ANALYSIS OF TEMPERATURE DISTRIBUTION IN COMPOSITE PLATES DURING THERMAL FATIGUE

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Summary

The paper discusses the character of the self-heating temperature distribution during thermal fatigue of laminated composite cantilever plate in the stress relaxation mode. The temperature distributions and their evolution were acquired on the own-designed test rig using infrared camera. The thermograms were compared with force and velocity of displacement measurements and dynamic properties of the investigated composite in order to evaluate characteristic distributions of a temperature for various phases of fatigue: the initiation of the self-heating, thermomechanical degradation, initiation and propagation of cracks etc. Basing on obtained results the correlation between self-heating temperature, stress relaxation and dynamic properties was presented. The characteristic temperature distributions were justified basing on plate theories.

Keywords: self-heating temperature distribution, thermal fatigue, dynamic properties

ANALIZA ROZKŁADU TEMPERATURY W PŁYTACH KOMPOZYTOWYCH PODCZAS ZMĘCZENIA CIEPLNEGO

Streszczenie

Artykuł omawia charakter rozkładu temperatury samorozgrzania podczas zmęczenia cieplnego laminowanej kompozytowej płyty wspornikowej w warunkach relaksacji naprężeń. Rozkłady temperatury i ich zmienność zostały zmierzone na zaprojektowanym stanowisku badawczym z wykorzystaniem kamery termowizyjnej. Termogramy porównano z pomiarami siły i przyspieszeń przemieszczeń oraz z właściwościami dynamicznymi badanego kompozytu w celu oceny charakterystycznych rozkładów temperatury w różnych fazach zmęczenia: inicjacji samorozgrzania, degradacji termomechanicznej, inicjacji i propagacji pęknięć itd. Na podstawie uzyskanych wyników przedstawiono korelację pomiędzy temperaturą samorozgrzania, relaksacją naprężeń i właściwościami dynamicznymi. Charakterystyczne rozkłady temperatury zostały uzasadnione na podstawie teorii płyt.

Słowa kluczowe: rozkład temperatury samorozgrzania, zmęczenie cieplne, właściwości dynamiczne

1. INTRODUCTION

The process of energy dissipation in viscoelastic polymeric composites subjected to cyclic loading leads to initiation of the self-heating effect, i.e. the dissipated energy is stored into the structure, which causes the heating-up of it. As it was described in early studies in this area [1] and validated in the previous studies [2,3], the self-heating effect may influence much on the fatigue process. Depending on the amount of the dissipated energy the fatigue process may evolve following two scenarios. In the first one the self-heating temperature increases to some small value and then stabilizes. This increase reveals negligible influence on mechanical properties of the structure and the fatigue process is mainly determined by mechanical degradation. Some examples of such cases could be found in [4]. However, when the amount of the dissipated energy exceeds much the convection boundary conditions the self-heating effect dominates and intensifies the fatigue process.

The studies on the thermal fatigue of polymers and polymeric composites were carried out by only several researchers. Luo et al. [5] investigated the temperature evolution in acrylonitrile-butadiene-styrene during tensile loading. They used for tests healthy and artificially damaged specimens and compare the external work during the cyclic loading to the generated heat and stated that the part of dissipated energy, which turns into heat may achieve up to 70% in the case of presence of cracks. Interesting results were presented by the authors of [6]. They tested glass-fiber reinforced polyamide 66 specimens under the various excitation frequencies and strain rates. The authors analyzed the stress and temperature evolution during fatigue and proposed simple fitting relationship in order to describe the process. The more accurate description with theoretical foundations of the self-heating temperature growth during thermal fatigue was proposed in [7]. The authors tested polyamide 6,6 specimens in the creep mode. They also presented an explicit formula of temperature growth basing on the loss compliance in function of an excitation frequency. Some theoretical and experimental studies of thermal fatigue and crack propagation have been carried out by Rittel [8-11]. He used poly(carbonate) and poly(methylmethacrylate) specimens in fatigue tests and described the obtained stress and temperature curves in order to evaluate the failure mechanisms of these polymers under the thermal fatigue conditions.

