ASSESSMENT OF MATERIAL DEGRADATION OF POWER STEELS USING DESTRUCTIVE AND NON-DESTRUCTIVE TESTING METHODS

Zbigniew L. Kowalewski (1, 2), **Tadeusz Szymczak**(2),
Katarzyna Makowska(2), **Bolesław Augustyniak**(3)

[1] *Institute of Fundamental Technological Research*
Warsaw, Poland,
[2] *Motor Transport Institute, Warsaw, Poland,*
[3] *Gdańsk University of Technology, Gdańsk, Poland*

An analysis of creep damage at elevated temperatures and structural degradation due to plastic deformation at room temperature is presented on the basis of tests on steels commonly applied in power plants (13HMF and P91). The materials were tested in the as-received state. Destructive and non-destructive testing methods were applied to assess material degradation. As destructive methods the standard tension tests were carried out after every kind of prestraining. The ultrasonic and magnetic techniques were used as the non-destructive methods for damage evaluation. A good correlation of mechanical and selected non-destructive parameters identifying damage of tested steels was achieved.

Key Words: *destructive test, non-destructive test, mechanical parameters variations, power steels*

1 Introduction

Depending on the working conditions the variations of selected mechanical parameters of engineering materials may attain such magnitudes that their further exploitation is risky due to possible damage development. Such situations are dangerous for the devices encountered in many branches of the industry. Power plants are the typical example. 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).

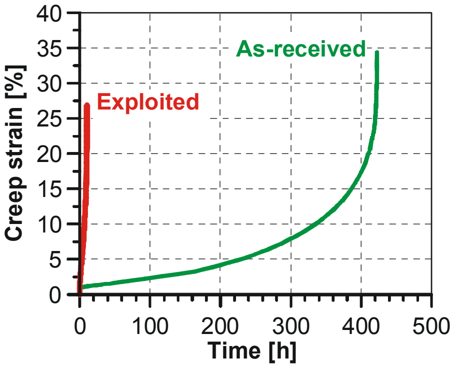

Figure 1. Comparison of tensile creep curves (σ = 230 MPa, T = 773K) for the 13HMF steel in the as-received state and after exploitation by a period of 144 000 h.

To avoid an unpredictable catastrophic accidents 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 a damage degree. Applying magnetic technique the classical Barkhausen effect (HBE) and magnetoacoustic emission (MAE) were measured.

2 Destructive tests

As destructive methods the standard tension tests were carried out after prestraining of materials. Subsequently, an evolution of the selected tensile parameters was taken into account for damage identification. In order to assess a damage development during the creep and plastic deformation the tests on steels were interrupted for a range of selected strain magnitudes. The representative results of tensile tests for the P91 and 13HMF are presented in Figs 2, 3, respectively. Taking into account the results presented for the P91 steel it is easy to note that this material in terms of typical stress parameters is almost insensitive on creep prestraining, i.e. the yield point and ultimate tensile stress variations are rather small. Only the extension is reduced significantly.

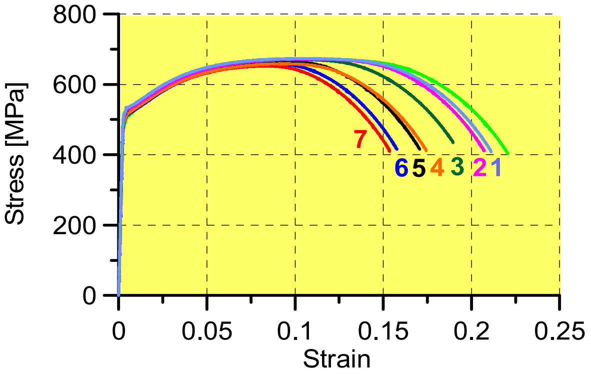

Figure 2. Tensile characteristics after creep prestraining of the P91 steel: 40h (1), 180h (2), 310h (3), 390h (4), 425h (5), 440h (6) and 445h (7).

