RESIDUAL STRESSES MEASUREMENTS WITH X-RAY DIFFRACTOMETRY ON ALUMINUM SPECIMENS – DETERMINATION OF THE MOST SUITABLE PARAMETERS OF MEASUREMENT

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Abstract

The work was done as a part of the IMPERJA Eureka Project. The goal of the IMPERJA project is to increase the fatigue life of riveted joints, which will lead to an increase of the aircraft service life, a smaller number of inspections and lower operation costs of an aircraft. The consortium intends to meet this goal by investigating and improving the riveting process as well as improving the prediction methods for fatigue life.

Riveting is the most commonly used method of joining sheet metal components of the aircraft structure. Typically, the number of rivets ranges from several thousands to some millions in a single aircraft depending on the specific aircraft type and size. The riveted joints are critical areas of the aircraft structure due to severe stress concentrations and effects such as fretting and secondary bending. Therefore the fatigue crack initiation will start at the rivets holes. Fatigue crack initiation usually occurs at a number of rivet holes (multiple site damage), which may lead to widespread fatigue damage and reduced residual strength.

Although the literature on the fatigue behaviour of riveted joints is quite abundant, many aspects are still not sufficiently understood and investigated and, therefore, they require a further study.

The work contains the results of stress measurements obtained with X-ray diffractometer. The aim of the work was to determine the stress values after different kinds of treatment, to check what are the limits of the x-ray measurement for aluminum alloys and to obtain the most suitable measurement parameters for this kind of alloy. There were 5 kinds of specimens:

- *specimen no. 1 - technically pure aluminum, specimen annealed in temperature 300°C for 1 hour,*
- *specimen no. 2 - technically pure aluminum, raw state without any additional treatment,*
- *specimen no. 3 - technically pure aluminum, squeezed perpendicularly to the axis direction, force: 100 kN, longitudinal intersection,*
- *specimen no. 4 - technically pure aluminum, squeezed perpendicularly to the axis direction, force: 100 kN, transverse intersection,*
- *specimen no. 5 - PA24 alloy, ∅5 bar, squeezed along the axis of the rod, force: 13,9kN, longitudinal intersection.*

The second part of the work contains the measurements of the stress distribution around the rivets. The specimen prepared to realize this kind of measurements had four areas. The rivets on every area were riveted with the different riveting force: 1.2 kN; 1.4 kN; 1.5 kN and 1.55 kN.

***Keywords**: X-ray diffractometry, residual stresses, fatigue, aluminum alloys*

1. Stress measurements with x-ray diffractometry

X-ray diffractometry serves as a one of a number of methods for residual stress evaluation. The essential advantage of this method is that it is the accurate and absolute. The diffraction of X-rays on a crystal lattice of a copper sulphate was detected by Max von Laue in 1912. The mathematical formula for this phenomenon was expressed by William Bragg and is as follows:

$$n\lambda = 2d\sin\Theta, \tag{1}$$

where:

n - is an integer determined by the order given,

λ - is the wavelength of diffracting X-ray,
d - is the spacing between the planes in the atomic lattice,
$\sin\Theta$ - is the angle between the incident ray and the scattering planes.

The formula shows that the diffraction will occur only for unique Bragg's angles. Since its publication in 1913 the Bragg's law has been a powerful tool for studying the crystals' structure. One of its applications is the residual stress measurement. The formula for stress calculation in a crystal is as follows:

$$\sigma_{\varphi} = \left(\frac{E}{1+\nu}\right)_{hkl} \frac{1}{d_0}\left(\frac{\partial d_{\varphi\psi}}{\partial \sin^2\psi}\right), \tag{2}$$

where:
φ - is the angle between the projection onto a plane of a specimen and the direction of σ_{11},
ψ - is the angle between the incident beam and the perpendicular to the sample surface,
σ_{φ} - is the surface stress in direction determined by angle,
E - is the Young modulus,
ν - is the Poisson ratio,
d_0 - is the stress-free lattice spacing,
$d_{\varphi\psi}$ - is the lattice spacing in the direction determined by the angles φ, ψ.

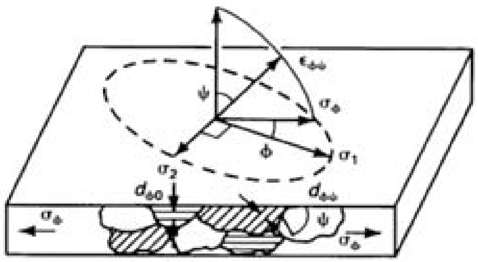


Fig. 1. X-ray diffraction parameters

The stress values are obtained from the graph of the function of $d_{\varphi\psi}$ depending on $\sin^2\psi$.

