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EVALUATION OF DAMAGE DEGREE OF INCONEL 718 USING NONDESTRUCTIVE INDICATORS OF DAMAGE

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Abstract

This paper presents the results of the quantitative evaluation of the degree of damage caused by plastic strain accumulated in static tensile tests and creep tests. To detect changes in the structure of the material and in order to determine the degradation of the materials, nondestructive methods were used, namely the ultrasonic and eddy current methods. In ultrasonic testing, attenuation and acoustic birefringence were used as damage indicators. In the case of the eddy current method, changes in the phase angle of impedance were observed in the material. The material tested was Inconel 718 alloy. Inconel alloys are often find application in extreme working conditions including in the power engineering industry, aviation and aerospace. A new type of specimen with the variable cross-sectional area of the measuring part was used in the tests. This allowed researchers to obtain a continuous distribution of plastic strain and enabled analysis of the material with respect to different damage degrees. The correlation between the degree of damage, expressed by the measure of deformation, and the value of nondestructive indicators was determined. On the basis of it, the dependence indicating the ability to nondestructive evaluation of the degradation degree of the material, subjected to loads exceeding the yield limit was obtained.

Keywords: damage parameter, nondestructive testing, Inconel 718.

INTRODUCTION

In engineering materials and structures, damage to the material can be defined as a decrease in resistance to destruction. Fatigue damage of the material is caused by cyclic loading and increases with the number of cycles in a cumulative way, which in effect may lead to the destruction of the object.

The difficulty of measuring the degree of damage of the material under load is related to a lack of well-defined measure of damage, the local character of the damage process, and different mechanisms of damage associated with the generation and types of loads and operating conditions. Depending on the character of damage in the material, or on the definition of destruction, the effectiveness of damage parameters can vary. Selection of an appropriate damage parameter is of key importance to modeling failure or life prediction. The measure of damages does not have a universal character. They are selected depending on the stage of development of defects, and may involve different mechanisms of defects' generation, and different stages of process failure and destruction.

Methods of measuring material damage are based on the assumption that there is a correlation between the degree of damage and the measurable physical quantity called damage indicator. Usually, the damage indicator is directly chosen out of a number of the mechanical quantities of interest, while the measuring parameters are selected from either mechanical or physical quantities. In order to determine the degradation of the material, both destructive and nondestructive methods are used. An important advantage of nondestructive methods is that they do not require taking a sample of the material from the tested object to determine its material properties. In this work, the ultrasonic and eddy current method were selected to detect changes in the structure of the material. In ultrasonic testing, attenuation of ultrasonic waves and acoustic birefringence were used as indicators of damage. In the case of the eddy current method, change in the phase angle of impedance in the material was selected as a damage indicator.

THE TEST MATERIAL AND SPECIMENS

Inconel 718 was the material used to test and evaluate the degradation. Inconel is a family of alloys of austenitic crystal structure based on nickel and chromium. These superalloys are characterized by high heat resistance, strength and creep resistance at high temperatures, surface stability and resistance to corrosion and oxidation. Therefore, Inconel alloys are typically applied in extreme working conditions including in the power engineering industry, aviation and aerospace.

In order to obtain a certain degree of deformation of the material samples, static tensile tests and creep tests were carried out. To investigate the material's degradation, a new type of specimen with variable cross-sectional area of the measuring part (Fig. 1.) was used. This allowed researchers to obtain a continuous distribution of plastic strain in that part of the specimen. The deformation that varies along the axis of the sample enables analysis of damage induced by plastic deformation. The proposed method enables replacing a series of specimens with a single sample. The test method and specimen are protected by patent.

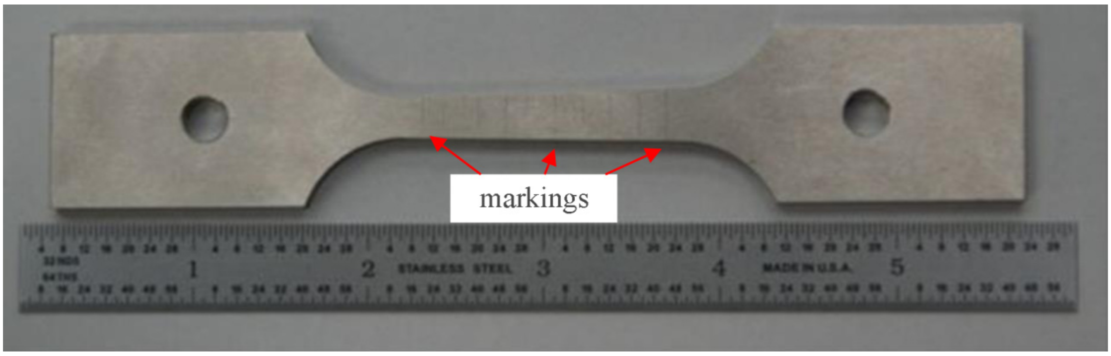

Fig. 1. Specimen used to test degradation of Inconel 718.