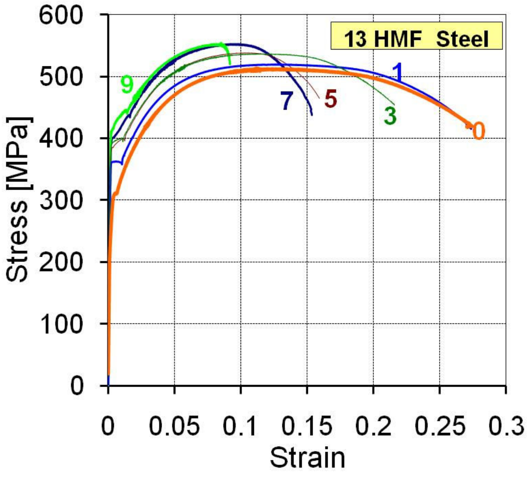

Figure 3. Tensile characteristics after creep prestraining of the 13HMF steel: 149h (1), 360h (3), 441h (5), 664h (7) and 1720h (9).

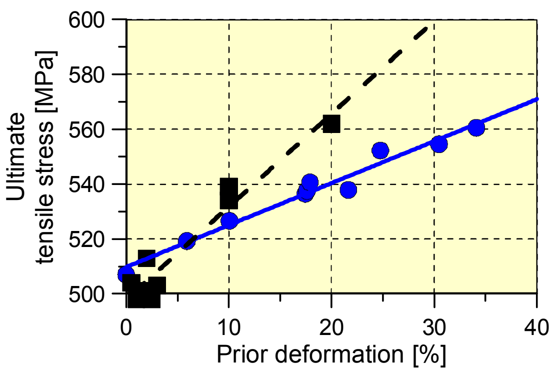

Figure 4. Variation of ultimate tensile stress of the 13HMF steel (broken line - plastic prestrain, solid line - creep prestrain).

An opposite effect can be observed for the 13HMF steel (Fig. 3) prestrained in the same way (creep conditions). In this case a prior deformation leads to the hardening effect. For all steels in question the same effect was achieved in the case of prestraining induced by means of plastic deformation at room temperature, i.e. the hardening. A representative result is presented in Fig. 4 for the 13HMF steel, where variation of the ultimate tensile stress with an increase of prior deformation is shown.

3 Non-destructive tests

The ultrasonic and magnetic techniques were used as the non-destructive methods for damage evaluation. Some selected results of such investigations are shown in Figs 5, 6 for the 13HMF steel.

Two magnetic techniques for non-destructive testing were applied, i.e. measurement of Barkhausen effect (HBE) and magneto-acoustic emission (MAE) [1-4]. 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, Fig. 5. 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.

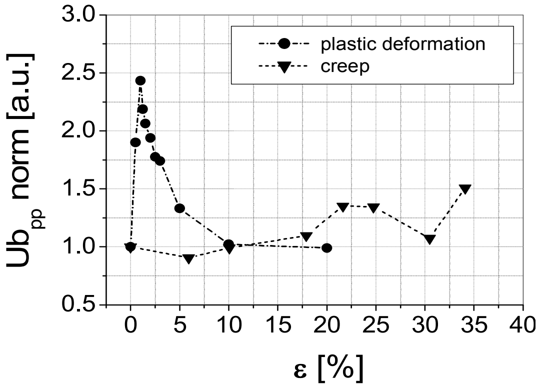

Figure 5. Variations of Barkhausen effect (Ub_{pp}) of the 13HMF steel.

An interesting feature of the material behaviour may be observed in Fig. 5. The curves 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.

Figure 6 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. Here it 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.

Another advantage of this parameter was achieved in the case of the 40HNMA investigations [1, 2]. Namely, it was very sensitive to the form of prior deformation. For specimens prestrained due to creep the increase of this parameter was 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 appeared 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. a decrease of the acoustic birefringence with an increase of deformation level.

