EAN 2012
50th annual coference on experimental stress analysis

A Comparison of Probable Magnitudes of the Microplastic Limit of CSN 411375 Steel Determined by the Inductance and Resistance Method

Ľubomír Gajdoš[1], Martin Šperl[1], Václav Mentl[2] & Jaroslav Kaiser[2]

Abstract: The paper takes up our preceding contribution in which an attention was paid to the significance of microplastic strains and to their measurement by means of changes in electrical impedance of specimens made from normalized low-C steel CSN 411375. In the present paper results are presented which enable a deeper insight into the problem of microplastic limit (MPL) in relation to the measuring methods used. The factor to be taken into account is the skin effect owing to which only dislocation-stress conditions in a narrow surface layer will affect the R_{ac} changes. This means that differences can exist between MPL magnitudes determined by the R_{ac} measurement and the inductance measurement because in the latter case the whole cross section of specimen affects the results.

Keywords: Electrical impedance; Microplastic limit; Steel

1. Introduction

The microplastic limit (MPL) can be considered to be a stress (strain) at which plastic strains begin to occur in some micro-volumes of metal. The occurrence of these strains can not be determined by common methods but they can be detected by means of monitoring changes in magnetic permeability of a ferromagnetic material during application of mechanical load to a specimen. Microplastic strains occur below the fatigue limit, namely as a result of dislocation movement in favourably oriented microregions in the metal lattice. As it is known a macroscopic yield stress is formed by several components the basic one being the friction stress Rf. Friction stress is interpreted as the stress needed to move unlocked dislocations along the slip plane. The magnitude of the friction stress is approximately Rf ≈ 40 MPa for the most low-C and low-alloy steels [1]. If it is considered that MPL corresponds to the applied stress upon which internal stresses around pile ups start to obstruct magnetic domains to rotate to the direction of tensile strains then the MPL magnitudes should be greater than 40 MPa. With increasing load the dislocations are gradually piling-up at obstacles, firstly at grain boundaries. When they are in the same plane, they repel each other if they have the same sign, and annihilate if they

[1] *Ing. Ľubomír Gajdoš, CSc.; Ing. Martin Šperl, Ph.D.; Institute of Theoretical and Applied Mechanics, Academy of Sciences of the Czech Republic, Prosecká 76, 190 00 Prague 9, Czech Republic; gajdos@itam.cas.cz, sperl@itam.cas.cz*
[2] *Prof. Ing. Václav Mentl, CSc.; Ing. Jaroslav Kaiser Ph.D.; University of West Bohemia, Faculty of Mechanical Engineering, Univerzitní 22, 306 14 Pilsen, Czech Republic; mentl@kmm.zcu.cz; kaiser@kmm.zcu.cz*

have opposite signs (leaving behind a perfect crystal). Thus dislocations of the same sign form short-distance stress fields which obstruct magnetic domains to rotate to the direction of the acting load (strain).

This physical phenomenon can be utilized for the measurement of the onset of local plastic strains in micro-volumes of metal. As it has been implied the basis of our measurements is monitoring of changes in magnetic permeability of steel specimens during their mechanical loading. Owing to the fact that direct measurement of magnetic permeability is rather difficult we have chosen an indirect measurement, namely (i) the measurement of changes in a.c. resistance, the frequency of alternating current being 2 kHz, and (ii) the measurement of changes in inductance of a cylindrical specimen with wound up a coil on it. A magneto-elastic effect (the Villari phenomenon) was utilized in both types of measurements. This effect is in fact inversion of the well-known magnetostriction and it means that changes in magnetic properties of feromagnetic materials are induced by deformation of a rod in the longitudinal direction. As a matter of interest it can be stated that nowadays the magneto-elastic effect is utilized in several engineering applications, e.g. in modern, highly sensitive magneto-elastic strain-gauges [2] or load cells [3].

The aim of this theoretical and experimental research is to explore the possibility of utilization of these methods for determination of the onset of microplastic strains in ferromagnetic materials (the microplastic limit MPL) and further to investigate and prove experimentally that MPL has a very strong linkage to the stress boundary between damaging and non-damaging cycles at fatigue loading of steels. As it follows from scientific literature [4] not only cyclic stresses above the fatigue limit but also stresses below this limit can affect the total life of a structure upon its non-stationary loading.

