MAGNETIC TECHNIQUE FOR EVALUATING THE FATIGUE STRENGTH OF FERROMAGNETIC STEELS

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ABSTRACT

A study has been undertaken of the correlation between mechanical Barkhausen noise caused by variations of stress in ferromagnetic materials and the structural changes attendant on metal fatigue. The test results indicate that the level of the magnetic noise occuring during metal fatigue is proportionale to stress amplitude as well as to changes in the structure and dynamic behaviour of dislocations. The tests indicate that the fatigue limit of a material can be quickly determined without breaking it by measuring for example the effective value of the magnetic noise.

KEYWORDS

Nondestructive evaluation, magnetic methods, fatigue, mechanical Barkhausen noise, ferromagnetism.

INTRODUCTION

It has been proved that there is a distinct interaction between dislocations and the magnetization of ferromagnetic metal /1, 2, 3/. It appears, among other things in changes taking place in the characteristics of the magnetic hysteresis loop as a function of the plastic deformation. It has also been proved that the domain walls that are moving during magnetization process can activate dislocation motion and stress relaxations /4/. These interaction phenomena have been used in the qualitative study of the deformation mechanisms of metal /5, 6, 7/.

The method of measuring the fatigue strength presented in this paper makes use of the mechanical Barkhausen noise. This phenomenon is connected with the irreversible movements of the magnetic domain walls /8/. When ferromagnetic material is under the influence of changing load the magnetic order of the material is changed by the magnetomechanical phenomenon. The changes in magnetization take place in the form of turns in the magnetization vectors of individual domains and with the aid of movements of the domain walls. While moving in the crystal lattice the domain walls are in interaction with various kinds of lattice defects, which produce discontinuous magnetization changes. These changes can be perceived in the form of noise coming from the measuring coil on the surface of test material /9/.

By measuring the changes in the magnetic noise induced during the loading, as a function of loading amplitude, for instance, changes taking place in the dislocation arrangement and in the dislocation movements can be discovered. By using measurements of this kind one is able to determine the absolute value of the fatigue limit of ferromagnetic materials. The experiments done so far have proved that the best results are obtained by using normal structural steels and HSLA-steels as test materials /10/.

EXPERIMENTAL DETAILS

The applied mode of fatiguing was sinusoidally varying loading with a constant stress amplitude and a mean value of zero. Frequency was 15 cps. The reference values of fatigue limit $\hat{\sigma}_W$ were determined destructively with a similar kind of fatiguing.

Fig. 1 presents schematically the equipment used in measuring the RMS-value of the magnetic noise induced during the fatiguing of metal. The actual measuring is carried out as follows:

The test specimen is under the influence of stepwise or continually increasing stress amplitude, as presented in Fig. 2a. Because of the irreversible magnetization changes in the material emf-pulses are induced in the measuring coil located close to the surface of the specimen. The effective value B_M of the pulses increases as a function of the stress amplitude $\hat{\sigma}$, as shown in Fig. 2b. After the stress amplitude has reached the arbitrary value $\hat{\sigma}_{max}$ the amplitude is decreased to zero level. Immediately after this the value of $\hat{\sigma}$ is raised again, measuring simultaneously the effective value B_M of the mechanical Barkhausen noise. If the preceding loading stage has been carried out with a sufficiently high amplitude $\hat{\sigma}_{max}$, a distinct maximum is seen in the effective value B_M of the induced magnetic noise at a certain value of the stress, as presented in Figs. 2c and 2d.

It is not necessary to know the sufficiently high stress amplitude $\hat{\sigma}_{max}$ mentioned above. It can be found experimentally by repeating the raising cycle of the stress amplitude and the measurements of the B_M-value and by increasing the maximum stress amplitude $\hat{\sigma}_{max}$ each time by a certain amount $\Delta\hat{\sigma}$.

It has been proved in the stress controlled fatigue tests that the value of the stress amplitude $\hat{\sigma}_B$ corresponding to the maximum of the effective value B_M of the magnetic noise is with great accuracy the same as the fatigue limit $\hat{\sigma}_W$ value of the material in question determined by the destructive method.

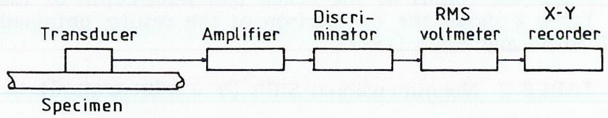

Fig. 1. Block diagram of the equipment for mechanical Barkhausen noise measurements.

