

Application of PhotoStress Method in the Analysis of Stress Fields Around a Notch

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Abstract The presented paper aims at the analysis of stress fields which occur while applying loads to a photoelastically coated notched sample. The analysis was done by means of PhotoStress[®] method using reflection polariscope and digital video camera. On the notched sample subject to loads by eccentric tension we determined the differences of principal normal stresses in specified point at loads 3 kN, 4.5 kN, 6 kN, 9 kN and 12 kN. In addition, we determined the value of principal normal stress at the edge of the sample during load of 12 kN which was later compared with numerical solution in programme SolidWorks. On the photo elastically coated sample we observed maximum elongation of the coating, too. As regards maximum elongation of applied photoelastic coating PS-1A, the manufacturer states the value of 5%.

Keywords: notch, stress field, photoelastic coating, PhotoStress[®] method

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1. Introduction

PhotoStress[®] is an experimental method in mechanics which enables, in addition to visual representation of strain and stress fields, quantitative determination of principal strains or principal normal stresses on the surface of analysed objects. The principle of PhotoStress[®] method is based on a photoelastic phenomenon, i.e. the ability of photoelastic coating to create temporary birefringence as a result of load applied to it and illumination by polarized light from reflection polariscope. For identification of direction and magnitude of principal normal stresses we use isoclinic and isochromatic fringes [7,8].

Compared to other experimental methods in mechanics, PhotoStress[®] method has the following advantageous features [1,3]:

- *visual overview of stress and strain fields throughout the whole photoelastically coated surface* and, in this way, the method offers information on critical stress concentrations around holes, notches and other areas of possible failures as well as information on maximum or minimum stressed areas etc.;
- *universal application* which enables us to determine stresses and deformations in any point of photoelastic coating applied in laboratory conditions or directly in the field;
- *non-destructive impact on surface* – the experiment can be carried out repeatedly with changing load parameters;

- *wide range of measurements* – the method enables us to measure individual parameters and determine differences and individual principal strains and stresses, residual stresses etc.

2. Specifications of Analysed Sample

The determination of stress fields around the notch was done by means of PhotoStress[®] method on a steel sample made of steel X70 of 12 mm. The shape and dimensions of the sample are depicted in Figure 1. The sample was cut from a steel plate with photoelastic coating PS-1A. The cutting technology used is called Waterjet Cutting. Steel X70 has only small volume of carbon and its bainitic microstructure secures its high toughness and ductility level.

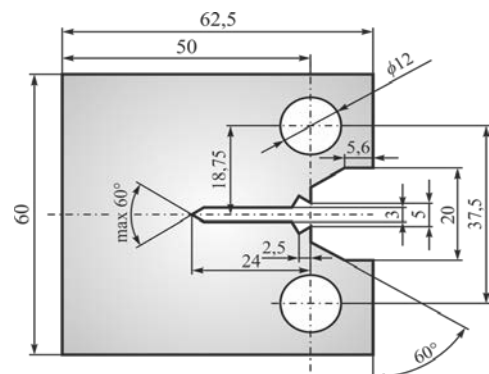


Figure 1. Shape and dimensions of analysed notched sample

Photoelastic coating PS-1A of 2.05 mm was chosen while following systematic selection methodology [9,10]. The coating was applied to the surface of the notched sample by two-component adhesive PC-1. Photoelastic coating PS-1A is highly sensitive and hence allows us to use it in elastic as well as in elastic-plastic areas. It is delivered as a plane plate with reflective layer.

Material characteristics of the PS-1A photoelastic coating used are listed in Table 1 [10].

Table 1. Material characteristics of photoelastic coating PS-1A

Photoelastic coating PS-1A	
Strain-optic coefficient K [-]	0.150
Modulus of elasticity E [MPa]	2500
Poisson's ratio μ [-]	0.38
Elongation A [%]	5
Maximum usable temperature [°C]	150

Photoelastic coating applied to the analysed notched sample Figure 2 transforms a part of the load and, simultaneously, strengthens the sample. As a result, deformations of the sample are lower than if no coating had been applied.



