON hydraulic machine was used to apply a controlled pulsating load at about 7 Hz for the fatigue tests. Theree specimens were tested for each of three load ranges, namely:

group A: $F = 0 \div 36.5$ kN
group B: $F = 0 \div 30.5$ kN
group C: $F = 0 \div 26.5$ kN

An electrical strain gauge showed that the stress concentration factor due to the presence of the semicircular notch was about 2.6. When this is taken into account, the notch root exceeds the elastic limit at a nominal stress σ nom (calculated as the longitudinal load over a minimum cross-section of about 90 mm^2) of nearly 150 MPa, i.e. with a load of about 13.5 kN.

All tests must thus be regarded as having been performed in the presence of a plastic zone.

σ nom is about 295 MPa at the maximum load in group C and only the notch root is plasticised, whereas in group A the whole cross-section is plasticised (σ nom = about 405 MPa). Group B is an intermediate state (σ nom = 340 MPs).

The noise sensor was placed on the specimen at the beginning of the test with the aid of a small aluminium mounting attached to the piece by two clamping screws and an elastic band to ensure constant contact.

Two electrical strain gauges (gauge length = 0.6 mm) were applied lengthwise (fig. 1), one in the middle of the arc opposite the sensor, the other on one of the two plane faces of the specimen along the crack direction, and as close as possible to the notch root (distance between gauge axis and root: about 1.2 mm).

The sensor and gauge signals were passed from the corresponding measurement units to a galvanometric YT, and recorded during two or three load cycles at time intervals corresponding to from 500 to 20,000 cycles, depending on the load level and the stage of the test. The frequency was reduced to about 0.1 Hz during the recording. At the same time, a 20 x light microscope with a resolution of 0.05 mm was used to look for and measure cracks.

Results

The mean value and amplitude (difference between maximum and minimum during the cycle) of the MP for the three specimens in each group are shown as a function of the number of cycles are shown in figs. 4, 6 and 8, normalised with respect to the number of cycles to failure as indicated in Table 3.

TABLE 3 - Failure cycles number Nf for the three groups of specimens

A1	18000	B1	31000	C1	320000
A2	16000	B2	42000	C2	282000
A3	12000	B3	34000	C3	360000

Good repeatibility was obtained at all three load levels. This was particularly true in terms of quality, though less significantly with respect to the MP values, which were influenced by the slight, but inevitable, scattering of the tensional and microstructural characteristics.

Closer examination of the MP mean value and amplitude trends shows that the life of a specimen passes through four stages:

— stage 1. Here there is an initial signal arrangement. This stage ranges from about 0.07 to 0.2 Nf, depending on the load level (the lower the load, the shorter the normalised duration). The signal is nearly sinusoidal with small noise at the maximum value. It is in phase with the load (fig. 10a), i.e. higher Barkhausen noise intensities correspond to higher loads, this being normal for a material with positive magnetostriction.

— stage 2. Here the signal is almost constant. This period goes as far as 0.5 – 0.55 Nf in groups A and B, and to about 0.8 Nf in group C. The wave is still sinusoidal and in phase with the load (fig. 10b).

stage 3. The signal now decreases with increasing score in mean value and especially in amplitude. This period lasts to about 0.8 Nf in groups A and B, and almost to the end of the fatigue life (nearly 0.98 Nf) in group C. A small intermediate noise appears in the wave form at the beginning of this stage, slightly below the mean in the rising segment of the cycle (fig. 10c). The signal is still in phase with the load.

The relative minimum introduced by the noise increases as the test proceeds (fig. 10d) until it becomes absolute (fig. 10e). At the same time, the wave form of the signal is gradually shifted ahead of the load cycle.

— stage 4. The amplitude increases, or decreases less rapidly. The mean value falls in a more regular manner. The signal regains its sinusoidal form, but is now 180° out of phase (fig. 10f).

The magnitude of the crack at the end of this stage results in major deformation and proper contact between the coil and the specimen cannot be ensured. Contact, in fact, is confined to one of the two edges of the coil. This abnormal behaviour is marked by a further abrupt decrease in the signal, especially in amplitude, as indicated by the asterisk in figs. 4, 6 and 8.