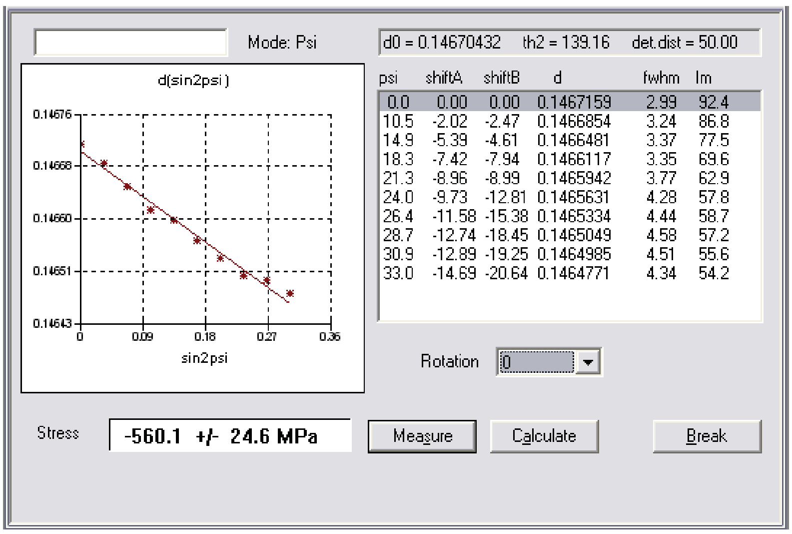


Fig. 2. The example of stress measurement results obtained with Xstress3000

All the stress measurement results presented here were obtained using a Stresstech Oy built X-ray diffractometer model Xstress3000. It is a mobile device capable of performing measurements in two modes: ψ and Ω, with Φ rotation and Ψ and Φ oscillation. There is a set of collimators from the 0.5 mm diameter to 5 mm. This equipment is fully automated with a software controlled X-Y table for sequential measurements at a programmable set of points with given X-Y coordinates.

2. Specimens

The work consists of two parts: the first part concerns the problem of measuring the stress values with the X-ray diffractometry on aluminum and the optimization of the measurement parameters and the second part concerns the problem of stress distributions around the rivets.

There were 5 kinds of specimens used during the first part of the measurement process:

- specimen no. 1 – technically pure aluminum, specimen annealed in temperature 300°C for 1 hour:

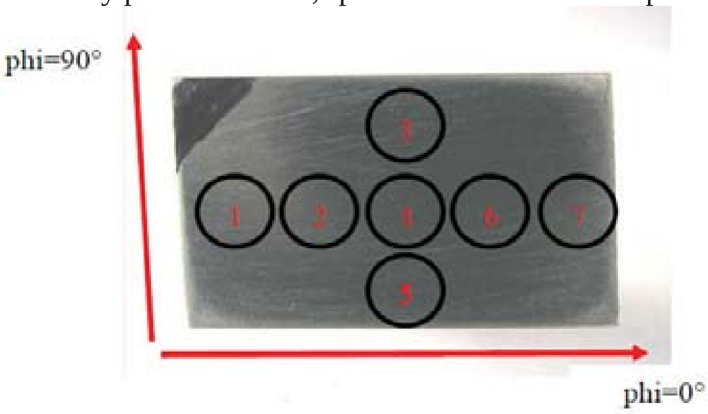


Fig. 3. Specimen no. 1

- specimen no. 2 – technically pure aluminum, raw state without any additional treatment:

Fig. 4. Specimen no. 2

- specimen no. 3 – technically pure aluminum, squeezed perpendicularly to the axis direction, force: 100 kN, longitudinal intersection:

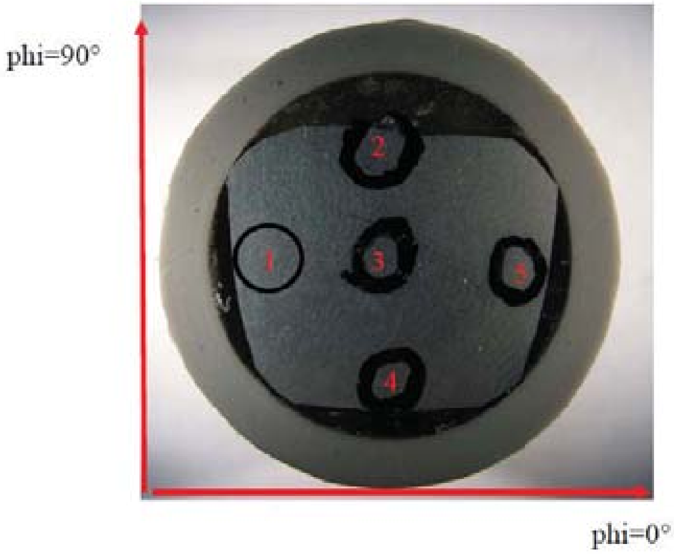


Fig. 5. Specimen no. 3

- specimen no. 4 – technically pure aluminum, squeezed perpendicularly to the axis direction, force: 100 kN, transverse intersection:

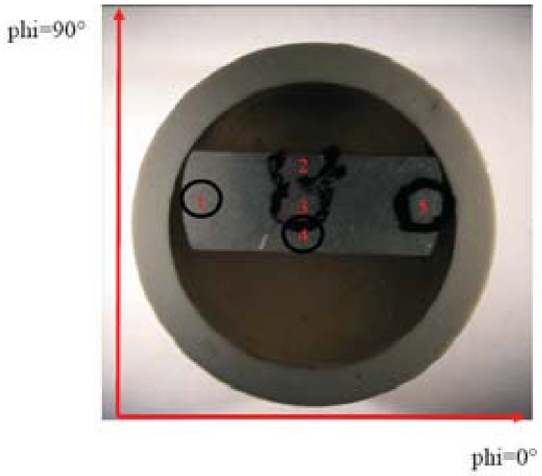


Fig. 6. Specimen no. 4

- specimen no. 5 – PA24 alloy, ∅5 bar, squeezed along the axis of the rod, force: 13.9 kN, longitudinal intersection:

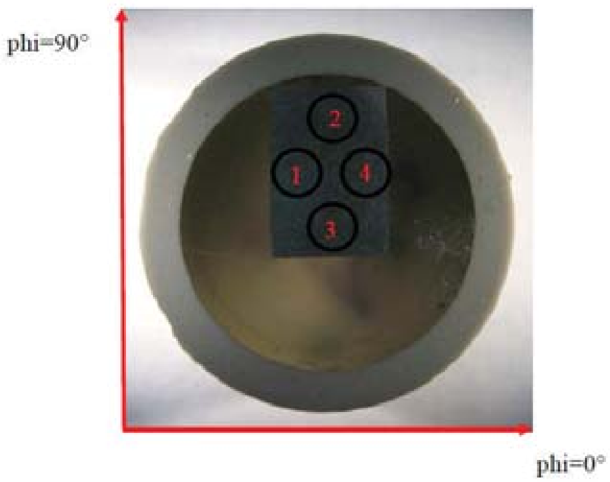


Fig. 7. Specimen no. 5

The second part of measurements was performed on a riveted specimen, with three riveted areas. Every area was riveted with a different riveting force. The area no. 1 was riveted with the force equal 1.2 kN; area no. 2 – 1.4 kN; area no. 3 – 1.5 kN and the area no. 4 – 1.55 kN.

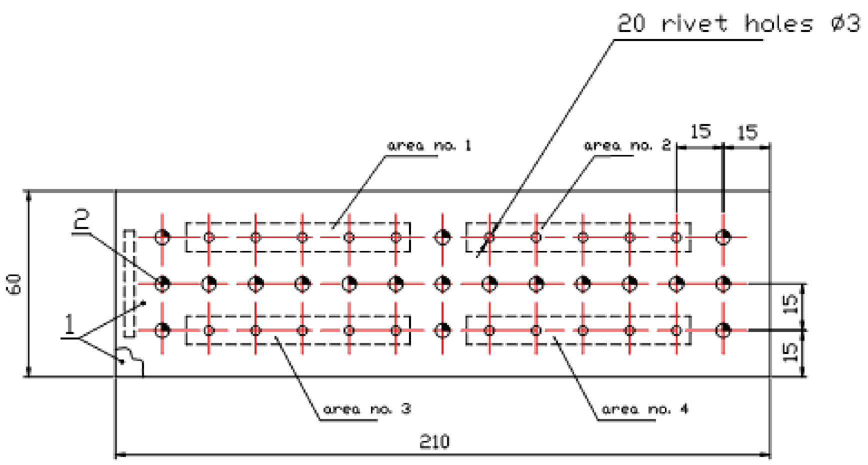


Fig. 8. Specimen for measurements of the residual stresses distribution around the rivets

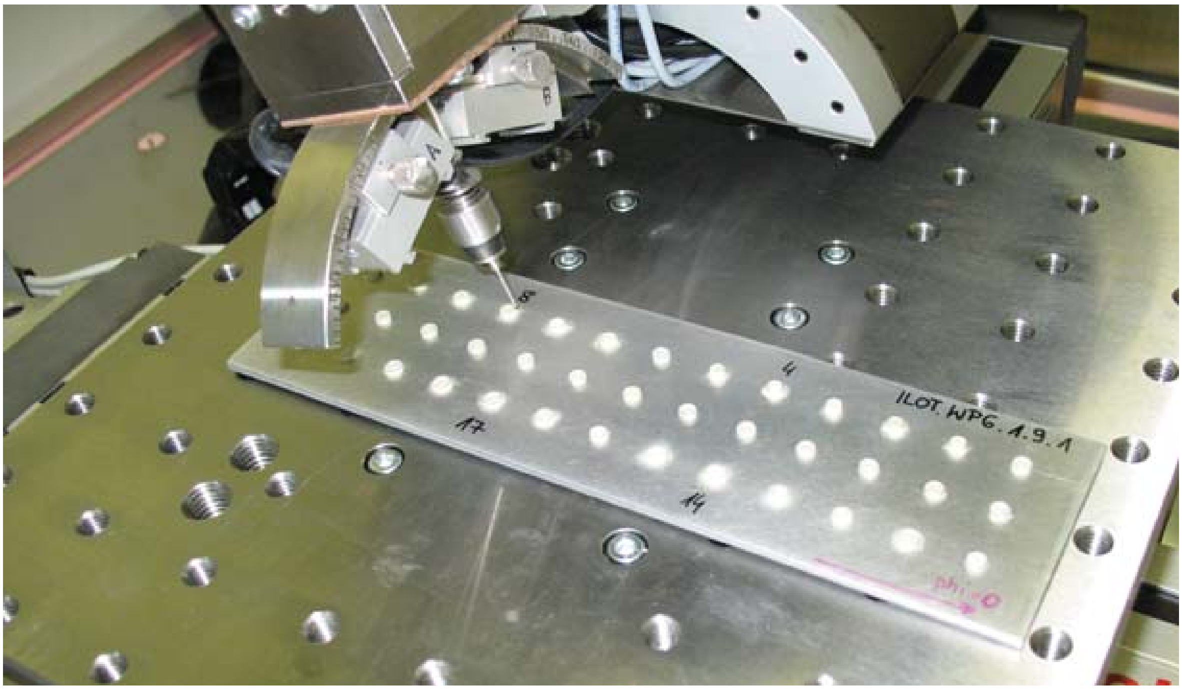


Fig. 9. Specimen for measurements of the residual stresses distribution around the rivets during the measurement

