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# INFLUENCE OF HEAT TREATMENT ON THERMO-MECHANICAL FATIGUE AND HIGH TEMPERATURE CREEP PROPERTIES FOR 316L STEEL

# WPŁYW OBRÓBKI CIEPLNEJ NA WŁAŚCIWOŚCI ZMĘCZENIA CIEPLNO-MECHANICZNEGO ORAZ PROCES PEŁZANIA W PODWYŻSZONEJ TEMPERATURZE DLA STALI 316L

*The main purpose of the work was to develop the characteristics of high-temperature structure degradation processes under the synergistic effects of thermo-mechanical fatigue and high temperature creep for samples made of 316L steel in the delivery condition and after heat treatment. The use of heat treatment consisting of solution treatment at 1100°C for 45 minutes and water cooling improved the mechanical properties of 316L steel. Moreover, in fatigue tests, in every case, increasing the strain value in a single cycle leads to a faster sample rupture. An additional aim of the research was also to develop and verify a new innovative research methodology concerning the combination of fatigue cycles with the creep process at elevated temperature, the aim of which is to better reflect the behaviour of the material in real working conditions.*

***Keywords:*** *316L steel, thermo-mechanical fatigue, high temperature creep, heat treatment*

*Głównym celem pracy było opracowanie charakterystyk wysokotemperaturowych dla procesów degradacji struktury pod wpływem synergicznego oddziaływania zmęczenia cieplno-mechanicznego i pełzania w podwyższonej temperaturze dla próbek wykonanych ze stali 316L w stanie dostawy i po obróbce cieplnej. Zastosowanie obróbki cieplnej polegającej na przesyceniu w 1100°C przez 45 minut i chłodzeniu wodą poprawiło właściwości mechaniczne stali 316L. Ponadto w testach zmęczeniowych w każdym przypadku zwiększenie wartości odkształcenia w jednym cyklu prowadzi do szybszego rozerwania próbki. Dodatkowym celem badań było również opracowanie nowej, innowacyjnej metodyki badawczej dotyczącej połączenia cykli zmęczeniowych z procesem pełzania w podwyższonej temperaturze, której celem jest lepsze odzwierciedlenie zachowania materiału w rzeczywistych warunkach pracy.*

***Słowa kluczowe:*** *Stal 316L, zmęczenie termomechaniczne, pełzanie w podwyższonej temperaturze, obróbka cieplna*

## 1. INTRODUCTION

A well-defined indicator of material structure degradation due to cyclical service loads is crucial for monitoring this process in laboratory research and in real-life conditions, enabling early detection of critical material states causing damage initiation. The measure of damage guarantees the observation of the behaviour of construction materials under the influence of cyclical loads. Laboratory research is aimed at developing the conditions for initiating damage. One of the fastest developing trends in strength tests is the development of a system of testing procedures and criteria for characterising the development of degradation of operating properties of construction materials used, for example, in energy, aviation or aeronautics industries used to forecast the remaining time of safe use of these components [1–3].

Fatigue and creep processes occurring in construction materials under the influence of long-term cyclic loads are a significant problem of modern technology. Cyclic thermo-mechanical loads changing periodically may shorten the service life of structural elements, because their destruction may occur at stresses with values much lower than the static strength of the material from which they are made. Very often, fatigue is the main cause of premature failure of structures. In practice, this term denotes the finite number of load cycles that the material is capable of carrying. There are many factors that directly influence this cycle limit. These include, among others: the nature of loads, the sequence of loads and the time of their duration [4–6].

Fatigue process always occurs wherever there are cyclical loads. Typical industries in which fatigue processes should be taken into account are:
- aviation (components of the winging and control of aircraft, components of engine turbines),
- road transport (suspension, engine components),
- machine departments (cutting tools),
- power industry (turbine blades, boilers, pipelines).

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Constant development and growing competition in, among others, the aviation and space industries forces the manufacturers of system components such as engine components or aircraft turbines to meet the increasingly higher requirements, not only in terms of design, but also economy. Currently, above-average requirements are placed on the materials used in the production of airplanes and spacecraft. Due to the minimisation of costs, including the reduction of fuel consumption, the current efforts are to reduce the weight of airplanes and spacecraft and, consequently, to use a new type of technological and material solutions. These materials are used for components with an 'extremely responsible' application, therefore, the main requirements are: high abrasion resistance, thermo-mechanical fatigue, creep resistance, low thermal expansion coefficient, high elasticity modulus, high mechanical strength in extreme temperature conditions and corrosion resistance [7–9]. Among other things, the application of an appropriate heat treatment can significantly improve the properties, thus the materials subjected to heat treatment can be in operation much longer in more harmful conditions [10, 11]. In this study, the behaviour of 316L steel subjected to a combination of fatigue cycles with the creep process at elevated temperature in the delivery condition and after heat treatment was analysed.

## 2. PURPOSE OF THE WORK

The main aim of the work was to develop material characteristics of high-temperature structure degradation processes under the synergistic interaction of thermo-mechanical fatigue and high-temperature creep compilation for samples made of 316L steel before and after heat treatment. An additional aim of the research was also the development and verification of a new innovative research methodology concerning the combination of fatigue cycles with the creep process at elevated temperature, the aim of which is to better reflect the behaviour of the material in real work conditions.

## 3. RESEARCH MATERIAL AND METHODOLOGY

The material for research was 316L steel. The chemical composition of this steel was consistent with the requirements of the PN-EN 10027-2 standard (Table 1).

The cyclic deformation experiments were conducted by combining the fatigue related cycles with the ones causing the creep process (Fig. 1) at elevated temperature, using the Gleeble 3800-GTC metallurgical simulator. The use of this type of combination of fatigue cycles with the creep process reflects the real working conditions much better. The simulation of this type of processes, additionally at an increased temperature of the process, was only possible with the use of a metallurgical process simulator. The view of a specially designed test sample and the mounting of the samples in the Gleeble simulator were shown in Figure 2. The characterisation of the structure in the as-delivered condition and after heat treatment as well as the fractographic analysis of the fractures obtained were carried out using the JOEOL JSM-7200F high-resolution scanning electron microscope.

