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A combined numerical-experimental method for determining the spatial distribution of a residual stress in a notch

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A combined numerical-experimental method for determining the spatial distribution of residual stress has been presented, which allows defining of the state and gradient of stress. The method is based on test measurements and numerical simulations by the finite elements method.

Keywords: *residual stress, finite elements method, deformation measurements*

1. Introduction

A review of dimensioning standards appertaining to immediate strength and durability shows that it is common practice to ignore residual stresses. Such stresses can occur as ta result of machining, forming moulding, welding, heat treatment, casting or phase changes of a given material [1–4]. The practice of ignoring residual stresses might be attributed to a lack of methods for determining its spatial distribution, especially in areas of maximum strain such as notches. It is even suggested [5] that the influence of residual stress should be ignored when dimensioning complicated welded objects, because of the lack of satisfactory methods for determining the condition of such objects after being subjected to such stress processes.

The influence of the manufacturing processes on the initial distribution of stresses within load bearing elements of machine components (i.e. as distinct from strain occurring later, during exploitation) is vital in view of the immediate strength as well as the ultimate durability of these elements. When these strain forces are later superimposed by strain forces occurring during exploitation, this often leads to premature failures or lower durability. Of course, in certain cases residual stress can also have

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a beneficial effect on durability – for example, shot peening or rolling can improve surface durability and surface resistance to fatigue stress.

Considering the above, the methods have been presented for determining the spatial distribution of a residual stress and for applying them in the design and dimensioning of machine components and load bearing elements. The method for determining the residual stress distribution in the notch areas of a cam shaft has also been presented.

2. Methods of measurement of residual stress

The methods of measurement of residual stresses can be divided into destructive and non-destructive ones. The non-destructive methods are following:

Acoustic methods relying on measurement of sound wave propagation through a material. These methods are generally used only for single axis loads and homogenous materials having a uniform structure.

Methods based on the Barkhausen effect. In magnetic materials, the Barkhausen noise is generated by movement of ferromagnetic domains. A change in this noise is a result of a mechanical stress. In practice, the method is useful for determining the strain direction (at lower stress levels).

Light diffraction methods. There are a variety of various methods based on light diffraction/interference. The application principles are the same as for the Newton ring apparatus. The method can be used for estimating the speed of crack propagation.

Moiré pattern method. A photographic method, where a pattern of parallel lines is printed onto a tested material. The method is difficult in use.

Elastooptic methods. The methods are based on the interference of electromagnetic waves (polarized light) after passing through a deformed, optically active transparent plastic material. In general, the method is only used for modeling, and has rather limited application.

X-ray and neutron diffraction based methods. The only methods providing the most accurate stress distribution measurements, having practically unlimited applications.

The most often used destructive methods of measurement of residual stresses are:

Methods based on exploiting a change in the shape of the material, after removing the deflection. This is a popular method for assessing residual stress in surface layers. When the upper material layer with residual stress is removed, this leads to a geometrical change in the object, and based on these changes it is possible to determine the distribution pattern of the earlier residual stress.

The hole-drilling method [6]. In this method, surface stress around a hole drilled in the material is relaxed. By measuring the stress relaxation (material extension) at appropriate spots distributed around a drilled hole (electric resistance strip strain gauges) it is also possible to determine the distribution pattern of the earlier residual stress. This is a destructive method (creating discontinuities in the material), used for material surface layers. The method consists of measurements of material extension around a small hole (ca. 2 mm in diameter) drilled in the tested element.

All of the discussed methods of measurement of residual stresses [6] have limited application, as they generally require flat or slightly curved, easily accessible surfaces. This basically disqualifies them for notch areas, as in our case, of a cam shaft and the transition areas between different shaft diameters. Nevertheless, these methods can be used to determine residual stress in the areas adjoining the notch, which was applied in the present work.

3. Method for determining residual stress in the notch shape area

The method is based on the assumption that in order to define residual stress in the notch area, it is sufficient to know its state and the gradient of the residual stress around this area. A two stage approach is used. First, experimental measurements on the test object are performed. The measurements of the residual stress may be based on any of the earlier mentioned destructive or nondestructive methods. The obtained results are then used as the input data for a numerical model of the object, where the finite elements method (FEM) is used [7–9] to define the residual stress in the notch shape area. A general diagram of this method is presented in Fig. 1.

