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Experimental Stress Analysis

Analysis of residual stresses in plastics using digital image correlation

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Abstract: The residual stresses and strains were measured on cast polyamide material. The material exhibits sudden rupture during drilling or sometimes even without any external loading. The classical methods, such as X-ray diffraction and hole drilling method were not able to provide meaningful results and, therefore, non-destructive optical method known as two-dimensional digital image correlation was used. A random high-contrast color pattern was applied on the surface of the samples and the surface was then photographed before and after cutting to smaller parts. The displacements of the same areas are determined from the corresponding digital images and consequently, the strain and stress components are calculated. The method proved to be suitable for this type of analysis.

Keywords: Optical, Plastics, Polymer, Polyamide, Nylon

1. Characteristics and application of polyamides

Polyamide (PA), also know as Nylon, is a linear polymer consisting of methylene groups and amide functional groups. Nylon 6, or PA6, unlike other polyamides, is produced from its precursor caprolactam by ring-opening polymerization

$$n\ (CH_2)_5C(O)NH \rightarrow [(CH_2)_5C(O)NH]_n\ . \tag{1}$$

The total number of carbon atoms within one monomer is then used in the designation. Nylon 6 was developed as a commercial competitor to Nylon 6,6 – a polymer prepared by condensation and previously patented by DuPont [2].

Nylon 6 is widely used both as plastics and as fibers. The material is wrinkle-proof, highly resistant to abrasion and chemicals such as acids and alkalis, and also insect or fungi, and it also possesses low friction ratio, significant stiffness and tensile strength, high elongation and durability. Therefore, it is widely used in military applications and for the production of gear wheels, pulleys, bearing cages, wall plugs, ice skates, ski boots, helmets etc. Applications in form of fibers include toothbrush bristles, surgical sutures, strings of musical instruments, and all kinds of threads, ropes and nets. The main degradation of material properties is caused by oxidation or water absorption [1].

2. Residual stresses and common measurement methods

Residual stresses are stresses that are present in material even after removal of external forces or temperature gradient. They occur for a variety of reasons, such as inelastic deformations or heat effects. The heat effects include for example heat treatment (heating and cooling) during casting or welding. The presence of residual stresses often leads to premature failure of the material because they can significantly reduce its strength, and they also initiate or speed up common damage mechanism, such as the corrosion of metals. The most dangerous situation is

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in the case of tensile residual stresses in layers close to the surface of a structure which can cause the initiation of surface cracks or even an abrupt rupture, especially during dynamic loading.

The typical methods used for the measurement of residual stresses are the X-ray diffraction, which is a non-destructive method, or hole drilling, which is semi-destructive method. X-ray diffraction uses X-ray beam which interacts with the crystallographic structure (the layers under the surface of the material) whereas the distance is a function of incident and scattered angle of the beam. Hole drilling is based on removing small regions of material and measuring the subsequent deformation field with strain gages.

The primary values obtained from these methods are strain components. In order to calculate the values of stress components, an adequate theory (material model) must be used, and simplifying assumptions about the stress state (plane stress, plain strain) must be made, too.

3. Digital image correlation

Digital image correlation (DIC) is a non-destructive optical technique for the measurement of deformation on the surface of an object. Typically, a random (speckle) pattern is applied on the surface of the object, and it is photographed before and after applied load. The positions of corresponding pixels in the two digitized images are compared, and thus the in-plane displacement fields are obtained. In this case, known as 2D DIC, the object's surface must be parallel with the camera's image plane (sensor, film). Moreover, the obtained image should be rectified, in order to minimize the undesired effect of lens distortion.

This approach can be used also for the measurement of out-of-plane deformations, so-called 3D DIC, provided that a more complex system with two calibrated cameras using the principle of stereophotogrammetry is engaged [5]. Moreover, volumetric data in terms of so-called voxels obtained for example by computer tomography or magnetic resonance can be used for fully three-dimensional deformation field reconstruction. This method is known as digital volume correlation (DVC) [3].

4. Material samples and experiments

The analysis of residual stresses or strains was performed on MAPA 6 material which is similar to the PA 6 material described above but filled with an elastomer. The material was produced by Dub-plast company by casting into cylindrical metal moulds at temperature of 150 °C. The primary sample (casting) was therefore in shape of a cylinder. The diameter of the sample was 150 mm and the height was approximately 500 mm. The bottom face was planar and even, while the top free face was irregular.

