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Experimental Stress Analysis

Microplastic Limit of Steel Determined by the Measurement of Changes in Electrical Impedance

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Abstract: Microplastic strains occurring at stresses less than the yield stress play a significant role at cyclic loading of metals in high cycle region. Microplastic strains can not be mesured by common methods due to the discontinuity of their distribution and a varying character of their level in the structure of metal but, however, owing to the magnetoelastic effect the threshold stress at which dislocation pile-up stresses begin to obstruct the magnetic domains in rotation to the direction of the tensile stress can be determined from changes in magnetic permeability during a tensile loading. In the work the changes in magnetic permeability were measured indirectly – by the measurement of changes in electrical impedance (a.c. resistance) for that there is a direct functional dependence between the a.c. resistance and the magnetic permeability. Measurement was performed on normalized low-C steel CSN 41 1375. The microplastic limit was determined by evaluation of $\Delta R - \sigma$ records. A comparison with the fatigue limit in an axial reversed loading showed that it was below the fatigue limit. The microplastic limit can be considered to separate non-damaging and damaging cyclic stresses.

Keywords: Microplastic limit, Magnetic permeability, Low-C steel

1. Introduction

A significant point in high-cycle fatigue of steel components is that of plastic strains which occur at stresses well below the yield. Using the technique of visualization of dislocations in silicon - iron it was proved [1] that microplastic strains can be found at stresses as low as the half of or even less than the yield point. Metallographic investigation showed that this pre-yield plasticity is discontinuous and occurs at isolated centers of locally high stresses which are the consequence of various additional effects of microstructure (for example the grain structure, inclusions, etc.). The microplastic strains (isolated pre – yield plastic strains) can not be measured by current methods owing to the discontinuity of their distribution and the varying character of their magnitudes in the structure. However, a threshold stress at which first plastic strains occur in the structure can be determined from changes in magnetic permeability during a tensile test. The variation of this quantity in elastic and plastic region is different. For positively magnetostrictive metals the magnetic permeability in elastic region increases with increasing the stress but in plastic region it starts to decrease due to an advance of the hardening of plastically deformed zones. It is therefore supposed that some changes in the character of the dependence $\Delta\mu - \sigma$ (where $\Delta\mu$ is a change in the magnetic permeability and σ is stress) determine the onset of microplastic strains. However, the measurement of magnetic permeability during a tensile test is difficult. From the experimental point of view it is easier to measure changes in magnetic permeability indirectly – by the measurement of the

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variation of the a.c. resistance R_{ac} or the inductance L during a tensile test [2]. The argument for this is that both the a.c. resistance and inductance are functions of magnetic permeability [3]. Moreover, a high-frequency alternating current passes over the specimen in a thin surface layer due to the skin effect; this point is favourable because the fatigue damage in the majority of cases occurs first on the surface.

A number of papers have been devoted to the study of magnetic properties of ferromagnetic materials in relation to their stress history. The research work was motivated mainly by a desire for determination of correlations between changes in magnetic properties and fatigue characteristics (e.g. [4-7]). There was also some work done on utilization of changes in magnetic permeability for studying the microplasticity in metals or for non-destructive investigation of residual stresses in ferromagnetic materials ([8-12]). Not much work has been done to damaging cyclic stresses below the fatigue limit in the context with variation of magnetic properties during an application of mechanical stress to a specimen. It is known that not only stresses above the fatigue limit are damaging but also some stresses below this limit [13], this being the case when a component is subjected to a spectrum loading in service and a strong interaction between very high and very low cyclic stresses takes place. The threshold value of damaging stresses below the fatigue limit in cyclic loading can be connected with the so called "true elastic limit", as termed by the authors of paper [2]. This point is also known as the "microplastic limit" or "microyield point".

Theoretical and experimental research is aimed at the connection between the pre-yield discontinuous plasticity in a ferromagnetic material, occurring at isolated centers upon macroscopic stresses well below the yield, and fatigue stress parameters. The basic idea is that due to the dependence between the a.c. resistance and the magnetic permeability it is possible to measure changes in magnetic permeability during mechanical loading by measuring changes in a.c. resistance.

2. A brief background

When a stress is applied to a ferromagnetic material the magnetic domains change their volume and rotate to the direction of the acting stress due to the magnetoelastic effect (opposite to the magnetostriction effect). The magnetization is eased so that the magnetic permeability is increased. However, when first dislocations start to move in some grains, the situation is changed. It is very likely that dislocations are arrested at some obstacles, like inclusions, precipitates, etc., which represent energy barriers of various magnitudes to the moving dislocations. The dislocations are piling-up at these barriers and cause the rise of stress fields around them. The stresses obstruct magnetic domains to rotate to the direction of the acting stress. Owing to this the resistance of the metal against magnetization is increased and magnetic permeability starts to decrease.

In this paper some partial preliminary results of a.c. measurements on specimens from low-C steel are presented with the aim to utilize the concept of microplastic limit for characterization of the threshold of fatigue damage in a ferromagnetic material.