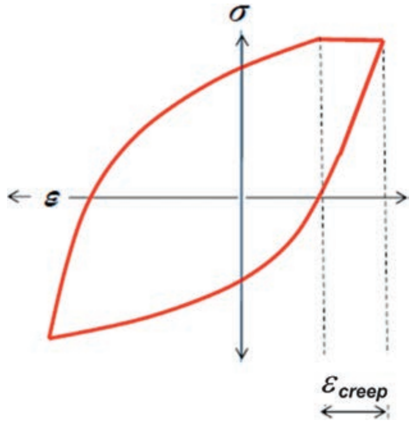


**Fig. 1. Schematic drawing illustrating the idea of combining fatigue related cycle with that causing creep process**

**Rys. 1. Schemat ilustrujący ideę połączenia cyklu związanego ze zmęczeniem wraz z procesem pełzania**

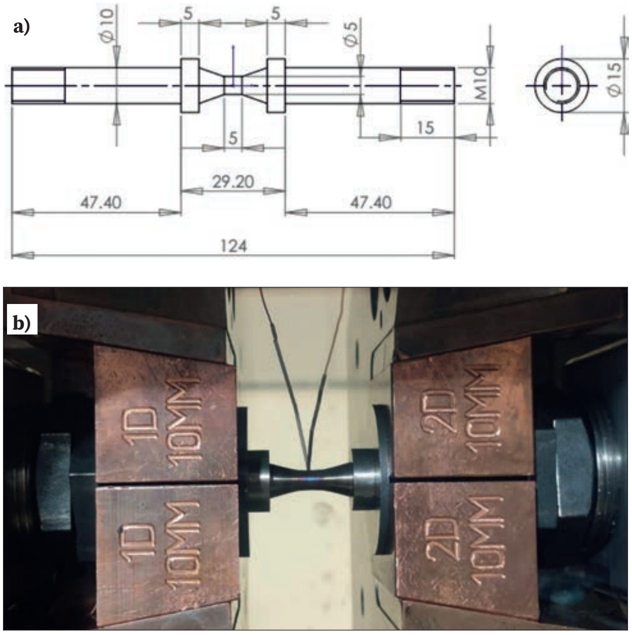


**Fig. 2. Specially designed test sample (a) and the sample placed in simulator handles (b)**

**Rys. 2. Specjalnie zaprojektowana próbka testowa (a) wraz z widokiem w uchwytach symulatora (b)**

## 4. RESEARCH RESULTS

The research was carried out on samples in the delivery condition and after solution treatment at 1100°C for 45 minutes and water cooling. The structure of the 316L steel in the delivery condition and after heat treatment was shown in Fig. 3. The analysed 316L steel is characterised by the

**Table 1. Chemical composition of steel in accordance with the PN-EN 10027-2 standard**

**Tabela 1. Skład chemiczny stali zgodny z normą PN-EN 10027-2**

| Cr | Ni | Mo | C | Mn | Cu | P | S | Si | N |
|---|---|---|---|---|---|---|---|---|---|
| 17–19 | 13–15 | 2.25–3 | < 0.03 | < 2 | < 0.5 | < 0.025 | < 0.01 | < 0.75 | < 0.1 |