EVALUATION OF A DAMAGE DEGREE OF INCONEL 718

After the tests, the measurements of permanent deformations in the directions of width and thickness of the specimen were performed. Then, from the condition of incompressibility of the material, the deformation values were calculated in the direction of the sample's axis. Based on the calculated deformation values, the values of a damage parameter D were calculated using the model of Johnson:

$$D = \sum \frac{\Delta\varepsilon}{\varepsilon^f} \tag{1}$$

where: $\Delta\varepsilon$ is the permanent deformation in the direction of the axis of the sample,
ε^f is the final parameter value corresponding to the breaking of the sample.

Figure 2 shows the distribution of the damage parameter calculated as the function of the distance from the fracture after the test (the distance from the smallest cross-section). The value of $\Delta\varepsilon$ in the marked places $\Delta\varepsilon_i$ was calculated from the relation:

$$\Delta\varepsilon_i = -\left(\frac{a_i - a_0}{a_0} - \frac{b_i - b_0}{b_0}\right) \tag{2}$$

where: a_0 is the width of the specimen in the marked place *i* before strength tests,
a_i is the width of the specimen in the marked place *i* after strength tests,
b_0 is the thickness of the specimen in the marked place *i* before strength tests,
b_i is the thickness of the specimen in the marked place *i* after strength tests.

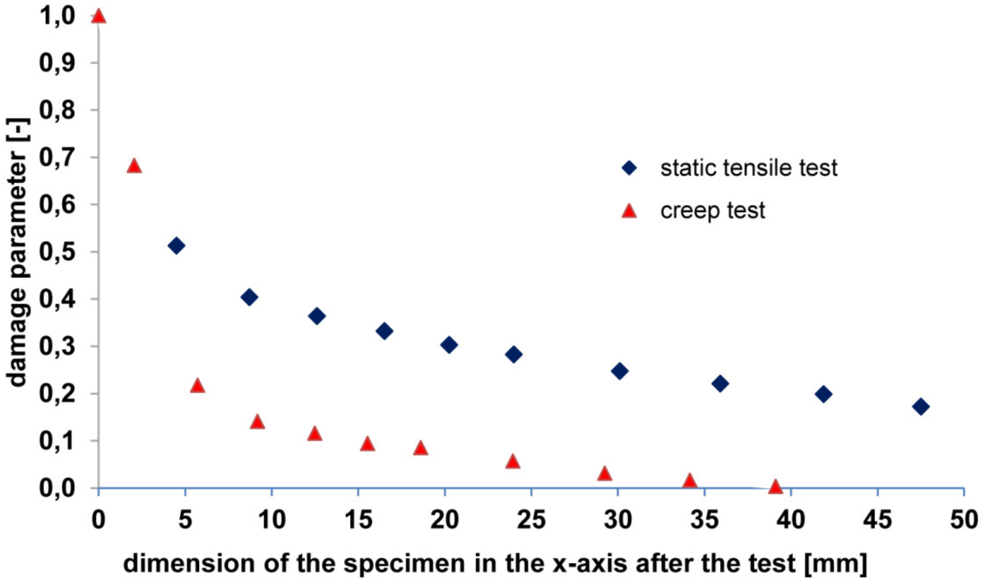

Fig. 2. Damage parameter as the function of the distance from the fracture for a specimen after static tensile test and after creep test.

EVALUATION OF A DAMAGE DEGREE IN INCONEL 718 USING THE ATTENUATION COEFFICIENT OF ULTRASONIC WAVES

The amplitude of the ultrasonic wave propagating in the material decreases with increasing distance. This phenomenon is associated with acoustic attenuation – loss of acoustic energy that occurs between any two points of travel. This loss is mainly due to scattering and absorption mechanisms and to geometric factors. Scattering in metallic materials is caused by very small discontinuities, such as precipitation, and also by larger areas such as grain boundaries. Dislocation along with magnetic and thermoelastic damping are major types of absorption mechanisms. Geometric factors include diffraction, beam spreading and coupling losses.

The measurement of ultrasonic attenuation (dB) or of the attenuation coefficient (dB/mm) allows nondestructive determination of certain material conditions and properties. Attenuation measurements may be a factor when the material is highly attenuative and the critical flaw size rather small. Attenuation mesurements are usually used to verify material uniformity and to assess material properties.

