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VALIDATION OF THE X-RAY STRESS MEASUREMENT METHOD

ABSTRACT

One of the most important characteristics of the material allowing us to predict its applicability for specific tasks as a single object or as an integral part of the whole structure is the presence of stresses. There are many methods to measure stress. Among them, increasingly important and recognised as the most accurate non-destructive method is the X-ray measurement technique. The aim of this study was validation of the results obtained by the X-ray stress measurement method. Stress measurements were performed on samples of the three materials subjected during measurement to the effect of tensile forces. Studies revealed close relationship between the stress values measured by X-ray technique and actual values present in the examined material. The summation of residual stresses present in the material and stresses caused by the effect of external forces was observed.

Key words: *stress measurement, residual stress, X-ray stress measurement*

INTRODUCTION

There are many methods to measure stress, and they fall into two main categories, i.e. the destructive methods and the non-destructive ones. Currently, the most important are the non-destructive methods – the fact quite obvious and easy to understand. In the latter group, the most popular are the methods of magnetic inspection and X-ray technique [1].

Magnetic methods rely on the measurement of changes in the magnetisation curve resulting from the effect exerted by local stress centres on the value and the amplitude of magnetic oscillations. One of these methods is used for the measurement of magnetic Barkhausen noise. It is based on the evaluation of magnetic noise which arises when the magnetic domain walls are abruptly pushed by stress accompanied by the effect of external magnetic field. With the help of proper instrument, using this method, one can measure stresses in a relatively short time even in objects varying in size [2].

X-ray methods measure changes in the interplanar distance. Under the impact of load resulting in deformation of the examined material, a displacement of components of the crystal lattice structure occurs. Changes in the interplanar spacing d_{hkl} can be a measure of stress, and this is the main principle on which the X-ray methods are based [3, 4].

Currently, in the group of X-ray methods, the most widely used is the $\sin^2\psi$ method. It is realized using X-ray diffractometer. The essence of the method is to determine variations in interplanar distances in the crystal lattice of the material under the influence of forces occurring therein.

Historically, the primary drawback of this method was considered to be the need for cutting out small specimens to fit the traditional goniometers, which obviously had to cause some changes in the state of stress in the examined material. Now, with the use of modern diffractometers, it is possible to measure stress in objects of practically any size and identify the state of stress not relaxed by excision of the specimen.

Compared to magnetic methods, the measurements by X-ray technique take longer time and measure stress in a layer of the thickness of about 10-20 μm, i.e. ten times shallower than the one used in magnetic inspection. On the other hand, the advantage of the X-ray method is that it requires no reference standards; what is required is the knowledge of material constants such as Young's modulus and Poisson's ratio. Stresses are measured in a particular direction, thus enabling the determination of a stress tensor.

The X-ray methods of stress measurement have been known for years, but never enjoyed great popularity, especially in industry, since the results obtained are not trusted, being rather difficult in interpretation.

For many years, the Institute of Non-Ferrous Metals, Light Metals Division Skawina, studies stresses by the X-ray technique. These are both research [5-10] and application works allowing, for example, verification of the applied technology or product control [11-13]. Recently, widespread popularity are gaining stress measurements supplying data necessary for the development of mathematical models of various technological processes [14].

The aim of this study was to demonstrate a relationship between the stresses measured by X-ray method and stresses actually present in the examined material.

EQUIPMENT

Residual stresses were measured with X-ray instruments used for the measurement of stress and retained austenite content:

- "Strainflex PSF 2M" made by Rigaku, Japan (Fig. 1),
- "PROTO iXRD" made by Proto, Canada (Fig. 2).

Both are portable X-ray diffractometers, fully computerized, used only for the measurement of residual stresses and retained austenite content. All instrument- and material-related parameters for the measurement of tensile specimens are shown in Table 1.

All specimens were subjected to the effect of constant tensile forces, using for this purpose either a specially designed machine for testing of small specimens or an Instron 5582 testing machine. On loaded specimens, stresses were measured by the X-ray technique (Figs. 3 and 4). The results of measurements are illustrated by graphs shown in Figures 5-9.

