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TESTS OF DAMAGE TO INCONEL 718 ALLOY USED IN AVIATION

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Abstract

Inconel 718 alloy was tested. A new type of specimens of variable cross-sectional area measuring part was used for the tests. This provided a continuous distribution of plastic strain in that part of the sample. The proposed method enables to replace a series of specimens by one specimen. The degradation of the material was obtained by static tensile test and the creep test. The permanent deformation that varies along the specimen axis allows for an analysis of damage induced by a plastic deformation. The degradation of the alloy corresponds with the changes of acoustics properties of the material - attenuation of ultrasonic waves. It allows to determine the degree of damage to the material using a non-invasive - ultrasonic method. Using the damage parameter proposed by Johnson allows to obtain correlation between the non-destructive results and a damage degree of the material. The presented testing method delivers information about changes in the material structure caused by permanent deformation.
Keywords: material degradation, ultrasonic wave attenuation factor, damage parameter, non-destructive testing.

1. MEASURES AND INDICATORS OF THE MATERIAL DAMAGE DEGREE

In experimental studies on the process of damage and failure of the material the material test methods, both destructive and non-destructive ones, are used. An important advantage of non-destructive methods is the fact that they do not require sampling of the material from the tested object in order to determine a degree of damage.

One of the first concepts of measuring the material damage was to introduce the maximum surface density of microcracks for planes perpendicular to a selected axis of the coordinate system in a representative unit of the material volume as an indicator of damage. The damage is defined in this case as a ratio of the sum of surfaces of voids and cracks lying on the distinguished critical plane to the critical plane area [1]. The damage parameter D is within the range of <0.1>, where 0 means the undamaged material, and 1 stands for material failure.

In the methods of measuring the material damage, the correlation of its damage degree with a measurable physical quantity, previously called the indicator of damage, is assumed. The applied material damage indicators are related to the observation of various kinds of changes in the material, such as: surface, mechanical properties, microstructural and physical quantities. In the group of changes in the material physical quantities, it is possible to distinguish the assessment of structural changes recorded through non-destructive tests, such as: eddy current methods, X-ray computed tomography and ultrasonic methods. They involve the monitoring of changes in the material physical quantities caused by the influence of specified physical fields, which do not result in permanent changes in the tested material properties. In case of eddy currents, it is, e.g. the impedance change resulting from a change of electrical conductivity and the material permeability. In case of the computed tomography, it is spatial reconstruction of recorded changes in absorption of X-ray radiation passing through the tested material. As far as ultrasonic tests are concerned, they can include changes in an acoustic attenuation coefficient of the material related to the structure degradation.

By analysing the possibilities of using a given technique of non-destructive tests for the assessment of the material damage degree, it is possible to determine the correlation between changes in the microstructure and changes in the physical field response, which affects it. Fig. 1 shows the possibility of using particular non-destructive techniques depending on the length of the microstructure defects.

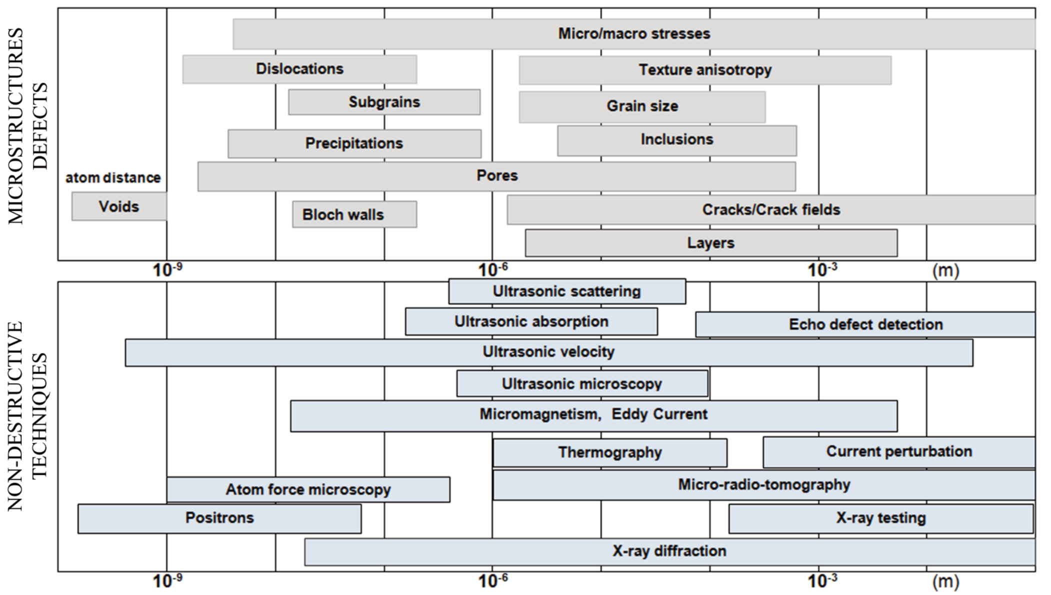


Fig.1. The lengths of the microstructure defects and the possibility of using non-destructive techniques in steel based on [2, 3]