Prior to creep tests and the static tensile tests, the attenuation coefficient of ultrasonic waves was measured. The average values of the attenuation coefficient in the measuring part of individual specimens fell in the range of 0.12-0.13 dB/m – the biggest difference between the mean values of the coefficient did not exceed 0.01 dB/mm. The differences of the attenuation coefficient measured along the x axis for individual samples did not exceed 0.04 dB/mm. Figure 3 shows the values of the attenuation coefficient in the measuring part of the specimens before strength tests.

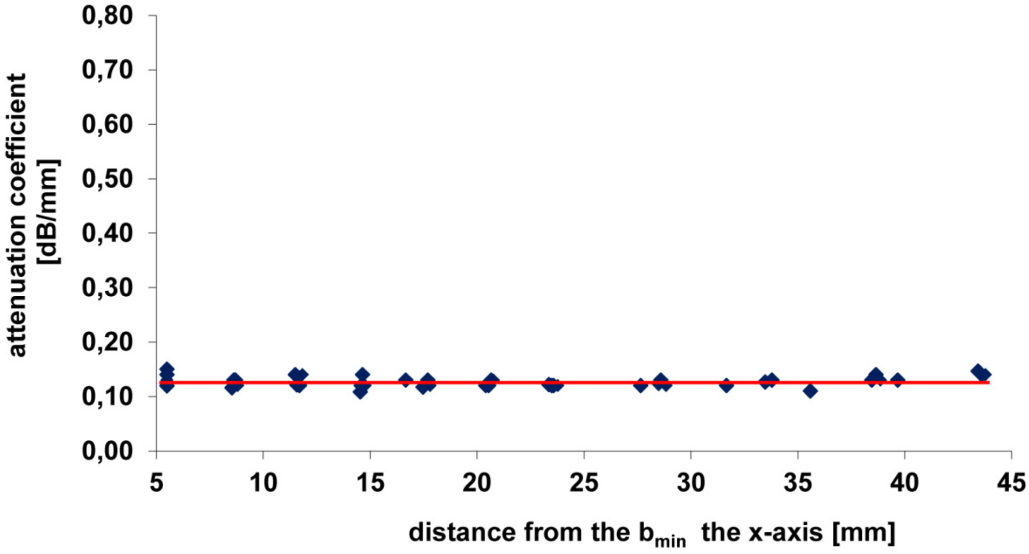

Fig. 3. The values of the attenuation coefficient in the measuring part of the specimens before testing.

The attenuation coefficient of the material, after degradation caused by creep or tensile tests, was differ than before testing. After creep testing, there was approximately a twofold increase in the value of the attenuation coefficient in the measurement part of the specimens. The damage parameter values in this area fell in the range of 0 – approx. 0.13 (Fig. 4.). However, the increase in the coefficient values in this area, despite some monotonicity, was characterized by local fluctuations. There was a large increase in the coefficient only for the damage parameter values of approx. 0.18, so in the measured area near the fracture.

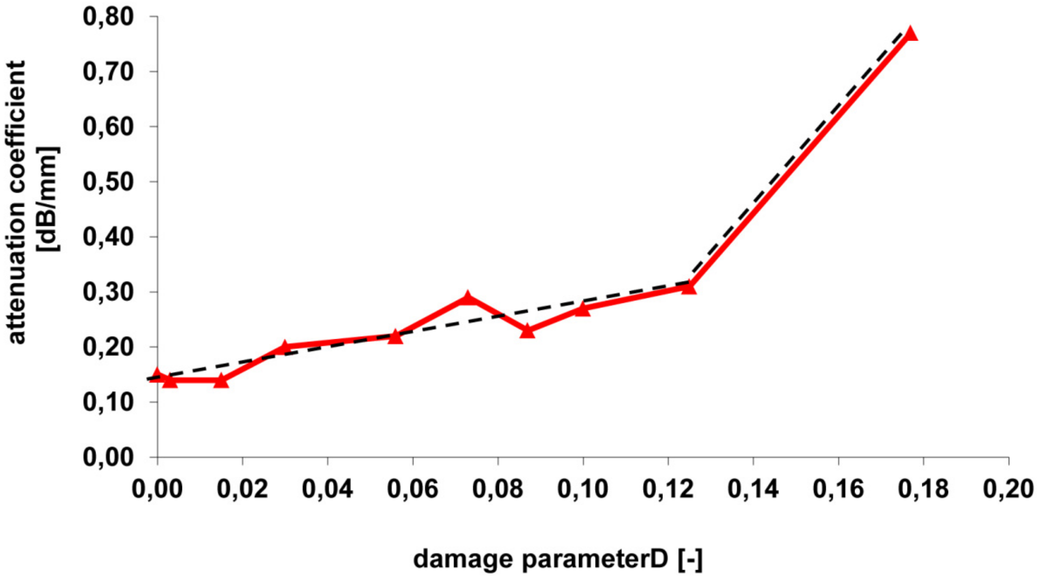

Fig. 4. The values of the attenuation coefficient in the measuring part of the specimens after creep tests.