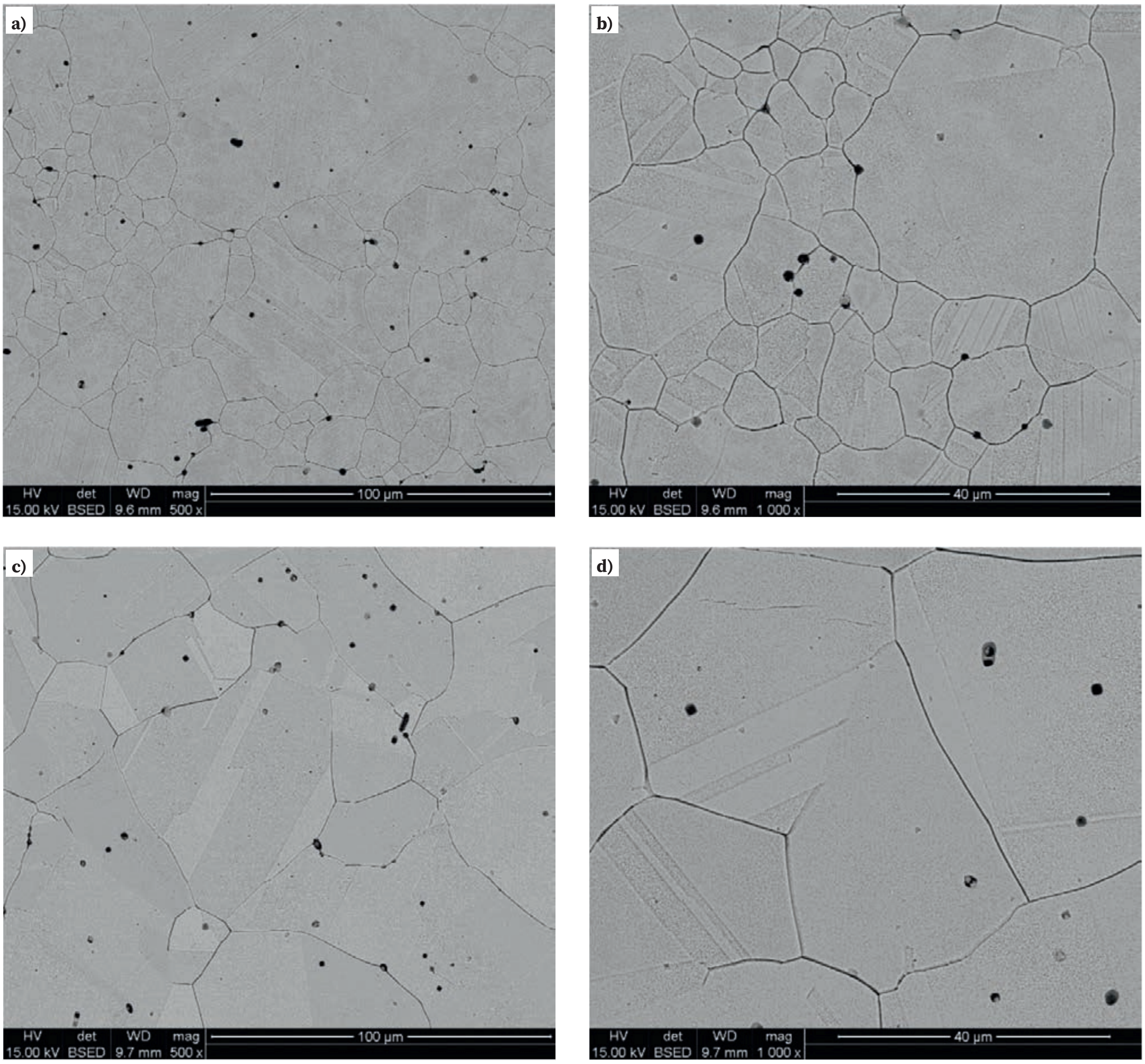


**Fig. 3. Structure of 316L steel; a, b) delivery condition; c, d) after HT**

**Rys. 3. Struktura stali 316L; a, b) stan dostawy; c, d) po OC**

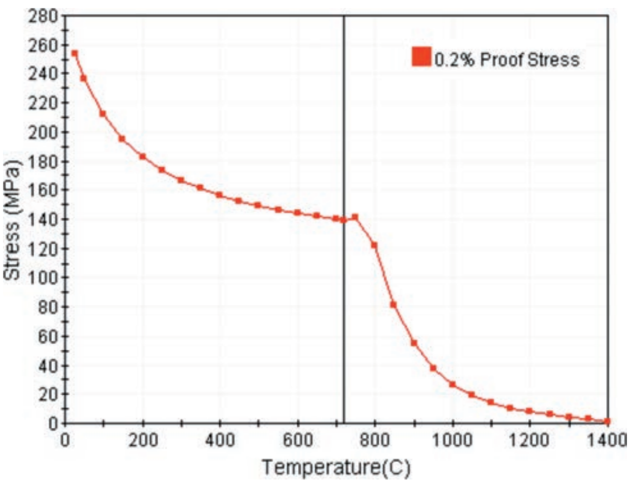


**Fig. 4. High-temperature properties of 316L steel calculated with JmatPro program**

**Rys. 4. Własności wysokotemperaturowe stali 316L obliczone z wykorzystaniem programu JmatPro**

presence of an austenitic structure containing twins and a large, differentiated grain. An increase in grain size was observed after the application of heat treatment.

Due to a large drop in the strength of 316L steel above 800°C (Fig. 4), the experiments were carried out at 600°C (this temperature also coincides with the maximal operating temperature for this steel under operating conditions).

### 4.1. STATIC TENSILE TEST RESULTS

In the first stage of the investigation, a static tensile test was carried out. The static tensile test was carried out at 600°C with a strain value equal to 1, and a strain rate of 0.002 $s^{-1}$. The results are shown in Fig. 5.

The analysis of the static tensile test results shows that in the initial stage of deformation, the sample in the delivery condition was characterised by a work hardening rate comparable to the sample after heat treatment. However, with strain increase, this tendency changed. Moreover, the sample in the delivery conditions exhibits a lower deformation at the fracture.

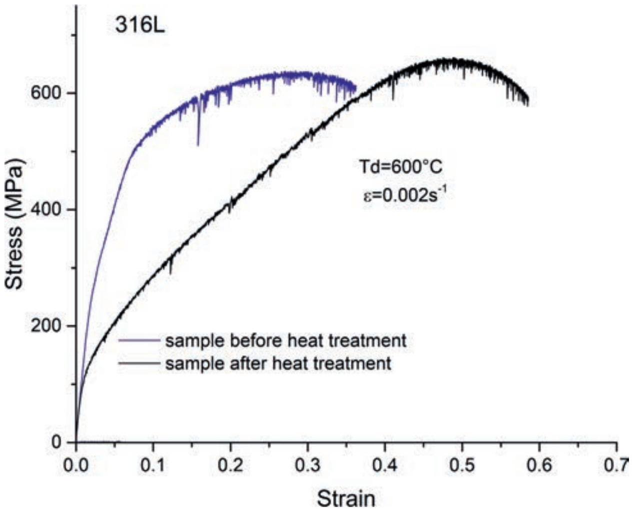


**Fig. 5. Results of static tensile test**

**Rys. 5. Wyniki statycznej próby rozciągania**

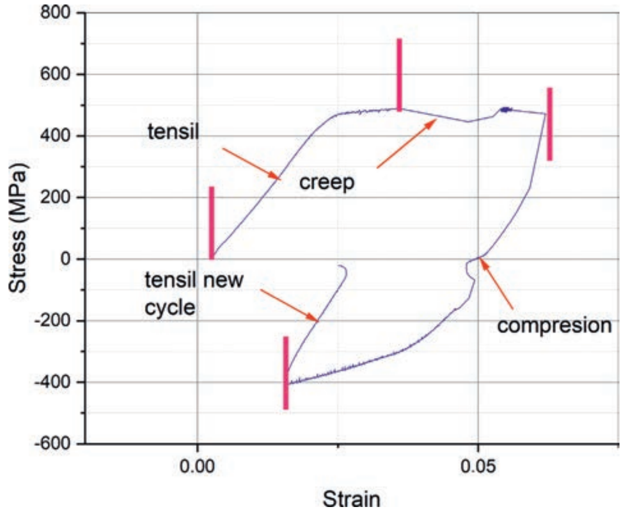


**Fig. 6. Material flow during creep process**

**Rys. 6. Zachowanie się materiału w połączeniu z procesem pełzania**

### 4.2. THERMO-MECHANICAL FATIGUE AND HIGH-TEMPERATURE CREEP RESULTS

In the subsequent stages of the research, cyclic strain tests were carried out, in which, after stretching for 60 seconds, creep (stabilisation of the stress value) was applied. Figure 6 shows a detailed methodology of fatigue tests with creep process. During the experiment, the value of compressive stress was constant during the creep process.

The research plan for cyclic fatigue in each case included tests with different deformation values: 0.01, 0.02, 0.04 and 0.06 at a constant deformation rate of 0.002 $s^{-1}$ at 600°C. The obtained test results are presented in Table 2 and in Figures 7 and 8 in the form of changes in the value of deformation as a function of deformation and in the form of changes in the value of the maximum stress for subsequent cycles of deformation.

During cyclic fatigue, the strain values were controlled. It was noticed, however, that during the experiments there was some influence of the elastic deformations of grips. In general, the heat-treated specimens sustained a greater number of cycles to failure for all strain values. The biggest difference was observed with the strain value $\varepsilon_1 = 0.01$. This sample withstood 1,881 cycles to fracture. In any case, increasing the strain value in a single cycle leads to a faster sample rupture. The analysis of the maximum stress changes during subsequent deformation cycles showed

**Table 2. Number of cycles to failure of the sample in the tests of cyclic fatigue combined with creep and stress relaxation stages**

**Tabela 2. Liczba zrealizowanych cykli do zniszczenia próbki podczas badań cyklicznego zmęczenia w połączeniu z procesem pełzania**

| | **Pre-HT sample – combination of fatigue cycles with the creep process** | | | | **Sample after HT – combination of fatigue cycles with the creep process** | | | |
|---|---|---|---|---|---|---|---|---|
| $\varepsilon_1$ | 0.01 | 0.02 | 0.04 | 0.06 | 0.01 | 0.02 | 0.04 | 0.06 |
| Number of cycles | 278 | 79 | 20 | 8 | 1881 | 134 | 21 | 10 |