The residual strains for one specimen from each group (measured by strain gauges 1 and 2 at zero applied load) are shown in figs. 5, 7 and 9. Similar values were given by the other specimens. The crack length a measured on each specimen is also indicated. The strain gauge readings indicate the degree of plastic deformation. In group A, both points at which the gauges were applied are well in the plastic field from the start and have the same residual strain value (about 14,000 $\mu\ \varepsilon$), in keeping with plasticisation of the whole cross-section at this load level mentioned earlier. As the test proceeds, the strain gradually increases (particularly that shown by gauge 1), until the rise corresponding to the presence of a crack, indicated first by gauge 2 and then gauge 1.

The initial strain at gauge 1 is zero in group B, and low (nearly 1000 μ ε) at gauge 2. Once again, this is in keeping with plasticisation near the notch root only. Further cycles are followed by a rapid strain increase to about 4500 μ ε at both points. This value remains almost constant until the final abrupt increase.

Lastly, in group C the initial strain is zero at both points in keeping with the smallness of the plastic zone of the notch root, and remains so until the final rise.

Crack lengths were slightly scattered in each group. Measurements were taken from 0.1 mm, this being the minimum accuracy for the resolution of the microscope employed. This dimension was reached after about 0.5 Nf in group A, between 0.5 and 0.6 Nf in group B, and nearly 0.85 Nf in group C. In all three cases, these numbers approximately correspond to the start of stage 3.

Discussion

The following observations can be put forward in the light of these findings:

— the arrangement of the noise signal in stage 1 is probably due to structural arrangement of the material, in other words the "softening" and "hardening" that usually take place at the commencement of a fatigue process. These phenomena are related to dislocation movement and hence to the degree of plastic strain. It has been pointed out that this parameter reduces the intensity of Barkhausen noise [11, 12].

In this connection, comparison of figs. 4, 5 and 8 with figs. 5, 7 and 9 shows that in stages 1 and 2 the signal amplitude is greatest (with small variations) in group C, where plastic deformation is always small and never shown by the strain gauges. It decreases rapidly as the extent of plasticity increases (gauge measurements for group B), and remains from the start at significantly lower levels in group A, where considerable plasticisation is indicated by the gauges at the outset.

Karjalainen et al. [23-25] performed alternate bending fatigue tests on annealed low-carbon steel specimens and measured Barkhausen noise intensity without loading at different times during the cycle. Their results also demonstrate a significant signal variation in stage 1. A similar conclusion was reached by Ruuskanen & Kettunen [26] during alternating axial fatigue tests on Araco iron specimens.

It may be pointed out that the duration of this stage is longer in proportion to the total fatigue life the higher the load.

— stage 2 with its small variations in noise intensity appears to correspond to the steady state of the fatigue process. The microscopic changes resulting in crack nucleation occur during this period, when the stationary behaviour of the material is characterised by the cyclic curve. This damage does not seem to have a significant influence on Barkhausen noise intensity. The duration of this stage is longer in proportion to the total life the lower the load.

— macroscopic evidence of crack nucleation at the beginning of stage 3 is reflected in a marked decrease in signal amplitude, plus a more gradual reduction of the mean value. The main reason for this decrease is probably progressive unloading of the crack edges on the coil contact surface. The formation of an increasing large air gap, however, cannot be overlooked, since this could explain the strange behaviour of the signal during crack propagation. Stage 4, when the amplitude falls less quickly, or even increases, and is shifted 180° out of phase, begins when the crack length is nearly 1 mm in all three groups. The effect of distortion on the magnetic flux lines inside a material near a crack has been extensively investigated by means of the nondestructive "magnetic flux leakage" technique to detect defects in ferromagnetic materials [27, 28]. These local distortions may result in marked changes in noise intensity in zones near a crack. Interpretation of these phenomena, however, is rendered more complicated by the fact that the air gap changes its size during the load cycle.

