MEASUREMENT OF RESIDUAL STRESSES

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Abstract

All stresses that exist in materials also without the application of any external loads are termed residual stresses. Residual stresses influence the behavior of mechanical components and can significantly affect the structural and dimensional stability of components. Therefore it is necessary to quantify them. There are several well-developed measuring techniques at the department of applied mechanics and mechatronics. Especially drilling methods are being developed there.

Key words: residual stress, hole-drilling, ring-core

INTRODUCTION

Residual stresses can exist in components and add to stresses induced by applied loads. These stresses can be caused by many factors like non-uniform heating or cooling of a component during manufacturing, and machining processes like stamping, grinding or shot-peening. They limit the loading capacity and safety of mechanical components during operation so it is necessary to quantify them.

Measuring techniques

The measurement of residual stresses can be extremely troublesome because of difficulty in measuring them nondestructively, unpredictable sense, magnitude and direction. Even when they are measured properly, it is difficult to remove them. The measuring of residual stresses in components cannot be successfully done by conventionally methods of experimental material analysis because strain sensors (gauge, photoelastic coating, etc.) are insensible to loading history. They measure only strains after their installation. The character of inside stress represents some kind of loaded condition. If we want to measure them, we need to enable the residual stress inside the specimen to relax to get an unloaded condition or to choose the method operating in loaded state.

Most common measuring techniques are hole-drilling method, ultrasonic method, x-rays, photoelasticity, ring-core method and finite elements. At the department of applied mechanics and mechatronics there is highly developed hole-drilling method and the research continues in developing of the Ring-core method.

Hole-drilling method

The hole-drilling method technique involves monitoring the change in stresses (or strains) produced when a hole is drilled into a component with residual stress. It is one of several material removal methods. The dimensions of drilled hole are very small: both diameter and depth about 2 mm. Therefore this method is only semidestructive, the produced hole may be insignificant or repaired after testing. The change in strain may be measured on the top of specimen using photoelasticity, brittle-coating or electrical strain gages. Blind rather than through holes are used and reading of strain change is in various depths to assess the variation depth [1].

Fig. 1 Hole-drilling method [2]

Most common hole-drilling method includes a special strain gage which is attached to the surface of specimen. The hole is then drilled through the gage middle. This will cause the change of inside force and moment balance, which can be observed on changing strain gage values. The shape of drilled hole and used strain gage affect the final strain values, therefore relaxed residual stresses are calculated from measured strains according to mathematical functions known as the relaxation functions or the calibration coefficients. These functions can be determined experimentally or by FE-analysis. Through the years there have been set various calculation methods. Nowadays determining the residual stresses by the hole-drilling strain gage method is performed according to the standard test method ASTM E387-08.

There have been done a lot of research work at the department of applied mechanics and mechatronics. The hole-drilling method is now a flexible, quick and well adapt method. One of the used equipment there is the drilling system RS200 [Fig. 2]. This system is easy to use, it represents the stand with centering device. Because it has no actuator, it requires a drill for making a hole. Static
strain gage system P3500 enables reading from strain gage rosette.

More sophisticated system is MTS 3000 produced by SINT [Fig. 3]. It is an excellent automated system for determining residual stresses by hole-drilling strain gage method. In contrast with RS200 this simplifies measuring process and is optimized for residual stresses calculations according to the standard ASTM E837-08.

Following operations are used for improving the measuring reliability [4]:
- fine adjustment of the position
- measuring of hole diameter also with its eccentricity
- centering drilling axes with strain gage by microscope
- online visualization of hole depth at each step of drilling process
- precision of each step is ensured by stepping motor
- high accurate and high speed turbine supplied by compressed air

Whole measuring and evaluation process is under full operator’s control. Data from strain gage rosette are amplified by digital amplifier SPIDER 8 from HBM which is connected to PC. Due the construction MTS3000 enables measuring residual stresses in components with worse accessibility.

One of the most significant disadvantages of hole-drilling method is its high sensitivity to drilling eccentricity.

**Ring-Core method**

Ring-Core method is another semidestructive method for determining residual stresses inside components. This method improves some disadvantages of hole-drilling method but brings a little more significant specimen destruction.

Unlike the hole-drilling method, ring-core method involves attaching to the specimen a specially designed strain gage rosette. And consequently instead of drilling a hole within the rosette, an annular notch is milled around the outside of the rosette [Fig. 4]. This process creates an isolated core in the specimen, within which the residual stresses are fully relieved. [5]

The department of applied mechanics and mechatronics owns the only fully automated system for determining residual stresses by the ring-core method. The machine itself enables precise centering of the mill. Stepping motor enables mill positioning in vertical direction and electric motor with high RPM provides the drilling [Fig. 5]. The inner diameter of drilled notch is 14 mm and the outer is 18mm. Maximum drilling depth is 5 mm and is divided into small step increments. After each drilled step the appropriate software reads the strain values from strain gage rosette.
The increased strain sensitivity is an advantage over the hole-drilling method. Also, stress concentration is not a concern with ring-core measurements, and so the method can be used even when the bulk residual stresses approach the material yield stress. The mill centering is also less important factor then in hole-drilling method [5].

Despite the advantages, the ring-core method is less popular than hole-drilling method. It requires more expensive machining and therefore there is no standard for residual stress evaluation.

Tab. 1 Strain gage rosettes used in the department of applied mechanics and mechatronics

<table>
<thead>
<tr>
<th>Strain gage rosettes</th>
<th>Ring-Core</th>
<th>Hole-drilling</th>
</tr>
</thead>
<tbody>
<tr>
<td>HBM K-RY 51/350</td>
<td>HBM RY61-1,5/120</td>
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</tbody>
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Routing of cables: through the hollow drilling spindle; out of the machining tool

Research tasks

As it was said before, the department of applied mechanics and mechatronics owned the only fully automated machine for ring-core. The current task is to develop the adequate measuring procedures and test the quality and performance of whole measuring string. This is the task of my doctoral work.