After static tensile tests, changes in the value of the attenuation coefficient depending on the damage parameter can be divided into a few stages (Fig. 5.). In the measuring part for damage parameter lesser than D ~ 0.25, the value of the attenuation factor, despite some variations, remained at a constant level, higher than those for the samples prior to destructive testing by about approx. 30%. While at the second stage, with the degradation of the material above D ~ 0.25 an approximately linear increase in the value of the attenuation was observed. For values of D ~ 0.37 this increase amounted to approx. 75%. Next, in the third measurement area for the damage parameter D = 0.41, the value of attenuation coefficient was around four times higher than for the specimens before the static tensile tests.

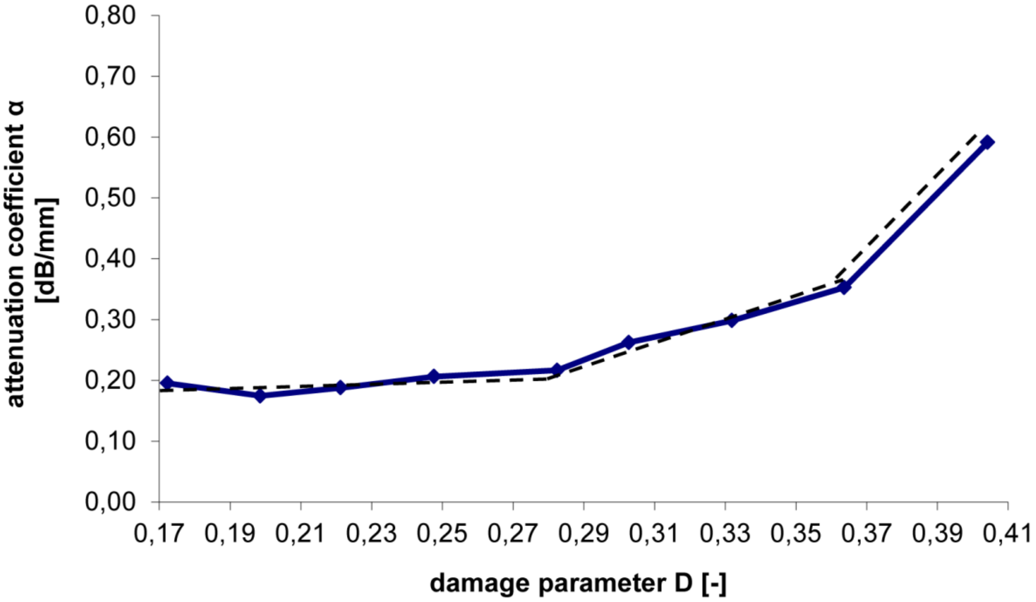

Fig. 5. The values of the attenuation coefficient in the measuring part of the specimens after static tensile tests.

EVALUATION OF A DAMAGE DEGREE OF INCONEL 718 USING ACOUSTIC BIREFRINGENCE

The anisotropy of the elastic properties are manifested by different velocities of the propagation of ultrasonic waves in the material. These speeds are dependent on the direction of wave propagation in the material or on their polarity. This type of anisotropy is known as acoustic birefringence. Acoustic anisotropy of the material may be characterized by the values of the algebraic combinations of different types of wave velocity in different directions of propagation and of different polarities.

The speed of transverse waves propagating in the thickness direction was measured at two mutually perpendicular positions of the ultrasonic probe, i.e. mutually perpendicular polarization of waves. In the tests, an ultrasonic probe with a frequency of 4MHz was used.

The coefficient of birefringence, is defined by the following relation:

$$B = \frac{V_{T2} - V_{T1}}{0{,}5\left(V_{T2} + V_{T1}\right)} \tag{3}$$

where: V_{T1}, V_{T2} – velocity of transverse waves propagating in the direction of the specimen thickness and polarized in mutually perpendicular directions.

