



# Efficacy and Application Areas of «**RIKOR**» Series Diffractometer

Every purchase of an instrument should bring to customer a direct or indirect benefit.

The efficacy of using a «**RIKOR**» Series diffractometer is determined by its intended purpose. «**RIKOR**» provides for nondestructive direct check for stress condition in parts and structures. Such inspection enables detection and remedy of adverse factors during manufacture and operation of parts and facilities. The adverse factor consists in creation of large tensile residual stresses, which, when imposed with effective tensile stresses, can result in defects during manufacture or a fault, accident or catastrophe during operation of parts and facilities.

## Efficacy of Using ‘**RIKOR**’ Series Diffractometer in Manufacturing Parts and Facilities

### **Metals Non-Cutting Shaping** **A20, A22, A23 ( Applications )**

In the course of non-cut shaping of metals, ‘**Rikor**’ Series Diffractometer allows, based on the level of residual stresses:

- determining the degree of material strengthening during cold rolling;
- optimizing the value of single and cumulative squeezing;
- determining anisotropy of the rolled material’s properties, etc.

### **Cutting**

For this technological operation, inspection with ‘**Rikor**’ Series Diffractometer delivers:

- optimization of the feeding value;
- optimization of the operation time of the cutter before sharpening, etc.

### **Welding** **A1, A9, A10, A11**

Through determining residual stresses in the thermally affected area, ‘**Rikor**’ Series Diffractometer permits assessing the weld seam quality.

### **Thermal Processing** **A1, A8**

Based on the achieved level of residual stresses determined with the help of ‘**Rikor**’ Series Diffractometer, one can assess practically any thermal processing operation.

### **Surface Strengthening** **A3, A5**

Определить It is possible to determine the quality of surface strengthening process operation without destroying the part only using ‘**Rikor**’ Series Diffractometer.

### **Assembly** **A21**

‘**Rikor**’ Series Diffractometer can be used during assembly of parts into units, nevertheless, this application is limited by the dimensions of the goniometer part of the instrument.

### **Testing** **A4, A5, A7, A12, A16, A18, A19, A20**

At the stage of manufacture of products, stress control enables gaining profit thanks to:

- Minimum defects and stabilized quality of products through optimization of existing process operations used in manufacturing parts and structures;
- Shorter recoupability period through faster debugging of new processes;
- Less losses of money through income inspection of outsourced blanks or introduction in technical conditions of release inspection at the manufacturer's facilities;
- Optimized expenses on process tools through monitoring of their operation life times;
- Higher profit thanks to better quality of products;
- Higher safety during operation of process tools and technological equipment;
- Establishing the reasons for defects and breakage of process tools and equipment;

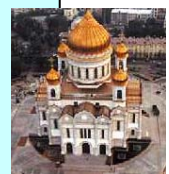
### **Efficacy of Using «RIKOR» During Operation of Parts and Facilities**

The new developed method of assessing the service life (Patent №2215280, Russia), which is based on determining the rate of changes in the stress conditions, delivers benefit thanks to:

- Unbiased determining of remaining life of parts when operation life is extended at the state of repair **A2, A6, A11, A13, A26**;
- Higher safety in operation of parts and objects **A5, A6, A8, A9, A11, A12, A13, A20**;
- Determining the reasons for faults, accidents and catastrophes **A14**;
- Exploitation control **A2, A3, A6, A9, A11, A12, A13, A26**;
- Stress definition methods comparison **A15, A24, A25**.

### **Application Areas**

- **Space Craft A1**
- **Aircraft A2, A3, A4, A5, A6, A15, A21, A26**
- **Railways A7, A8, A24**
- **Vehicles A4**
- **Nuclear and Thermal Power Plants A9, A10**
- **Product Lines, Vessels under Pressure A11, A20, A26**
- **Metal Erections A12, A14**
- **Bridges, Tunnels A13**
- **Science, Education A2, A14, A15, A22, A23, A24, A25, A26**
- **Metallurgy A18, A22, A23**
- **Mechanical Engineering A17, A19**
- **Electronic Industry A16**



# Application 1. Analysis in Parts of a Satellite Made of Titanium Alloy



Part of satellite

Check was performed at the premises of S.P. Korolev ENERGIA RKK OJSC, the participants being A.V. Lyuttsau, Dr. Eng. Sc. A.V. Kotelkin, Dr. Phys. Math. Sc. A.D. Zvonkov, Dr. Eng. Sc. D. B. Matveev, Dr. Eng. Sc. V.N. Sereda, A.V. Gollandtsev.