3. Stress measurements on specimens squezzed with different force values

To obtain possibly best parameters for stress measurements with X-ray diffractometry there were performed test measurements on specimens no. 1-5. Problems with obtaining reliable X-ray stress measurements could be connected with the texture of the material, big grain size or with the stress gradient deep into the material. Because of those reasons there were no possibility to obtain reliable stress values for specimens no. 2 and 5. Below, on Fig. no. 10 - 12, are presented X-ray diffractometry measurements results for textured specimen, for the specimen with the big grain size and for a specimen were stresses are different deep into material.

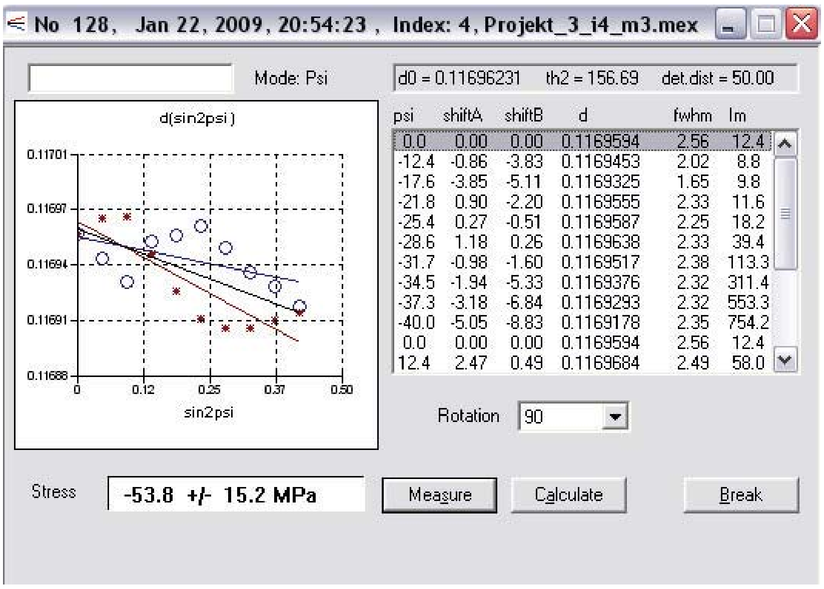


Fig. 10. Stress measurement results for textured specimen; specimen no. 3, point no. 4, phi=90

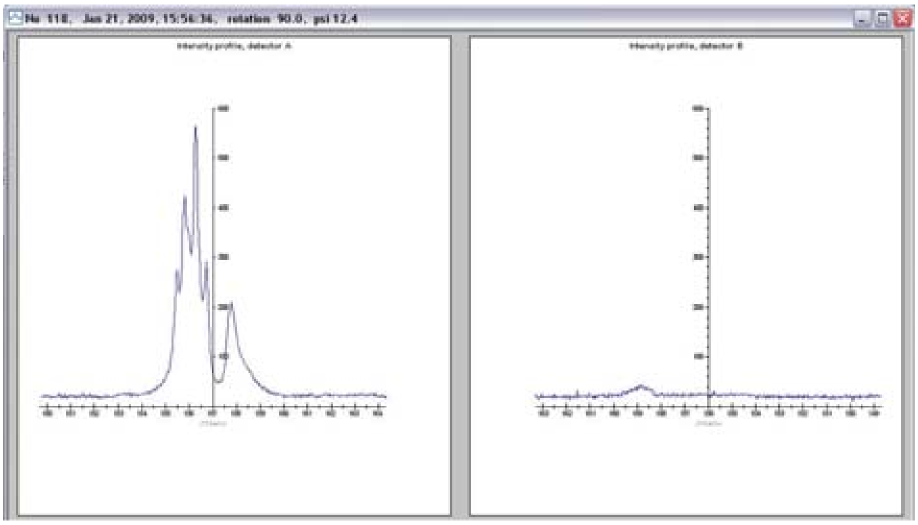


Fig. 11. Peaks for specimen with big grain size; specimen no. 2, point no. 1, phi=90