2. ATTENUATION OF ULTRASONIC WAVES

Ultrasonic tests are among the most commonly used non-destructive methods in defectoscopy. They constitute a basis, together with the radiographic tests, with a volumetric method, that is a method mainly used for assessing the object internal structure – detection of material, technological and operational defects. The physical basis in testing with the use of an ultrasonic method includes phenomena of the impact of acoustic waves with the frequency of > 20 kHz (ultrasonic waves) with the tested material. The analysis of changes to a waves propagating in the tested object provides information on the material physical condition – tests allow to detect structural discontinuities, but also to determine their size and location. Moreover, a choice of the appropriate type of waves makes it possible to detect the internal structure discontinuities, as well as sub-surface and surface discontinuities. Apart from defectoscopy, the ultrasonic tests are used for assessing the material physical properties. The ultrasonic techniques are more and more frequently applied in the assessment of the material degradation degree. The damage parameter can be determined by measuring the attenuation coefficient of ultrasonic waves propagating in the material.

Together with an increase in the distance, the pressure amplitude of a wave propagating in the material decreases. This is due to the losses related to the beam spread, as well as the processes of energy dispersion and absorption. The beam weakening associated with absorption and dispersion is referred to as attenuation. It depends on a type and condition of the material, in which this wave propagates. For each material, it is possible to determine the attenuation coefficient of ultrasonic waves. It means reduction of the pressure amplitude per unit of the wave path length in a given medium, on which this reduction occurs. The attenuation coefficient is expressed for a given material in dB/m or dB/mm.

The factors affecting the attenuation of waves can be divided into two basic groups: the first one is formed of factors of a structural nature, and the second one – factors of a geometric nature. The group of structural factors, the so-called absorption, is associated with irreversible processes, absorption and transmission of energy, and its conversion into heat. In case of metals, the group of factors with a geometric nature, generally called the wave scattering, fundamentally affects the weakening of the wave intensity. They are associated with the dispersion process of waves at the material grain boundaries, and also with anisotropy. The orientation of grains, which exhibits different elastic properties, for various directions in the material is random. Furthermore, the scattering is the result of macroscopic defects, inclusions of foreign bodies, material cracks, and voids. This part of the beam energy, which was scattered, does not turn into heat, but it propagates in the material in different directions. The wave attenuation coefficient α can be expressed as the sum of two components α_t - structural associated with absorption and α_r - geometric related to the scattering of waves at the grain boundaries and heterogeneity. The absorption (structural) coefficient α_t is proportional to the frequency f and mainly depends on the chemical composition [4,5]. It is usually lower than a scattering factor, which constitutes the main part of the attenuation coefficient in polycrystalline metals. The geometric (scattering) coefficient α_r of waves by monocrystalline grains strongly depends on the size of grains and the frequency of waves. This coefficient is also affected by elastic constants of anisotropic grains and orientation of grains [4]. The scattering factor for grains, much smaller than the wave length, is proportional to the grain size and the wave frequency, however, for gains much larger than the length of waves, it does not depend on the frequency and is inversely proportional to the size of grains [5].

3. SPECIMENS FOR TESTING INCONEL 718 ALLOY DEGRADATION CAUSED BY PERMANENT DEFORMATION

Inconel 718, an age-hardened nickel-chromium alloy, is characterised by high heat-resistance, strength and resistance to creep at high temperatures, good surface stability and resistance to corrosion and oxidation. It is the material used in the aerospace industry and also in the automotive and energy industry. Inconel 718 is also commonly applied in cryogenic tanks, shafts and drilling heads.

The tests were carried out for a batch of six specimens of Inconel 718 alloy (Fig. 2). The ultrasonic measurements of the attenuation coefficient were performed on the specimens prepared for tensile and creep tests. By the creep test (three specimens) and the tensile testing (three specimens), the material degradation was introduced. Then, the attenuation coefficient measurements, the measurements of permanent deformation, as well as the microstructure analysis and fractographic examinations were performed again.

Fig. 2. Test specimen from Inconel 718 alloy [9]

A new type of specimens with the gage part of a variable cross-sectional area (Fig. 3), applied for testing the material structure damage, allows to obtain a field of deformation which changes along the axis of the specimen. Determination of permanent deformation in a given cross section of the specimen, in conjunction with an analysis of the structure of this place, allows to investigate the evolution of the material structure damage caused by its permanent deformation. Therefore, a series of specimens in the tests can be replaced with one specimen. The test method and the specimen were registered in the Patent Office [6].

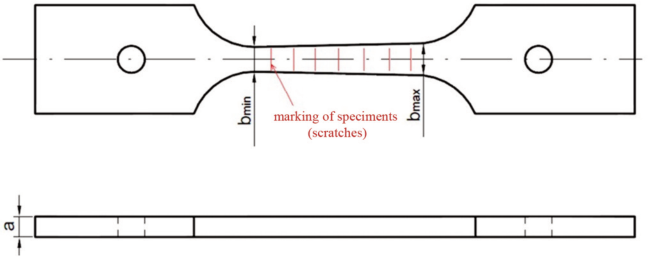


Fig. 3. Specimen for testing Inconel 718 alloy degradation [6]

In the marked cross sections of specimens, the measurements of permanent deformation were performed for specimens after creep tests and after tensile testing in the direction of the specimen width and thickness. Then, on the basis of the material incompressibility condition, the deformation in the direction of the specimen axis was calculated Based on the obtained deformation, damage parameters *D* were determined in accordance with the relationship provided by Johnson [7]:

$$D = \frac{\Delta\varepsilon}{\varepsilon^f} \quad (1)$$

where: $\Delta\varepsilon$ – permanent deformation, in the direction of the specimen axis, ε^f – final deformation, corresponding to the specimen rupture.