Similar material samples were tested previously by X-ray diffraction and also by hole drilling methods [3], nevertheless, without success. The X-ray diffraction did not provide any results, because the material structure lacks the crystal structure to interact with the applied beam. The hole drilling method revealed that the material is subjected to very high heat generation during drilling, which causes the material to melt in the surrounding region.

Therefore, the digital image correlation technique was tested for the measurement of residual strains and stresses. In this case, one day after production, images of samples were taken in three consecutive stages – at first, the image of the face (or base) of the whole cylinder (designated as A), then, the surface of a thin disc (5 mm thick) cut out from the whole cylinder (designated as B), and lastly, surface of small plate (ca 30 × 30 × 5 mm) cut from the thin disc. The upper irregular face was first made even. The thin discs were cut directly at the upper (U) and lower (L) bases, and in the middle (M) section of the cylinder. The small plates

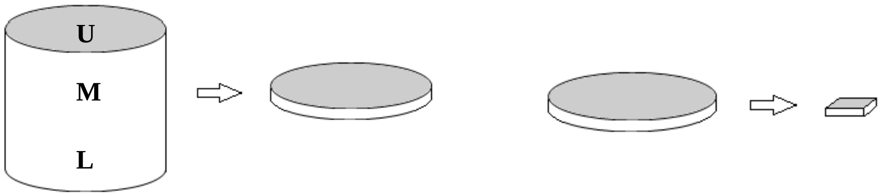

Fig. 1. Cutting of samples from stage A to B (left), and from stage B to C (right)

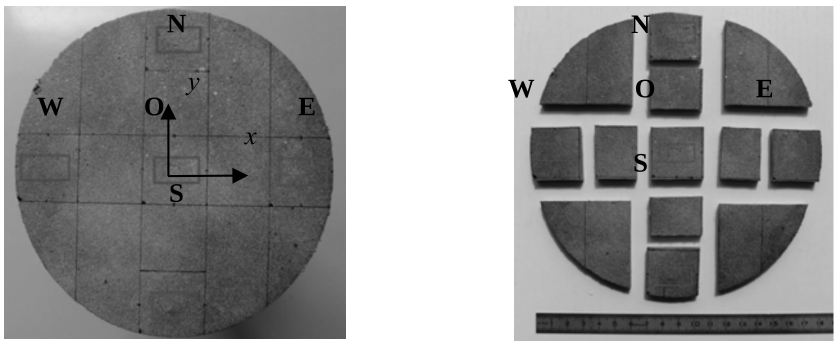

Fig. 2. Photographed areas and cutting lines on disc (stages A and B) and on plates (stage C)

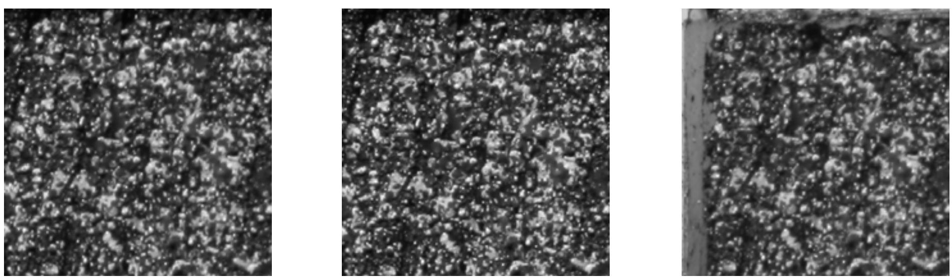

Fig. 3. Details of images of the same region at stages A (left), B (middle) and C (right)

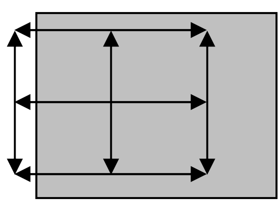

Fig. 4. Upper, center and lower lines for the calculation of ε_x strain, and left, center and right lines for the calculation of ε_y strain on each image