It was reported earlier [3], that the thermal fatigue process could be divided to three characteristic phases with respect to the character of self-heating temperature evolution. The first phase is dominated by the self-heating effect, i.e. the temperature grows exponentially. The second phase reveals quasi-linear growth of the temperature, which caused by mechanical degradation of a structure. At the end of the second phase the thermal fatigue crack initiation occurs. The last phase is characterized by rapid nonlinear growth of the temperature until breakdown. Several phenomena have and influence on the temperature growth in this phase: among the stiffness loss resulted from the increased temperature the initiated crack propagates and additionally intensifies the process.

The aim of this study is to investigate characteristic distributions of the self-heating temperature during whole process of the thermal fatigue of polymeric composites and to find the correlations with the stress relaxation and dynamic properties evolution and relationships with theoretical fundamentals of this process. Obtained results could be useful for condition monitoring purposes of the structures made of polymers and polymeric composites.

2. THE THERMOVISCOELASTICITY

The description of linear thermoviscoelasticity could be given by the modified Boltzman-Volterra integral equation:

$$\sigma(t)=\varepsilon(t)E_0(\theta)-\int_0^t \varepsilon(\tau)R(t-\tau,\theta)dt\,, \quad (1)$$

where $\sigma(t)$ and $\varepsilon(t)$ are the stress and strain histories respectively, θ is the temperature, $E_0(\theta)$ is a temperature dependent instantaneous modulus of elasticity, τ is the relaxation time and $R(t\text{-}\tau, \theta)$ is the temperature dependent relaxation kernel.

Applying the Fourier transform to equation (1), it is possible to present an equation of thermoviscoelasticity in the frequency domain:

$$\sigma(\omega)=R^*(\omega,\theta)\varepsilon(\omega), \quad (2)$$

where $R^*(\omega,\theta)$ is the frequency and temperature dependent relaxation kernel. Basing on (2) the complex modulus could be introduced:

$$E(\omega)=\frac{\sigma^*}{\varepsilon_0}=\Re[E'(\omega,\theta)]+\Im[E''(\omega,\theta)], \quad (3)$$

where

$$E'(\omega,\theta)=\omega\int_0^\infty E(t,\theta)\sin\omega t dt\,, \quad (4)$$

$$E''(\omega,\theta)=\omega\int_0^\infty E(t,\theta)\cos\omega t dt \quad (5)$$

are the storage and loss moduli, respectively. The dissipated energy averaged over a cycle could be then determined from:

$$Q(t)=\frac{2\pi}{\omega}\int_0^{\omega/2\pi}\sigma_{ij}\frac{\varepsilon_{ij}}{dt}dt\,. \quad (6)$$

The self-heating temperature evolution could be determined from substitution of (6) into heat transfer equation as a source function [12]. The simplified relation of self-heating temperature evolution was proposed in [13]:

$$\frac{d\Delta\theta}{dt}=\frac{\omega\varepsilon_0^2}{2\rho c_p}E''(\omega,\theta), \quad (7)$$

where $\Delta\theta$ denotes the temperature increment from the initial temperature, ρ is the mass density and c_p is the specific heat at constant pressure.

3. TESTS AND ANALYZES

The tested specimens were fabricated from glass/epoxy laminate with a symbol of EP GC 201 and supplied by Izo-Erg S.A. The laminate consisted of 12 unidirectional layers with total thickness of 2.5 mm. A detailed description of specimens manufacturing and preliminary strength tests could be found in [14]. The specimens of width of 10 mm and lengths of 40, 45, 50 and 55 mm were prepared for tests. During the tests the specimens were loaded cyclically with various excitation frequencies: 20, 25 and 30 Hz.

The tests were performed on own-designed test rig, which allowed for cyclic excitation of the cantilever specimen in the stress relaxation mode with constant definable frequency. The measurement system contained an infrared camera, force sensor mounted on the excitation rod and a laser vibrometer used for measurement of velocity of displacements of the specimen near the clamp. The picture of the test rig is presented in Fig.1. The detailed description of the measurement system could be found in [2,3].