The measurements of acoustic birefringence were carried out before strength tests – static tensile tests and creep tests. The average value of birefringence in the measuring part was -0.0151, and the difference value of birefringence for the individual areas was lesser than 0.0013. Figure 6 shows the values of birefringence in the measuring part of specimens before strength tests.

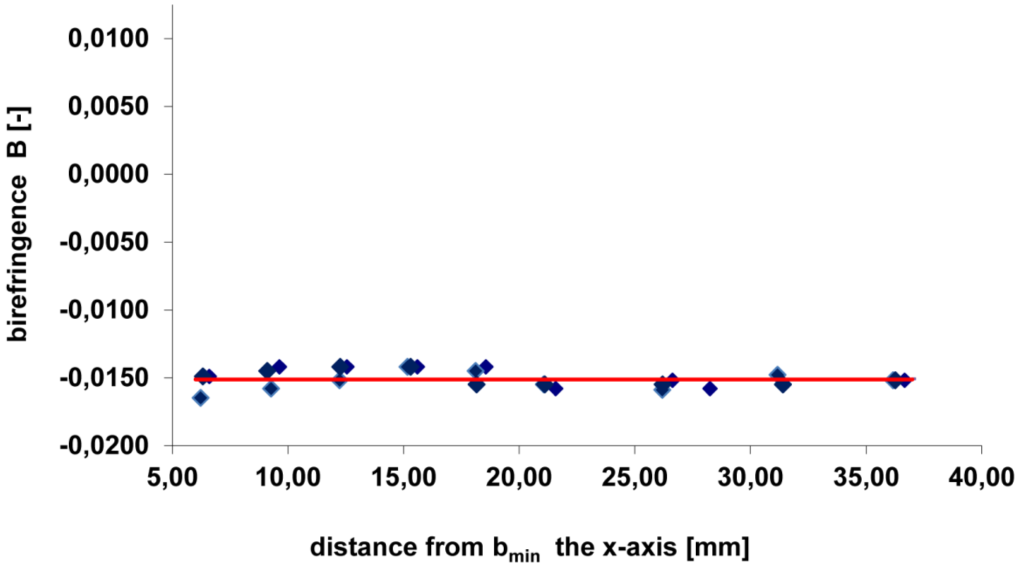

Fig. 6. The values of birefringence in the measuring part of the specimens before testing.

The values of acoustic birefringence after static tensile tests fell in the range from -0.0127 to 0.0026 for the measuring areas with the greatest degree of damage. Across the whole of the measuring part the change in birefringence totaled 0.0153. The results of tests for the measuring part are shown in Figure 7.

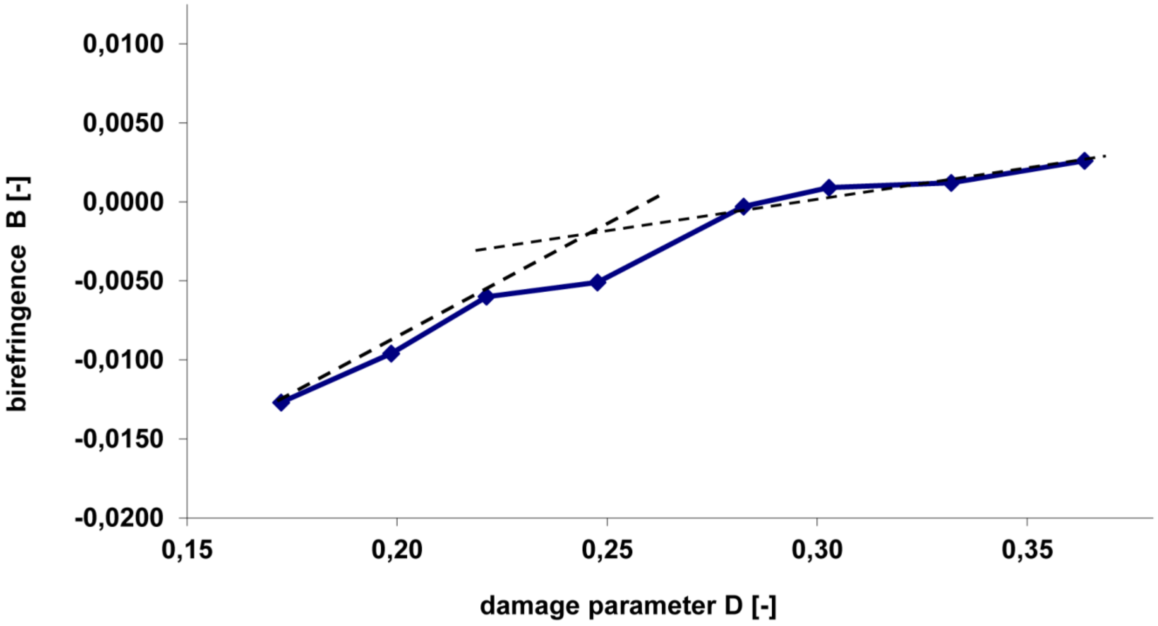

Fig. 7. Changes of birefringence after static tensile tests in the measuring part depending on the damage parameter.