Figure 4 shows the distribution of a damage parameter, calculated in this manner, as the function of distance from b_{min} (minimum width of the specimen) on specimens after tensile testing and the creep test [8].

The damage parameter, expressed by a measure of local deformation, on both graphs, changes with the distance from b_{min}. It allows for quantitative assessment of the degradation state for any place on the specimen. Therefore, it is possible to correlate the obtained results with the results of non-destructive tests with the use of a ultrasonic method – measurements of the material acoustic attenuation coefficient.

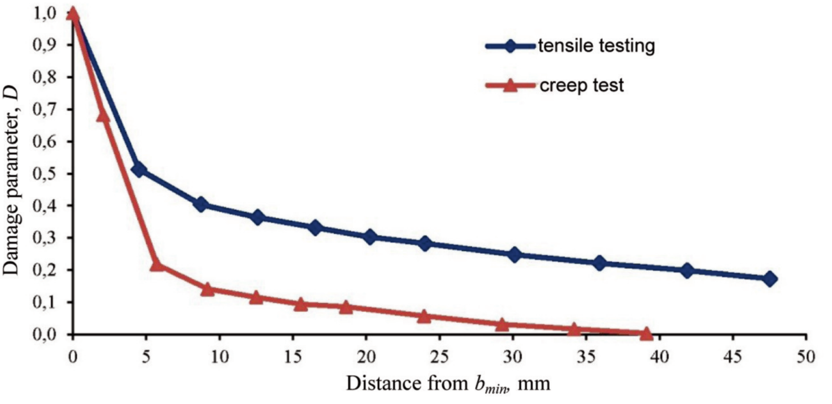


Fig. 4. Damage parameter in the distance function from b_{min} for the specimen after strength tests [8]

4. ATTENUATION COEFFICIENT DEPENDENCE ON INCONEL 718 ALLOY DEGRADATION DEGREE

The ultrasonic measurements of the attenuation coefficient were performed on the specimens before tests and in the marked areas after the tests, for which *D* parameter was calculated. Phasor XS flaw detector equipped with a transducer with the frequency of 13 MHz was used for testing.

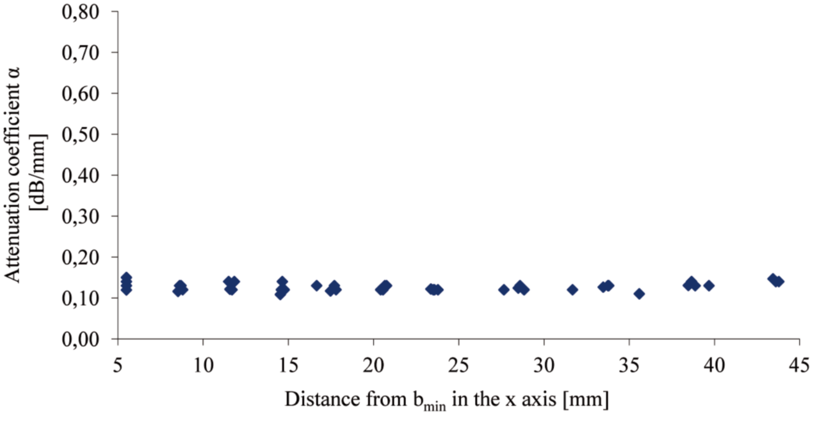


Fig. 5. Values of the attenuation coefficient of specimens intended for strength tests [9]

Figure 5 shows the measurement results of the attenuation coefficient in the marked places for the specimens intended for strength tests. The distances, provided in the ultrasonic test results, refer to the centre of the face surface of the transducer – in the below cases, it is a distance in the x axis of the specimen between the smallest width b_{min} of the specimen and the centre of the face surface of the transducer. The obtained average values of the attenuation coefficient for the entire measuring range of individual specimens are in the range of 0.12 ÷ 0.13 dB/mm – the greatest difference of average values between specimens does not exceed 0.01 dB/mm. However, the differences in values of the attenuation coefficient measured along the x axis in the marked places of the measuring range of individual specimens do not exceed 0.04 dB/mm. The distribution of the attenuation coefficient's values along the x axis for each sample does not indicate its dependence on the measurement place.

Thus, there was no influence of changes in the geometry of specimens (variable width of the measuring part) on the attenuation coefficient value. The differences in the obtained values of the attenuation coefficient may result from non-homogeneity of the material and accumulated measurement errors, including those related to coupling conditions.