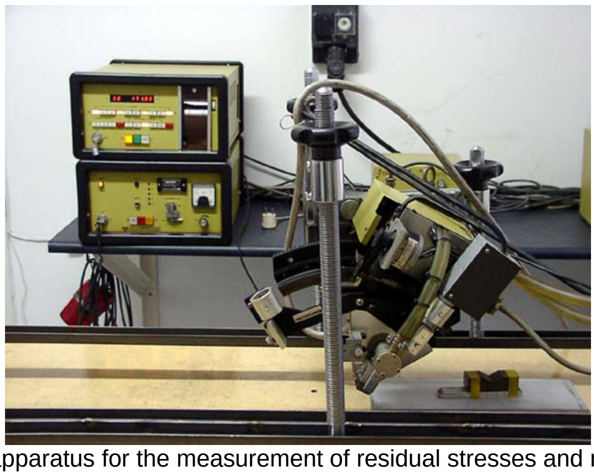

Fig. 1. Strainflex PSF 2M apparatus for the measurement of residual stresses and retained austenite content

Fig. 2. PROTO iXRD X-ray diffractometer for the measurement of residual stresses and retained austenite content

Table 1. *Measurement conditions*

Apparatus for X-ray measurement of residual stresses		"STRAINFLAX-PSF 2M" made by Rigaku - Japan	PROTO iXRD
Voltage		30 kV	20kV
Current in tube		5 mA	4 mA
Type of X-ray tube		Cr	Cr
Radiation length λCr		2.103 [Å]	2.103 [Å]
Planes of reflection		222 for Al and 211 for Fe	Fe 211
Measured angular range 2θ		140° - 170°	145° - 165°
Size of X-ray beam incident on sample		4x2 mm	5x1mm
Tested material		Al, Fe	Ferritic steel
Bragg angle in unstressed material $2\theta o$		156.7°for Al, 156.08° for Fe	156,41
Materials constans	E	$7.03x10^3$[kG/mm^2] for Al $21x10^3$[kG/mm^2] for Fe	S1=1.28 E-6[1/MPa]
	ν	0.345 for Al 0.28 for Fe	S2=11.42 E-6[1/MPa]
Penetration depth of X-rays		≈26 μm for Al and ≈13μm for Fe	≈10μm for Fe

MATERIAL

Tests were performed on samples of four different materials:

- from the wall of profile extruded in PA9 aluminium alloy, a flat specimen of 3x9.5 mm cross-section was cut out. Using the X-ray method, residual stress was measured on the specimen surface and was reported to amount to -11 MPa. The specimen was subjected to the effect of tensile forces, and additionally to the effect of compressive forces,
- from the ST12 steel a specimen of 2x10 mm cross-section was prepared; in this specimen, the measured residual stress was -62 MPa,
- from the HSS tool steel two specimens with cross-sections of 0.65x9.75 mm each were prepared. In the first specimen, the value of the residual stress was 14 MPa; after grinding the surface of the specimen with sand paper, the residual stress increased to -388 MPa.

The second sample showed the presence of the residual stress of 33 MPa. After grinding the surface of the specimen with sand paper, the residual stress increased to -177 MPa. After electrochemical etching of a layer of approximately 0.03 mm thickness, at a selected point, the measured residual stress assumed the value of 2.4 MPa.

Measurements of stress under load were carried out at two points, i.e. at the point where the surface of the sample was only ground, and at the point where the surface was ground and electrochemically etched,

- from the S235J2 steel a specimen of 6x15 mm cross-section was prepared. The residual stress measured on the surface of the specimen by X-ray method amounted to -56MPa, and after the removal by electrochemical etching of a 0.1 mm thick layer, the residual stress amounted to +25 MPa.

In all specimens, stresses were measured in the direction of the operating tensile forces.

