Proceedings of the 3rd International Conference on Nonlinear Dynamics
ND-KhPI2010
September 21-24, 2010, Kharkov, Ukraine

AN INFLUENCE OF LONG-TERM EXPLOITATION ON MATERIAL BEHAVIOUR UNDER CONSTANT AND MONOTONICALLY INCREASING LOADING

Z.L. Kowalewski [1]
S. Mackiewicz
J. Szelążek
Institute of Fundamental Technological Research
Warsaw, Poland

T. Szymczak
Motor Transport Institute
Warsaw, Poland

B. Augustyniak
Gdańsk University of Technology
Gdańsk, Poland

ABSTRACT

The paper is devoted to an analysis of creep damage at elevated temperatures and structural degradation due to plastic deformation at room temperature of selected steels commonly applied in power plants (40HNMA, 13HMF). The materials were tested in the as-received state, however, in the case of the 13HMF steel also after different periods of exploitation (76000h and 144000h at elevated temperature (813K) under internal pressure (14 bars)). Destructive and non-destructive testing methods were applied to assess a material degradation. As destructive methods the standard tension tests were carried out after every kind of prestraining. Subsequently, an evolution of the selected tension parameters was taken into account for damage identification. In order to assess a damage development during the creep and plastic deformation the tests for both steels were interrupted for a range of the selected strain magnitudes. The ultrasonic and magnetic techniques were used as the non-destructive methods for damage evaluation. The last step of the experimental programme contained microscopic observations. A good correlation of mechanical and selected non-destructive parameters identifying damage was achieved for the tested steels. It gives very promising tool for degradation assessments appearing in pipelines at power stations.

INTRODUCTION

All kinds of materials subjected to exploitation loadings suffer variations of their mechanical properties. Depending on the working conditions the variations of some selected parameters of these materials may attain such magnitudes that their further exploitation is risky due to possible failures. Such situations are dangerous for the devices posing a major threat to environment and human security. Power plants are the typical examples. Figure 1 presents the results showing a drastic reduction of creep lifetime of the 13HMF steel used for pipeline subjected to the long time exploitation at elevated temperature (813K) under internal pressure (14 bars). To avoid an unpredictable catastrophic accidents due to such effect as that shown in Fig.1 a systematic monitoring must be carrying out.

There are many testing techniques commonly used for damage assessments. Among them we can generally distinguish destructive, and non-destructive methods. Having the parameters of destructive and non-destructive methods for damage development evaluation it is worth to analyze their variation in order to find possible correlations.

The ultrasonic and magnetic techniques were selected as the non-destructive methods for damage development evaluation. In the case of ultrasonic method the acoustic birefringence coefficient was used to identify damage development in the tested steels. In the case of magnetic technique the classical Barkhausen effect (HBE) and magnetoacoustic emission (MAE) were measured. It is shown that both magnetic parameters are sensitive on the level of material damage.

(a) (b) (c)