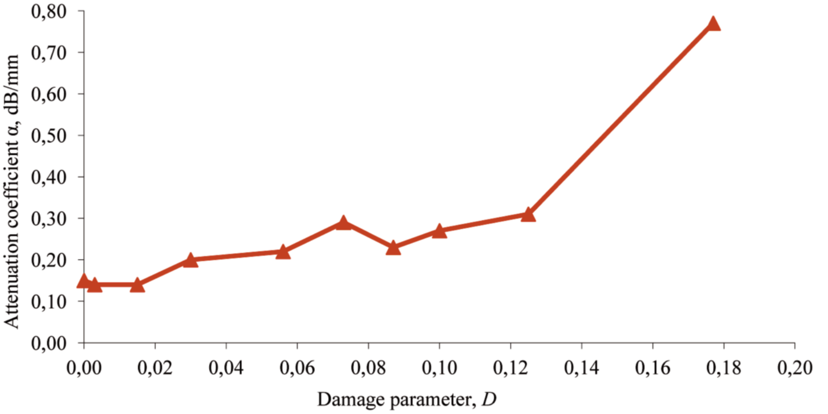


Fig. 6. Attenuation coefficient depending on the damage parameter after creep tests [9]

The material attenuation coefficient, both after degradation by creep, and also after tensile testing, changed in relation to the attenuation coefficient before the tests. The average material attenuation coefficient before tests was approx. 0.13 dB/mm. No effect of the specimen shape (variable width of the gage part) on the obtained material attenuation coefficients was found.

For Inconel 718 alloy subjected to creep tests, attenuation coefficient α increased to approx. 0.30 dB/mm for the area with the damage parameter $D = 0.13$ (Fig. 6). However, starting from $D > 0.03$, the attenuation coefficient was $\alpha > 0.20$ dB/mm. Then, together with the increase in D damage parameter (within the range of approx. 0.13), there were both increases and decreases in the attenuation coefficient within the range of 0.20 ÷ 0.30 dB/mm. A significant increase in the attenuation coefficient to approx. 0.77 dB/mm occurred only in the area closest to the fracture.

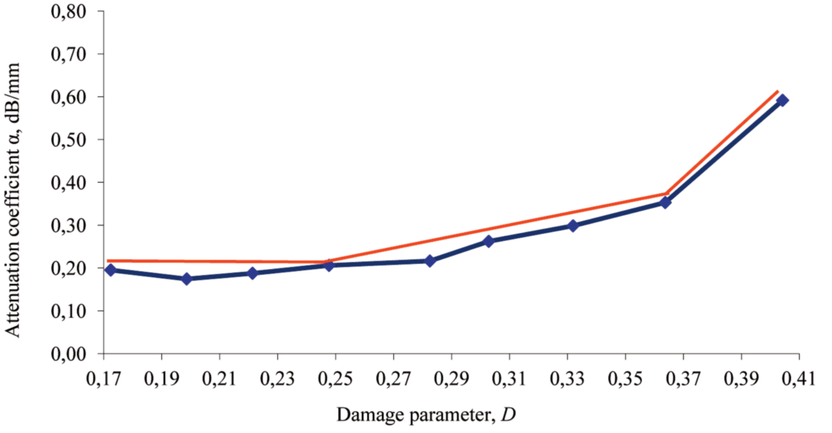


Fig. 7. Attenuation coefficient depending on the damage parameter after tensile testing [9]

For Inconel 718 alloy subjected to tensile testing, greater damage parameters D were obtained in the gage parts of specimens - 0.17÷0.40 than for the material after creep tests - 0.00 ÷ 0.18. In this case, the attenuation coefficient changes depending on the material damage degree can be divided into three stages marked with solid lines on the graph (Fig. 7). In the first stage, below $D \sim 0.25$ parameter, the attenuation coefficient is maintained at the average level of 0.20 dB/mm with local increases and decreases. In the second stage, starting from $D \sim 0.25$ parameter, there is an almost linear increase in the attenuation coefficient, which increases up to approx. 0.35 dB/mm. This corresponds to the increase of parameter D by approx. 50% ($D \sim 0.37$). This attenuation coefficient is a greater by approx. 150% than for the base material, and by approx. 75% greater in relation to the coefficient in the first stage. In the third stage, for the measurement area nearest to the fracture, for damage parameter $D > 0.40$, there is a significant increase in the attenuation coefficient up to approx. 60 dB/mm - that is approx. 70% in relation to the maximum one obtained in the second stage.

5. STRUCTURAL ANALYSIS AND FRACTOGRAPHIC EXAMINATIONS

Inconel 718 alloy specimens after strength tests were subjected to fractographic examinations, structure analysis and X-ray computed tomography.

The fractures of specimens, both after tensile testing (Fig. 8), and after creep tests (Fig. 9), had a nature of ductile fractures. The plastic deformation and holes, at the bottom of which there are carbide particles, were visible. The presence of voids at the grain boundaries was also found.