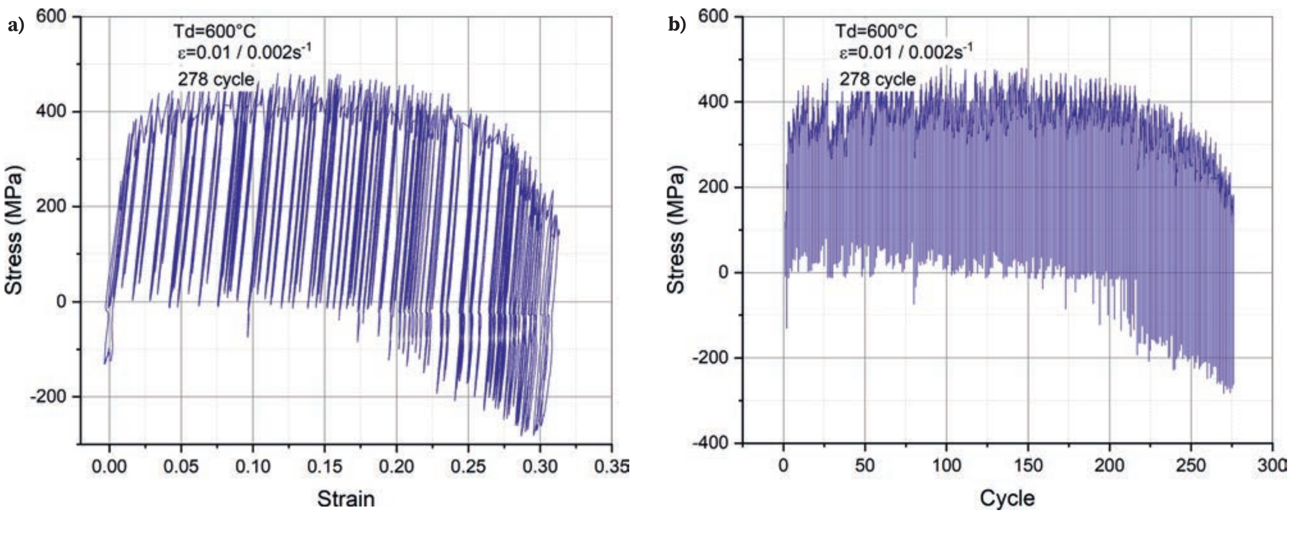


**Fig. 7. Results of cyclic fatigue before HT along with creep process after deformation; a, b) 0.01**

**Rys. 7. Wyniki dla cyklicznego zmęczenia w połączeniu z procesem pełzania po odkształceniu przed OC; a, b) 0,01**

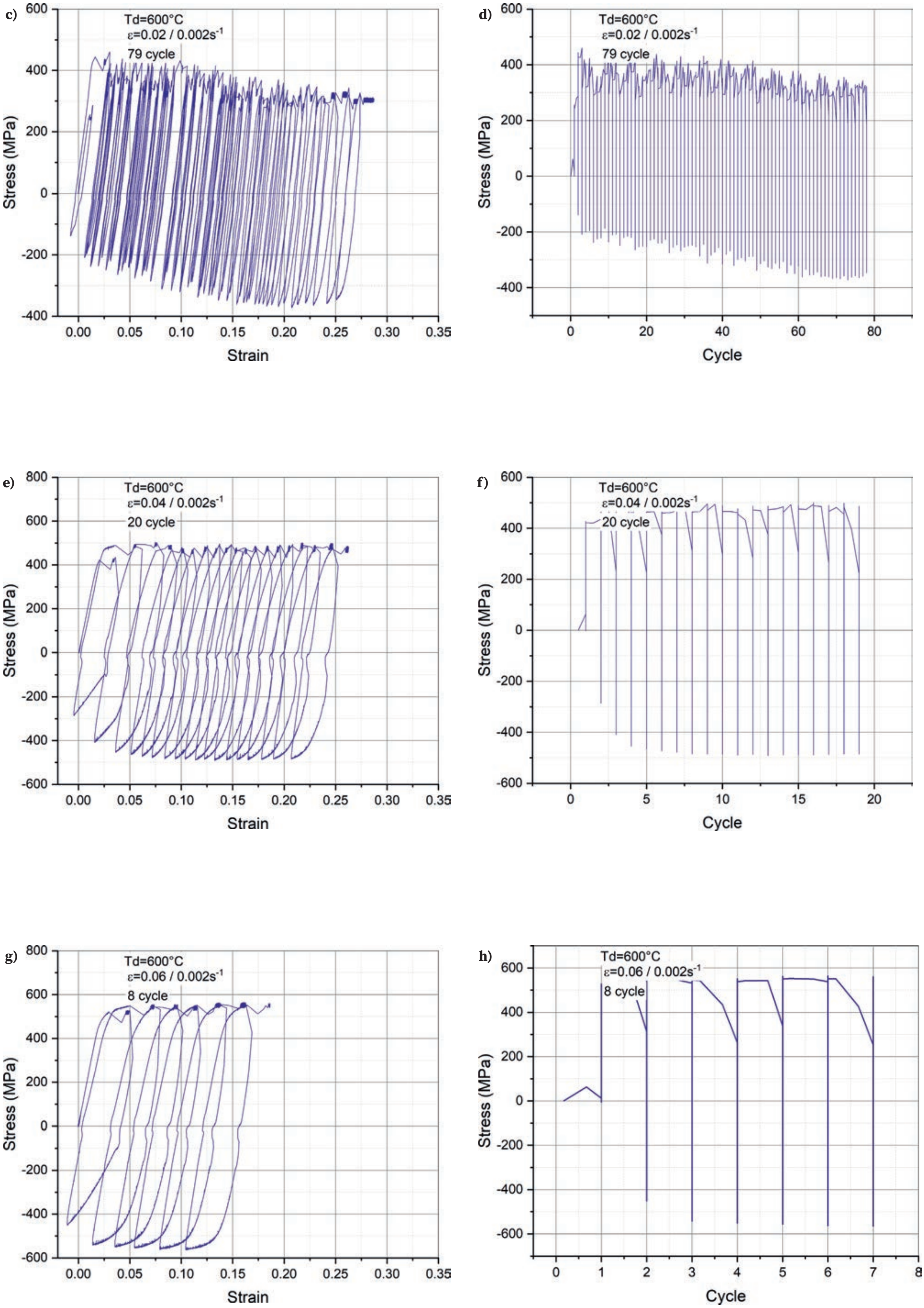


**Fig. 7 cont. Results of cyclic fatigue before HT along with creep process after deformation: c, d) 0.02; e, f) 0.04; g, h) 0.06**

**Rys. 7 cd. Wyniki dla cyklicznego zmęczenia w połączeniu z procesem pełzania po odkształceniu przed OC: c, d) 0,02; e, f) 0,04; g, h) 0,06**