[1] E-mail: zkowalew@ippt.gov.pl

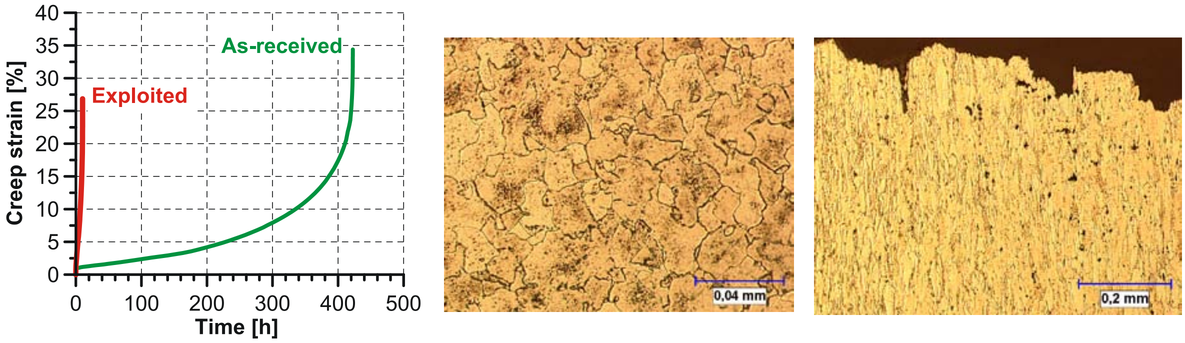


Fig. 1 Comparison of tensile creep curves (σ=230 MPa, T= 773K) for the 13HMF steel in the as-received state and after exploitation by a period of 144000 h (a), and its metalographic structures for the initial state (b) and after 144000 h of work (c)

1. DETAILS OF EXPERIMENTAL TECHNIQUE

Uniaxial tension creep tests were carried out using plane specimens for two kinds of steel, i.e. 40HNMA and 13HMF. All tests were conducted in the same conditions for each steel, i.e. the stress level was equal to 250 MPa, and temperature - 773 K. In order to assess a damage development during the process of creep the tests were interrupted for a range of the selected time periods, which correspond to the increasing amounts of creep strain. Some selected magnitudes of deformation were also applied to prestrain specimens by means of plastic flow at room temperature.

After prestraining the ultrasonic and magnetic investigations were carried out to identify a damage development in the tested steels. In the next step of the experimental procedure, the same specimens were mounted on a hydraulic servo-controlled MTS testing machine and then stretched until failure was achieved. The results of standard tensile tests were used to evaluate variation of typical mechanical parameters, i.e. Young's modulus, yield point, ultimate tensile stress. The last step of the experimental programme contained microscopic observation using optical and scanning microscopes.

In order to assess damage development during creep the tests for the 40HNMA steel were interrupted after 100h, 241h, 360h, 452h, 550h, 792h, 929h and 988h, which correspond to increasing amounts of creep strain from 0.34% up to 6.5%. In the case of 13HMF the tests were interrupted after 149h, 300h, 360h, 407h, 441h, 587h, 664h, 796h and 1720h (strain range 5.92% - 34.1%).

2. EXPERIMENTAL RESULTS OF THE DESTRUCTIVE TESTS

In order to assess damage development of the steels prestrained due to creep or plastic flow the standard tensile tests were carried out. The tensile characteristics for the tested materials after prestraining are presented in Fig. 2a for the 40HNMA steel and in Fig. 2b for the 13HMF steel. In all of these diagrams the characteristics for the prestrained steel are compared with the tensile curve of the steels in the as-received state.

On the basis of these tensile characteristics, Fig. 2, variations of the basic mechanical parameters of both steels, due to deformation achieved by prior creep or plastic flow were determined. It was observed for both materials, that the Young's modulus is almost insensitive to the magnitude of creep and plastic deformations. Contrary to the Young's modulus the other considered tension test parameters, especially the yield point and the ultimate tensile stress, Figs 3 and 4, exhibit clear dependence on the level of prestraining.

Taking into account the results presented for the 40HNMA steel in Figs 2a and 3 it is easy to note that this material exhibits a significant softening effect due to the creep prestraining, expressed by a large decrease of the yield point and ultimate tensile stress. An opposite effect can be observed for this material prestrained due to plastic deformation at room temperature. In this case the prior deformation leads to a hardening effect.

More details of investigations on the 40HNMA steel are described in [1, 2].

On the basis of tensile characteristics for the 13HMF steel after creep prestraining, Fig. 2b, it is easy to notice that the results are different than those for the 40HNMA obtained. The material exhibits a significant hardening effect for both types of prestraining, expressed by an increase of the yield point, Fig. 4a, and ultimate tensile stress, Fig. 4b. The effect is slightly weaker for the prior deformation due to creep. Such results achieved for the 13HMF steel do not allow to distinguish a type of an initial loading history in the same way as it is possible for the 40HMNA steel.