For the specimens after a creep tests, changes of acoustic birefringence fell in the range from -0.0148 to -0.0122. The value of birefringence was the lowest in the gripping part. In the measuring part there was a slight increase reaching the maximum in the highest value of the parameter of damage. In the measuring part the increase in birefringence totaled 0.0029. Figure 8 shows the change of birefringence B as a function of damage parameter D in the measuring part of the specimen.

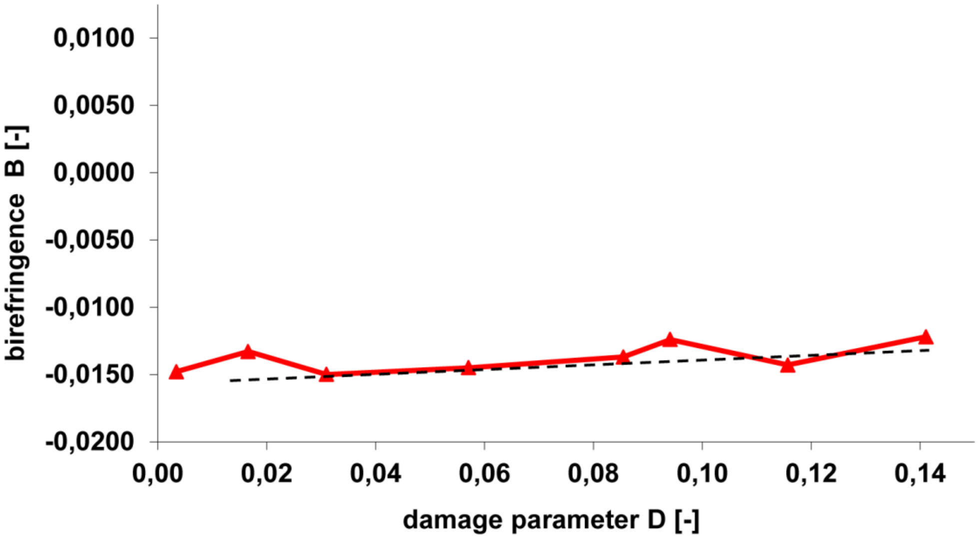

Fig. 8. Changes of birefringence after creep tests in the measuring part depending on the parameter of damage.

EVALUATION OF A DAMAGE DEGREE OF INCONEL 718 USING THE EDDY CURRENT PHASE ANGLE

The eddy current method is used for materials which show electrical conductivity. It can be performed both on ferromagnetic and non-ferromagnetic materials. The method makes possible to detect surface and subsurface discontinuities such as cracks and corrosion and can be also used to measure coating thickness and to compare the structure of materials. The eddy current method can be used to detect discrete defects in metallic materials and to assess selected conditions and material properties. It is also becoming more widely used for research and evaluation of changes in the physical properties of materials. The degradation of the material microstructure associated with the development of local plastic deformation leads to changes in the phase angle of complex impedance of the eddy current in the material. The phase angle value of eddy currents in the material depends mainly on the electrical conductivity and magnetic permeability of the material. Subtle changes in these parameters due to either the change in stress or a local change in the composition or density of the material affect a change of the phase angle. Measuring the phase angle shift allows not only to assess the stress changes, but it also yields information about changes in the properties and/or the microstructure resulting from the degradation processes.

Measurements of the angle phase in specimens before strength test was performed for evaluating the homogeneity of the measured parameter over the entire surface of the sample. Tests were performed at the frequency of the electromagnetic coils between 50-150 kHz, allowing to obtain depth of the eddy currents penetration into the test material, suitably 2.53 mm and 1.46 mm. The frequency was chosen so that the depth of penetration did not exceed the thickness of the specimen in the smallest cross section. The phase angles on the specimens before, and next, after strength tests were measured.

For the specimens before strength tests, the value of the phase angle was approximately constant. The differences in the measuring parts of specimens fell within the range of 1.3° (Fig. 9.).