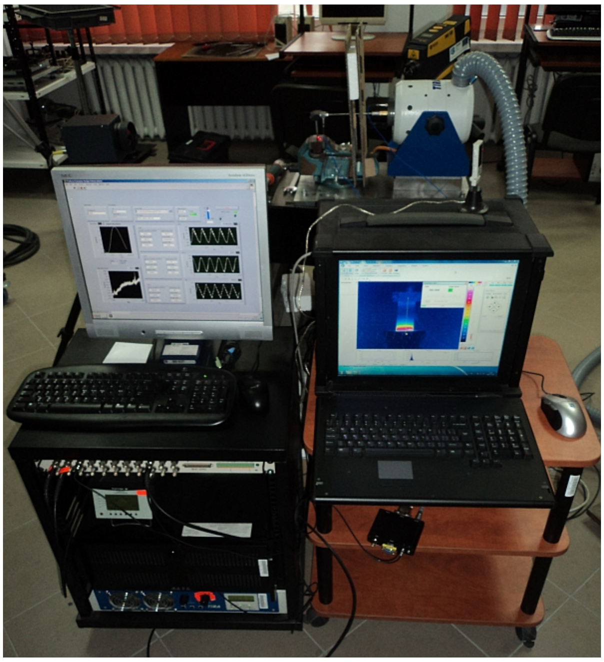

Fig. 1. A test rig during measurements

3.1 ANALYSIS OF THE TEMPEATURE DISTRIBUTION

The characteristic changes in self-heating temperature distributions in various phases of thermal fatigue were compared with other acquired signals during the tests. Moreover, the characteristic points of the storage and loss moduli and phase lag acquired in dynamic mechanical analysis (DMA) [14] were also compared with the thermograms. The comparison of a typical set of discussed parameters for the specimen of the length of 45 mm excited with a frequency of 20 Hz was presented in Fig.2. The solid line denotes temperature, the dashed line denotes displacements envelope and the dotted line denotes the force envelope. The characteristic points were chosen as follows: a (30 s) – for phase I of the thermal fatigue, b (108 s) – for the stabilization of an exponential growth (the beginning of phase II of the thermal fatigue), c (300 s) ,d (404 s) – for phase II of the thermal fatigue, e (560 s) – for the crack initiation (beginning of phase III of the thermal fatigue and f (632 s) – for the crack propagation.