(a) (b)

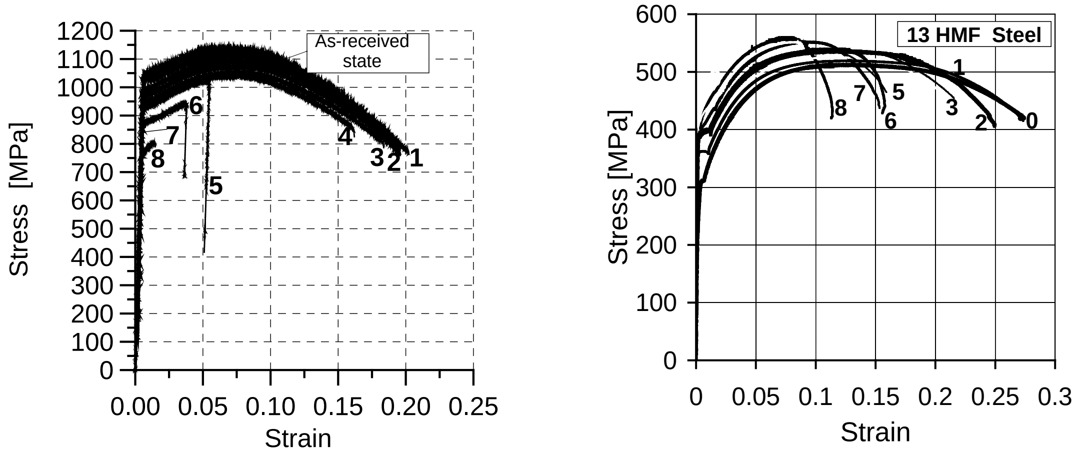


Fig. 2 Tension characteristics of: (a) the 40HNMA steel after creep for 100h (1), 241h (2), 360h (3), 452h (4), 550h (5), 792h (6), 929h (7) and 988h (8) , and (b) the 13HMF steel after creep for 149h (1), 300h (2), 360h (3), 407h (4), 441h (5), 587h (6), 664h (7), 796h (8) and 1720h (9)

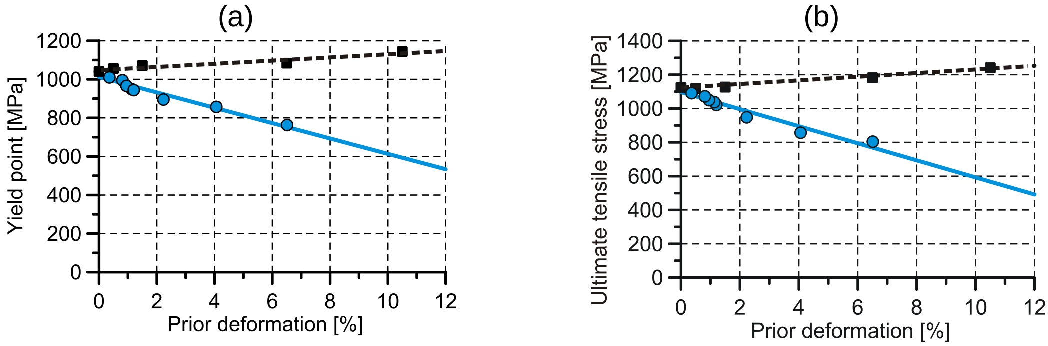


Fig. 3 Variation of the tensile parameters for the 40HNMA steel due to creep (solid lines) and plastic (broken lines) deformations: (a) yield point; (b) ultimate tensile stress