2. A brief background

When comparing both indirect methods for measurement of magnetic permeability of specimens tested it is necessary to take into account several aspects in which the methods are different. First it is to say that in an a.c. resistance measurement the magnetic flux lines are oriented in planes perpendicular to the specimen axis whereas in inductance measurement the direction of magnetic flux lines is identical with the longitudinal direction of a specimen. Another difference is that in a.c. resistance measurement the alternating current passes through the specimen in a narrow surface layer due to the skin effect so that the results of the measurement reflect permeability changes predominantly in this narrow layer. From the viewpoint of cyclically loaded specimens this phenomenon is very important and useful because the most of fatigue fractures are initiated at the surface. In contrast to this method is the measurement of inductance; here the results correspond to changes ocurring in the whole bulk of metal. This means that differences can exist between MPL magnitudes determined by the Rac measurement and the inductance measurement. In the paper results of these measurements are presented and are compared not only between themselves but also with the results of measurements made by the metal magnetic memory (MMM) method. This method is rather new and is based on detection and analysis of distribution of self-magnetic leakage fields in a ferromagnetic metal in relation to the position of the probe upon a constant stress and/or on the applied stress level upon a constant position of the probe. The magnetic memory of metal, from which a component is made, is in fact a consequence of the process of manufacture of a component in a weak magnetic field (e.g. geomagnetic field) which is demonstrated in the form of residual magnetization or irreversible changes in magnetization in local areas of stress concentration or damage. The measurement by the MMM method itself was carried out in cooperation with Preditest company which utilizes this method for diagnostic purposes of damage in pressure vessels and pipelines in power supply.

The resistance and inductance of a wire carrying a high-frequency current have often been used for determination of permeability. This is based on Eq. (1) for the resistance and Eq. (2) for the inductance [5].

$$\frac{R_{ac}}{R_0} = \frac{x}{2} \cdot \frac{ber\ x\ bei'\ x - bei\ x\ ber'\ x}{ber'^2 x + bei'^2\ x} \tag{1}$$

$$\frac{L_i}{L_{i0}} = \frac{4}{x} \cdot \frac{ber\ x\ ber'\ x + bei\ x\ bei'\ x}{ber'^2 x + bei'^2\ x} \tag{2}$$

where Rac is the a.c. resistance and R0 is the d.c. resistance of a conductor, Li is the inner inductance of a straight wire at a given frequency f and Li0 is the inner inductance at the frequency f = 0, the ber and bei functions are the real and imaginary parts of Bessel functions and

$$x = \pi d \sqrt{2\mu f\ /\ \rho}$$

where *d* is the diameter of a conductor

f frequency of a current

ρ resistivity of a conductor

and μ permeability of a conductor

The relations (1) and (2) are graphically represented in Fig.1.

3. Experimental procedure and results

Tensile testing specimens of a circular cross-section were manufactured from CSN 411375 steel rods of 20 mm in diameter. For obtaining homogeneous mechanical properties of specimens the semiproducts cut from the rods were normalized at 9150C for 45 min followed by air cooling. Machining of specimens to their final form (10 mm in dia and 60 mm in gauge length) was carried out afterwards on an NC lathe. The yield stress and the ultimate tensile strength were determined as an average from three specimens to be R_e = 255 MPa and R_m = 394 MPa. For the a.c. resistance and inductance measurements a tensile testing machine was furnished with a special jig to insulate grips for preventing current from flowing in parallel through the machine. The experiments were carried out on electro-mechanical testing machine Wolpert-Testatron with a load cell Lucas 100 kN. The a.c. resistance and inductance were measured using specially developed apparatuses enabling the output to be sampled and stored by means of the measuring bridge Peekel – Autolog 18 bit, software Autosoft NT. Fig.2 shows an aggregate system for measuring inductance changes during tensile loading.