Figure 2. Analysed sample with photoelastic coating PS-1A

For the above-stated purposes a correction of reinforcement effect of the photoelastic coating was done through correction coefficient for reinforcement while considering plane stress

$$C_{PS} = 1 + E^* t^* \quad (1)$$

where $E^* = \frac{E_c}{E}$ is the relation of Young's modulus of photoelastic coating and Young's modulus of the analysed sample;

$t^* = \frac{t_c}{t}$ is the relation of coating thickness and thickness of the analysed sample.

After calculations the value of correction coefficient, by which the order of isochromatic fringes is multiplied, is 1.0122.

3. Load Specification

Experimental measurement was done on a tearing machine Zwick 1387 Figure 3 while loading the sample with eccentric tension. In order to fulfil the conditions of static loading the movement of the machine jaws was set to 0.5 mm/min.



Figure 3. Tearing machine Zwick 1387 with reflection polariscope LF/Z-2

Reflection polariscope LF/Z-2 with usual source of white light Figure 3 was used to observe isoclinic and isochromatic fringes which occur when loading the notched sample. Compensator 832 was used to read order values of isochromatic fringes in pre-selected points. The compensator was based on the principle of null balance. Digital video camera was used to record isochromatic fringes during gradual loading of the sample.

The measurement of notch opening was done with a strain gauge and a converter Figure 4 which assessed the notch opening in mm [6] on the basis of electric voltage calculation. Every 1.3 s the converter registered the set of 8000 values of electric voltage within 300 ms.

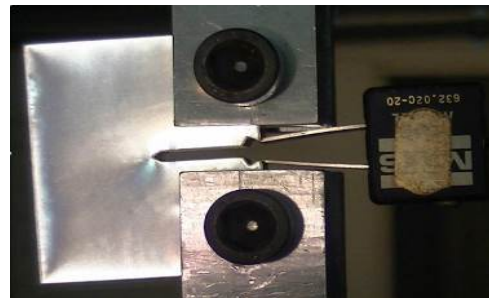


Figure 4. Notch opening sensor

A computer programme was written for the assessment of recorded data. The programme synchronized forces and notch openings in a time line. In order to synchronize measured data it was needed to launch the tearing machine and the converter simultaneously.

The relation of force F in kN to elongation f in mm was a direct outcome of the tearing machine software Figure 5.

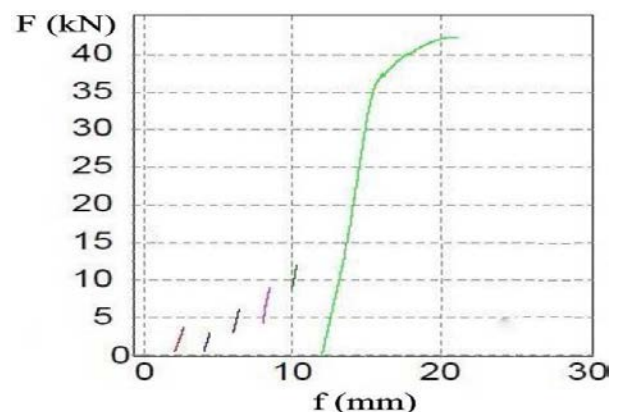


Figure 5. Notch opening in relation to loading force

The relation in Figure 5 consists of a number of curves. The light green curve represents force distribution while loading the sample until crack. The notch opening increased without increasing force. The cause of this effect is that after fastening the sample in the device both surfaces had to fit firmly and adjust to each other [6]. The short curves in the initial part of the diagram (red, blue, brown, violet, dark green) represent force distributions during analysis of isoclinic and isochromatic fields while applying loads 3 kN, 4.5 kN, 6 kN, 9kN and 12 kN.

For the sample under examination were determined the following relations [6]:

- notch opening in relation to time Figure 6;
- force in relation to time Figure 7;
- force in relation to notch opening Figure 8.