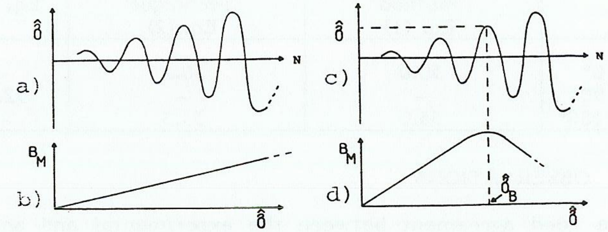

Fig. 2. Measurement of the stress amplitude $\hat{\sigma}_B$ corresponding to the maximum of the effective value B_M of the mechanical Barkhausen noise.

TEST MATERIALS

Two types of structural steels and two types of high strength steels were used as test materials. The chemical composition and the monotonic yield strength values are presented in Table 1. Material A is a hot rolled fine grained steel, material B is a hot rolled normal structural steel and materials C and D are soft annealed tool steels.

The specimen geometry used is shown in Fig. 3. Test specimens were made of a plate 5 mm thick. The gauge length was mechanically ground and electrolytically polished. Finally the specimens were annealed in 550°C for one hour. In addition to this specimens out of the material B were made of plate 2.7 mm thick, but these specimens were neither polished nor annealed (marked with the symbol B2 in Table 2).

The magnetic measuring of $\hat{\sigma}_B$-values and the conventional destructive measuring of the reference values of fatigue limit $\hat{\sigma}_W$ were performed by using similar types of specimens.

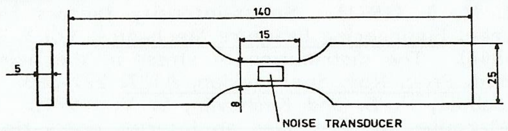

Fig. 3. The shape and dimensions of the fatigue test specimens.

Table 1. Chemical composition and monotonic yield strength R_e of the test materials.

Material	C	Si	Mn	P	S	N	Cr	Mo	V	W	R_e [MPa]
A	0.15	0.32	1.21	0.02	0.02	0.006					400
B	0.12	0.19	0.66	-	0.03	0.005					380
C	1.55	0.30	0.25				12.0	0.80	0.8		600*
D	0.90		1.20				0.5	0.1		0.5	450

* (proof stress, 0.2 % offset)

RESULTS

Fig. 4 presents the results received by using the magnetic method described above when fine grained steel A has been used as test material. The curves presented in the figure have been determined gradually by first increasing the stress amplitude $\hat{\sigma}$ to the value 100 MPa where it has been kept constant for one thousand stress cycles. Then the stress amplitude has been increased by steps of 25 and 12 MPa to the value of 260 MPa. The stress amplitude has been kept constant for one thousand cycles at each stress amplitude level. The effective value B_M of the induced mechanical Barkhausen noise has been measured each time $\hat{\sigma}$ has been held constant. The stress amplitude has been decreased from the level of 260 MPa to zero value and then applied again, increasing it stepwise and measuring the values of B_M at the same time. The stepwise increasings of the stress amplitude have been repeated several times in each case increasing the maximum amplitude $\hat{\sigma}_{max}$ by about 12 MPa.

As the curves in Fig. 4 present, the behaviour of the effective value B_M of the magnetic noise changes considerable after the third fatiguing. At that stage B_M rises sharply, reaches the maximum at a certain value of $\hat{\sigma}$ and starts to decrease after that. When the cycling is done for the fifth time the rise of B_M is even sharper than before and the B_M vs $\hat{\sigma}$-curve reaches the maximum at the stress amplitude value 252 MPa. If the measurements are continued after this, the B_M vs $\hat{\sigma}$-curve follows repeatedly the shape of the curve 5 in Fig. 4. The B_M vs $\hat{\sigma}$-curve has then reached its stable form. It has been proved experimentally that the stress amplitude $\hat{\sigma}_B$ corresponding to the maximum value of B_M is very accurately the same as the value $\hat{\sigma}_W$ of the fatigue limit of the material, which has been determined by the conventional destructive fatiguing method.

For the sake of comparison the B_M vs $\hat{\sigma}$-curves measured from material B have been presented in Fig. 5. As seen in the figure, these curves are in principle similar to those in Fig. 4. Nevertheless, the effective value B_M of the magnetic noise induced from material B does not change between the various loading stages as markedly as the noise obtained from material A. Besides, the fatiguing of material B had to be done at higher

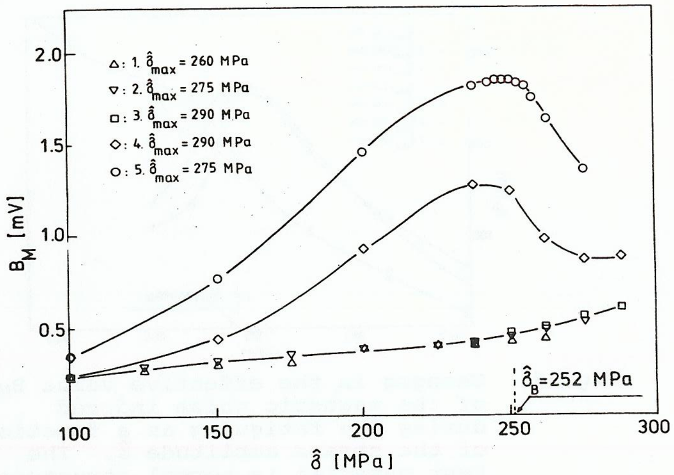

Fig. 4. Changes in the effective value B_M of the magnetic noise induced during the fatiguing as a function of the stress amplitude $\hat{\sigma}$. The test material is fine grained steel A.