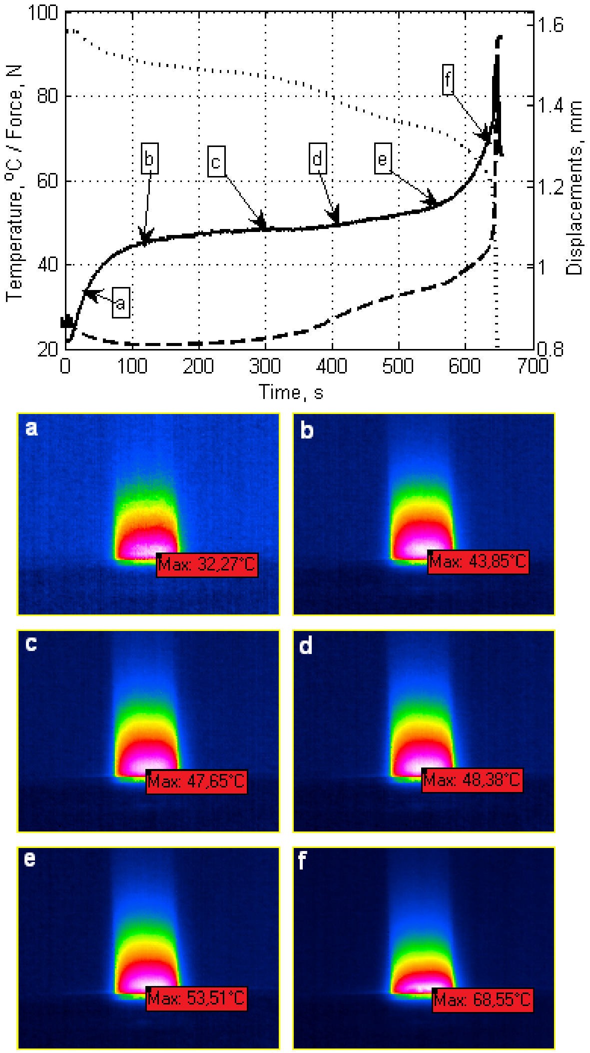

Fig. 2. Self-heating temperature, displacements and force curves with corresponding thermograms in characteristic points

It could be observed that the temperature distribution is non-uniform along the width, i.e. the edges of the specimen have lower temperature. This phenomenon is resulted by several factors. The main reason of such a shape of distribution is the stress distribution in the specimen: following the Kirchhoff-Love plate theory (see e.g. [15]), during the bending of a cantilever plate two components of the stress tensor (bending stress and transverse shear stress) influences on this distribution. Moreover, there is an influence of the thermal convection, which is greater on the edges, because of additional convection surfaces perpendicular to the observed one.

In the Fig.2 the characteristic drop on the force curve and increase on displacements curve is observable in the location of the point d. This drop could be explained by the two-term Maxwell-Wiechert rheological model, which describes the investigated material [16]. It could be also observed that the temperature gradient moves in the direction of specimen's clamp during the increase of the temperature. This phenomenon is caused by local drop of the stiffness in the hottest region and thus the stress concentration in this region, which also explain the region of the crack initiation. For detail analysis of the stiffness drop the evaluation of evolution of dynamic properties of the composite could be performed basing on DMA-like temperature plots (Fig.3). For this purpose the temperature plots of dynamic properties for testing frequency was reconstructed from the master curves presented in [14]. The solid line denotes storage modulus, the dotted line denotes loss modulus and the dashed line denotes tangent of the phase shift.

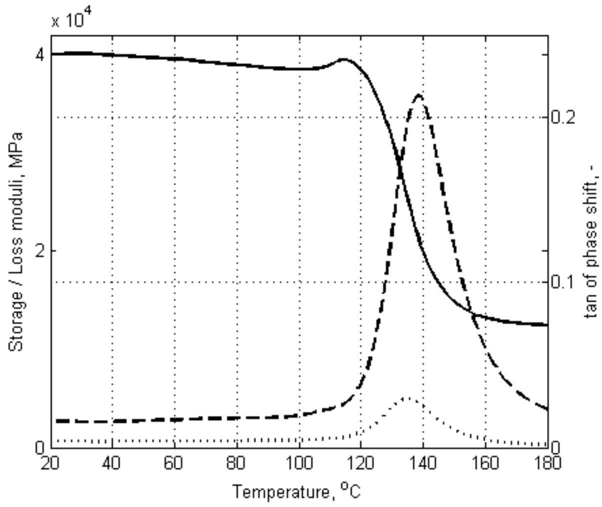

Fig. 3. Dynamic properties of the investigated composite for the excitation frequency of 20 Hz

As it could be noticed, there is a monotonic decrease of the storage modulus (4) and the monotonic increase of the loss modulus (5). The storage modulus represents elastic part of the complex modulus (3), while the loss modulus the viscous part of (3). The decrease of the storage modulus in the temperature region of interest explains the softening of the material and stress concentration near the clamp of a specimen. The increase of tangent of the phase shift in this temperature region denotes the increase of the area of a hysteresis loop, thus the dissipation energy amount still increase.

3.2 ANALYSIS OF THE TEMPEATURE DISTRIBUTION OF PRE-CRACKED SPECIMENS

In order to analyze the specific temperature distributions in the pre-cracked specimens and compare them with distributions in healthy specimens the additional tests were carried out. The specimens were artificially damaged on various distances from the clamp (2.5, 5 and 10 mm), the crack depths in each case was 0.5 mm. The tests were carried out for specimens with the length of 50 mm excited with a frequency of 30 Hz. In order to analyze the character of the self-heating temperature growth the measurement point was defined on the thermograms in the location as it was shown in Fig.2, i.e. in the hottest region. The temperature histories were presented in Fig.4. For the comparison purposes the temperature history defined in the same way was added to the previous three cases in Fig.4.