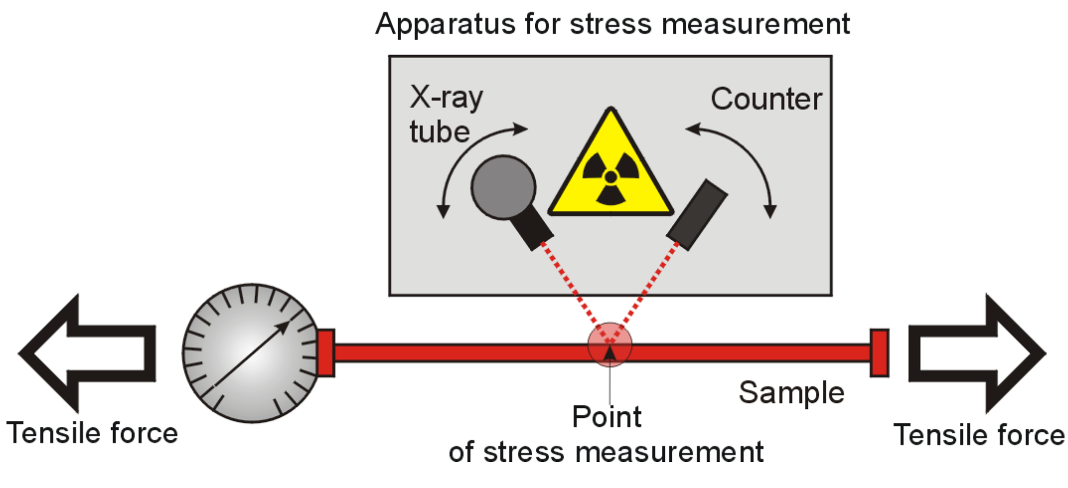

Fig. 3. Schematic representation of the X-ray stress measurement technique as performed on a specimen under the effect of constant load

Fig. 4. Stress measurement by the X-ray method using a PROTO iXRD apparatus and specimen stretched on an Instron 5582 machine

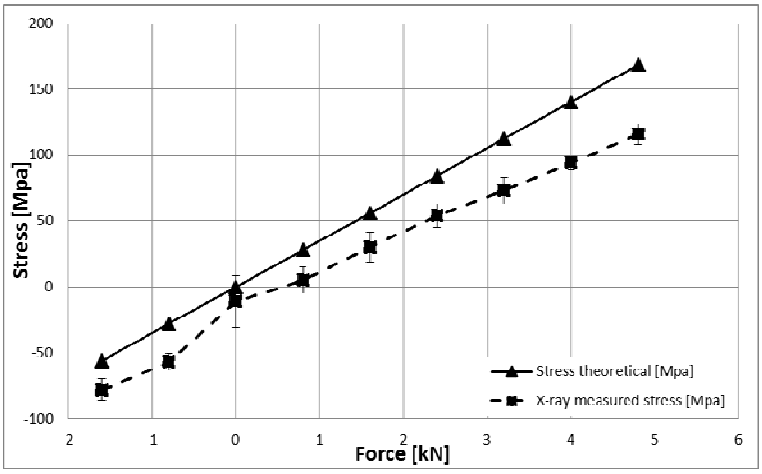

Fig. 5. Graph showing tensile force-dependent stress variations in the aluminium alloy specimen

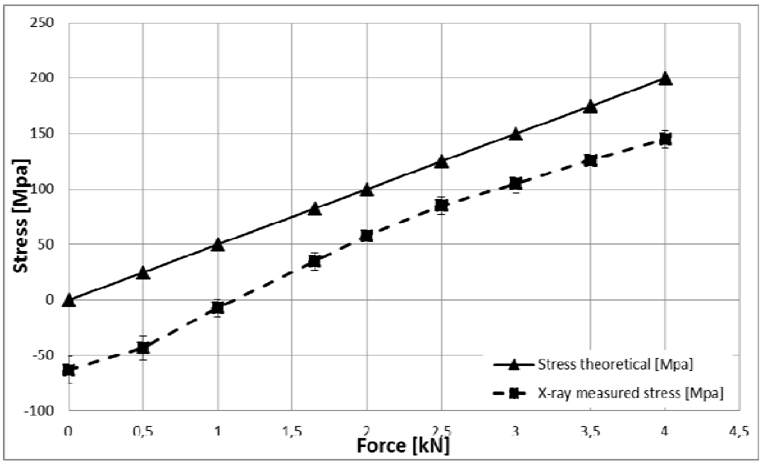

Fig. 6. Graph showing tensile force-dependent stress variations in the ST12 steel specimen

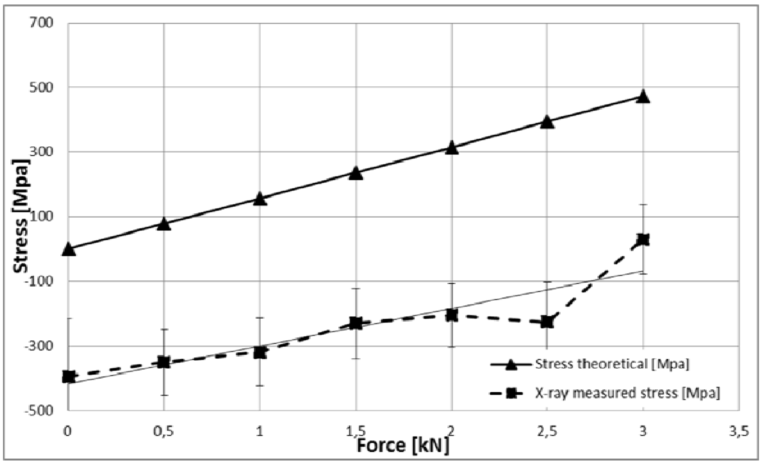

Fig. 7. Graph showing tensile force-dependent stress variations in the HSS steel specimen after surface grinding with sand paper