Conclusions

Three conclusions can be drawn from this experimental study:

1) The mean value and amplitude of Barkhausen noise during a fatigue process reflects a pattern that is qualitatively similar for the specimens in a given group, with little scattering of the quantitative values. A certain significance can thus be ascribed to this parameter as a result of these preliminary findings.

2) Comparison of the patterns of the Barkhausen noise signals recorded for three load levels gives analogies whereby the fatigue life of a specimen can be divided into four stages. In addition, signal amplitude appears to be the parameter most sensitive to changes occurring during a fatigue test.

Stage 1 is accompanied by arrangement of the Barkhausen signal apparently related to "softening" and "hardening" of the material. Stage 2 is marked by an almost constant signal and probably represents the steady-state period, as characterised by the cyclic curve, during which microdamage in the material leads to crack nucleation. This interpretation is supported by comparison of these two stages in relation to the load. Longer initial arrangement and shorter nucleation times in proportion to the total fatgue life, in fact, correspond to higher cyclic loads.

Marked reduction of signal amplitude accompanies macroscopic crack nucleation and its microscopic detection. This reduction is probably caused by decreased stress in the crack edges, which becomes more marked as propagation proceeds. This pattern is reversed in stage 4, when the influence of the air gap created by a large crack is presumably substantial.

3) Other important information can be derived from examination of the wave form of the noise intensity during the load cycle. In stages 1 and 2, this is nearly always sinusoidal and in phase with the load, as would be expected for a material with positive magnetorestriction. Progressive distortion and phase displacement begin in stage 3 after appearance of the crack and during its growth, whereas a nearly sinusoidal signal, though 180° out of phase, is re-established in stage 4. No reasons can as yet be assigned for this pattern. The presence of the air gap, however, would seem to be relevant in this respect, since its size varies during the load cycle. Further evidence could perhaps be gained by placing the Barkhausen Sensor in a different position, for example on one of the plane surfaces of this specimen, with the measuring coil in the crack nucleation zone.

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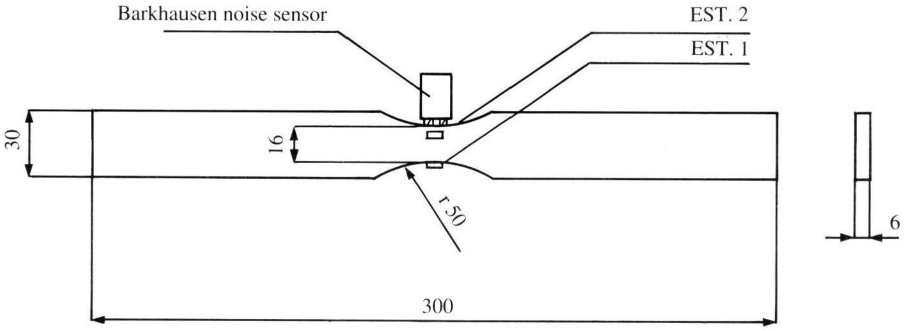

Fig. 1:
Shape and dimensions of the specimens.

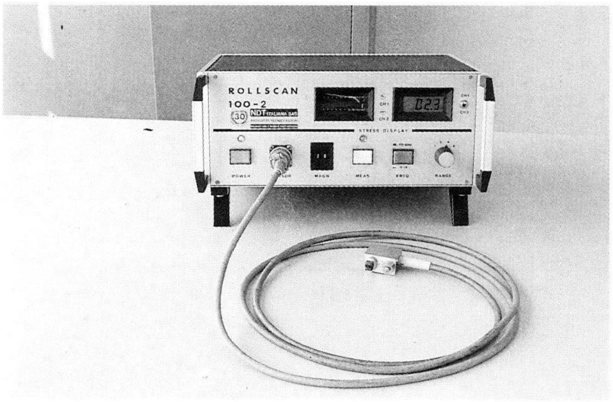

Fig. 2:
The instrument for the Barkhausen noise measurement.