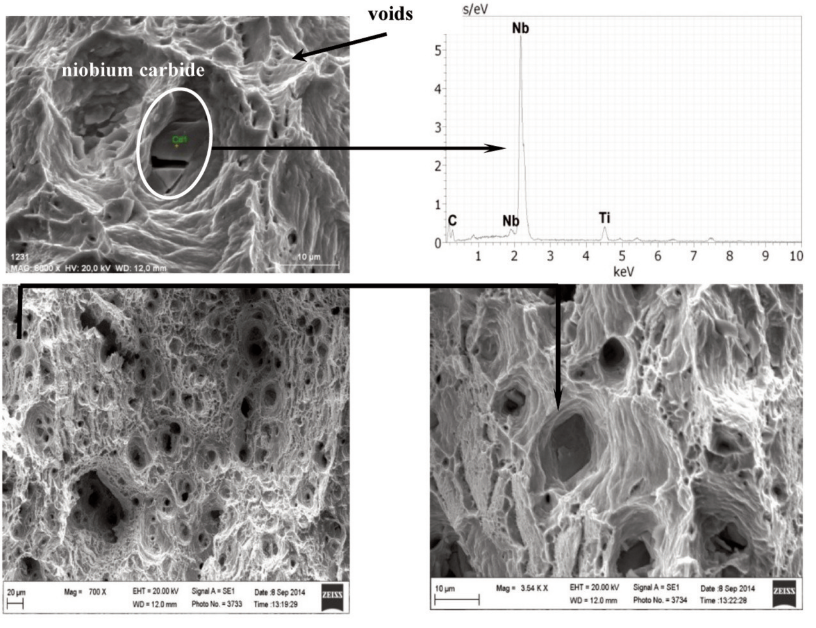


Fig. 8. Images of the specimen fracture after tensile testing [9]

The surface roughness of the majority of the measurement area of specimens after creeping was approximately constant and its significant increase occurred only in the fracture zone (Fig. 10). For the material after tensile testing, roughness increased proportionally with decreasing the distance from the fracture, and its significant increase occurred also in the fracture zone (Fig. 11).

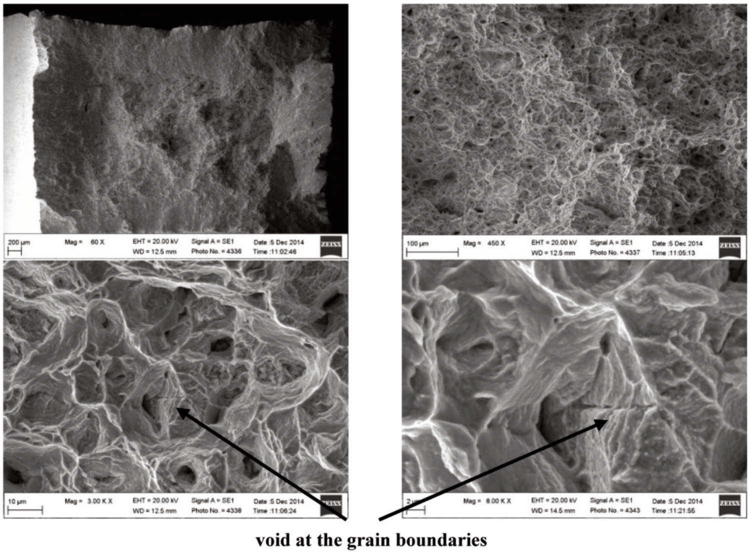


Fig. 9. Section of the specimen fracture after the creep test [9]

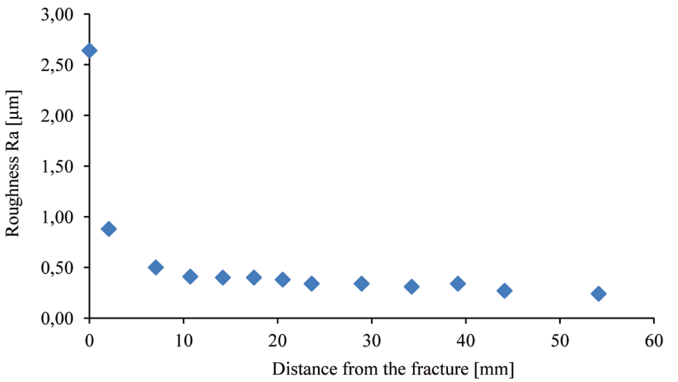


Fig. 10. Results of the roughness measurements for the specimen after creep tests [9]

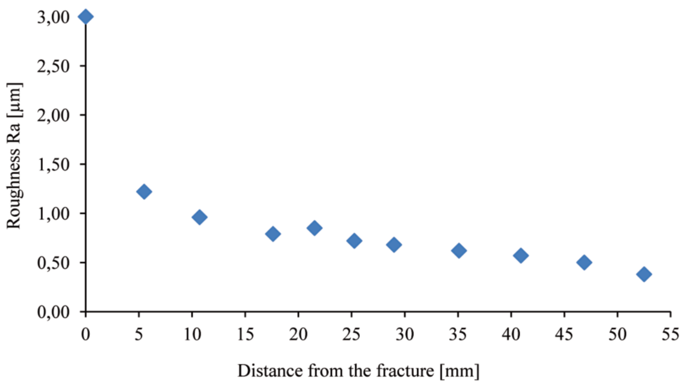


Fig. 11. Results of the roughness measurements for the specimen after tensile testing [9]