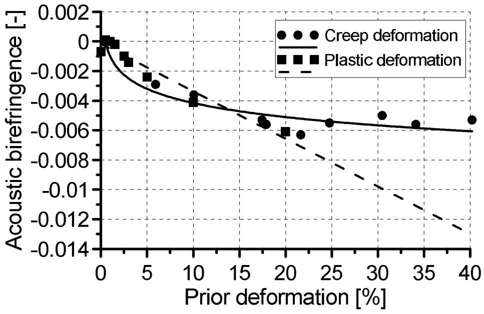

Figure 6. Acoustic birefringence as a function of prior deformation level for the 13HMF steel.

4 Relationships between the yield point and damage sensitive parameters of NDT tests

Having parameters of destructive and non-destructive methods of damage assessments their mutual relationships were considered in order to find their character. The representative results are presented in Figs 7-9 for the 13HMF steel, and in Figs 10-12 for the P91 steel.

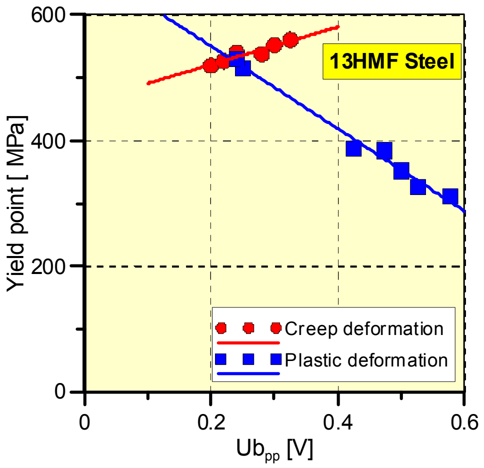

Figure. 7. Relationship between yield point and amplitudes of Ub envelopes (peak to peak values - Ub$_{pp}$).

As it is seen the yield point variation exhibits with good agreement the linear relationships with respect to the damage sensitive parameters of selected non-destructive methods. The same result was also achieved for the ultimate tensile stress.

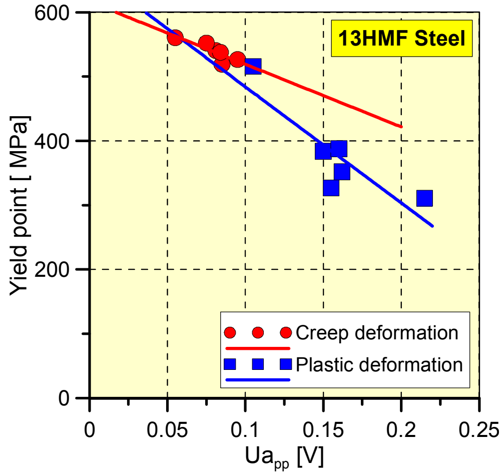

Figure. 8. Relationship between yield point and amplitudes of Ua envelopes (peak to peak values - Ua$_{pp}$).

Knowledge of such behaviour of the materials tested enables better predictions of the remaining lifetime of industrial elements on the basis of non-destructive monitoring of exploited constructions, and as a consequence, provides a basis for new promising experimental method of damage analysis.

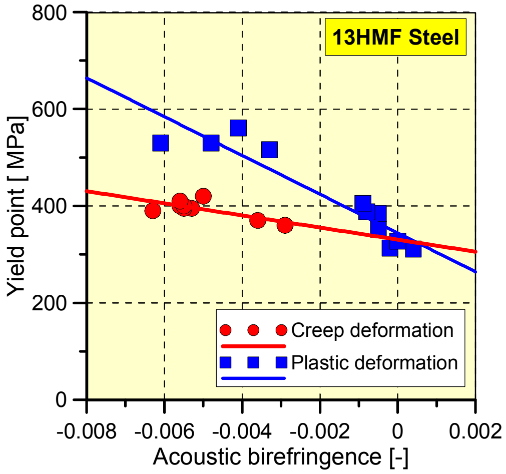

Figure. 9. Relationship between yield point and acoustic birefringence.