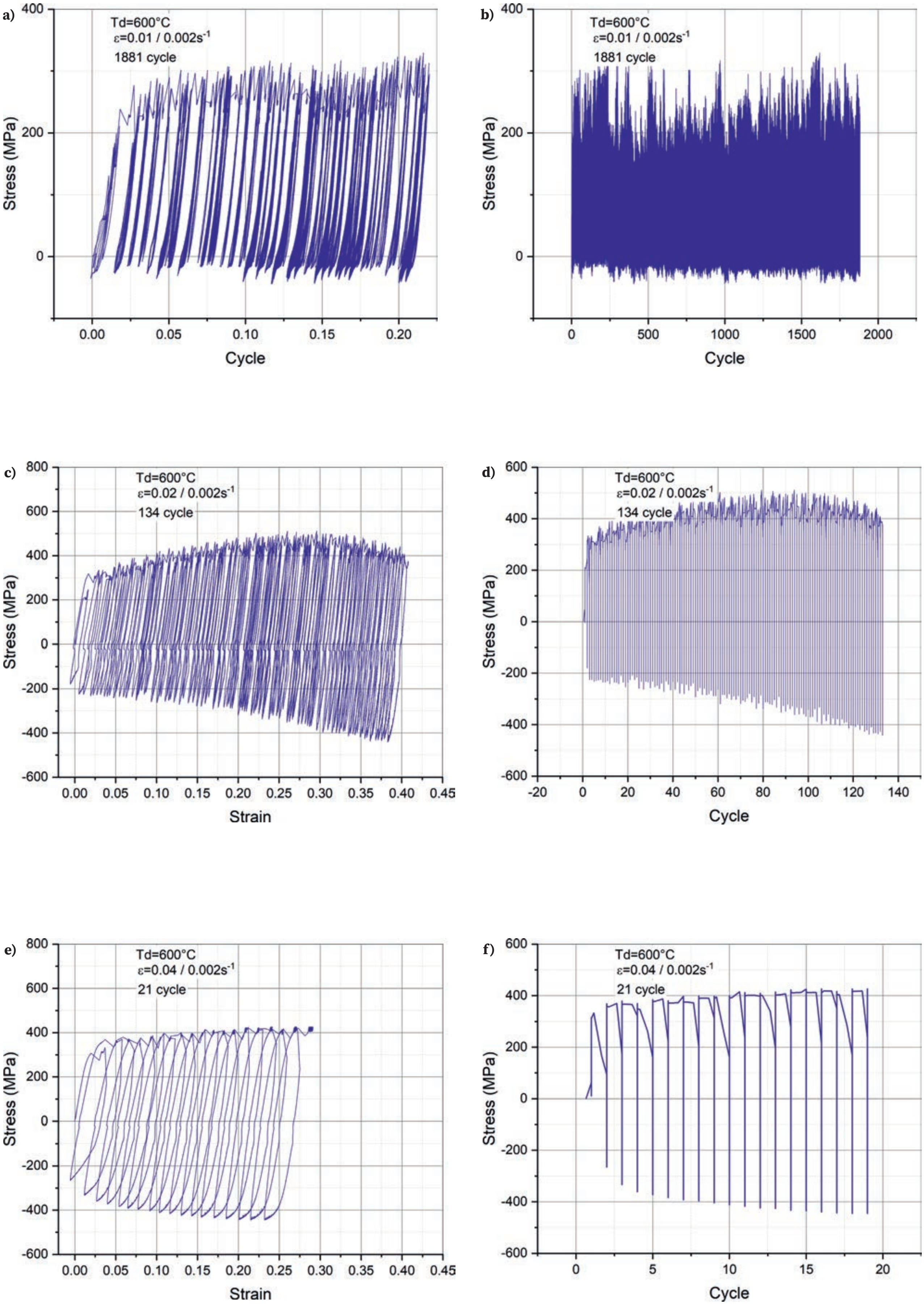


**Fig. 8. Results of cyclic fatigue after HT combined with creep process after deformation: a, b) 0.01; c, d) 0.02; e, f) 0.04**

**Rys. 8. Wyniki dla cyklicznego zmęczenia w połączeniu z procesem pełzania po odkształceniu po OC: a, b) 0,01; c, d) 0,02; e, f) 0,04**

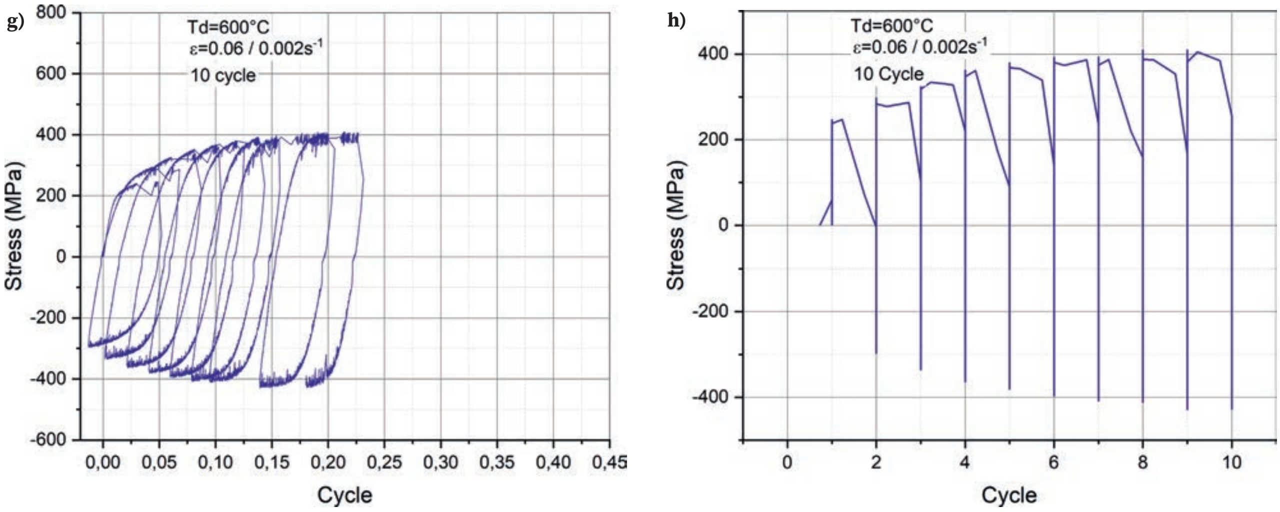


**Fig. 8 cont. Results of cyclic fatigue after HT combined with creep process after deformation: g, h) 0.06**

**Rys. 8 cd. Wyniki dla cyklicznego zmęczenia w połączeniu z procesem pełzania po odkształceniu po OC: g, h) 0,06**

that in some cases the stress value increases in the initial deformation cycles, and stabilises in the next, or vice versa. In order to determine the reasons for this behaviour, a fractographic analysis of the samples' fracture surfaces was performed.