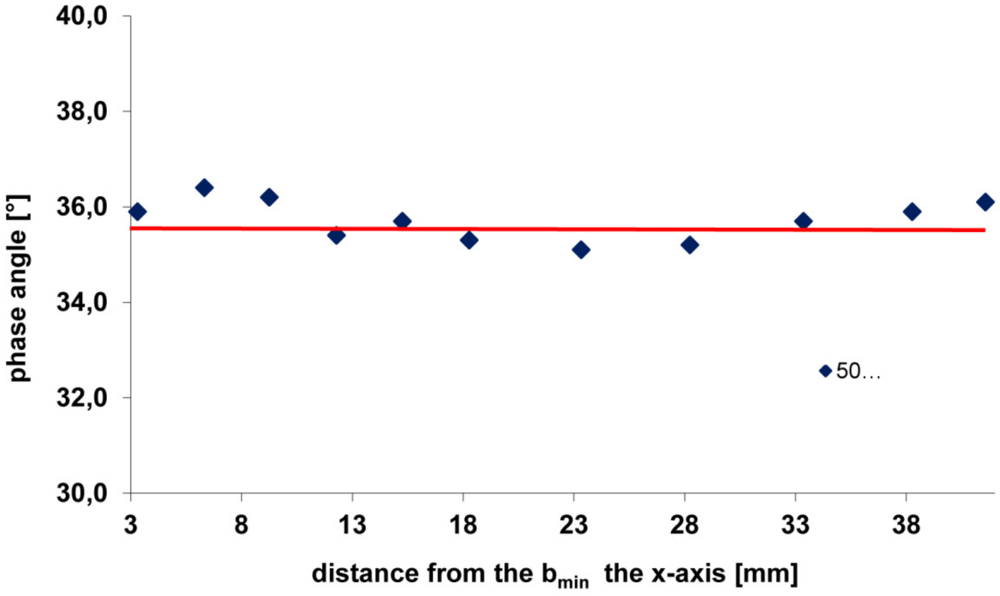

Fig.9. The values of the phase angle in the measuring part of the specimens before testing.

In the case of specimens after creep testing, the changes in the phase angle had a similar distribution to that of the specimens prior to creep testing (Fig. 10.). But the obtained degree of deformation in the measurement part was limited to the value of the damage parameter D = 0.22 at a distance of 5.71 mm from the fracture.

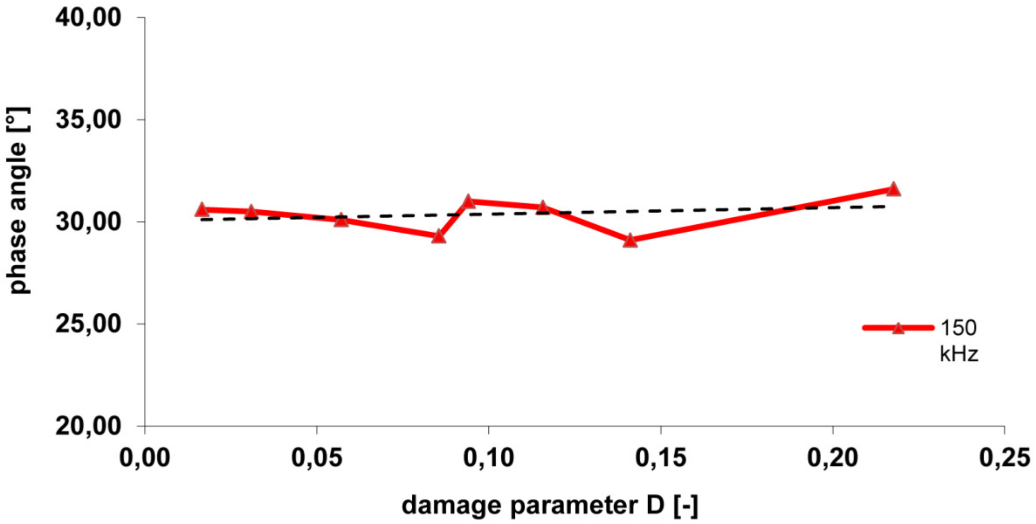

Fig. 10. The values of the phase angle in the measuring part after creep tests

Figure 11 shows changes in the angle phase impedance depending on the value of the damage parameter of the material after static tensile tests. For the measurement purposes, the eddy current transducers with frequencies of 50 kHz and 150 kHz were used. For both frequencies, it was found that the value of the phase angle decreased while the damage parameter increased. For the entire sample, a decline in the value of the phase angle was approx. 25° and 10° for the frequencies of 150 kHz and 50 kHz, respectively. In both cases, there are two stages of the changes in the phase angle. In areas of damage parameter below D ~ 0.25 there are smaller changes of the angle phase and smaller stability of the direction of change. Above D ~ 0.25 decrease in the value of the phase angle is dynamic and almost linear (large changes of value, greater stability of direction changes). The described stages of the changes in the phase angle indicated by broken lines in Figure 11.