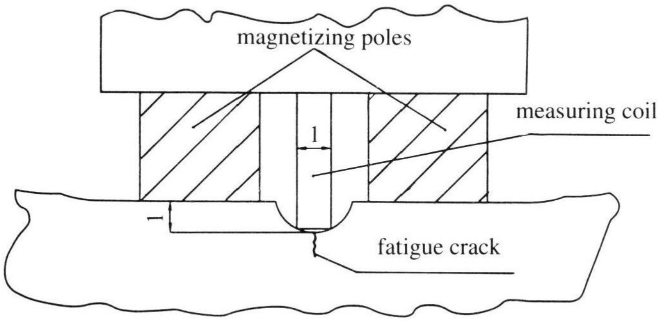

Fig. 3:
Geometry of the sensor-specimen contact zone.

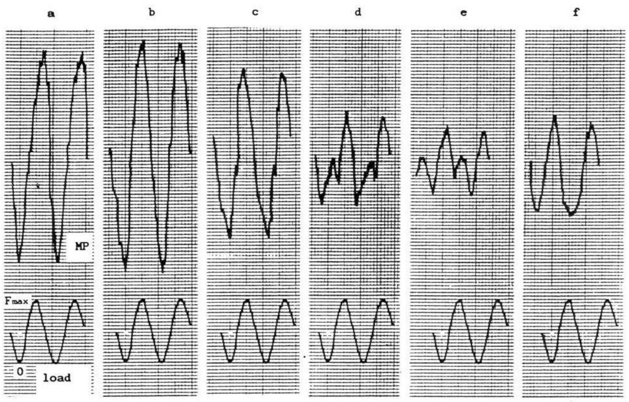

Fig. 10:
Wave form of the Barkhausen signal at different instants of the fatigue life.

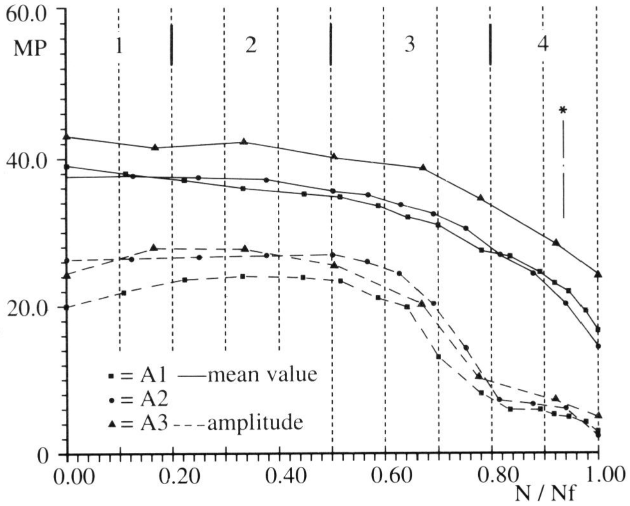

Fig. 4:
Magnetoelastic parameter as function of the normalized cycles number - group A (F = 0 ÷ 36.5 kN).

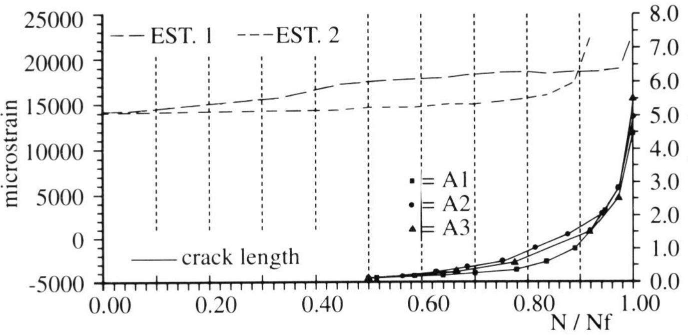

Fig. 5:
Residual strains and crack lenght as function of the normalized cycles number - group A.