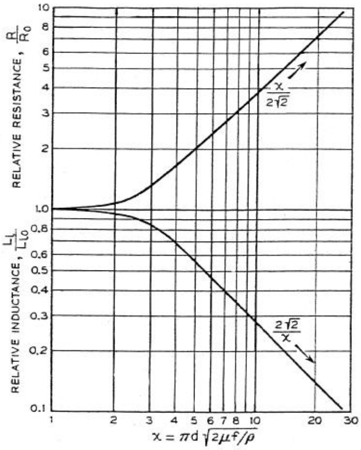

Fig. 1. Effective resistance and inductance of wire carrying current.

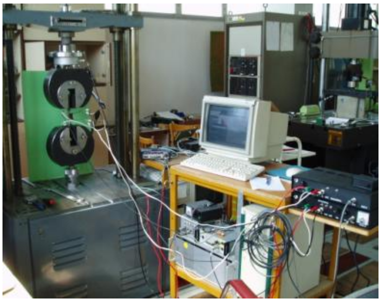

Fig. 2. Measurement of inductance variation of a specimen with a tensile load.

The apparaturs for measuring a small a.c. resistance changes was developed for measuring the absolute magnitudes of the electrical impedance of metallic specimens at the frequency 2 kHz. It makes also possible to carry out the measurement of relative a.c. resistance changes. The magnitude of the field current is 2 A and the measuring range of the impedance is 10μΩ – 10 mΩ. The apparatus is described in a more detail in [6]. The apparatus for measuring inductance changes works on the principle of converting the measured absolute value of the impedance to a direct current voltage. The magnitude of the field current of a coil is 2 A and its frequency is 2 kHz. A connection of the measured coil to the apparatus, including the measured specimen is schematically represented on Fig.3.

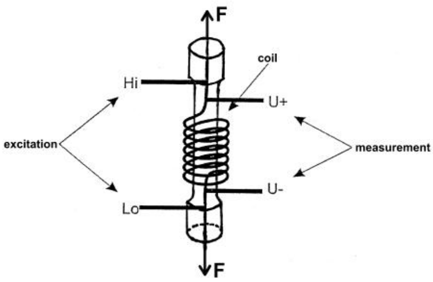

Fig. 3. Connection of the measured coil to the apparatus, including a measured specimen.

The results of our measurements (ΔR, ΔL in relation to σ) and their relations to the tensile diagram and the S-N curve are presented on the aggregate diagram of Fig.4.

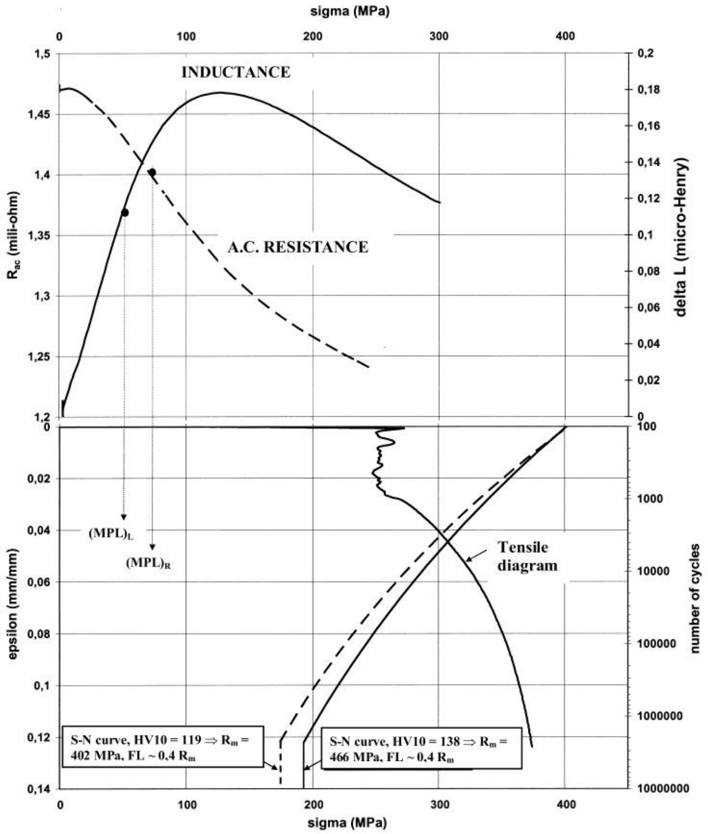

Fig. 4. An aggregate diagram of experimental results concerned with the a.c. resistance, inductance, tensile properties and fatigue characteristics of specimens from CSN 411375 steel as related to the applied tensile stress.