### 4.3. FRACTOGRAPHIC ANALYSIS OF FRACTURE SURFACES

Images of the fracture surfaces obtained during the static tensile test are shown in Figure 9. Images of the fracture surfaces obtained during cyclic fatigue combined with

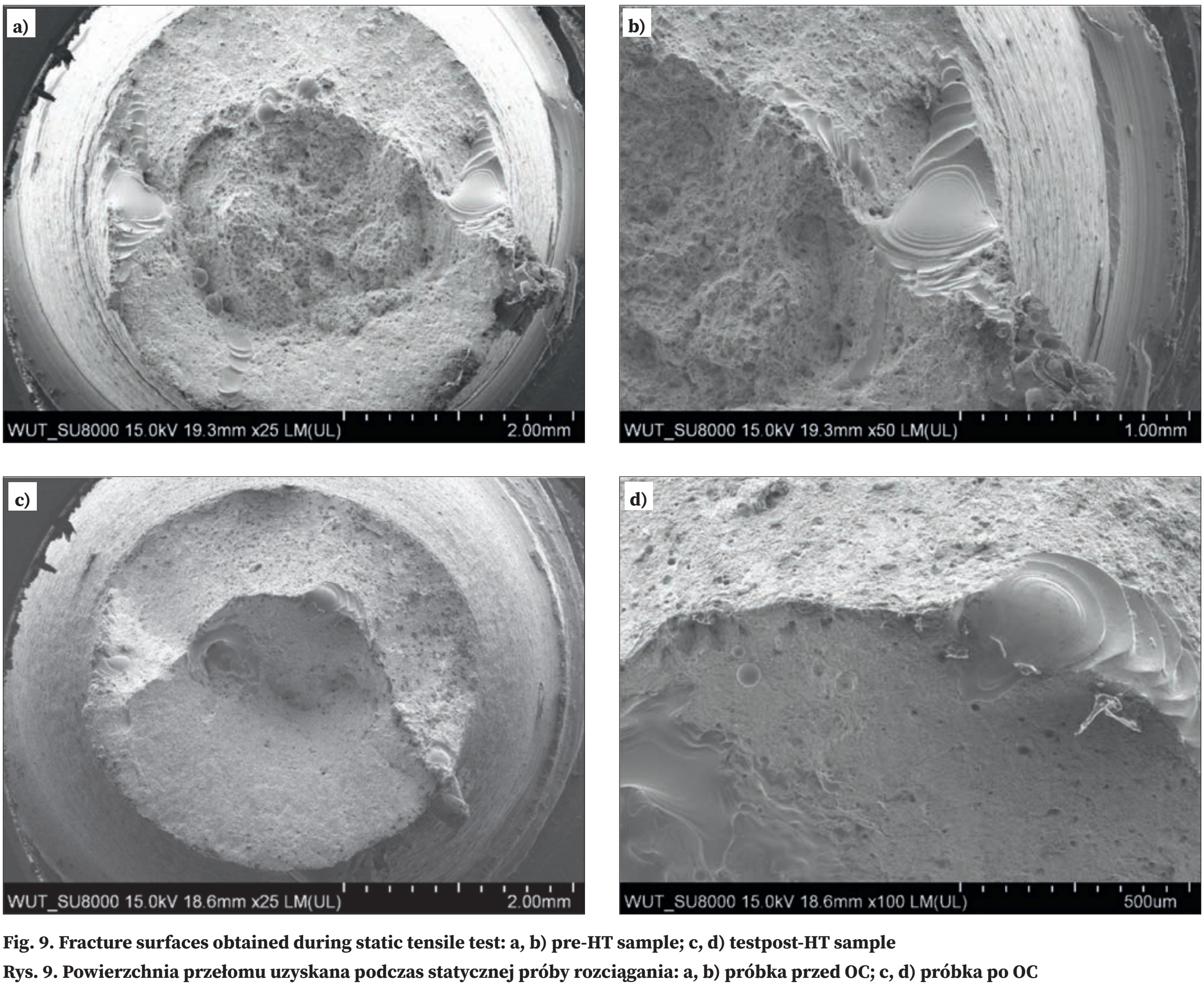


**Fig. 9. Fracture surfaces obtained during static tensile test: a, b) pre-HT sample; c, d) testpost-HT sample**

**Rys. 9. Powierzchnia przełomu uzyskana podczas statycznej próby rozciągania: a, b) próbka przed OC; c, d) próbka po OC**

the creep process for the delivery condition and after heat treatment are shown in Figures 10 and 11.

The fracture surfaces obtained during the tensile test and during cyclic fatigue along with the creep process were characterised by the ductile fracture structure in each case. In the case of fracture surfaces obtained in the cyclic fatigue tests with the creep process for samples before heat treatment, local remelting of the material was observed, which could have resulted in faster breaking and a reduction in the number of cycles for samples in the delivery condition. In no case was porosity or carbides in the fracture structure observed.