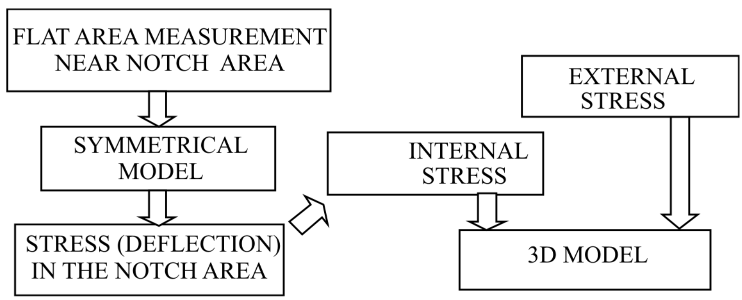

Fig. 1. Diagram presenting the method for creating a 3D model of a residual stress in the notch area

4. Application of the method

Forged elements with varying cross-sections often have significant residual stresses resulting from the technology of their manufacture. Considering this fact, we have chosen a cam shaft as a prime example, for describing the spatial distribution of residual stress in the notch area – the transition of the cylindrical shaft into the cam shape.

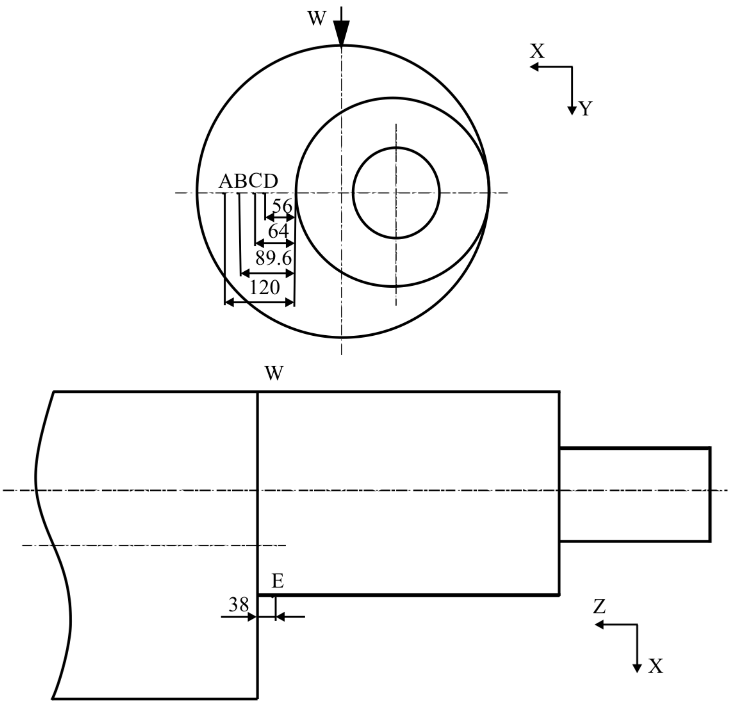

Fig. 2. Distribution of the measurement points

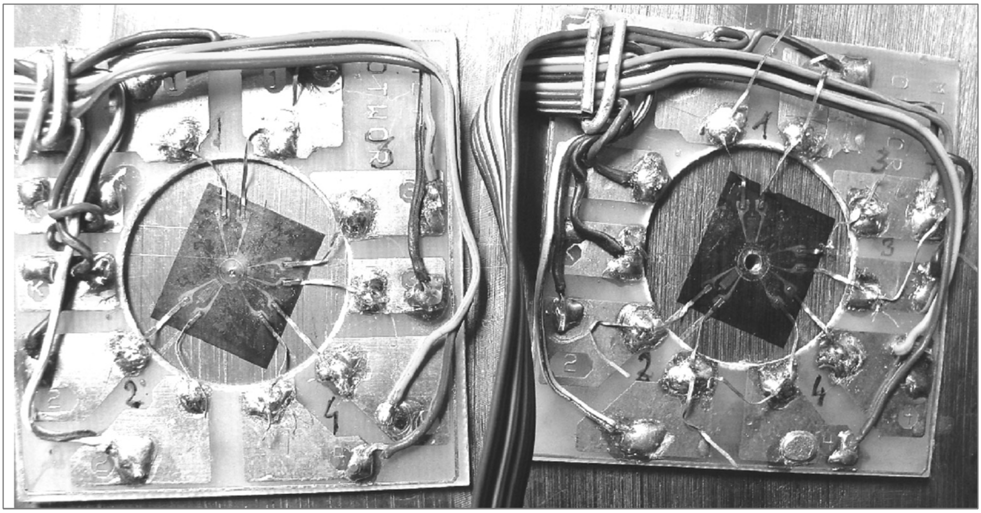

Fig. 3. Exemplary measurements points (A and B, cf. Fig. 2)
before (left) and after (tight) drilling of the relaxing hole

The first step requires measurement of residual stress near the notch. In our case, the hole-drilling stress relaxation method has been applied. Measurements were taken at points specified in Fig. 2, whilst Fig. 3 presents a picture of points A and B with strain gauges installed in a star arrangement, before and after drilling the hole in the shaft. Measurement data showed the presence of high compressive forces, with the gradient oriented towards the notch area. The maximum