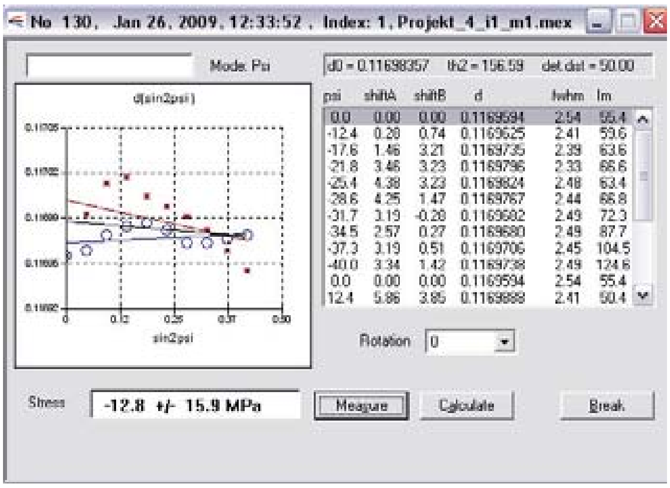


Fig. 12. Stress measurement results for specimen with different values of stresses with depth; specimen no. 4, point no. 1, phi=0

The measurement parameters for which the stress values were reliable enough are presented in Tab. 1. It was necessary to use phi and psi oscillation to eliminate the influence of mentioned material features, which can make diffractometry measurements harder.

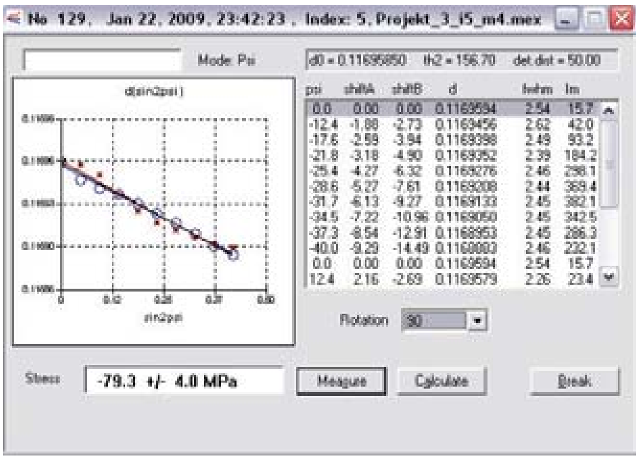


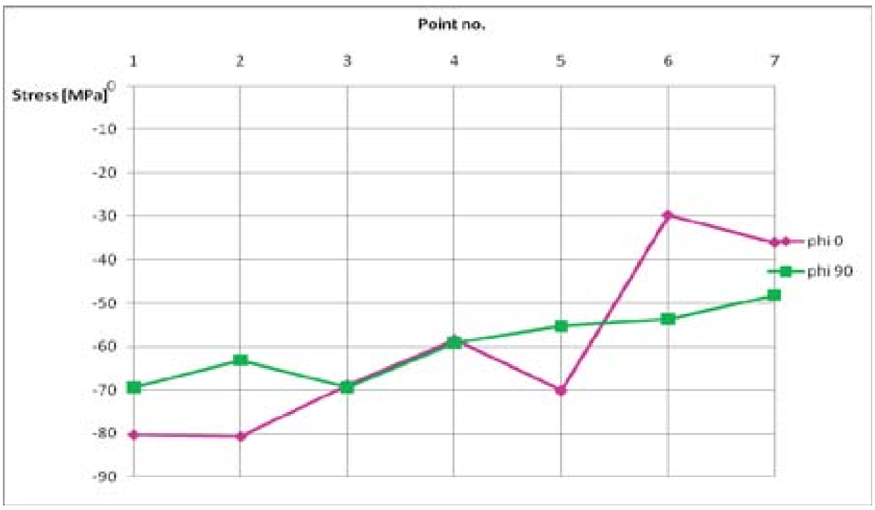
Fig. 13. Reliable stress measurement results; example

Tab. 1. Measurement parameters for specimens no. 1, 3 and 4

Date:		06.02.2009
Calculations:	2theta Background substraction Detectors Peak limits Pick shift	Library Linear AB No Cross corr.
Collimator – specimen distance:	d=9.73 mm	
Material data:	Material Young's modulus E Absorption coefficient μ Poisson's ratio ν	Al (156) 70600 MPa 42.7 1/mm 0.3
Measurement parameters:	2Θ/hkl Exposure time Φ values φ oscillations ψ values ψ oscillations Tube	156.7° / 222 60 s 0, 90 5°/ liczba - 3 5/5 -40/40 ± 5 CrKa
Collimator:		2 mm

Tab. 2. Stress values for specimen no. 1

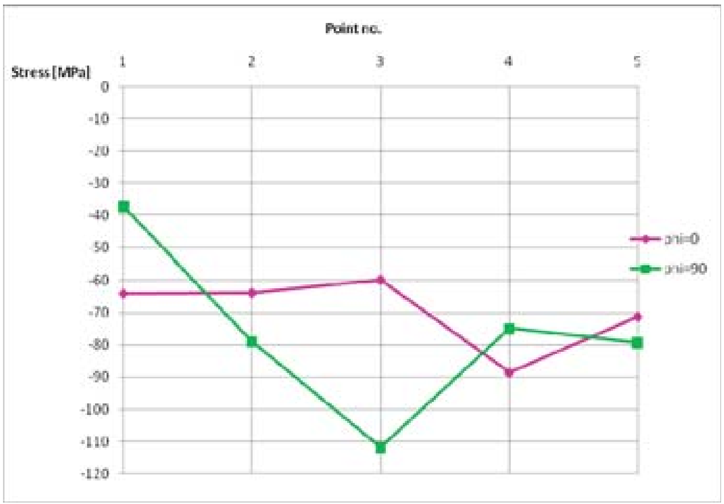
Point no.	phi=0		phi=90	
	σ [MPa]	Δσ [MPa]	σ [MPa]	Δσ [MPa]
1	-80.3	13.5	-69.4	11.5
2	-80.7	35.3	-63.1	13.2
3	-68.8	30.8	-69.4	13.0
4	-58.3	16.9	-59.1	9.4
5	-70.1	13.1	-55.2	17.7
6	-29.8	15.1	-53.6	16.3
7	-36.1	18.1	-48.1	7.3