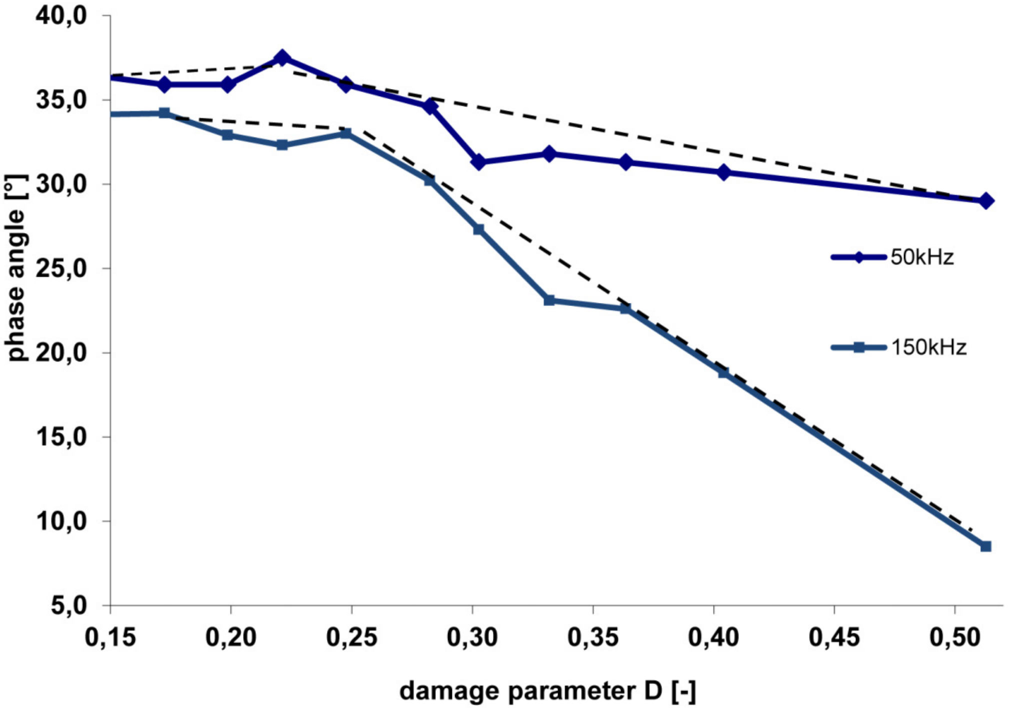

Fig. 11. The values of phase angle in the measuring part of the specimens after static tensile tests.

SUMMARY AND CONCLUSIONS

Inconel 718 was the material used to test and evaluate the degree of the material's degradation. For the tests, specimens with a variable cross-sectional area of the measuring part were used. In order to obtain a certain deformation of the material, static tensile tests and creep tests were carried out. To evaluate the degree of damage to the material, the nondestructive indicators were used. With an increasing degree of material deformation, changes in the values of the nondestructive indicators were received. The changes in damage indicators after the tensile tests were definitely higher than those after creep tests. Also, the deformations of the material estimated by the parameter of damage were lesser for the specimens after creep testing than after static tensile testing.

In the case of the attenuation coefficient, for deformation caused by creep and static tensile tests, the damage indicators increased significantly in the areas close to the fracture.

A acoustic birefringence of the material subjected to creep tests increased slightly. The maximum increase in the value of the birefringence was approx. 20% compared to the state before the test. Changes in the value of birefringence for the specimens after creep tests had the character of local increases and decreases. Upon subjecting the material to static tensile testing the values of acoustic birefringence increased approx. 100% compared to the state before the tests. The increases in birefringence were approximately proportional to the increase in the damage parameter.

The measurements results of the phase angle of eddy currents showed a nearly linear decrease in their values with an increase in the damage parameter of the material. This only applies to the material after static tensile tests. In the case of specimens after creep tests (small value of damage parameter) there was no change of the phase angle – there were only local fluctuations recorded.

To summarize, all three indicators showed changes in damage degree of the material subjected to degradation. The increase in the attenuation coefficient was observed following strength tests in all areas of the samples. However, its significant growth occurred at in the final stage of the process of destruction. The high dynamics of changes in the phase angle was found at about the damage parameter above D = 0.25, while acoustic birefringence changed significantly at earlier stages of destruction.

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