**Object of check** – a satellite part made of titanium alloy VT23.

**Purpose of check** – to assess stress condition in semi-spheres of satellite part at different state of their manufacture: before the flanges are welded in (operation 1), after the flanges are welded in (operation 2), and after thermal processing (operation 3).

**Method used for stress condition assessment** – « $\sin^2\psi$ » method and vertical exposure technique.

**Radiation used** –  $\text{CrK}\alpha$ .

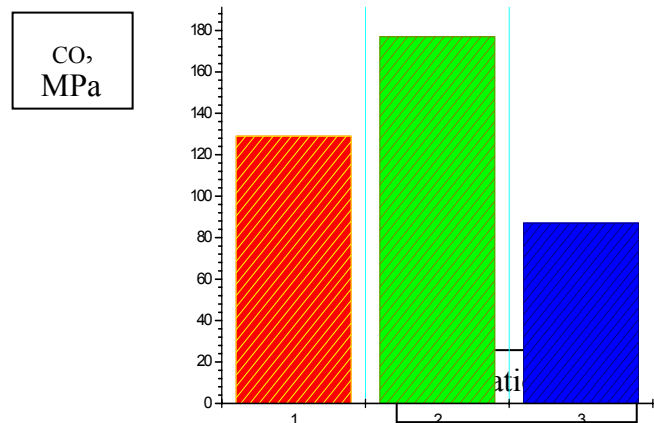
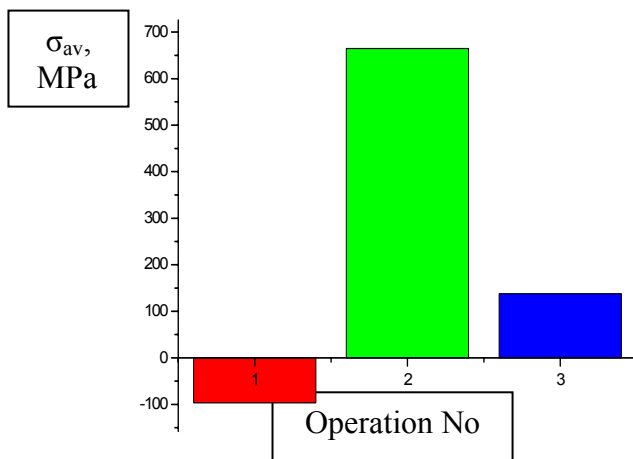
**Check Points** - between holes for flanges, along the perimeter of the holes, and at a 5 - 8 mm distance from the hole, and on the flanges being welded in.

**Stress Condition Index** – since it was required to assess, in each operation, the stress condition of the part on the whole, the stress condition index was selected as the mean stress value of all checkpoints. Stability of each technological operation was assessed by the standard deviation of reference sample.

## Results Obtained

If before flange welding the mean stress made  $-97$  MPa, then after flanges were welded in, a change in the stress polarity into tensile stresses was observed:  $+665$  MPa, and after thermal processing almost five-fold decrease in tensile stresses was noted:  $+138$  MPa.

The most stable operation is thermal processing (the minimal reference sample deviation =  $87$  MPa), and the most unstable – welding in flanges ( $\text{CO} = 177$  MPa).



## Publications of the Subject

Determining residual stresses in parts and structures made of different steels and alloys, A.V.Kotelkin, A.D.Zvonkov, A.V.Lyuttsau, D.B.Matveev, D.V.Dubrovin, V.N.Sereda, Abstracts Second International Conference on X-ray and Neutron Capillary Optics, Zvenigorod, Russia, September 22-26, 2004.