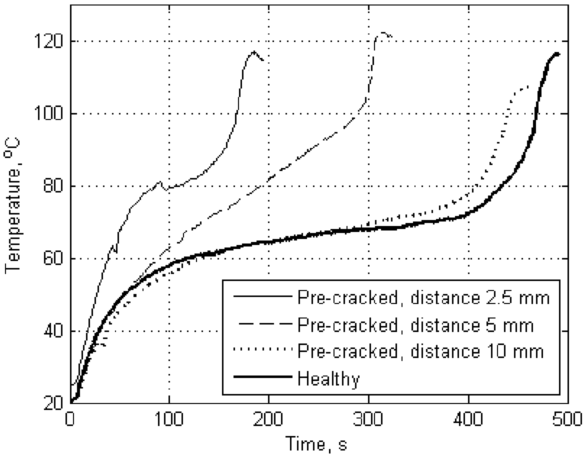

Fig. 4. Self-heating temperature histories of the pre-cracked and healthy specimens

It could be noticed that the presence of crack and its position has a great influence of the temperature histories. It could be explained by the relocation of the stress gradient to the position of a crack due to the local softening of material in the area of a crack location. This causes more rapid temperature increase and shorter fatigue life cycles. Each of the temperature curve for the pre-cracked specimens consists singularities, which were caused by the relocation of a stress gradient. In order to investigate these singularities the set of thermograms for the pre-cracked specimen on the distance of 2.5 mm was presented in Fig.5.

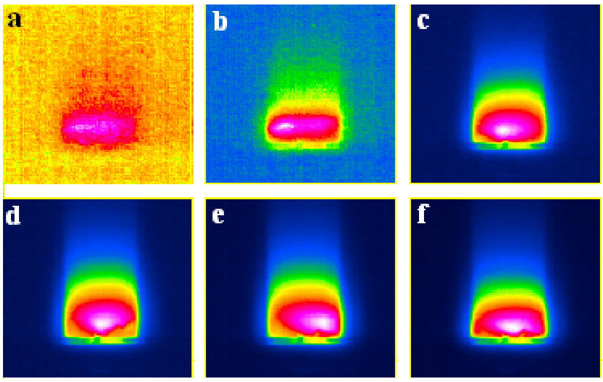

Fig. 5. Selected thermograms for the pre-cracked specimen on the distance of 2.5 mm, max. temperature: a – 26.40°C, b – 31.92°C, c – 67.16°C, d – 81.15°C, e – 94.80°C, f – 117.85°C

The stress concentration is clearly visible from the first steps of the analysis (see Fig.5a,b). This phenomenon could be used for the fatigue damage detection and localization. Based on these observations the method of non-destructive damage evaluation (NDE) was developed [17]. The singularities observed in the temperature history curve in Fig.4 were caused by the movement of the temperature gradient during propagation of a crack (cf. Fig.5b-f).

The temperature distributions in other two cases of the pre-cracked specimens reveal slight different behaviour. The selected thermograms for these cases were presented in Fig.6 and Fig.7, respectively.

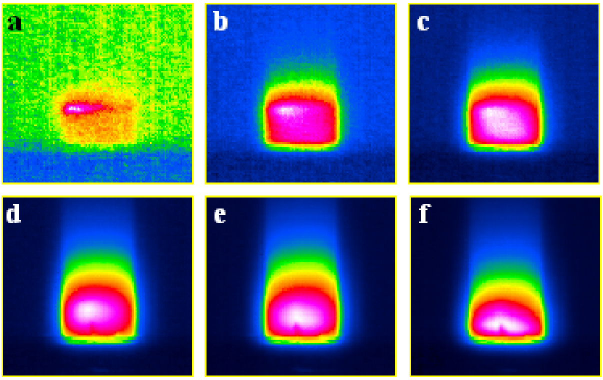

Fig. 6. Selected thermograms for the pre-cracked specimen on the distance of 5 mm, max. temperature: a – 25.57°C, b – 31.63°C, c – 40.94°C, d – 77.84°C, e – 96.06°C, f – 122.62°C