Table 1. Strain components on MAPA 6 sample calculated between A and C stages

U – Upper disc	0	W	E	N	S
Upper ε_x	0.0039	0.0003	–0.0026	0	0.0032
Lower ε_x	0.0036	–0.0003	–0.0044	–0.0009	0.0027
Center ε_x	0.0039	–0.0003	–0.0032	–0.0006	0.0029
Left ε_y	0.0056	0.006	–0.0005	–0.0014	0.0023
Right ε_y	0.0043	0.002	–0.001	–0.0032	–0.0009
Center ε_y	0.0052	0.003	–0.0015	–0.0023	0.0009
M – Middle disc	**0**	**W**	**E**	**N**	**S**
Upper ε_x	0.0036	0	–0.0006	0.0033	0.0041
Lower ε_x	0.0036	–0.0012	–0.0003	0.0009	0.0047
Center ε_x	0.0042	–0.0006	–0.0003	0.0021	0.0042
Left ε_y	0.0053	0.0093	0.0057	0.0005	0.0019
Right ε_y	0.0029	0.002	0.0051	–0.0035	0.0024
Center ε_y	0.0039	0.0049	0.0052	–0.002	0
L – Lower disc	**0**	**W**	**E**	**N**	**S**
Upper ε_x	0.0164	0.0025	–0.0022	0.0038	0.0026
Lower ε_x	0.0171	0.0044	–0.0006	0.007	0.0039
Center ε_x	0.0169	0.0034	–0.0009	0.0054	0.0032
Left ε_y	0.0177	0.0073	0.0034	0.0011	0.001
Right ε_y	0.0148	0.0078	0.0019	–0.0005	–0.001
Center ε_y	0.0168	0.0078	0.0024	0.0005	0

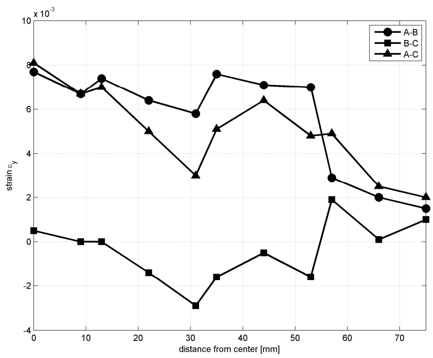

Fig. 5. Strain distribution between the three different stages

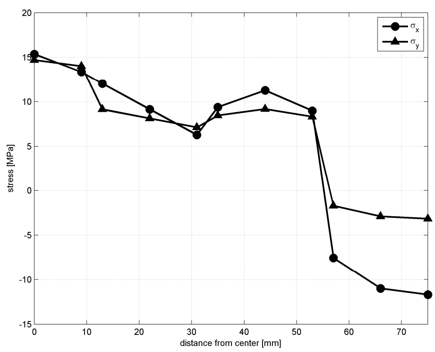

Fig. 6. Stress distribution between stages A and C

were cut in the center (O) and at the circumference (N, S, E, W) of each disc. The cutting was performed using band-saw (band speed 40 m/min, descent 22 mm/min).

The stages are shown in Fig. 1 and 2. The gray rectangles in Fig. 2 denote the individual areas having size of 22 × 15 mm photographed with resolution 3888 × 2592 pixels. The digital still camera Canon EOS 400D with Sigma 105 mm macro lens were used (zoom 1:1, F10, 1/8 s). Examples of images showing the surface detail of the same area in the three stages is shown in Fig. 3. The random pattern applied on the surface is composed of three color sprays – black Graphit 33 with carbon particles, white acrylic Dupli-Color Platinum, and common red acrylic spray.

The displacements were determined in 8 points (corners and midsides) and the corresponding strain components were calculated as shown in Fig. 4. The resulting values are summarized in Table 1. The values show almost no trend, except the fact that the largest residual strains are present at the lower base of the casting.

Six days after the first analysis, a slightly more detailed analysis was performed on another layer (disc) of material obtained from the middle section. The strain components were measured at 11 regions along the x axis between the center and the edge of the disc (see Fig. 5). Then, the stress components were calculated assuming plane stress, for the sake of simplicity, and elastic constants $E = 1754$ MPa and $\nu = 0.35$ (see Fig. 6) [1]. The strain values were significantly lower compared to the earlier results from Table 1, which was probably caused by relaxation of the material.

5. Conclusions

The non-destructive optical method – two-dimensional digital image correlation – was successfully tested on the analysis of residual stresses of mould-cast polyamide material, and can be recommended for further use. The material samples were cut and photographed at three stages. The cutting allowed the residual stresses to invoke quite large strains possible to be determined within the digital images. The results in this case showed no significant trend, which leads to conclusion that the stress state after cooling of the material within the moulds is more or less random. Moreover, the effect of cutting of the samples was not analysed.

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