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Experimental Stress Analysis

Residual Stress Analysis using ION-C Device

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Abstract: The device for non-destructive measurement of residual stresses using magnetostriction method is described. Some applications of using this device are given. The method of device calibration and the way for measured data evaluation and device limitation are explained.

Keywords: Residual, Nondestructive, Stress, Analysis, Magnetic method

1. Introduction

The knowledge of the state of residual stresses in products is indispensable for the comprehensive experimental research into their working fatigue strength and fatigue life. In the course of the time a wide number of methods have been developed which differ in many respects and are complementing each other in accordance with the varying tasks to be performed. However, the damage of the specimen is not allowed in many cases and non-destructive methods such as X-ray, neutron diffraction, ultrasonic and magnetic technique are then used. In this article, the device ION-C using magnetic technique is described. Magnetic stress testing methods rely on interaction between elastic strain and magnetization in a ferromagnetic body.

2. Magnetostriction method

Magnetostriction method utilizes the inversion magnetostrictive effect under low magnetic field H, where the linear part of magnetization curve $M = \mu \cdot H$ is used. Magnetic domains magnetize spontaneously in easy magnetization directions and elongate according the material magnetostriction constant. Due to acting stress the domains rearrange to minimize the elastic energy and additional magnetic poles appear on the surface. The compressive stress in comparison with tensile stress increases the elastic energy, which makes the magnetization more difficult. This is why the compression part of simplified magnetization curve under uniaxial stress is decreasing, while the tension part is constant (see Fig. 1). Permeabilities μ under

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biaxial stress are shown in Fig. 2, expressed with contour lines. Here, the origin gives the high permeability, which decreases monotonously with the distance from the origin.

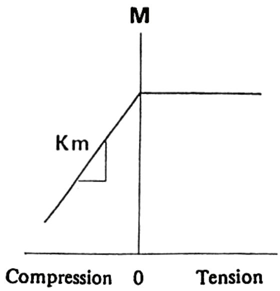

Fig. 1. Variation of magnetization during uniaxial stress.

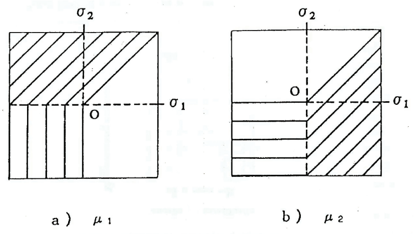

Fig. 2. Permeabilities under biaxial stress.

The simplest magnetic sensor is one-direction U-shaped one. However, this sensor detects not only the permeability μ_1 in the sensor direction //, but also some amount of the permeability μ_2 in transversal direction ⊥, so that its output voltage V// decreases with increasing tensile stress (see Fig. 3). If this sensor is turned 90° to be placed perpendicular to the acting stress, the output voltage V⊥ has similar character, but the sensitivity is changed. The difference of output voltages is utilized for measurement of difference of principal stresses. Combining two U-shaped magnetic cores it is possible to detect this difference directly through one output signal.

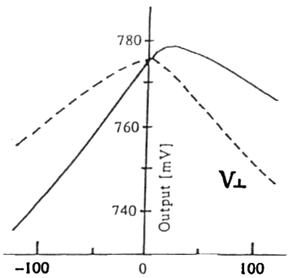

Fig. 3. Output signal of U-shaped sensor under uniaxial stress.

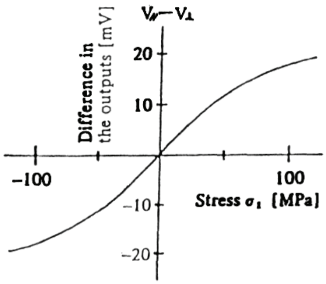

Fig. 4. Difference of output voltages between two directions from Fig. 3.

The method has however several restrictions. The magnetization is non-linear function of the strength of magnetic field, so that appropriate magnetic field has to be chosen for each material. The magnetization also depends on lift-off of the sensor from the object, on material property and state and also on object size. The stress history effect causes significant hysteresis loop in magnetization curve, caused due to the frictional resistance of movement of magnetic domain walls. That is the way the demagnetizing of the material has to be performed before measurement and after each stress step. The calibration curves for measuring the stress difference is also function of the stress state itself, so that they have to be created as shown in Fig. 2. Rotating the sensor on an object to be measured, the principal stress direction can be determined for the maximum output voltage. The principal stresses can be obtained only in the case when both principal stresses are compressive; only the difference in principal stresses can be measured in all other cases. For an object with stress-free edge or for a point where stress is known, the measurement method of biaxial stress was proposed [2]. This procedure utilises the method of integrating differences in sheering stress. Using this technique, the stresses σ_x and σ_y are evaluated from pairs of measurements in equal distance steps farther from known point.