3. Experimental procedure and results

An experimental investigation was made on normalized low-C steel CSN 41 1375 of the following strength characteristics: R_{eH} = 344 MPa; R_m = 432 MPa. Four copper clamp-terminals were placed on the surface of each flat specimen according to the schematic picture on Fig. 1 and then the specimens were insulated from the grips of the tensile testing machine to prevent current flowing in parallel through the machine.

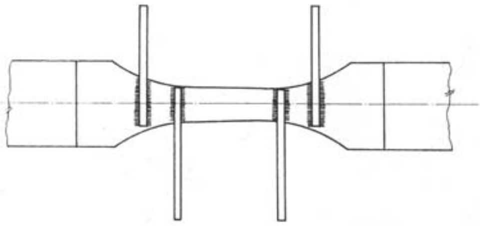

Fig. 1. Location of copper clamp-terminals

The changes in a.c. resistance during tensile straining of the specimens were measured using a specially developed apparatus. A block diagram of the apparatus for direct a.c. resistance measurement is in Fig. 2. A field current from the a.c. generator **Gen** is led through the resistor $\mathbf{R_i}$ to the terminal connector **Hi** through which it is connected to one end of the specimen. The resistance $\mathbf{R_i}$ of 4 Ω ensures an excitation of the specimen with a constant current since $R_i \geq R$. The other end of the specimen is connected to the ground through the terminal connector **Lo.** The resistor R_c is used to pick up the magnitude of the field current upon calibration.

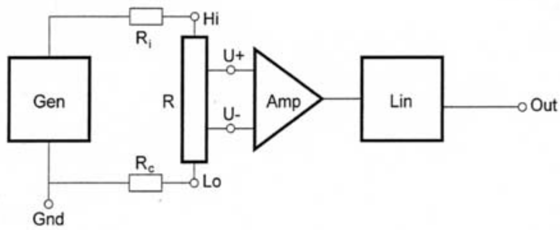

Fig. 2. A block diagram of the direct a.c. resistance measurement

The measuring amplifier **Amp** is connected to the terminal connectors $\mathbf{U^+}$ and $\mathbf{U^-}$ of the specimen. The gain of the amplifier is A = 100. The amplified alternating voltage from the measuring amplifier is led to the input of the linear rectifier **Lin.** The magnitude of the direct-current voltage output corresponds to the effective value of the alternating voltage input and is led to the connector Out.

Results of (ΔR, σ) measurements were stored in the form of digital records. They provided $\Delta R_{a.c.}$ - σ dependences of the form represented in Fig. 3. It is to be said that in straining a specimen longitudinally the electromagnetic flux lines are perpendicular to the (tensile) axis of a specimen where material of the specimen experiences contraction. Complying with statements of paragraph 2 magnetic domains in the steel change their volume and rotate to the direction of the acting stress (due to the magnetoelastic effect) when subjected to loading. Providing the flux lines are parallel to the direction of elongation of a specimen the magnetization is facilitated by elongation for positively ferromagnetic materials so that the magnetic permeability increases. If the flux lines are parallel to the direction of contraction, as it is when the alternating current passes through the specimen longitudinally, the magnetization is more difficult so that the magnetic permeability decreases. This is illustrated on Fig. 3.

For very low stresses the boundaries between magnetic domains (Bloch walls) in a ferromagnetic material move freely following the tendency of magnetic domains to have the direction of their magnetization parallel with the acting mechanical stress (elongation or

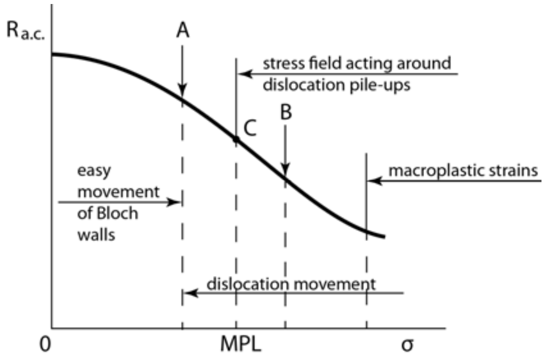

Fig. 3. Schematic representation of changes in a.c. resistance with stress

contraction of the specimen). When the stress reaches a certain value (point A on the figure) dislocations start to move in the most favourably oriented slip planes. Arbitrarily is marked in the figure the point C representing the formation of stress fields around the dislocation pile-ups and thus the retarding effect of the stress fields on the movement of Bloch walls. The point B is the point of departure of the $R_{a.c.}$ – σ curve from linearity. It is believed that this point characterizes the situation when dislocations move and form pile-ups also in grains that are less favourably oriented. In a some distance apart from the point B there is an onset of macroplastic strains. Factual $\Delta R_{a.c.}$ – σ dependences for two specimens from CSN 41 1375 steel are represented here on Fig. 4 and Fig. 5.