Graph 1. Stress values for specimen no. 1

Tab. 3. Stress values for specimen no. 3

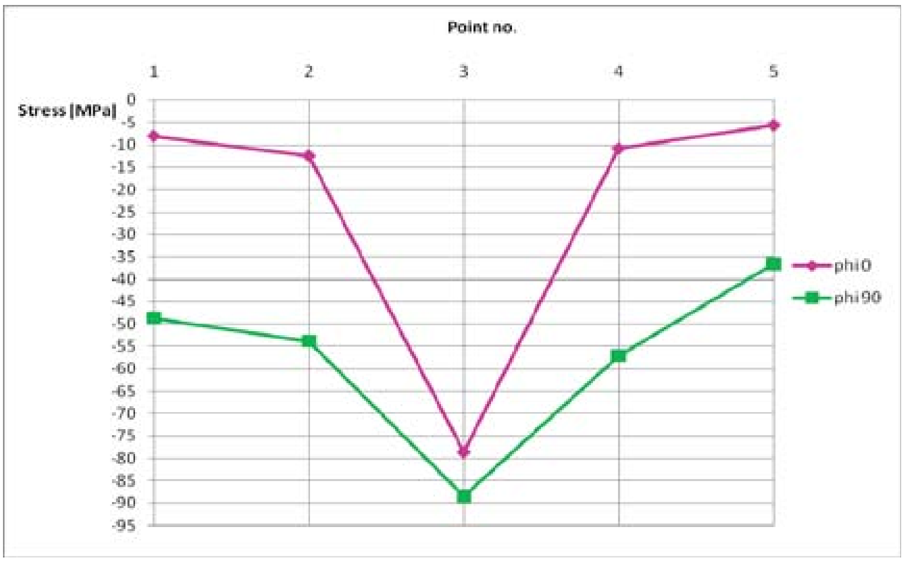
Pkt	phi=0		phi=90	
	σ [MPa]	Δσ [MPa]	σ [MPa]	Δσ [MPa]
1	-64	5.6	-37.2	5.6
2	-63.8	4.2	-78.9	13.4
3	-59.8	12.1	-111.9	9.4
4	-88.6	33.9	-74.9	13.4
5	-71.2	4.2	-79.3	4



Graph 2. Stress values for specimen no. 3

Tab. 4. Stress values for specimen no. 4

Pkt	phi=0		phi=90	
	σ [MPa]	Δσ [MPa]	σ [MPa]	Δσ [MPa]
1	-8.1	28.6	-48.7	3.1
2	-12.5	7.3	-53.8	6.7
3	-78.6	15.8	-88.4	14.4
4	-10.9	8.3	-57.0	6.3
5	-5.7	20.1	-36.6	4.8



Graph 3. Stress values for specimen no. 4

4. Stress measurements around the rivets riveted with different forces values

Measurements were performed for four rivets – one rivet in one area, marked with numbers 4, 8, 14 and 17. Measurement were performed along two segments for every rivet: along the rolling direction and perpendicular to the rolling direction. Two types of stresses were measured: tangential and radial stresses.

The example results are presented below for rivets 4 and 17:

Tab. 5. Stress measurement results for rivet no. 4 along rolling direction

		phi			
Distance from the edge of the rivet head (r) [mm]	Distance normalized to the radius of the rivet shank (r/R)	0 - radial		90 - tangential	
		σ [MPa]	Δσ [MPa]	σ [MPa]	Δσ [MPa]
0.4	1.27	-86.9	13.1	-5.5	14.1
1.2	1.81	-28.1	6.4	-21.9	8.6
2	2.34	-17.4	16.4	-11.3	12.2
2.8	2.88	-33.1	7.2	-14.7	9.2
3.6	3.42	-54	8.4	-28.2	11.4
4.4	3.95	-19.3	8.4	-12.7	10.8
5.2	4.49	-42.4	14.7	-75.6	9.2

Tab. 6. Stress measurement results for rivet no. 4 perpendicularly to rolling direction