stress amplitudes in relation to the value of $\hat{\sigma}_B$ than with material A. The B_M vs $\hat{\sigma}$-curves in Fig. 5 reach their stable form after the sixth cycle of stress amplitude increasing. Thus the curve 7 gives 179 MPa as the value of the stress amplitude $\hat{\sigma}_B$ corresponding to the maximum effective value B_M of the magnetic noise.

Table 2 illustrates the correlation between $\hat{\sigma}_B$ and $\hat{\sigma}_W$ in all the materials studied. As the values of the table show the correspondence is good.

The curves shown in Figures 4 and 5 were measured nearby the maximum of B_M with steps of 2 MPa. Because the changes in the value of B_M were distinctly notable the accuracy of measurement can be said to be ± 2 MPa. When the values of $\hat{\sigma}_B$ are measured from the different specimens of same material the scattering of the results is about the same.

The level of the noise pulses measured from the soft annealed high strength steels was about a tenth compared with that measured from the structural steels. This has an effect also on the accuracy of measurement so that distinct changes in the value of B_M can be noticed with loading steps of about 5 MPa.

The behaviour of the magnetic noise pulses has not been investigated of stress amplitudes higher than those presented in Figs. 4 and 5.

The changes in the RMS-value of the magnetic noise induced during the fatiguing are also reversible as a function of the

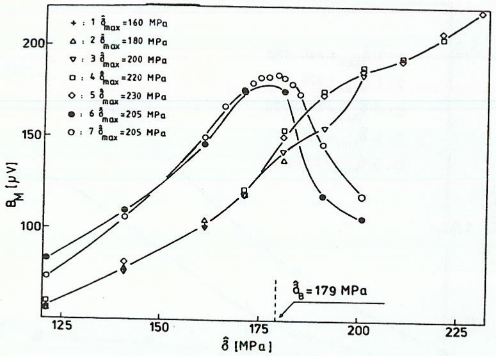

Fig. 5. Changes in the effective value B_M of the magnetic noise induced during the fatiguing as a function of the stress amplitude $\hat{\sigma}$. The test material is normal structural steel B.

Table 2. The correlation between magnetically measured stress amplitude $\hat{\sigma}_B$ and the fatigue limit $\hat{\sigma}_W$ of the test materials.

Material	$\hat{\sigma}_B$ [MPa]	$\hat{\sigma}_W$ [MPa]	
A	252 ± 2	250 ± 5	5 mm thick
B1	179 ± 2	180 ± 5	– " –
B2	187 ± 2	192 ± 5	2.7 mm thick
C	290 ± 5	290 ± 5	5 mm thick
D	263 ± 5	265 ± 5	– " –

applied stress amplitude. Fig. 6 presents the B_M vs $\hat{\sigma}$-curves measured from material A during the increasing of the stress amplitude and the decreasing following immediately after that. As the figure shows both curves follow the same line. When the stress amplitude is decreased one is able to see, however, that $\hat{\sigma}_B$ has moved about 5 MPa downwards.

In addition to these experiments of the effect of artificial ageing on the effective value of the magnetic noise was studied. Test material in this case was a normal structural steel, marked in Table 2 with symbol B2. The results of these measurements have been presented in Fig. 7. The test specimen has first been fatigued so that the measured B_M vs $\hat{\sigma}$-curve has reached its stable form. This is presented by the curve 1 in Fig. 7. After that the specimen has been aged in 250°C for one hour whereupon measurements of the changes in B_M have again been made. It was then noticed that the maximum of the B_M vs $\hat{\sigma}$-curve disappeared as a result of the ageing as seen in the curve 2. Only after a loading up to 365 MPa a maximum is formed in the value of B_M and it moves over to its original place after the fourth fatiguing. As the figure shows the level of the noise has risen a little, but it does not have any effect on the value of the stress amplitude $\hat{\sigma}_B$.