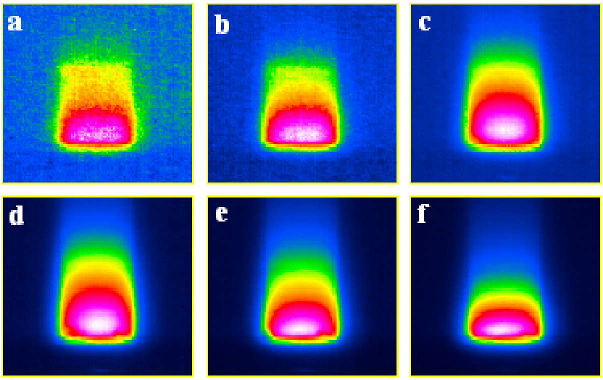

Fig. 7. Selected thermograms for the pre-cracked specimen on the distance of 10 mm, max. temperature: a – 26.62°C, b – 31.08°C, c – 49.46°C, d – 76.16°C, e – 87.93°C, f – 108.47°C

In the case of a pre-cracked specimen on the distance of 5 mm at the beginning of a test the highest values of a stress and a temperature were located in the crack position (Fig.6a), further the stress/temperature distribution homogenizes (Fig.6b) and then the gradient moves to the clamp (Fig.6c-e). During the first phase of the thermal fatigue the crack position is still detectable, but in further phases the movement of a gradient is observed. This movement is caused by exceeding of the local material softening with respect to the drop of stiffness near the clamp caused by the self-heating effect. In the last investigated case only the boundary of a stress/temperature distribution is observed in the first steps of a test (see Fig.7a,b). From the beginning of a test the highest values of a temperature were observed near the clamp, as for the healthy specimens (cf. Fig.2). The thermal fatigue process proceeds almost the same way as for the healthy specimen, which confirmed the temperature histories presented in Fig.4 for these cases.

The damage propagation of the case of pre-cracked specimen on the distance of 5 mm was not typical, thus the visual inspection of the fractured specimen after a test was carried out. The resulted observations shows, that the crack propagated in the direction to a clamp an caused additional delamination. Further detailed observations were carried out using confocal microscope, the results of observation were presented in the next subsection.

3.3 MICROSCOPIC EVALUATION OF THE FRACTURED SPECIMENS

The observations were carried out on the confocal stereoscopic microscope with the magnification of 10x. The resulted microphotographs were presented in Figs. 8-10.