For a correct description of the measured characteristic variations of the inductance and a.c. resistance with stress (strain) it is important to have an idea what is going on in the steel on the atomic level during application of a tensile load. Following the paragraph 1 the processes occurring in the lattice during loading can be concisely described by the following flow diagram (Fig.5).

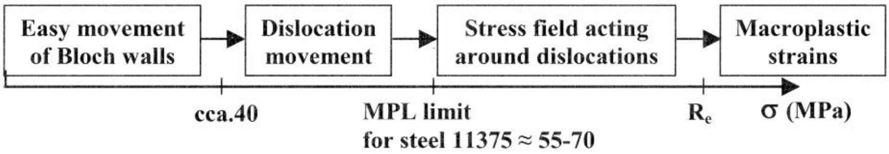

Fig. 5. The course of changes in the lattice upon the action of tensile stress.

The measured MPL values are denoted by black points on Fig.4. It is noteworthy that there is a difference between MPL values determined by inductance and a.c. resistance measurement. The latter method provided a slightly higher value of MPL. The main reason for this difference is the skin effect which manifests itself in a.c. resistance measurement. This effect consists in the tendency of an alternating electric current to distribute itself within a conductor with the current density being largest near the surface of the conductor, decreasing at greater depths. The electric current flows mainly at the "skin" of the conductor, between the outer surface and a level called the skin depth. The skin effect causes the effective resistance of the conductor to increase at higher frequencies where the skin depth is smaller, thus reducing the effective cross-section of the conductor. The skin effect is due to opposing eddy currents induced by the changing magnetic field resulting from the alternating current. As a result of machining, the surface layer of specimens was hardened. Conversion from the hardness provides the tensile strength of the surface layer Rm = 466 MPa. Removing the hardened layer by a mild lathing (thin chip and low speed of the turning tool) yielded the hardness which, converted to strength, provided the tensile strength Rm = 402 MPa. This was practically the same as the strength obtained by an ordinary tensile test.

It is also noteworthy that the a.c. resistance is decreasing during tensile loading while the inductance is increasing up to its maximum. The reason for this behaviour is the orientation of loading (straining) direction relatively to that of the magnetic flux lines. If the directions are concurrent then the measured quantity (for a positively magnetostrictive material) is increasing as the tensile load increases; if they are not concurrent the quantity is decreasing as the tensile stress increases. The former case holds for the inductance measurement and the latter one for the a.c. resistance measurement.

Coming back to MPL measurements: the inductance measurement provided the MPL value ≈ 50 MPa, which was about 12% of the U.T.S. for the core of the specimens (Rm = 402 MPa) and the a.c. resistance measurement provided the MPL value ≈ 70 MPa, which was about 15% of the U.T.S. for the hardened surface layer of the specimens. This gives an evidence that comformity of the methods used is good and also that determination of MPL values is appropriate.

In accordance with [6] when determining the MPL by the a.c. resistance measurement the middle point of the linear part of the Rac vs. σ dependence, and/or the point of inflexion of the Rac vs. σ dependence is taken as a decisive one, while when determining the MPL by the inductance method the point of deviation from linearity is taken as a decisive one. This corresponds to the situation when stress fields, induced by dislocation pile-ups, begin to obstruct magnetic domains to rotate to the direction of tensile strain.

The magnitudes of the microplastic limit are designated in Fig.4 by full circles. For a comparison with static and cyclic characteristics of the steel investigated there are also drawn (i) the static stress-strain diagram and (ii) S-N curves for specimens with/ and without a hardened surface layer. Both S-N curves were constructed on the basis of fatigue tests in a reversed stress cycle; the curve corresponding to specimens with a hardened surface lies naturally above that for specimens with the hardened layer removed.