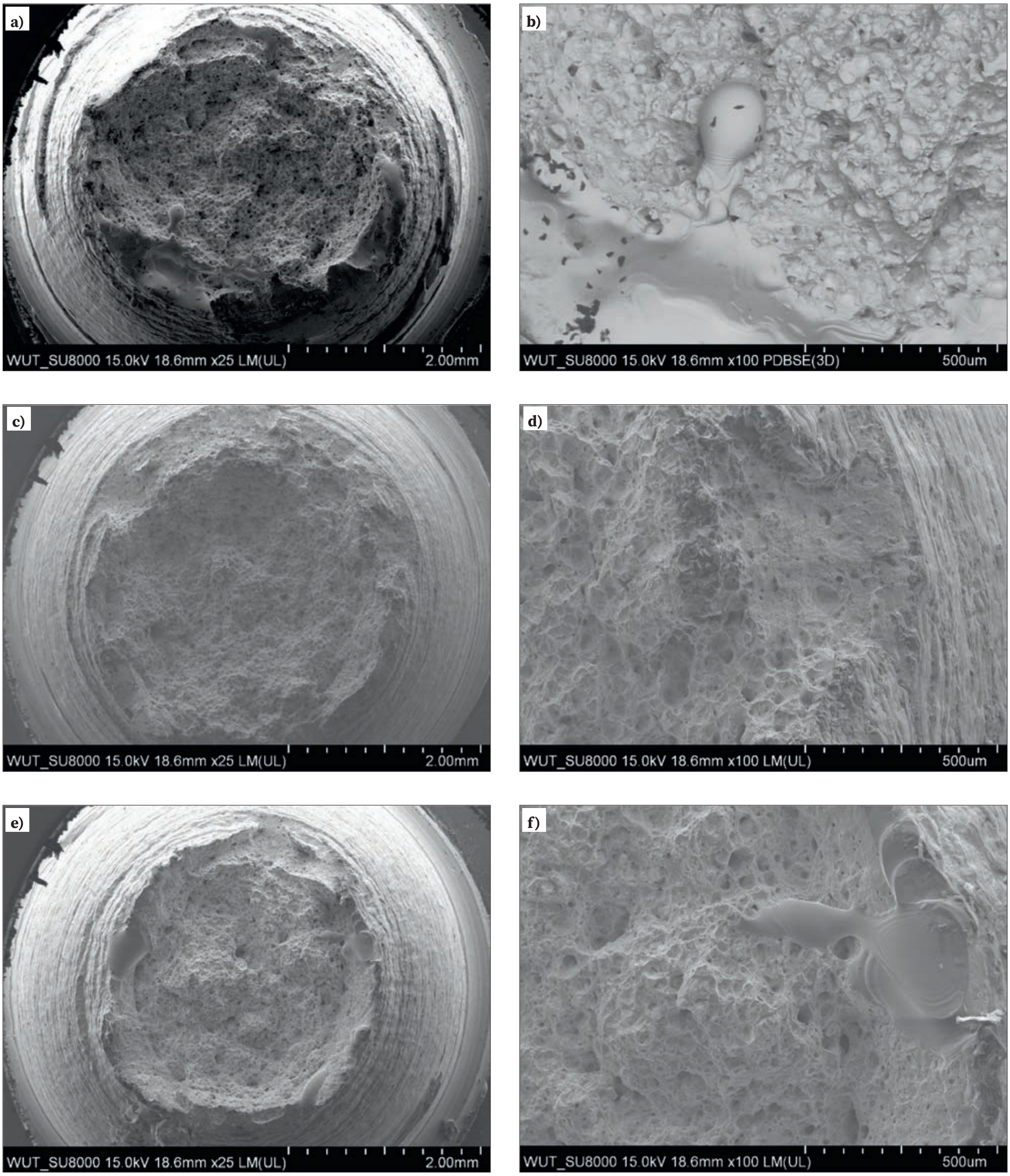


**Fig. 10. Fracture surfaces obtained during cyclic fatigue together with creep process for the delivery condition, for different deformation values; a, b) 0.01; c, d) 0.02; e, f) 0.04**

**Rys. 10. Powierzchnia przełomu uzyskana podczas cyklicznego zmęczenia wraz z procesem pełzania dla próbek w stanie dostawy dla różnych wartości odkształcenia; a, b) 0,01; c, d) 0,02; e, f) 0,04**

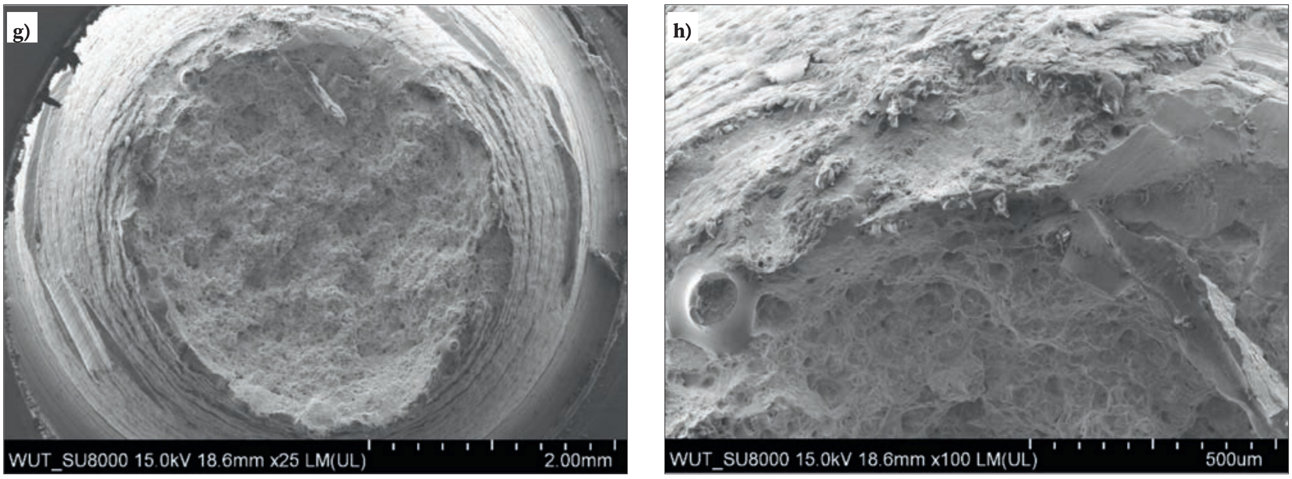


**Fig. 10 cont. Fracture surfaces obtained during cyclic fatigue together with creep process for the delivery condition, for different deformation values: g, h) 0.06**

**Rys. 10 cd. Powierzchnia przełomu uzyskana podczas cyklicznego zmęczenia wraz z procesem pełzania dla próbek w stanie dostawy dla różnych wartości odkształcenia: g, h) 0,06**