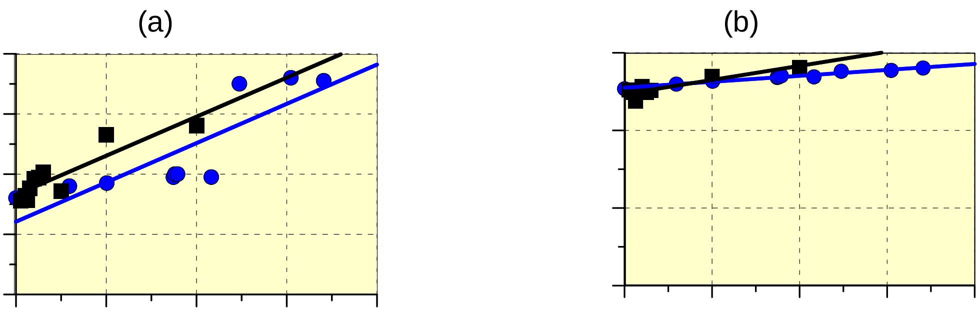


Fig. 4 Variation of tensile parameters of the 13HMF steel due to creep (solid lines) and plastic (broken lines) deformations: (a) yield point; (b) ultimate tensile stress

3. EXPERIMENTAL RESULTS OF THE NON-DESTRUCTIVE TESTS

3.1 Evaluation of damage development using ultrasonic techniques

Figure 5 presents mean values of the acoustic birefringence measured in specimens after creep or plastic deformation. The birefringence was measured in the fixtures, where the texture of the material was assumed to be unchanged during creep testing, and in the working part of the specimen. Values of birefringence measured in the fixture exhibit some scatter around zero, Fig.5a. This scatter is a picture of birefringence evaluation accuracy and the initial acoustic homogeneity of the specimen. In the deformed part of specimen the birefringence depends on the amount of deformation. It can be noticed that birefringence variations due to creep are significantly higher than birefringence scatter for the non-deformed material. The acoustic birefringence was measured at several points along the working part of each specimen, thus enabling its maximum to be found. For the maximum creep prestrained specimen, where the necking was visible, the birefringence maximum was measured in the specimen neck. For less deformed specimens, in which necking was not observed, one can expect that the birefringence maximum indicates the region of maximum micro defect concentration. These regions can be treated as the sources of future macro defects leading finally to failure. The plots presented in Fig. 5 indicate that the acoustic birefringence is sensitive to the amount of prior deformation. Another advantage of this parameter is also well represented in Fig. 5a. Namely, it is very sensitive to the form of prior deformation. This feature is especially well revealed in the case of the birefringence determined for the 40HNMA steel, Fig. 5a. For specimens prestrained due to creep the increase of this parameter is observed with the increase of prior deformation. An opposite effect was achieved for specimens prestrained due to the plastic deformation at room temperature, i.e. with the increase of prior deformation a decrease of the birefringence was obtained. The effects obtained for the 40HNMA steel were not confirmed by the ultrasonic tests carried out on the 13HMF steel. In this case the same tendency may be observed independently on a type of prior deformation, i.e. degrease of the acoustic birefringence with an increase of deformation level. It has to emphasized however, that such effect corresponds in some way to that which can be observed on basis of the results of destructive tests presented in the previous section. More details concerning the results and testing technique are available in [3-5].

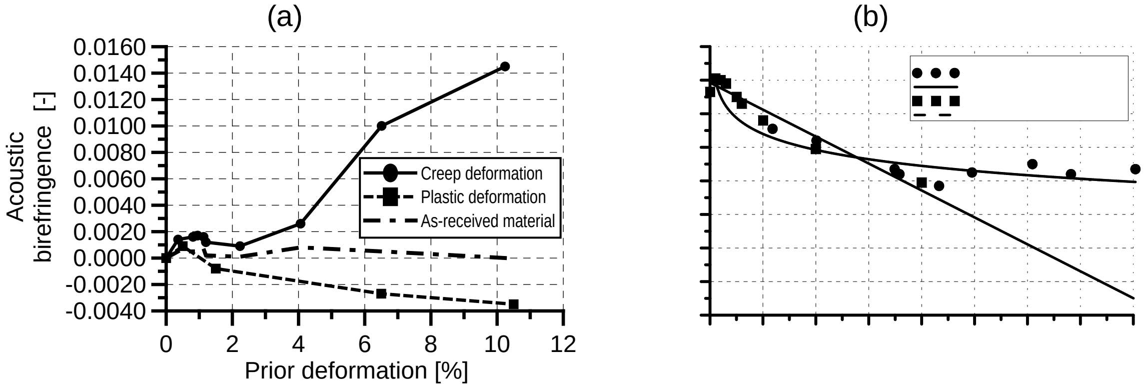


Fig. 5 Acoustic birefringence B variations due to prior deformation for: (a) 40HNMA steel; (b) 13HMF steel