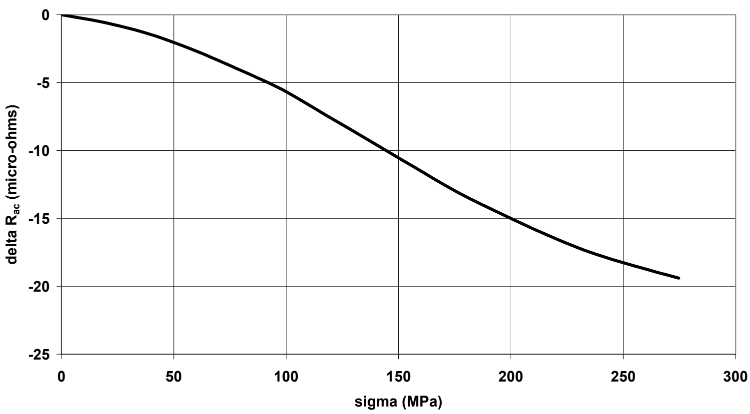

Fig. 4. Variation of the a.c. resistance change with stress (specimen no. 1)

By analyzing the curves on Fig. 4 and Fig. 5 we find that σ_A = 109 MPa; σ_B = 151 MPa; σ_C = (σ_A + σ_B)/2 = 130 MPa for specimen no. 1, and σ_A = 96 MPa; σ_B = 144 MPa; σ_C = (σ_A + σ_B)/2 = 120 MPa for specimen no. 2.

Altogether 10 specimens were tested. Magnitudes of the stresses σ_A, σ_B and σ_C are presented on Tab. 1.

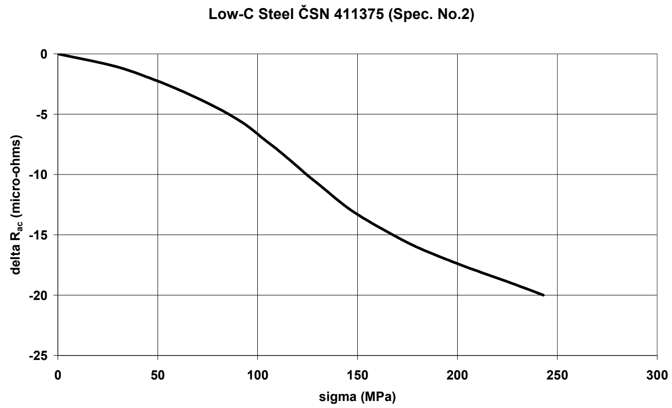

Fig. 5. Variation of the a.c. resistance change with stress (specimen no. 2)

Table 1. The results of analysis of $\Delta R_{a.c.} - \sigma$ curves

Specimen No.	σ_A (MPa)	σ_B (MPa)	σ_C = MPL (MPa)
1	109	151	130
2	96	144	120
3	107	159	133
4	68	146	107
5	109	168	138.5
6	120	151	135.5
7	81	105	93
8	99	147	123
9	76	145	110.5
10	72	127	99.5

It is seen that the results are scattered. Because we are mainly interested in the magnitudes of the stress σ_C (identified with the microplastic limit) we shall suppose that the microplastic limit obeys the Gaussian distribution. It can be found by statistical analysis that the mean of the microplastic limit is $\overline{MPL}$ = 119 MPa and the standard deviation is s = 15 MPa. The results in the form of Gaussian distribution are presented in Fig. 6.

In the figure there is also shown the position of the fatigue limit in symmetrical reversed stress cycle taken as 35% of the ultimate tensile strength R_m. Considering that R_m = 432 MPa the fatigue limit comes to 0.35 × 432 = 151 MPa. It is seen from Fig. 6 that in no case the magnitude of the microplastic limit exceeded the fatigue limit.

4. Conclusion

Measurement of changes in electrical impedance (a.c. resistance) of tensile specimens from low-C steel CSN 41 1375 during monotonic tensile loading showed that the $\Delta R_{a.c.} - \sigma$ dependence exhibits a linear part in a certain stress interval (σ_A ; σ_B). An average value of these two stress magnitudes (denoted σ_C) is believed to represent the so called microplastic limit or a „true elastic limit“. For all specimens tested this value was found to be less than the fatigue limit in symmetrical reversed loading; this indicates that the measurement of a.c. resistance variation during a tensile test could be used as a suitable tool for determining a threshold value of damaging stresses below the fatigue limit in cyclic loading of steel components.

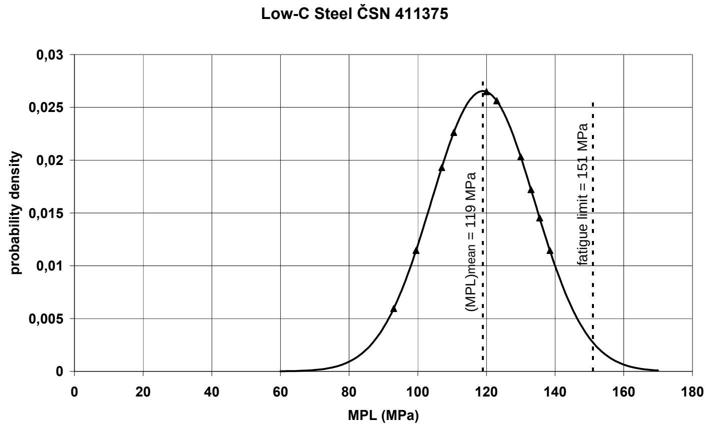

Fig. 6. The probability density of Gaussian distribution of MPL

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