As a matter of interest it can be specified that while the ratio of the fatigue limit σf to the respective tensile strength Rm was approximately 0.4 for surface hardened as well as for non-hardened specimens the ratios of the microplastic limits to respective fatigue limits and tensile strengths were slightly less for specimens with the hardened layer removed, namely: 0.30 vs. 0.37 for the fatigue limit and 0.12 vs. 0.15 for the tensile strength. This can be caused by an inexact knowledge of the real hardness of the skin layer.

A note to the measurement by the MMM method:

From the description of the method it is clear that its principle is similar to that of inductance measurement for that it is based on detection and analysis of distribution of self-magnetic leakage fields in a ferromagnetic metal in relation to the position of the probe upon a constant stress and/or on the applied stress level upon a constant position of the probe. Therefore it can be expected that the course of variation of the intensity of magnetic field with stress will be similar to that of inductance variation with stress. The results are presented in Fig.6. They are compared with the results of inductance measurement.

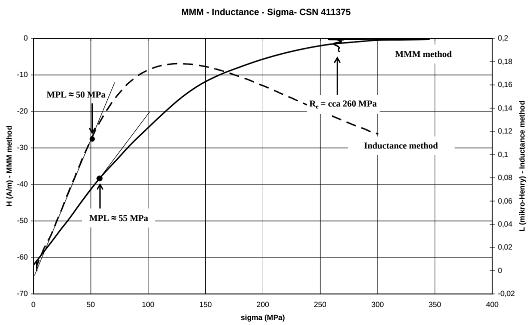

Fig. 6. The results of measurement by the MMM method as compared to results obtained by the inductance measurement.

It can be stated that the MMM method appears to be a suitable means for determination of the microplastic limit of steel. Like in inductance measurements the point of deviation from linearity can be considered also here to characterize the onset of plasticity at local micro-regions.

4. Conclusions

Methods for indirect measurement of changes in magnetic permeability (the a.c. resistance and inductance) of tensile steel specimens during their tensile loading appeared to be a suitable tool for determination of the microplastic limit. The results obtained on specimens from CSN 411375 steel showed that the MPL values were greater than the friction stress, needed for unlocked dislocations to move in the lattice, but they were less than the fatigue limit in symmetrical reverse loading. The Rac measurement method is particularly advantageous for specimens with a hardened and/or a softened surface layer for that the results reflect the situation in the surface layer due to the skin effect. This is very important for cyclically loaded steel components because the fatigue damage mostly begins at the surface. For assessment of integral fatigue properties (in the bulk of material) it is again more convenient to use the method of measuring changes in inductance.

Verification of the possibility of the use of the MMM method for determination of the microplastic limit showed that this method provides very similar results to those obtained by the measurement of the inductance so that it appears to be suitable for MPL determination. Next experimental work will be directed to examination of changes in the magnitude of the microplastic limit during application of stress cycles in relation to their amplitude and number.

Acknowledgements

This work was supported by RVO: 68378297 and by the grant projects P105/10/2052 and P105/10/P555 of the Grant Agency of the Czech Republic

References

[1] Macek K., Cejp J., and Ganwarich Pluphrach, Yield Strength of Low Carbon Cast Steels. *Materials Engineering*, Workshop 2005, pp. 446-447.

[2] Bydžovský J., Jančárik V., Kollár M., Kraus L., Švec P. and Ušák E., Magnetoelastické tenzometre vhodné pre stavebnictvo a geotechniku. Acta Avionica, 5/2003, pp. 42-49. ISSN 1335-9479.

[3] Stefanescu D.M., Handbook of Force Transducers – principles and components. Springer, Verlag Berlin Heidelberg, 2011. ISBN 978-3-642-18295-2.

[4] Linhart V. and Jelínek E., Engineering Calculations of the Fatigue Life of Components and Accumulation of Damage (in Czech), Strojírenství (Machinery), No. 9, Vol. 25, 1975.

[5] Bozorth R. M., Ferromagnetism, New York, Van Nostrand, 1951.

[6] Gajdoš Ľ., Šperl M., Kaiser J., Mentl V., Microplastic Limit of Steel Determined by the Measurement of Changes in Electrical Impedance. *Proc. Experimental Stress Analysis 2011*, June 6-9, 2011, Znojmo, ISBN 978-80-214-4275-7.