Figure 6, Figure 7 and Figure 8 show us a little bounce of distribution at 38 kN. This bounce is the result of a crack in photoelastic coating.

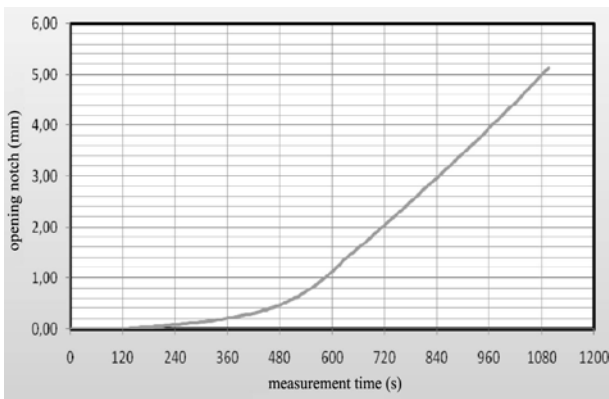


Figure 6. Notch openings in relation to time

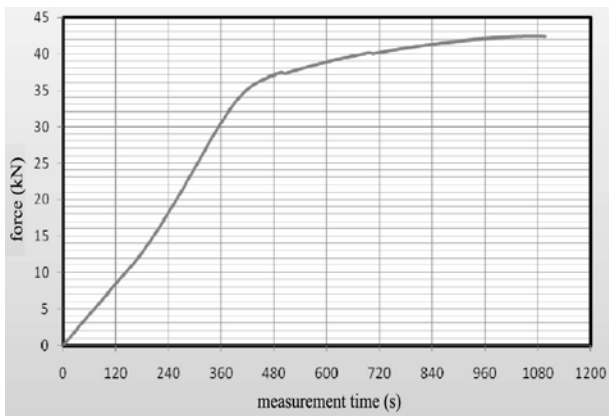


Figure 7. Loading force in relation to time

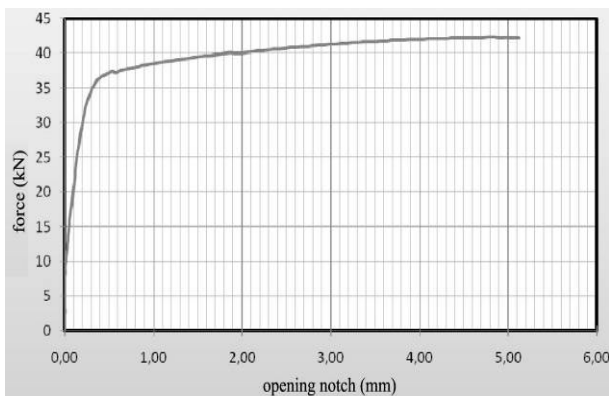


Figure 8. Loading force in relation to notch opening

4. Isoclinic and Isochromatic Fringes on the Notched Sample

Figure 9 depicts isoclinic fringes on the notched sample with angle parameter α 0° to 90° and 10° increase. Isoclinic fringes were gained by reflection polariscope LF/Z-2 at plane polarized light. During examination, the analysed notched sample was loaded by eccentric torsional force of 3 kN. Isoclinic fringes are areas in which directions of principal normal stresses are equal.