σ_{min} value was –146 MPa. The measured principal stress levels (σ_{max}, σ_{min}) as well as the stress direction α related to axis x_1 (see Fig. 3) for the individual points shown in Fig. 2 are given in Table 1.

Table 1. Measured residual stress levels
for points shown in Fig. 2

Measurement point	σ_{max} [MPa]	σ_{min} [MPa]	α [deg]
D	–126	–146	–10
C	–79	–129	–9
B	44	2	–2
A	24	–4	3
E	–24	–53	–2

We then built a numerical model of the shaft. It was symmetric with respect to the axis. The loads of compressive forces at the cross sections were representative of data obtained from experimental measurements. The dimensions of the shaft model as well as the dimensions of the notch areas under investigation are exactly the same as in the investigated object. The loaded and restrained fragment of the model, as shown in Fig. 4, was then analysed numerically to ascertain the spatial distribution of residual stress in the notch area.

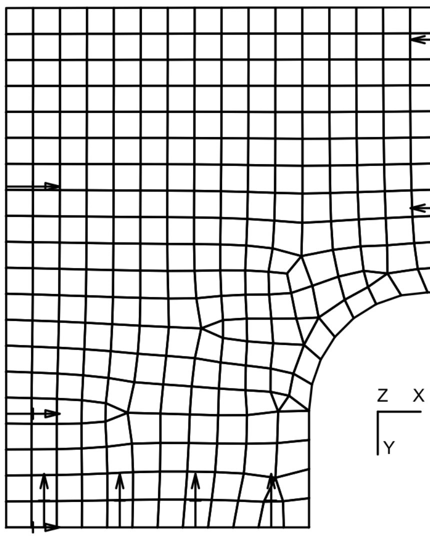

Fig. 4. Axis-symmetrical model of the shaft, showing the view of the notch area, along with the input forces

In Figures 5 and 6, prsent the main stress distribution patterns σ_{max} and σ_{min} are shown on an axis-symmetrical model of the analyzed cam shaft notch area.