The ION-C measuring instrument, producer NIIPT Mash Kramatorsk [3], for measurement of residual stresses is intended for non-destructive measurements of mechanical stresses and residual and operational stresses on flat and wavy surfaces of machines and various parts of ferromagnetic materials at various production stages at laboratory and workshop conditions. The measuring MAS (magnetic anisotropy sensor) is provided with two pairs of U-shape coils, driven with alternating voltage from the square pulse generator with frequency of 800 Hz, just measuring directly the difference of perpendicular stress components difference.

Fig. 5. Device ION-C.

Fig. 6. Calibration sample with sensor.

3. Method of device calibration and its sensitivity

Through calibration the ION-C instrument data are set for a precise determination of strains and stresses by means of standard testing machines. The calibration curves detected for various sorts of material are shown in Fig. 7; there is obvious the considerable difference of method sensitivity for individual materials. The calibration curves for high strength material for longitudinal and transversal position of the sensor to the uniaxial stress direction are given in Fig. 8. Their sum, as shown in Fig. 9, can be used for stress determination in real sample. Here, the new method of turning the sensor from 0°to 180°in steps of 145°was used, from which the diagram, given in Fig. 10 was obtained. This technique of calibration does not require adjusting the device zero using the unloaded “zero” calibration sample; the zero is put to the mean value of the obtained curve (see Fig 10). A special device for calibration of bi-axial stress state has to be used (Fig. 11), because the sensitivity is not linear for various combinations of principal *stresses*. This is shown in Fig. 12, where the ratio K_m (Fig. 1) between magnetization and principal stress difference σ_1-σ_2 is plotted for several stress states.

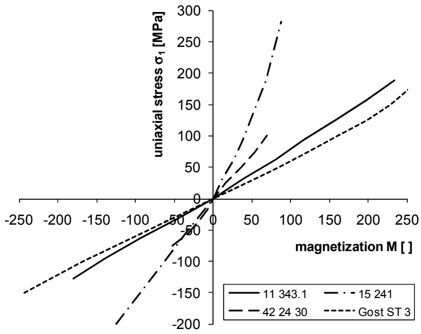

Fig. 7. Calibration diagram of testing samples for various ferromagnetic materials under uniaxial stress.

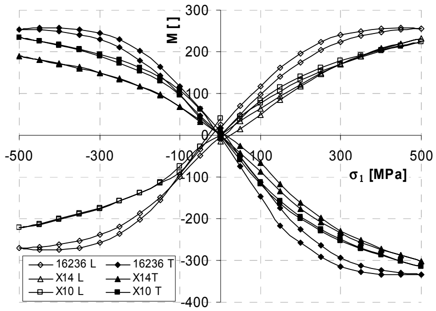

Fig. 8. Calibration diagrams for special high strength steels – at longitudinal (L) and transversal (T) sensor position.

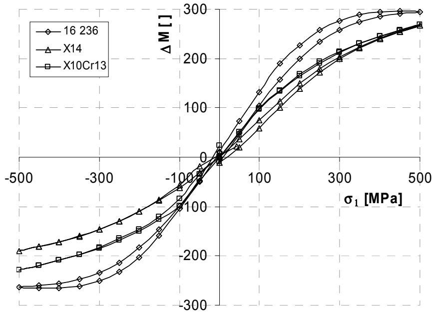

Fig. 9. Calibration diagram for the magnetization difference $\Delta M=(M_L-M_T)/2$ at longitudinal and transversal direction.

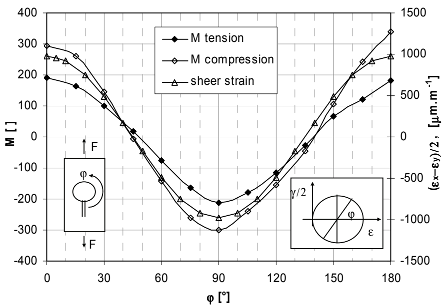

Fig. 10. Resulted magnetization M during turning the sensor at angle φ.

4. Method application

4.1. Device applicability

Application of the device is above all for the cases of uniaxial stress state (stress in railways, stress at object edges (e.g. railroad wheel tires), residual stress near welds). For biaxial stress state the device is suitable for the cases, where the stress difference is satisfactory for solving the problem, or can be theoretically expressed. It concerns pressure vessels, press-on joints etc. Very suitable application for magnetostriction method is the separation of residual stresses in railway wheel rims, required in EN 13 262, where the tangential residual stresses exceed several times the radial stresses. In this standard, the measurement is recommended with acousto-elastic method, measuring the stress difference through the whole wheel thickness contrary of the magnetostriction method.