3.2 Evaluation of damage development using magnetic techniques

Two magnetic techniques for non-destructive testing were applied, i.e. measurement of Barkhausen effect (HBE) and magneto-acoustic emission (MAE) [6-8]. Both effects are due to abrupt an movement of magnetic domain walls depicted from microstructural defects when sample is magnetised. The samples at laboratory tests were magnetised by the solenoid and a magnetic flux generated in the sample was closed by C-core like shaped yoke. Magnetizing current (delivered by current source) had a triangular like waveform and frequency of order 0.1 Hz. Its intensity was proportional to the voltage *Ug*. Two sensors were used: (a) the pickup coil (PC), and (b) the acoustic emission transducer (AET). Voltage signal induced at PC was used for magnetic hysteresis loop *B*(*H*) evaluation (low frequency component) as well as for HBE analysis (high frequency component). Intensity of HBE is given by rms (root mean square) voltage *Ub* envelopes. In this case the maximum (Ub_{pp}) of *Ub* for one period of magnetisation is compared. Analogue analysis is performed for MAE voltage signal from the AET. The magnetic coercivity *Hc*, evaluated from the *B*(*H*) hysteresis loop plots, is also compared. An influence of plastic flow and creep damage on the basic magnetic properties can be analysed using *B*(*H*) hysteresis loops. The representative results showing variations of the *B*(*H*) hysteresis loops are presented in Figs 6 and 7 for the 13HMF steel. The curves obtained for an undamaged specimen (ε = 0%) and for all the damaged ones are compared. The quantity *Ug* denotes the voltage proportional to the driving current intensity, and hence – magnetic field strength *H*. The as described features of the HBE intensity are well presented by means of plots showing a dependence between the amplitudes of *Ub* envelopes and magnitudes of prior deformation - peak to peak values Ub_{pp} in Fig. 8. Thus, one can say that the HBE intensity as a function of the resulting prestrain peaks firstly and then decreases monotonicaly when amplitudes of the *Ub* envelopes are compared. The curves in Fig. 8 reveal also that creep damage leads to a smaller 'decrease' of the HBE intensity than that observed for specimens after plastic flow. Comparing two plots in the figure it can be seen that the *Ub* signal properties such as the amplitude for the highest strain after creep damage are roughly the same as for the analogous signals for the last stage of plastic flow.

A synthetic description of the MAE properties as a function of prior deformation is given by plots shown in Fig. 9 (amplitudes of the MAE envelopes). Amplitudes of the MAE intensity decrease for both cases but the dynamics of their change is different.

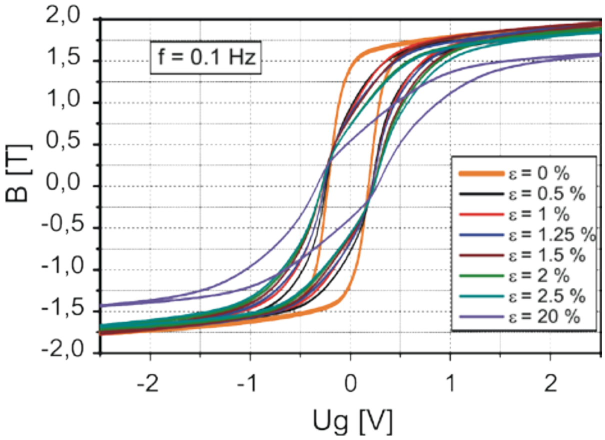


Fig. 6 Magnetic hysteresis loops of undamaged and damaged specimens due to plastic flow of the 13HMF steel