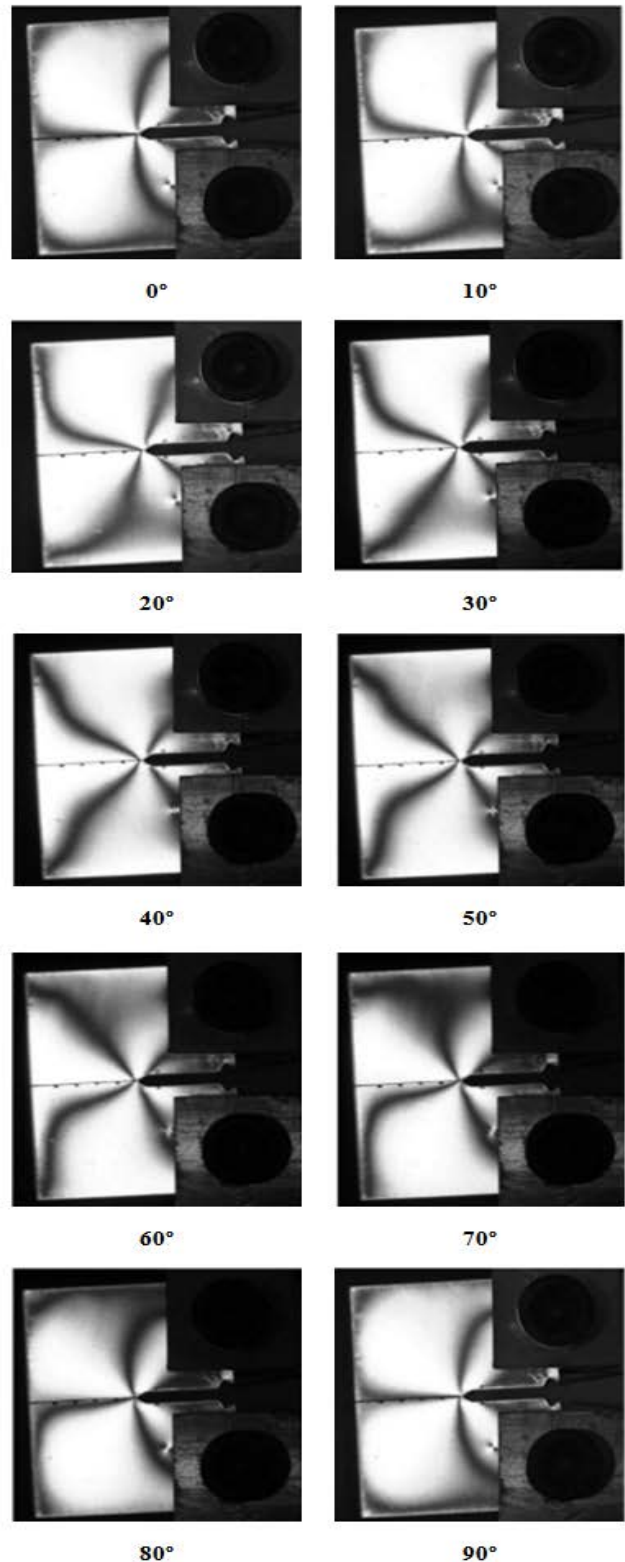


Figure 9. Isoclinic fringes on the notched sample under examination

Figure 10 depicts isochromatic fringes during gradual loading of examined notched sample with force from 0 to 12 kN. Isoclinic fringes were observed by reflection polariscope LF/Z-2 at circularly polarized light. At loads 12 kN and higher it is possible to observe stress gradient around notch root. The high gradient is a result of high stress concentration in the point of crack occurrence [6].