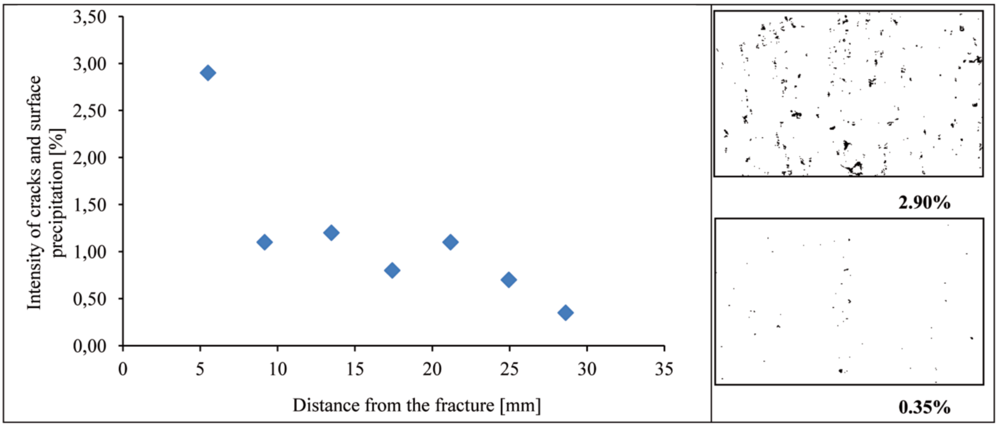


Fig. 12. Intensity of cracks and surface precipitation of the specimen after tensile testing and SEM-BSE images of selected areas of the specimen after graphic processing [9]

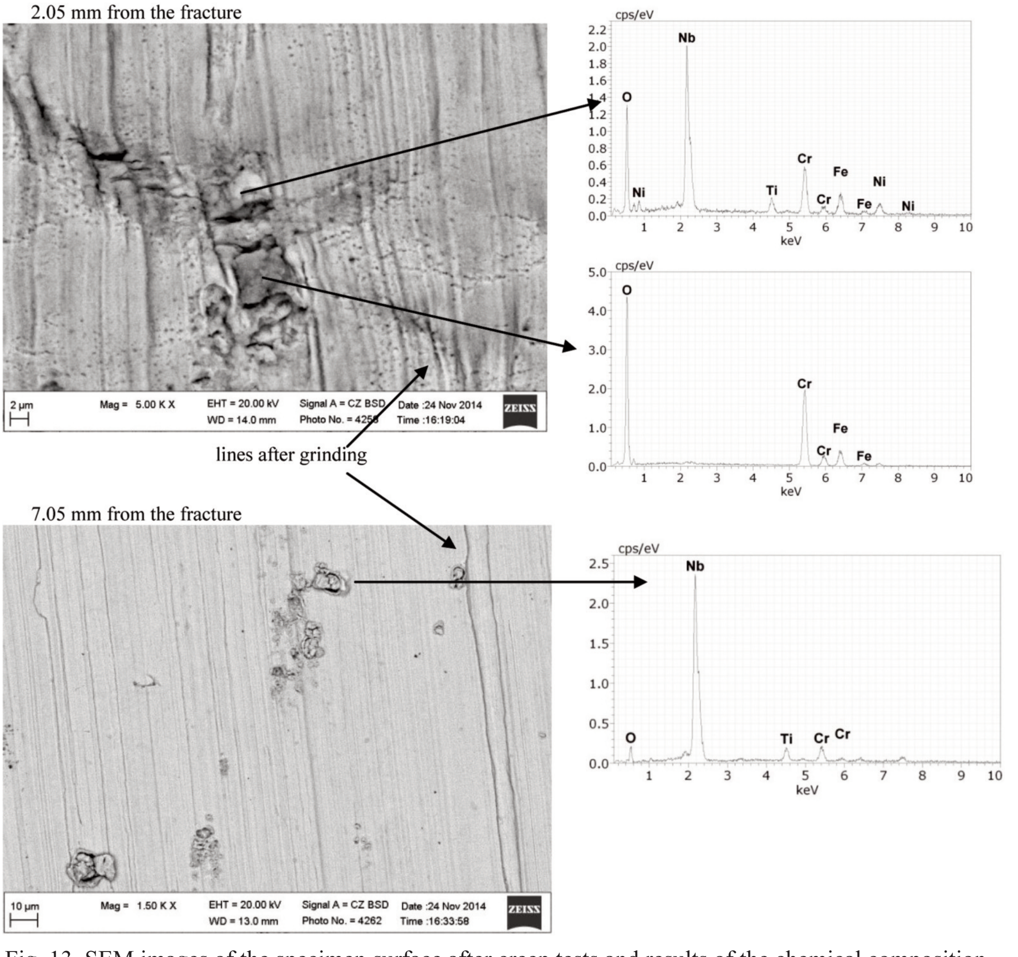
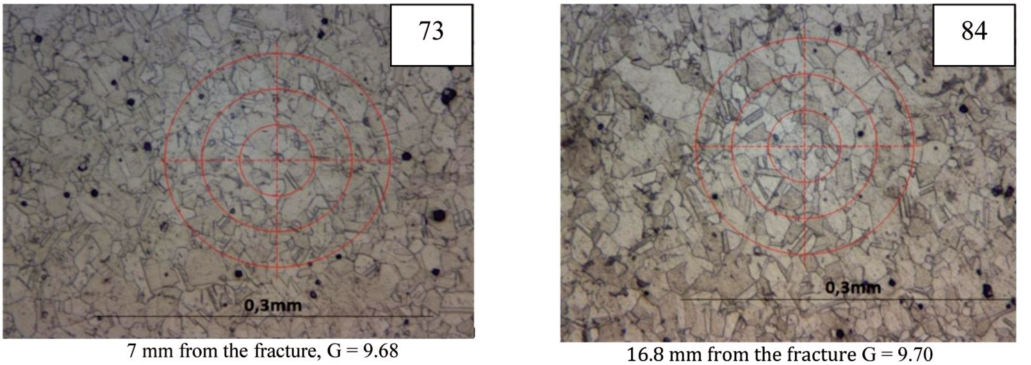


Fig. 13. SEM images of the specimen surface after creep tests and results of the chemical composition of precipitates. [9].