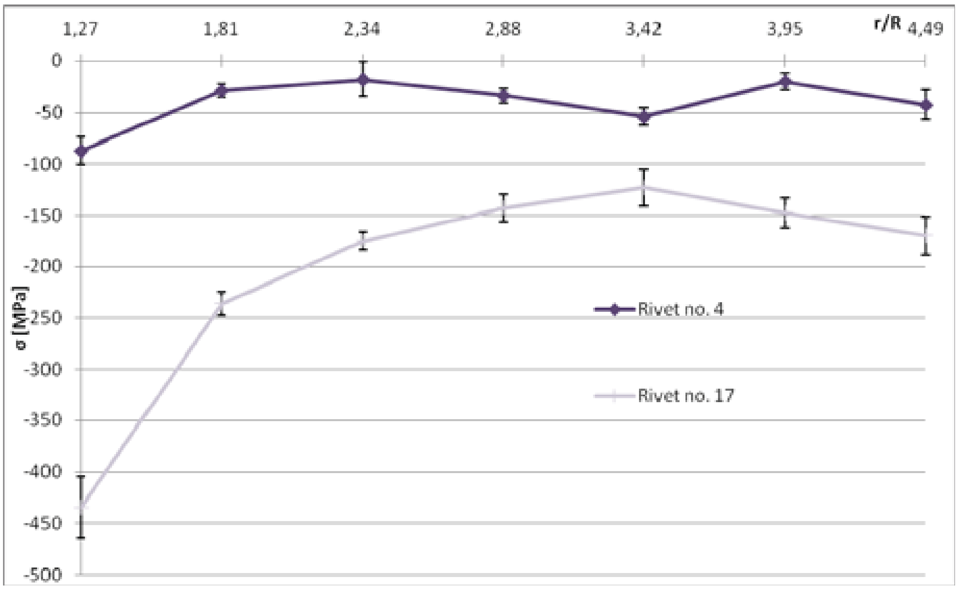
		phi			
Distance from the edge of the rivet head (r) [mm]	Distance normalized to the radius of the rivet shank (r/R)	0 - tangential		90 -radial	
		σ [MPa]	Δσ [MPa]	σ [MPa]	Δσ [MPa]
0.4	1.27	7.4	9.9	-65.5	16
1.2	1.81	-18.7	15.9	-31	10.2
2	2.34	-17.1	15	-51.3	6.5
2.8	2.88	-32.7	9.1	-48.9	6.8
3.6	3.42	-19	17.6	-72.4	8.7
4.4	3.95	-10.5	11.9	-100.2	11.5
5.2	4.49	8.4	17.8	-69.2	9.7

Tab. 7. Stress measurement results for rivet no. 17 along rolling direction

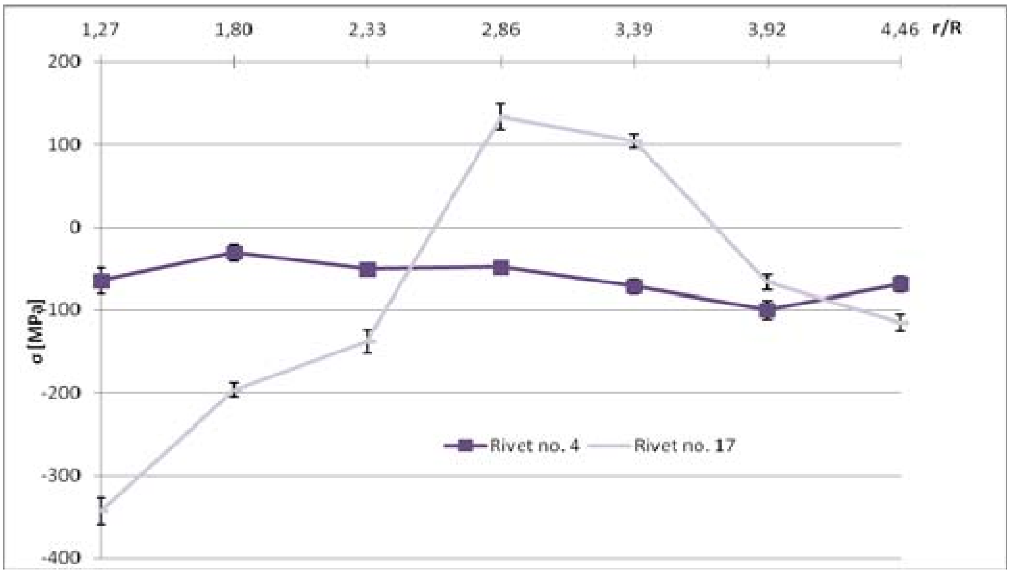
		phi			
Distance from the edge of the rivet head (r) [mm]	Distance normalized to the radius of the rivet shank (r/R)	0 - radial		90 - tangential	
		σ [MPa]	Δσ [MPa]	σ [MPa]	Δσ [MPa]
0.4	1.27	-434.4	30	83.5	8
1.2	1.81	-235.9	11.6	134.4	13.3
2	2.34	-174.9	9.3	131	12.8
2.8	2.88	-142.8	13.5	62.7	10.3
3.6	3.42	-123.1	17.6	69.9	10.9
4.4	3.95	-147.9	14.2	107.5	16
5.2	4.49	-169.7	18.6	65.3	6.6

Tab. 8. Stress measurement results for rivet no. 17 perpendicularly to rolling direction