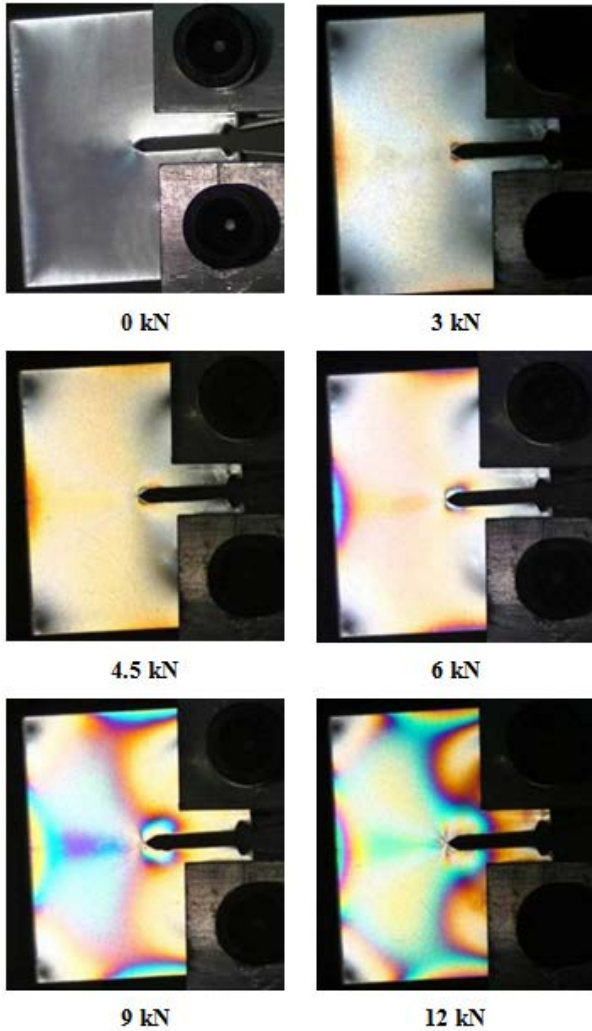


Figure 10. Analysed sample with photoelastic coating PS-1A

5. Principle Stress Analysis

Determination of principal normal stresses' difference was performed in point 1 Figure 11 at loading forces 3 kN, 4 kN, 6 kN, 9 kN and 12 kN.

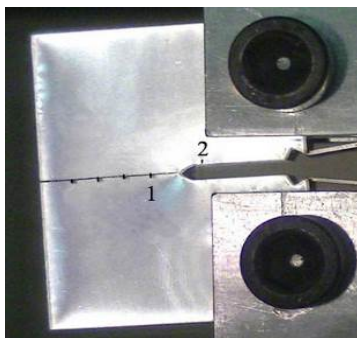


Figure 11. Fringe order measurement points

At the above-stated loading force values we used compensator 832 to determine the isochromatic fringe order N . Differences of principal normal stresses in point 1 at individual loads were determined by means of the following relation:

$$\sigma_1 - \sigma_2 = \frac{E}{1 + \mu} f \cdot N, \tag{2}$$

where E is the Young's modulus of sample material;
 μ Poisson's ratio of sample material;
 f fringe constant of photoelastic coating.

Listed in Table 2 are isochromatic fringe orders N at point 1 under loading force f 3 kN, 4 kN, 6 kN, 9 kN and 12 kN and differences of principal normal stresses $\sigma_1 - \sigma_2$ corrected by correction coefficient C_{PS} and derived from the relation (2) [6].

Table 2. Fringe orders and difference of principal normal stresses at individual loads

Measurement No.	F (kN)	N (-)	$\sigma_1 - \sigma_2$ (MPa)
1	0	0	0
2	3	0,28	37.39
3	4.5	0,47	62.77
4	6	0,62	82.80
5	9	0,97	129.54
6	12	1,27	169.61

As it is known from the theoretical background, biaxial stress state requires additional measurement to determine individual values of principal normal stresses. For these purposes we use separation methods. However, there are cases when the equation (2) can be transformed to the following form:

$$\sigma_1 = \frac{E}{1 + \mu} f \cdot N. \tag{3}$$

One of these cases requires free unloaded edge of an object subject to analysis. In each point of such edge we find one principal normal stress, which is non-zero tangential to the edge, and another zero normal stress. In an experimental way we used a compensator with null balance to specify the isochromatic fringe order in point 2 on the notched sample at loading force 12 kN Figure 11. Its value was 1.57. Using the relation (3) we subsequently determined the value of principal normal stress

$$\sigma_1 = 209,67 \text{ MPa.}$$

Numerical stress analysis was done in programme SolidWorks Figure 12 in order to verify previously gained value of principal normal stress σ_1 in point 2. Principal normal stress in point 2 determined by computer simulation has the value 200.2 MPa. The difference between principal normal stress σ_1 gained in an experimental way and numerically is 3.6%. As a result, we can state that the experimental measurement was relatively precise. This way of verification is easily applicable in everyday practice since the majority of structural elements include free edges.