Although the ring-core method firstly appeared in the 50’s it is still not fully developed. The first task was to search for all information and contributions about this topic. The easiest way how to start the research was to create the FE model. Based on similar studies there have been created the model of specimen in which the notch will be drilled. Model was created in Solidworks 2012 and in behalf of better calculation performance just a quarter of the specimen will be calculated [Fig. 6].

Fig. 6 The quarter model for FE-analysis

In FE calculation it is possible to simulate the reading from strain gage rosette at each step of drilling. Like in hole-drilling method the residual stresses are calculated from measured strains according to some mathematical functions, which represents the relaxed coefficients. This coefficients depend on the used rosette and the mill. It is possible to obtain them with FE-analysis.

Next important factor is the type of the residual stress distribution. It could be uniform or in the components more often non-uniform one. There are different evaluation methods for different cases. Generally for the uniform stress distribution there is an incremental and a differential method. Integral method is suitable for the non-uniform ones.

Fig. 7 Different types of stresses

a) uniform b) non-uniform

Incremental method assumes constant increment of the stress at each step of drilling procedure. The assumptions are that the actual drilling step is not influenced by the previous one and the stress in vertical direction (perpendicular to the rosette face) is negligible to the planar stress values. The principal stresses \( \sigma_1 \) and \( \sigma_2 \) are calculated according equations (1) and (2) [6].

\[
\sigma_1 = \frac{E}{K_1^2 - \mu^2 K_2^2} \left( K_1 \frac{d \varepsilon_1}{dx} + \mu K_2 \frac{d \varepsilon_2}{dx} \right) \tag{1}
\]

\[
\sigma_2 = \frac{E}{K_1^2 - \mu^2 K_2^2} \left( K_1 \frac{d \varepsilon_2}{dx} + \mu K_2 \frac{d \varepsilon_1}{dx} \right) \tag{2}
\]

Where \( E \) is Young’s modulus, \( \mu \) is Poisson number, \( z \) is the depth, \( \varepsilon_1, \varepsilon_2 \) are relaxed strains and \( K_1, K_2 \) are calibration coefficients.

Special type of incremental method is the differential method. For evaluating by this method there is needed to drill the final depth only in two steps. Residual stresses are calculated according the following equations [6]:

\[
\sigma_1 = \frac{E}{K_1^2 - \mu^2 K_2^2} \left( K_1 \Delta \varepsilon_1 + \mu K_2 \Delta \varepsilon_2 \right) \tag{3}
\]

\[
\sigma_2 = \frac{E}{K_1^2 - \mu^2 K_2^2} \left( K_1 \Delta \varepsilon_2 + \mu K_2 \Delta \varepsilon_1 \right) \tag{4}
\]

\[
\Delta \varepsilon_1 = \left( \varepsilon_1 \right)_{z=2z_l} - \left( \varepsilon_1 \right)_{z_l} \tag{5}
\]

\[
\Delta \varepsilon_2 = \left( \varepsilon_2 \right)_{z=2z_l} - \left( \varepsilon_2 \right)_{z_l} \tag{6}
\]

Size of differential \( \Delta z \):

\[
\Delta z = 2z_l - z_l = z_l; \quad z_l = 1,2,3,4 \text{ mm} \tag{7}
\]

Unlike the previous evaluation methods, integral method is based on assumption that each drilling step is influenced by the previous one.
Therefore this method is suitable for calculating of non-uniform residual stresses. Principal stresses $\sigma_{1j}$, $\sigma_{2j}$ in the j-th layer of milled notch, as a product of $i=1..n$ step increment are calculated [6]:

$$\sigma_{1j} = \frac{1}{4} \left( \varepsilon_{aij} + \varepsilon_{cij} \right) A_{ij}$$

$$\sigma_{2j} = \frac{1}{4} \left( \varepsilon_{aij} - \varepsilon_{cij} \right) B_{ij}$$

(8)

Where $\varepsilon_{aij}$, $\varepsilon_{cij}$ are strains read from strain gage rosette in principal directions and $A_{ij}$, $B_{ij}$ are calibration coefficients for integral evaluation method.

When the relaxed strains from FE-analysis are known, it is possible to calculate the adequate residual stresses in the specimen according to one of the previous methods. For this purpose calibrated coefficients are set from the simplified model. But what if the dimensions of specimen are much different from our simplified model? The task is then to calculate the calibration coefficients for different dimensions. It means coefficient for different thickness, width and length. It is important to set the dependence of the coefficients on these dimensional parameters.

After the research of calibration coefficients and influential factors will be done, the next step will be to design the specimen for experimental testing. The specimen should be designed according to load machine which will create the load simulating the residual stresses. Parameters of the ring-core machine have to be also considered [Fig. 8].

![Fig. 8 Specimen for experimental testing](image)

FE-analysis will be created on designed specimen and then compared with experiment test on the real specimen using the ring-core machine owned by the department of applied mechanics and mechatronics.

**CONCLUSION**

The measuring and evaluating of the residual stresses are important tasks for mechanical engineers. It can save maintenance and increase safety.

Ring-core method is relatively low developed method in contrast with hole-drilling method. It means there are still a lot of factors which need to be adequately considered in case of ring-core standardization.

Fully automated ring-core system owned by the department of applied mechanics and mechatronics enables comparing results from FE-analysis with experimental results, which is a great assumption for future expansion of this method.

**References**


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