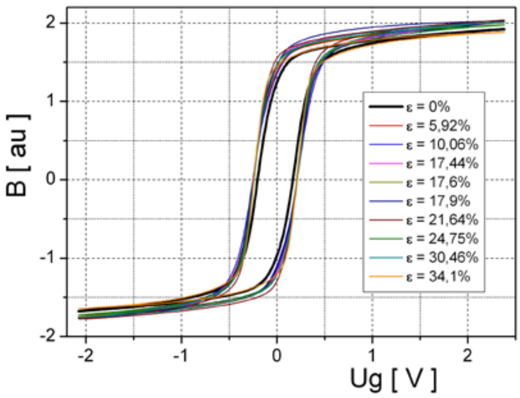


Fig. 7 Magnetic hysteresis loops of undamaged and damaged specimens due to creep of the 13HMF steel

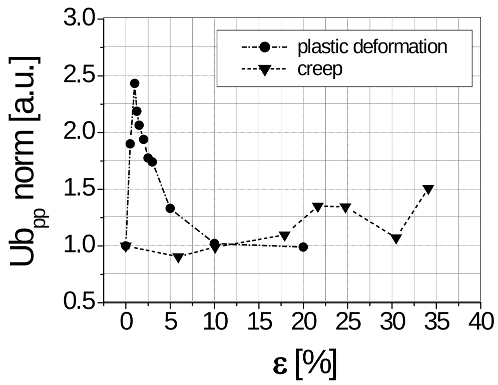


Fig. 8 Relation between the amplitudes of Ub envelopes and prior deformation due to plastic flow (circles) and creep (triangles)

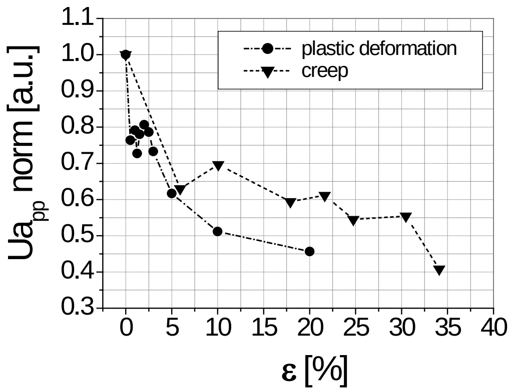


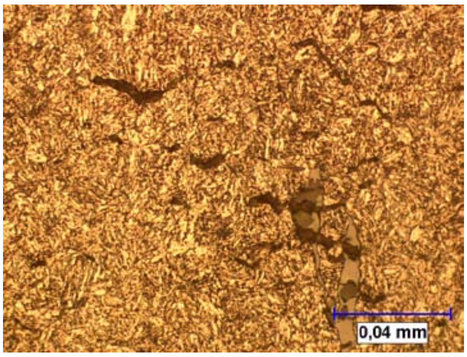
Fig. 9 Relation between amplitudes of Ua envelopes and prior deformation due to plastic flow (circles) and creep (triangles)

4. IDENTIFICATION OF DAMAGE USING METALLOGRAPHIC OBSERVATIONS

In the final step of the experimental programme microscopic observations were carried out. The metallographic assessments were performed by means of optical microscope (Olympus PMG3 - in macro- and micro- ranges) as well as by means of scanning electron microscopy (SEM - JEOL 6360 LA) techniques [9]. All observations were done in non-etched and etched state. The effect of voids formation was observed along the longitudinal metallographic sections prepared from specimens after completion of the mechanical tests. Then, the selected geometrical parameters of existing voids were determined by means of the image analysis in the optical microscopy range. The following parameters were determined: depth of void [mm], mean area fraction of voids (A_A [%]) related to the unit area of metallographic sample (1 mm^2) and mean quantity of voids - N_A [1/mm^2], Fig. 10b.