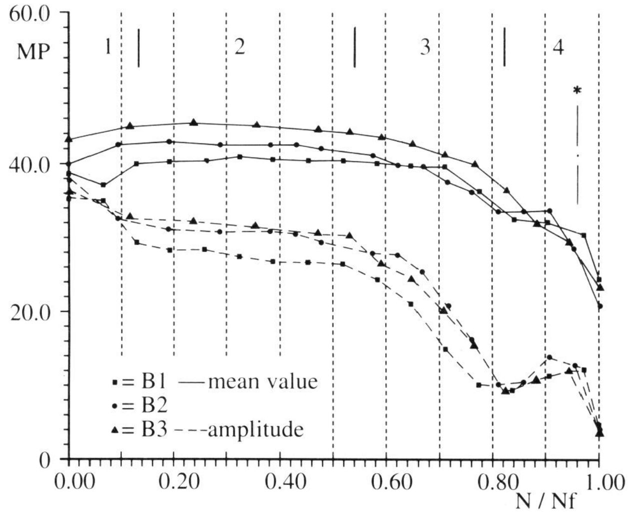

Fig. 6:
Magnetoelastic parameter as function of the normalized cycles number - group B (F = 0 ÷ 30.5 kN).

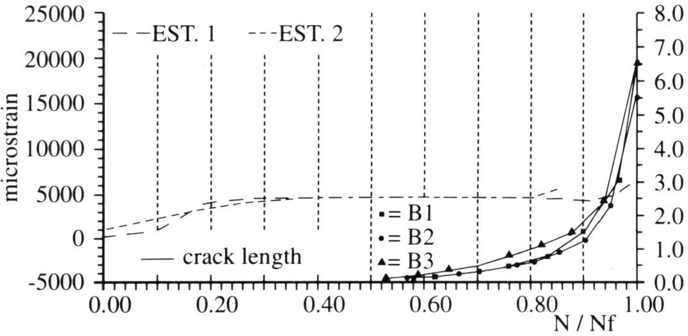

Fig. 7:
Residual strains and crack length as function of the normalized cycles number - group B.

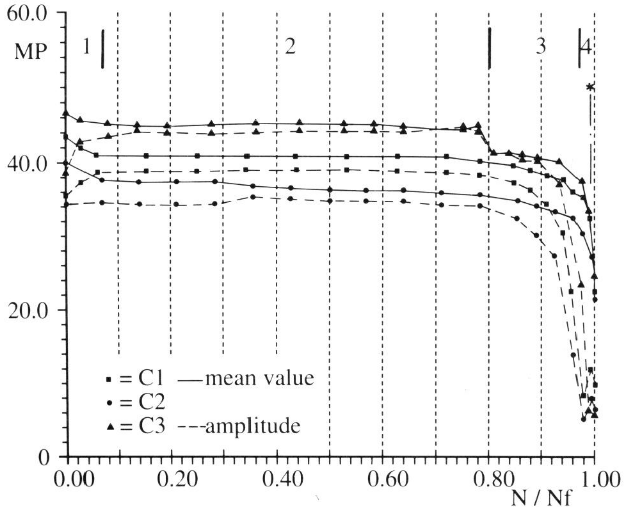

Fig. 8:
Magnetoelastic parameter as function of the normalized cycles number - group C (F = 0 ÷ 26.5 kN).

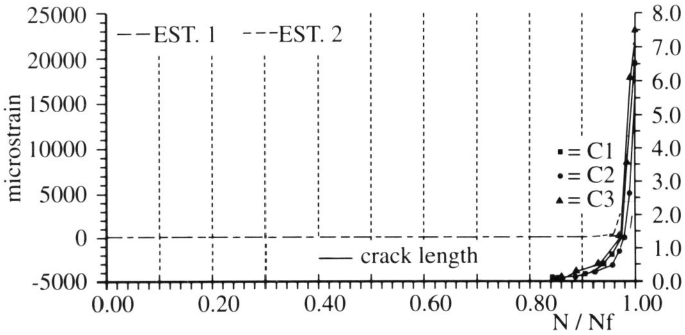

Fig. 9:
Residual strains and crack length as function of the normalized cycles number - group C.