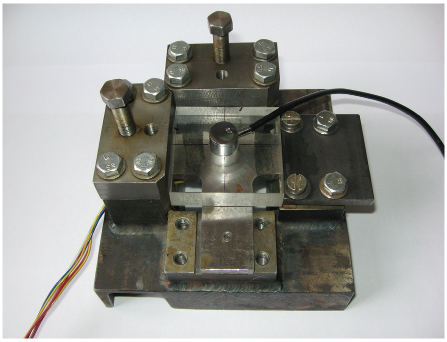

Fig. 11. Device for bi-axial stress state calibration using ION-C.

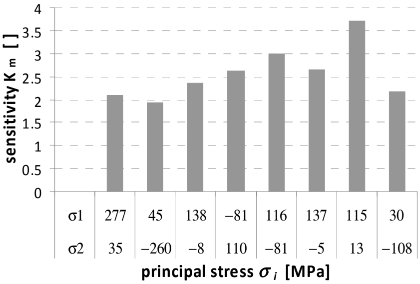

Fig. 12. Measured ION-C sensitivity for various bi-axial stress states.

4.2. Examples of device application

The non-destructive magnetic method has been successfully used e.g. in residual stress measurement on a gear wheel rim, on the rotating platform weldment of articulated bus, on the bogie frame weldment of the electric locomotive and on welded steel girders in ŠKODA VÝZKUM s.r.o. An example of using this method of residual stress investigation after surface hardening on a gear wheel rim for electric locomotives is given in Fig. 13. The relations of tangential and radial residual stress difference vs. radial distance from the gear top circle are given in three sections separated at 120°. The measurement was verified with cut-off method and hole-drilling method with very good agreement. The change of residual stress during grinding was also investigated (Fig. 14). Application of the method using turning the sensor is given in Fig. 15 and 16. Here the residual stress was investigated on refurbished turbine shaft. The principal stress directions were found in longitudinal and tangential directions; the stress difference was lower than 40 MPa.

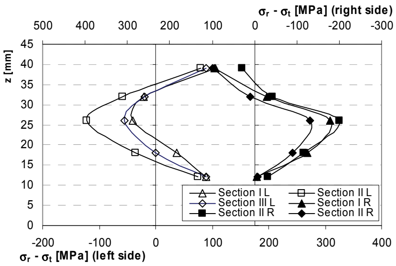

Fig. 13. Diagram of difference of residual stresses on the surface of the pinion rim in the tooth area.

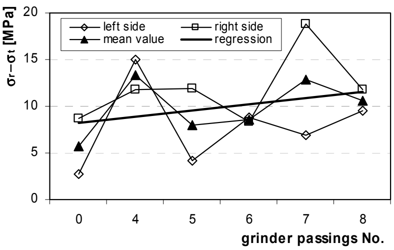

Fig. 14. Change of residual stresses in the pinion rim in tooth area during several passes of grinding.

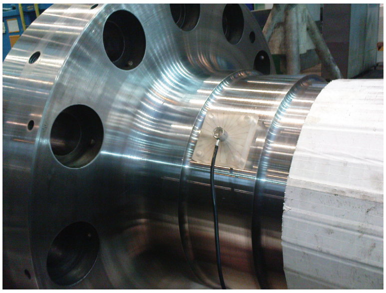

Fig. 15. Investigated turbine shaft.

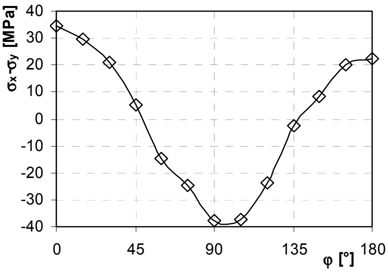

Fig. 16. Evaluated stress difference on turbine shaft.

5. Conclusion

Based upon the experience and verified work the ION-C can be advantageously used under the observance of the set conditions for measurement of operational and residual stresses at the uniaxial state of stress. There are several limitations for using this device for measurement of biaxial stress state. The measurement method is sensitive only for difference of stresses in sensor measured perpendicular directions, i.e. for sheer stress. However, additional sensitivity of magnetization output as a function of stress state was observed. The direction of principal stresses can be determined reliably. There is a solution which could be based on the use of a non-destructive measurement method with ION-C instrument in combination with one of the semi-destructive methods of residual stress measurement, e.g. hole-drilling method.

Acknowledgements

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