On the surfaces of the specimens after tensile testing, the presence of niobium and titanium carbides, was found. Intensity of cracks and surface precipitation for those carbides increased above damage parameter $D \sim 0.25$ (Fig.12) In case of specimens after creep test, chromium and niobium carbides were detected (Fig. 13). On the surface of specimens after tests, the deformed lines, as a result of plastic deformation, were visible (Fig. 13). In the strongly deformed areas after tensile testing, in addition to plastic slip-lines, the so-called "orange peel" structure was formed.

There were no significant changes in the grain sizes (Fig. 14), and the volume fraction of precipitates significantly increased only in the final stage of the destruction process.



7 mm from the fracture, G = 9.68 16.8 mm from the fracture G = 9.70

Fig. 14. Image of the material structure with the marked circles used for determining the grain size in the cross-section perpendicular to the axis of the specimen after creep tests [9]

The grain measurements demonstrated changes of anisotropy depending on the distance from the fracture, that is the material damage degree. Anisotropy, both in case of the material after tensile testing (Fig. 15) and after the creep test (Fig. 16) increased reaching the highest value in the areas closest to the fracture.

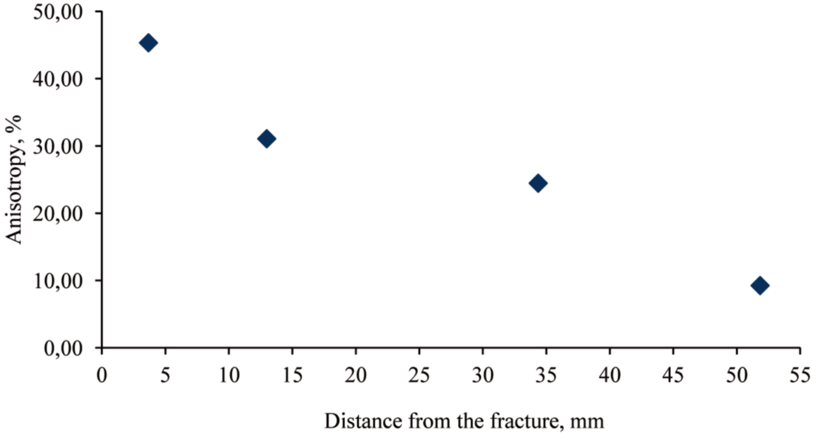


Fig. 15. Dependence of anisotropy on the distance from the fracture in the plane parallel to the axis of the specimen after tensile testing [9]

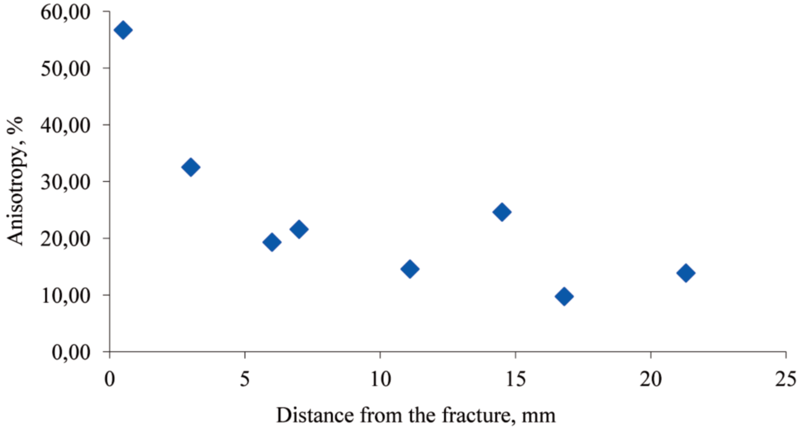


Fig. 16 Dependence of anisotropy on the distance from the fracture in the plane parallel to the axis of the specimen after creep tests [9]

The tomographic studies revealed the presence of voids in the neck zone (Fig. 17A). The found discontinuity was also formed in the final stage of the material degradation process. The size of the largest found void did not exceed 0.1 mm. In the zone close to the fracture, the voids were located throughout the entire material volume, but their intensity was the greatest in the central part. Along with increasing the distance from the fracture, the number and the size of voids decreased. Apart from the neck, only single voids with the size not exceeding 0.012 mm occurred (Fig. 17. B).