The comparison of microstructural effects in the 40HNMA steel and determined geometrical parameters show the greatest damage at test 8 (Fig. 2), Fig. 10. It is characteristic that the voids dimensions are bigger in the perpendicular direction with respect to the specimen axis than those observed parallel one. For lower magnitudes of prior creep deformation the damage was connected rather with the nonmetallic inclusions. In all these cases the fragmentations of existing nonmetallic inclusions, and subsequently, voids formation were observed. The microstructure for all specimens was the same, i.e. sorbite with remaining the needle martensite configuration.

(a) (b)



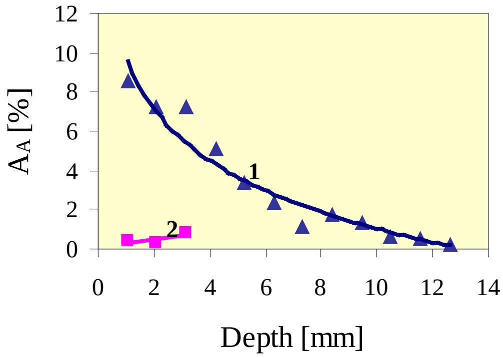


Fig. 10 Microstructural observations of the 40HNMA: (a) strong damage close to fracture surface, magnification 500x; (b) changes of the void area fractions (A_A [%]) as a function of distance from the fracture surface for 40HNMA steel deformed due to: (1) creep up to 6.5%; (2) plastic flow up to fracture (19%)

CONCLUSIONS

The results show that ultrasonic and magnetic parameters can be good indicators of material degradation and can help to find the regions where material properties are changed due to prestraining.

In order to evaluate damage progress in specimens made of the 40HNMA and 13HMF steels, instead of velocity and attenuation measurement typically used in ultrasonic investigations, the acoustic birefringence *B* measurements were succesfully applied.

In the case of magnetic investigations for damage identification the measurements of the Barkhausen effect (HBE) and the magneto-acoustic emission (MAE) were applied. Both effects show that the magnetic properties are highly influenced by prior deformation, and moreover, they are sensitive not only to the magnitude of prior deformation, but also to the way it is introduced.

ACKNOWLEDGEMENT

The support from the National Centre for Research and Development (Poland) under grant NR 15-0049-04/2008 is greatly appreciated.

REFERENCES

[1] Kowalewski Z.L., Szelążek J., Mackiewicz S., Pietrzak K., Augustyniak B. *International Journal of Modern Physics Letter B*, Vol. 22, No 31/32, p. 5533, 2008.

[2] Kowalewski Z.L., Szelążek J., Mackiewicz S., Pietrzak K., Augustyniak B. *Journal of Multiscale Modeling*, Vol. 1, No 3&4, p. 479, 2009.

[3] Kowalewski Z.L., Mackiewicz S., Szelążek J., Deputat J. *Proc. of XXI Symp. on Experimental Mechanics of Solid Body*, ed. J. Stupnicki, Warsaw University of Technology, 2004.

[4] Mackiewicz S., Kowalewski Z.L., Szelążek J., Deputat J. *Mechanical Review*, Vol. 7/8, p. 15, 2005.

[5] Szelążek J., Mackiewicz S., Kowalewski Z.L. *NDT and E International*, Vol. 42, p. 150, 2009.

[6] Sablik M.J., Augustyniak B. *Wiley Encyclopedia of Electrical and Electronics Engineering*, ed. J.G. Webster, J. Wiley&Sons, New York, 1999.

[7] Augustyniak B., Chmielewski M., Sablik M.J. *IEEE- Trans. on Magnetics*, Vol. 36, No. 5, p. 3624, 2000.

[8] Augustyniak B., Chmielewski M., Piotrowski L., Kowalewski Z. *IEEE Transactions on Magnetics*, Vol. 4, No. 11, p. 3273, 2008.

[9] Pietrzak K., Kowalewski Z.L., Rudnik D., Wojciechowski A. *Proc. of the XIV International Symposium on Plasticity and Its Current Applications*, ed. A. Khan, NEC Press, Baltimore, 2008.