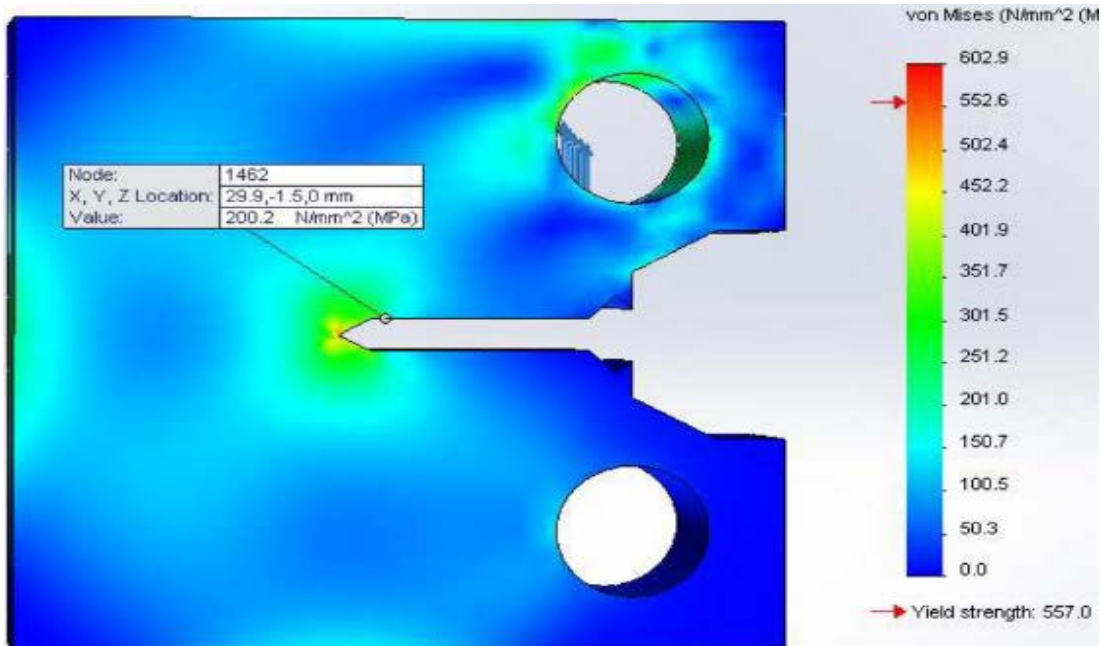


Figure 12. Field of reduced stresses according to von Mises

6. Verification of Endurance Limit of Photoelastic Coating

As regards tensibility of used photoelastic coating PS-1A, the manufacturer states the value of 5%. This implies that photoelastic coating is able to transform 5% of relative elongation value. Examinations were carried out on the photoelastically coated notched sample regarding the value of relative elongation at which the failure of photoelastic coating occurs.

The failure of photoelastic coating on the notched sample occurred at loading force 38 kN and relative elongation 4% Figure 13. The fracture was clearly visible immediately while the crack was accompanied with sound effect.

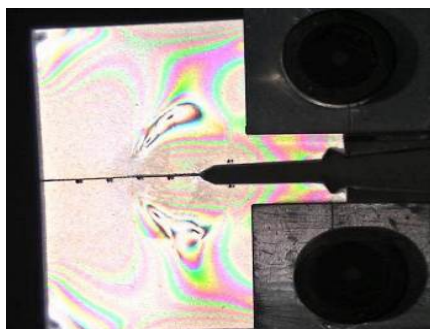


Figure 13. Failure of photoelastic coating

For the completeness of this issue we analysed video recording which was recorded by HD video camera and cut to individual shots of JPEG format. Figure 14 depicts shots which are representations of characteristic moments throughout the analysis. It is obvious from Figure 14 that stress gradient around the notch is high when the photoelastically coated sample is gradually loaded. Considering the shot No. 13 and higher it is obvious that photoelastic coating loses its ability to transform deformations and, at the same time, the ability to display isochromatic fringes. Figure 14 no. 17 depicts the first

moment when failure of photoelastic coating occurred. The shot No. 19 shows the crack spreading throughout the whole width of the sample, whereas the shot No. 20 depicts the coating peeled off under applied stresses and deformations.