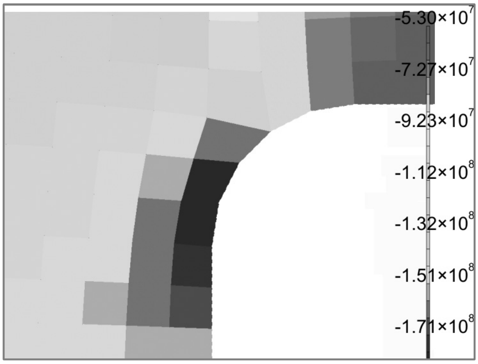

Fig. 5. Stress σ_{min} in the notch area

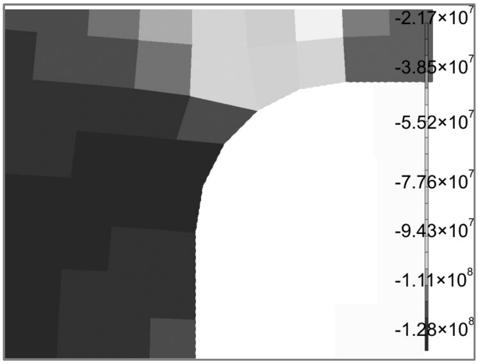

Fig. 6. Stress σ_{max} at the notch area

Figures 7 and 8 present plots of σ_{min} and σ_{max} stresses in function of the distance from the notch area, as determined from the numerical model, with superimposed strain gauge measurement values. Point 'zero' on the plot represents the geometrical centre of the notch curve (the bottom of the notch). The stress measurements and the stresses predicted by the numerical model are clearly marked by arrows and a short textual description. As one can see, the plot based on physical measurements (strain gauge) matches the predictions of the numerical model. The maximum stress level noted in the notch area is $\sigma_{min} = -184$ MPa.

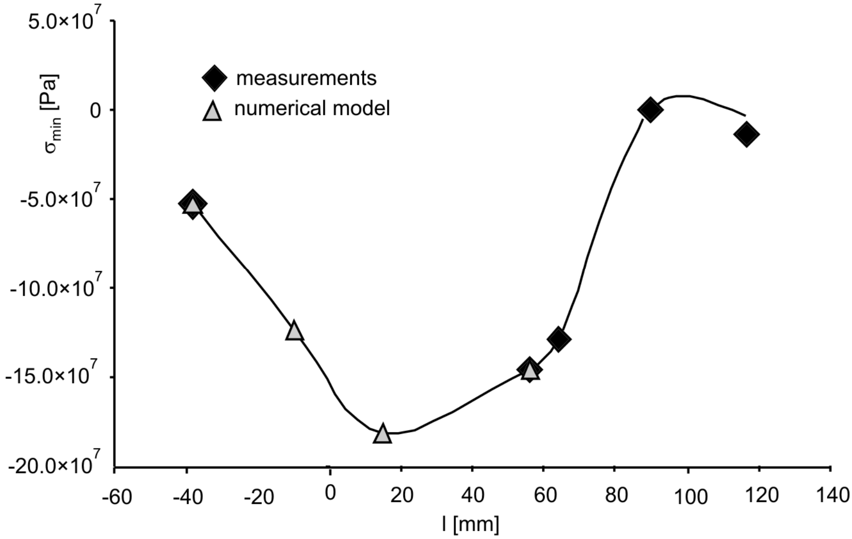

Fig. 7. Stress plot σ_{min} for the notch area [Pa]

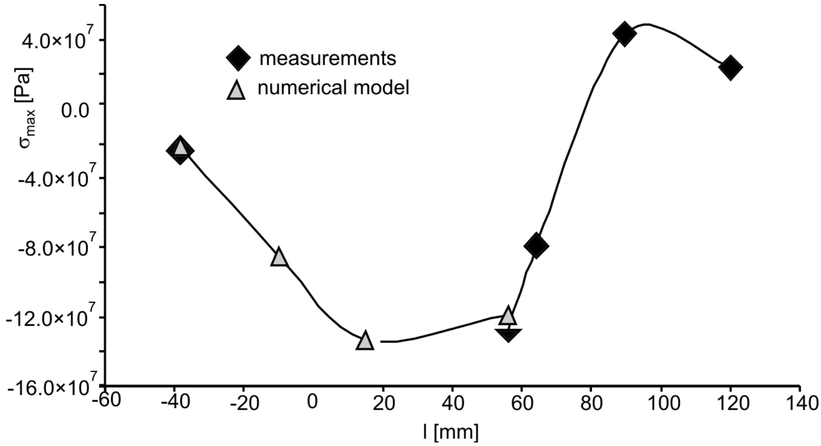

Fig. 8. Stress plot σ_{max} for the notch area [Pa]

5. Summary

The numerical–experimental method presented in the paper makes it possible to determine the spatial distribution of a residual stress in cam shaft notch areas. The method may also be generalized to include other objects. The method requires verification by using destructive testing. It can be applied to assess the strength and durability of load bearing elements, as well as for dimensioning purposes. An advantage of the method is, that knowing the residual stress in the notch area, it is possible to take it into account when assessing fatigue stress exploitation durability, for the notch area where failure is most likely to occur. An example of such analysis is given in [10].

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