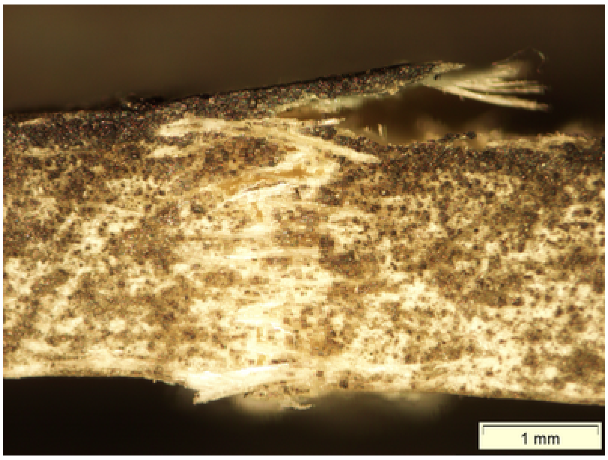

Fig. 8. Microphotograph of the pre-cracked specimen on the distance of 2.5 mm

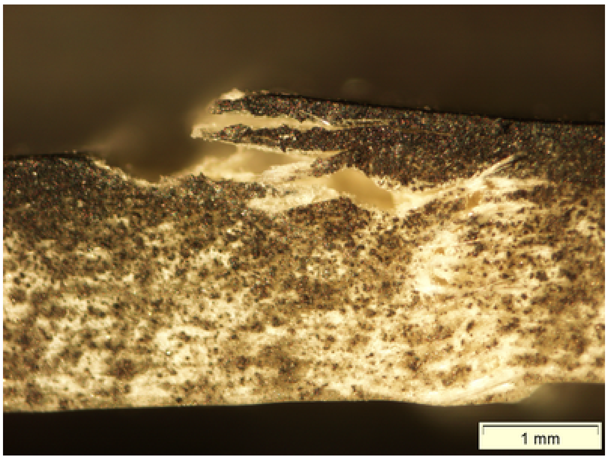

Fig. 9. Microphotograph of the pre-cracked specimen on the distance of 5 mm

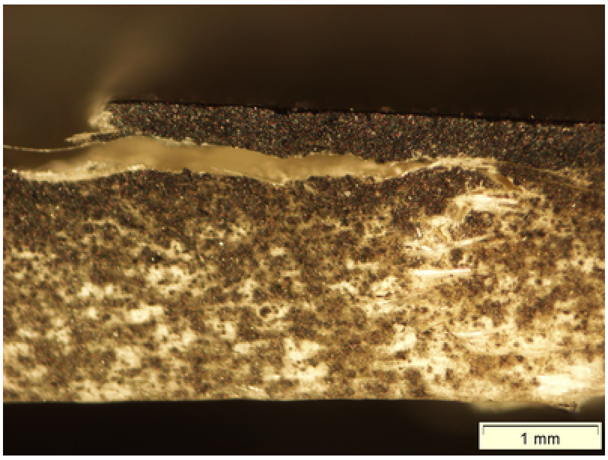

Fig. 10. Microphotograph of the pre-cracked specimen on the distance of 10 mm

The microscopic observations show that in each case of the pre-cracked specimens discussed in the previous subsection the movement of a stress/temperature gradient was caused by the propagating delamination. This specific type of fracture is caused by a stress concentration in the crack area and simultaneously near the clamp. Considering the beam theory (Bernoulli or Timoshenko) the highest values of the shear stress could be obtained on the top and bottom surfaces of the investigated specimens. In the case of pre-cracked specimens the shear stress dominated the bending stress, which causes the stress propagation in the planar direction. When the delamination front reaches the clamp location the bending stress became dominant due to the material softening in this area caused by the self-heating effect. Thus, the further propagation of a crack occurred in the direction normal to the surface of a specimen.

4. CONCLUSIONS

Presented research was concentrated on the temperature distribution of polymeric laminated composite plates during the thermal fatigue. The analyzed of the temperature histories and thermograms during this process allow to explain the physics of the phenomenon of degradation and fracture processes. The analysis of the temperature distributions together with the stress relaxation and displacement curves and the curves of dynamic properties of a composite in function of a temperature allows for global analysis of the self-heating phenomenon during whole life cycle of the investigated specimens. Additional thermal and microscopic analyzes of pre-cracked specimens give new information about specific type of fracture of the structures with defects. Obtained results may be useful for the design of the life cycle of composite elements and evaluation of workloads and other operation parameters for elements made of these materials. The presented results could be also used for evaluation of structural health of the elements made of polymeric composites. The observation of thermograms during slight heating of such structures allows for NDE and location of the stress concentration areas, which confirmed the authors of [5]. The fundamentals of the NDE method of such materials was developed and presented in [16]. However, there are several open questions in the investigated problem. The mechanisms of structural degradation and failure could be different from polymer to polymer due to the specific properties of these materials. Moreover, it is expected that these mechanisms will be strongly dependent on the material, type and orientation of the reinforcement in polymeric composites. The great influence of the degradation mechanisms and fracture may have also the material anisotropy of the investigated structures. Thus the additional studies should be carried out in order to confirm the findings and statements presented in the following paper.

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