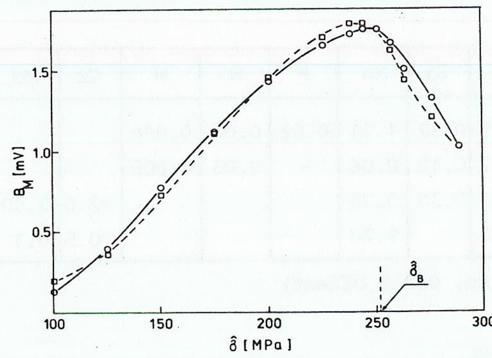

Fig. 6. Changes in the effective value of the magnetic noise induced during the fatiguing as a function of the stress amplitude $\hat{\sigma}$. The test material is fine grained steel A.
—o—: stress amplitude is increasing.
--□--: stress amplitude is decreasing.

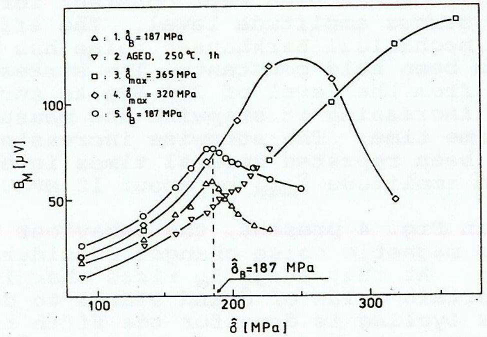

Fig. 7. The effect of ageing on the behaviour of the magnetic noise induced during fatiguing.

DISCUSSION

As the results in Table 2 and also the previously presented results show, the stress amplitude values measured with the magnetic method correspond fairly well to the fatigue limit $\hat{\sigma}_W$ values measured with the conventional destructive method. The magnetic method can thus be used to measure the fatigue strength of metal nondestructively. The advantages of this method are its quickness and the fact that only one test specimen is needed to determine the value of $\hat{\sigma}_B$. It thus takes about fifteen minutes to measure the B_M vs $\hat{\sigma}$-curves shown in Figs. 4 and 5.

Earlier publications have suggested that the changes in the mechanical Barkhausen noise as a function of stress amplitude are possibly connected with the changes taking place in dislocation arrangements and in the mobility of individual dislocations /9, 10/. Because the domain walls as well as the individual dislocations move in the material during the deformation, the mechanical Barkhausen noise can be assumed to consist of mainly two kinds of interactions:

1) interactions between moving domain walls and stable lattice defects
2) interactions between domain walls and moving dislocations.

The stress field around the moving dislocation is different from that around the stationary dislocation. Thus one might assume that the dislocations which have dissimilar mobility have a dissimilar effect on the domain walls and thus on the nature of the induced magnetic noise.

The microstructure of the structural steels used in the experiments consists of ferrite and perlite. The grown-in dislocations formed in ferrite during slow cooling are locked in their place by C and N atoms. When this kind of structure is loaded with a stress amplitude high enough the grown-in dislocations are gradually loosened from the binding C and N clouds. In the case shown in Fig. 4 the loosening of dislocations takes place during the first four cycles of stress amplitude increasing. Thus it can be assumed that the large changes of B_M result, at least indirectly, from the interactions between the domain walls and the dislocations loosened from obstructions. At amplitudes higher than the fatigue limit, there are strong changes in the dislocation structure and the dislocation mobility. This causes the interactions between the domain walls and the dislocations and thus the level of the induced pulses to decrease. As shown in Fig. 6 the changes of the induced magnetic noise are reversible as a function of stress amplitude. That is why also the interaction mechanisms of the domain walls and the dislocations must also be reversible. The results presented in Fig. 7 also support the view that the changes in the dislocation movement have an effect on the level of B_M. The most essential point in Fig. 7 is the fact that the maximum of the original B_M vs $\hat{\sigma}$-curve disappears when the dislocations are locked by artificial ageing. The maximum reverts again, if the test specimen is being loaded with a sufficiently high stress amplitude because the dislocations loosen again of the obstructions composed of C and N clouds.

SUMMARY

It is suggested that a distinct connection does exist between the structural changes taking place in the fatiguing of ferromagnetic material and the changes of the mechanical Barkhausen noise induced simultaneously. The results that have been obtained can be summarized in four points as follows:

1) The effective value B_M of the magnetic noise induced during the deformation of ferromagnetic material changes strongly, if the test material is loaded with a stress amplitude higher than its fatigue limit.
2) The stress amplitude $\hat{\sigma}_B$ corresponding to the maximum in the B_M vs $\hat{\sigma}$-curve is shown to be very accurately the same as the value of the fatigue limit $\hat{\sigma}_W$ determined with a destructive method.
3) The changes in the effective value B_M of the magnetic noise are reversible as a function of the stress amplitude, as presented in Fig. 6.
4) If the test specimen is aged, the maximum of the B_M vs $\hat{\sigma}$-curve disappears. The maximum reappears if the specimen is loaded with a stress amplitude higher than its fatigue limit. The maximum corresponds the same stress amplitude value than before the ageing.

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