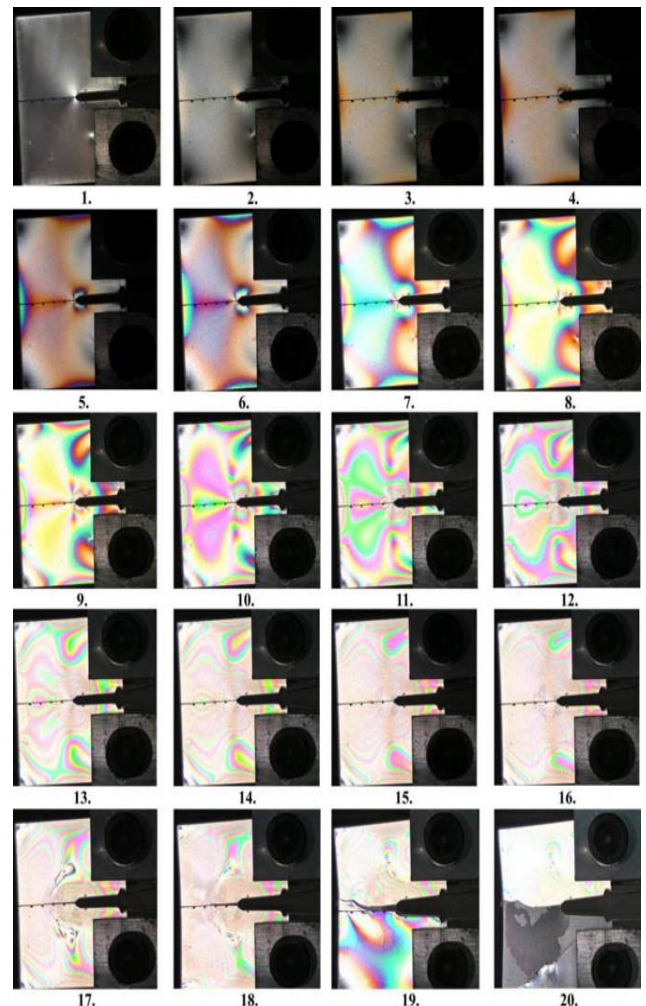


Figure 14. Analysed sample with photoelastic coating PS-1A

Figure 15 depicts damaged photoelastic coating PS-1A with the notched sample and relative elongation 4%.



Figure 15. Damaged photoelastic coating PS-1A with the notched sample and relative elongation 4%

7. Conclusion

Using PhotoStress[®] method we were able to determine the difference of principal normal stresses in a particular point at various values of loading force. The correctness of experimentally gained data was verified through determination of one of principal normal stresses on the free edge of photoelastically coated notched sample. This measurement was verified by means of numerical simulation in programme SolidWorks. Stress value σ_1 determined by means of PhotoStress[®] method in point 2 on the edge of the sample was $\sigma_1 = 209.67$ MPa. After numerical simulation the stress in the same point revealed the value of 202.2 MPa. The difference of these values is 3.6%, what implies that the experimental measurement was relatively precise. In the following papers we will present individual values of principal normal stresses in selected point out of free edge of photoelastically coated notched sample while using experimental separation methods [2,4,5].

Additionally we examined the maximum elongation of the applied photoelastic coating PS-1A of the sample. The

value provided by the manufacturer is 5%. Through measurements we finally determined that maximum elongation of the photoelastic coating PS-1A of 2.05 mm is 4%. This difference might have been caused by the structure of bonded joint.

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