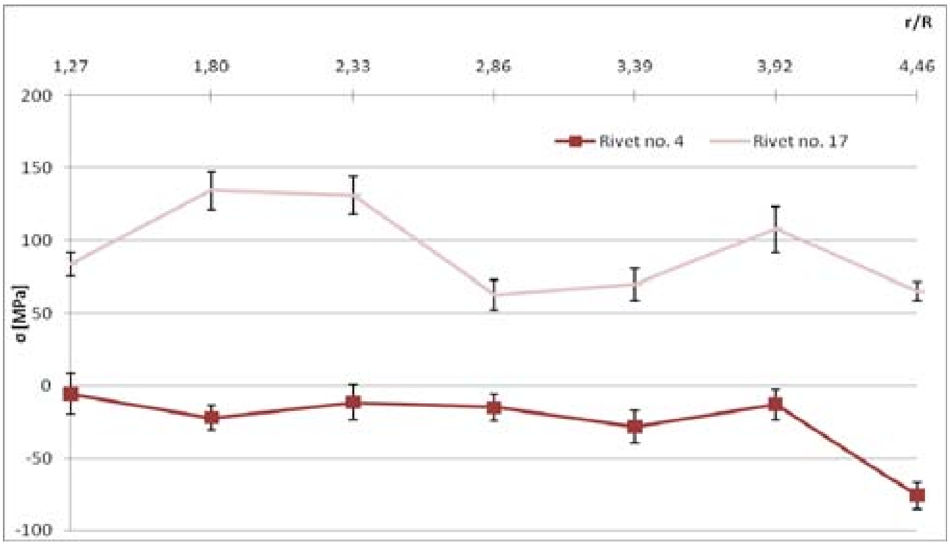
		phi			
Distance from the edge of the rivet head (r) [mm]	Distance normalized to the radius of the rivet shank (r/R)	0 – tangential		90 - radial	
		σ [MPa]	Δσ [MPa]	σ [MPa]	Δσ [MPa]
0.4	1.27			-343.2	16.6
1.2	1.81	65.4	14.1	-196.5	8.8
2	2.34	13.2	10.3	-137.3	14
2.8	2.88	34.4	13.9	133.4	15.4
3.6	3.42	46.3	11.3	104	8.3
4.4	3.95	41.3	8.1	-67	9.3
5.2	4.49	59.7	14	-114.6	9.5



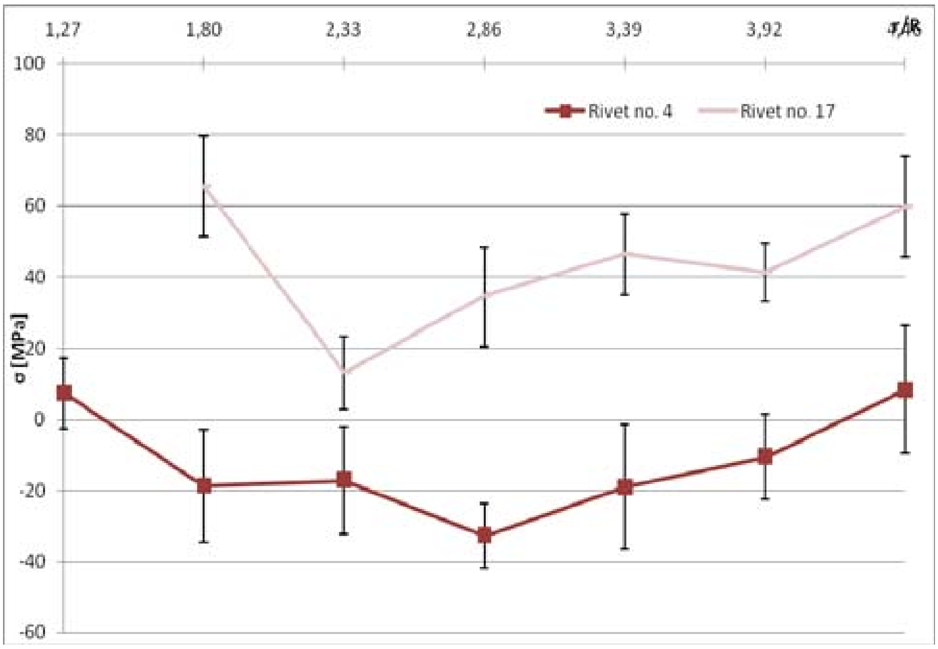
Graph 4. Radial stress distribution around the rivets no. 4 and 17. Segment along the rolling direction



Graph 5. Radial stress distribution around the rivets no. 4 and 17. Segment perpendicular to the rolling direction



Graph 6. Tangential stress distribution around the rivets no. 4 and 17. Segment along the rolling direction



Graph 7. Tangential stress distribution around the rivets no. 4 and 17. Segment perpendicular to the rolling direction

5. Conclusions

The method for reliable X-ray stress measurements for aluminum alloys was worked out. This kind of measurements are possible but very difficult and time consuming. It is necessary to repeat every measurement to make the measurement credible.

Reliable results for stress distribution were obtained. Absolute values of measured stresses are in accordance with predictions: the bigger riveting force was used the bigger stresses value were measured. There is the necessity to repeat those measurements to obtain reliable stress distribution curve. There can be some problems with measuring stresses along the segment perpendicular to the rolling direction.

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