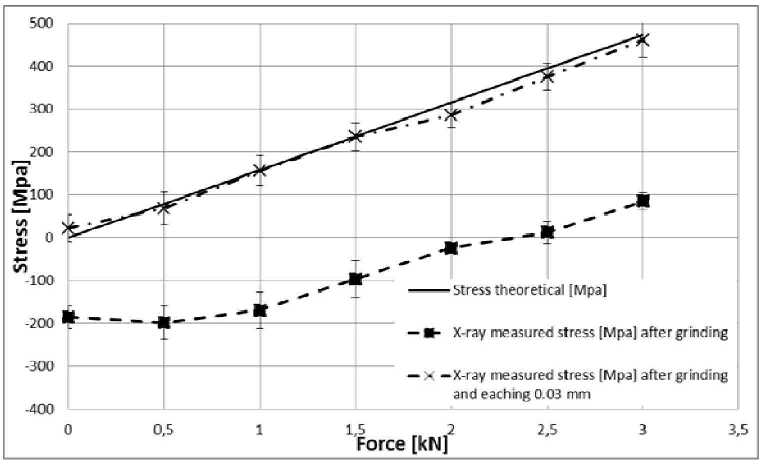

Fig. 8. Graph showing tensile force-dependent stress variations in the HSS steel specimen after surface grinding with sand paper and electrochemical etching of a 0.03 mm thick layer

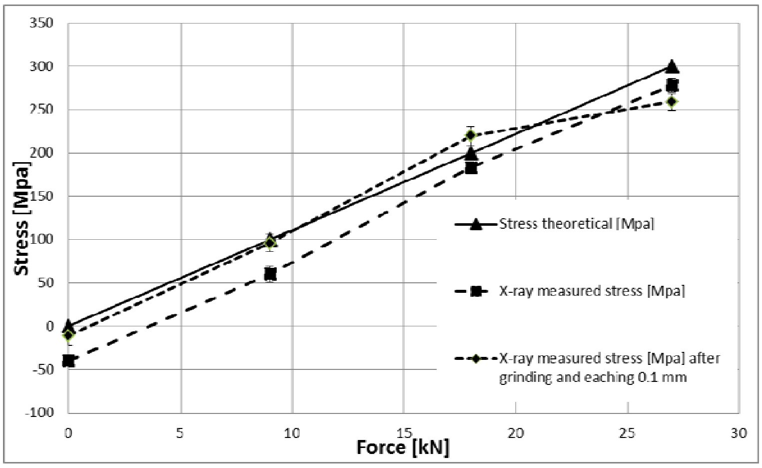

Fig. 9. Graph showing stress variations in the S235J2 steel specimen stretched on an INSTRON 5582 machine

DISCUSSION

As follows from the plotted graphs, in all the examined specimens, the X-ray measured stress values were either close to the theoretical values resulting from simple calculation of a ratio between the force acting on a specimen and the specimen cross-section (Figs. 5 and 8 for the point after electrochemical etching), or revealed a similar character of changes. The X-ray measured stress values different from the corresponding theoretical values were shifted by a value constant for a given specimen and close to the value of residual stress measured by the X-ray technique in unloaded specimens.

Close examination of graphs presented in Figures 7 and 8 shows that grinding of the specimen surface with sand paper introduces additional stresses to the specimen surface, which not only shift the values measured by X-rays, but also disturb the linear character of changes in these values. It was also noted that electrochemical polishing of the specimen surface shifts the stress values practically to the level of the corresponding theoretical values, which is consistent with previous observations [15].

CONCLUSIONS

- Stress measurements taken by the $\sin^2\Psi$ X-ray method in aluminium and steel specimens loaded with the external stress of preset value confirmed close relationship between the stress values measured by the X-ray method and those actually present in the examined material.
- Using portable apparatus for the stress measurement (PSF Strainflex 2M, PROTO iXRD) it is possible to measure stresses occurring in the components of finished metal structures without damage done to this structure and without the need to use standard reference samples.
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