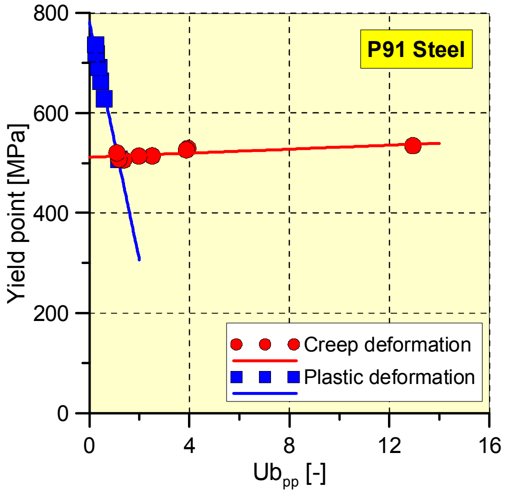

Figure. 10. Relationship between yield point and amplitudes of Ub envelopes (peak to peak values - Ub_{pp}).

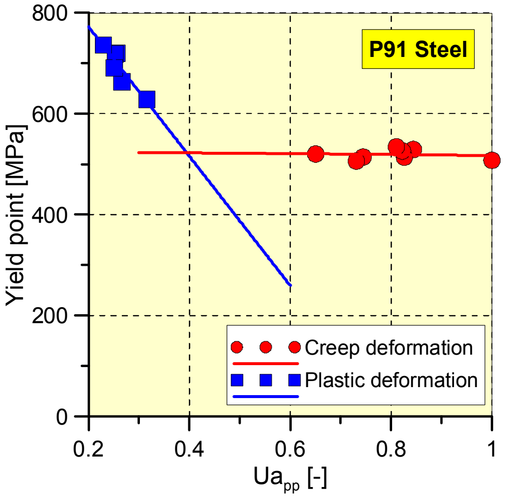

Figure. 11. Relationship between yield point and amplitudes of Ua envelopes (peak to peak values – Ua_{pp}).

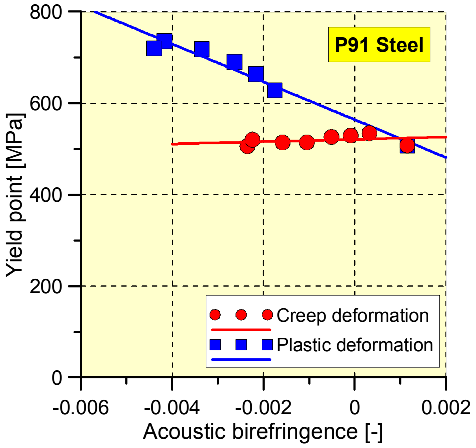

Figure. 12. Relationship between yield point and acoustic birefringence.

5 Conclusions

In order to evaluate damage progress in specimens made of the steels tested the acoustic birefringence measurements was successfully applied. In the case of magnetic investigations the measurements of the Barkhausen effect (HBE) and the magneto-acoustic emission (MAE) were applied. It is shown that magnetic parameters used as a measure of these effects are sensitive not only to the magnitude of prior deformation, but also to the way of its introduction. The linear relationships were obtained between destructive and non-destructive damage sensitive parameters.

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., 2008, ”International Journal of Modern Physics Letter B”, 22, No 31/32, 5533.

(2) Kowalewski, Z.L., Szelążek, J., Mackiewicz, S., Pietrzak, K., Augustyniak, B., 2009, “Journal of Multiscale Modeling”, 1, No 3&4, 479.

(3) Sablik M.J., Augustyniak B., Wiley Encyclopedia of Electrical and Electronics Engineering, ed. J.G. Webster, J. Wiley&Sons, New York, 1999.

(4) Augustyniak B., Chmielewski M., Piotrowski L., Kowalewski Z., IEEE Transactions on Magnetics, 4, no 11, 3273, 2008.