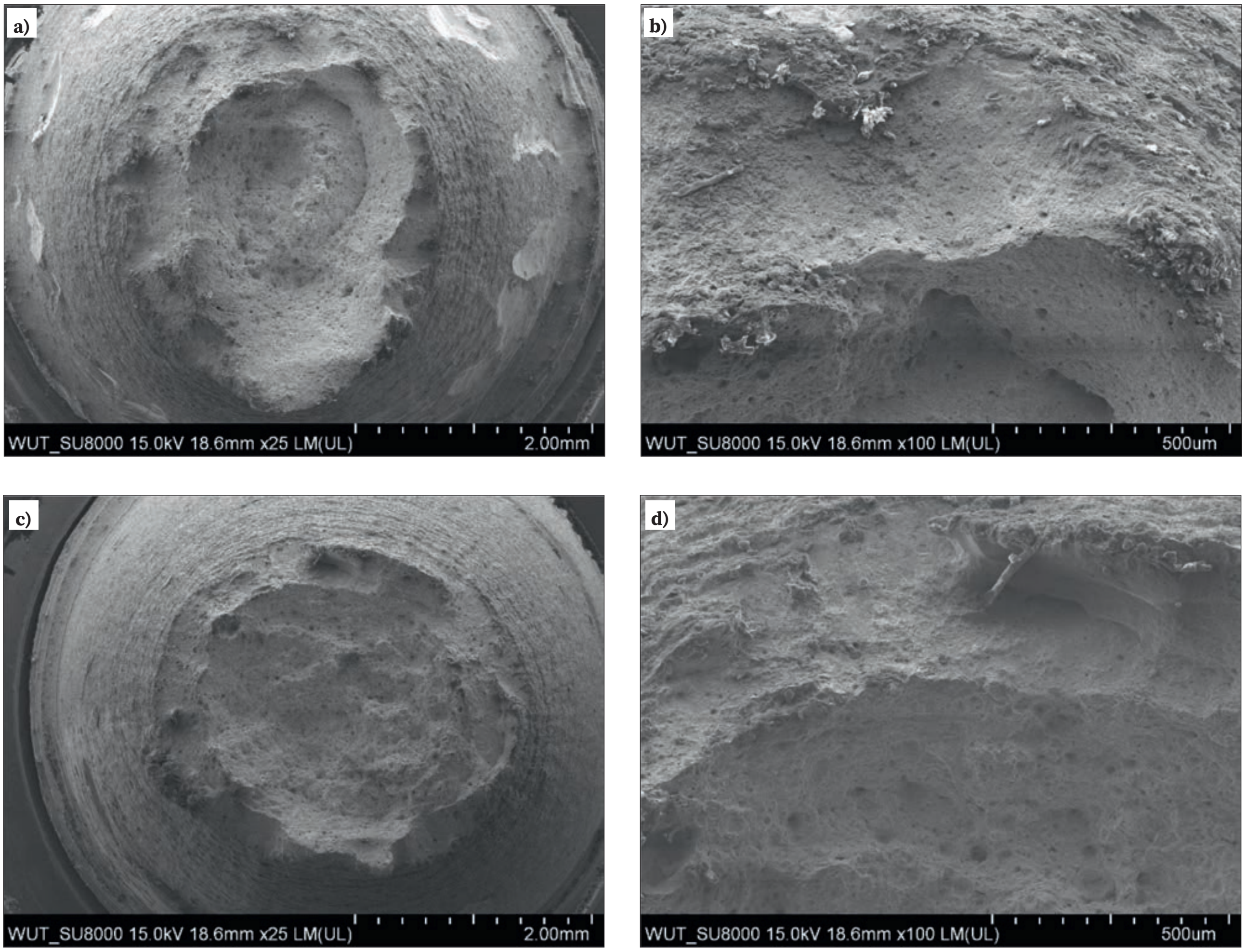


**Fig. 11. Fracture surfaces obtained during cyclic fatigue together with creep process for samples after HT, for different values of deformation; a, b) 0.01; c, d) 0.02**

**Rys. 11. Powierzchnia przełomu uzyskana podczas cyklicznego zmęczenia wraz z procesem pełzania dla próbek po OC dla różnych wartości odkształcenia; a, b) 0,01; c, d) 0,02**

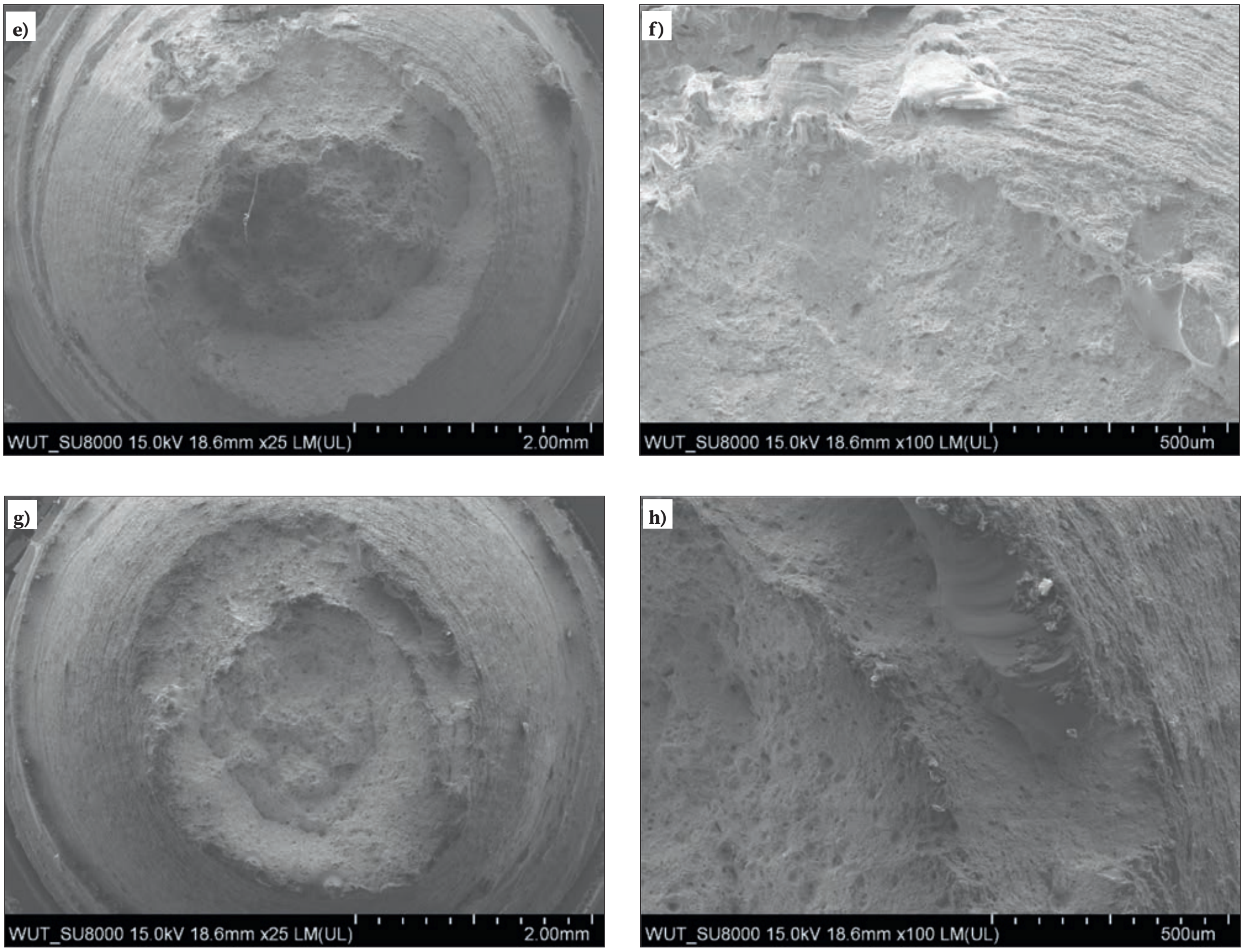


**Fig. 11 cont. Fracture surfaces obtained during cyclic fatigue together with creep process for samples after HT, for different values of deformation: e, f) 0.04; g, h) 0.06**

**Rys. 11 cd. Powierzchnia przełomu uzyskana podczas cyklicznego zmęczenia wraz z procesem pełzania dla próbek po OC dla różnych wartości odkształcenia: e, f) 0,04; g, h) 0,06**

## 5. CONCLUSIONS

1. After heat treatment, 316L steel was characterised by better mechanical properties and showed a much greater number of cycles necessary to fracture the sample.
2. Increasing the strain value in a single cycle during the combination of fatigue cycles with the creep process leads to a faster sample rupture.
3. The newly developed research methodology concerning the combination of fatigue cycles with the creep process at elevated temperature effectively allows to study this type of behaviour and thus reflects the real working conditions of the material much better.
4. The Gleeble 3800-GTC simulator, which is located at the Łukasiewicz Research Network – Institute for Ferrous Metallurgy, allows to carry out this type of research at up to 1600°C, which allows for a very wide use of the newly developed research methodology, for example in the aviation or space industry

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