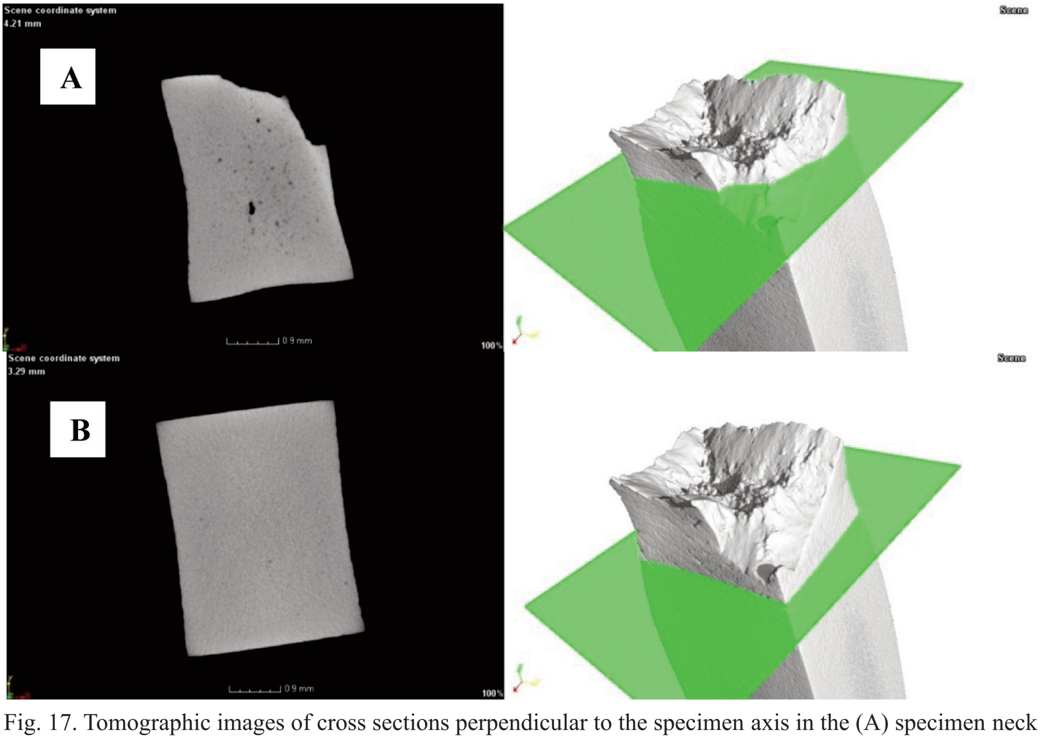


Fig. 17. Tomographic images of cross sections perpendicular to the specimen axis in the (A) specimen neck zone and in the measuring part outside the neck (B) [9]

6. CONCLUSIONS

The specimens of Inconel 718 alloy before and after deformation introduced by tensile and creep test were subjected to ultrasonic tests. An increase in the attenuation coefficient (in relation to the material prior to testing) was found. For the material after tensile testing and larger permanent deformation in the gage parts the attenuation coefficient increase is higher than for the specimens after creep tests, i.e.:

The attenuation coefficient increases along with the increase in the material damage degree. This increase was approx. 50% in the initial tested stage of degradation, i.e. for $D \sim 0.03$ in case of the material after creep tests and $D \sim 0.17$ in case of the material after tensile testing.

In the next stage, up to $D \sim 0.13$ for creeping and $D \sim 0.37$ for tensile testing, the attenuation coefficient increased by additional 50%, however, these increases were slow, and especially, in case of the material after creep fluctuations of the attenuation coefficient occurred.

A significant coefficient increase – multifold in relation to the material before testing – occurred only in the final stage of the degradation process.

The implemented structural studies of Inconel 718 alloy subjected to degradation did not indicate changes in the sizes of grains. However changes in anisotropy of the grains was found. Those changes of anisotropy suggest that acoustic birefringence can be a good indicator for non-destructive assessment of this material degradation degree.

The use of the damage parameter proposed by Johnson [7] in conjunction with the proposed investigation method resulting in obtaining continuous distribution of permanent deformation in the specimen gage makes it possible to find the correlation between the non-destructive test results and the damage parameter in the entire range of the deformation possible to be obtained.

The test method, which was applied in the presented paper, allows for obtaining information on changes in the material structure caused by deformation.

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BADANIA USZKODZEŃ STOPU INCONEL 718 STOSOWANEGO W LOTNICTWIE

Streszczenie

Badaniom materiałowym poddano stop Inconel 718. Do badań użyto nowy rodzaj próbki o zmiennym polu przekroju części pomiarowej. Dzięki temu uzyskano ciągły rozkład odkształceń plastycznych w tej części próbki. Zaproponowana metoda badania uszkodzenia struktury prowadzi do zastąpienia w badaniach serii próbek jedną próbką. Degradację materiału zadano poprzez statyczną próbę rozciągania i próbę pełzania. Deformacja trwała, która zmienia się wzdłuż osi próbek, umożliwia analizę uszkodzenia wywołanego odkształceniem plastycznym. Z degradacją badanego stopu wiążą się zmiany jego właściwości akustycznych -współczynnika tłumienia materiału. Pozwala to na określenie stopnia uszkodzenia materiału za pomocą bezinwazyjnej metody nieniszczącej – metody ultradźwiękowej. Stosując parametr uszkodzenia zaproponowany przez Johnsona uzyskano korelację pomiędzy wynikami pomiarów nieniszczących a stopniem uszkodzenia materiału. Zastosowana w przedstawionym artykule metoda badawcza dostarcza informacji na temat zmian struktury materiału wywołanych deformacją trwałą.

Słowa kluczowe: parametr uszkodzenia, współczynnik tłumienia fali ultradźwiękowej, degradacja materiału, badania nieniszczące.