X-ray method of determining residual stresses in moldings and parts made of titanium, aluminum, nickel; and other alloys / Kotelkin A.V., Zvonkov A.D., Lyuttsau A.V., Matveev D.B., Kumakhov M.A., Ibraimov N.S. – In Collected Articles: Die forging: perspectives and development (collected science reviews) – GOU VPO «UGTU-UPI», 2005. – pp. 784-790. (In Russian)

## Application 2. Stress Condition Check in Main Rotor Blades of Helicopter MI-8 Made of Aluminum Alloy

Check was done in the environment of one of Air Force divisions, with participation of A.V. Lyuttsau, Dr. Eng. Sc. A.V. Kotelkin, Dr. Phys. Math. Sc. A.D. Zvonkov, Dr. Eng. Sc. D.B. Matveev, Dr. Eng. Sc. V.N. Sereda, Dr. Eng. Sc. V. Ya. Maklashevsky.

**Object of check** - seven main rotor blades of MI-8 helicopter made of alloy AVT-1. In this instance, vanes 0, 1, 2, 3, 4, 5, 6 had operation time of 370, 795, 795, 1588, 1588, 1588 hrs, respectively.



**Purpose of check** – to determine correlation between stressed condition of the lower berth of blade longeron and operation time.

**Method used for stress condition assessment** – vertical exposure method.

**Radiation Used** – CrK $\alpha$

**Check Points** – 21 points along the lower berth of blade longeron, equally spaced in between.

**Stress Condition Index** – since it was required to assess the condition of the part on the whole in each operation, the stressed condition index was selected as the mean stress of all checkpoints.

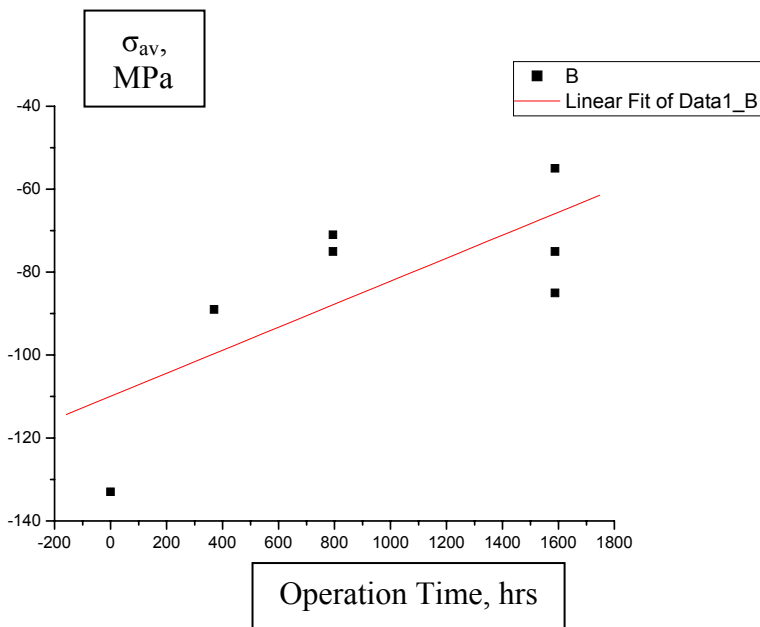
As the stressed condition index in each checkpoint, the first invariant of the principal stresses tensor was used:  $\sigma = (\sigma_1 + \sigma_2)/3$ . The confidence interval of the calculated stresses values under the exposure conditions used does not exceed 10 MPa (relative error is  $\Delta\sigma_{av} = +5$  MPa).

### Results Obtained

For all checked blades on the lower berth of longeron, strongly expressed heterogeneity of residual stresses lengthwise was observed, characterized by existence of areas where the residual stresses had undergone significant changes compared to original (vane 0). For each blade, the mean stress value along the length  $\sigma_{av}$  was determined (see the table). The resulting from correlation

analysis Pearson coefficient equal to 0.73 evidences good correlation between  $\sigma_{av}$  and operation time.

Linear approximation of the dependence between the blade mean stress and operation time is shown on the figure. It follows from the obtained functional dependence that operation of the helicopter main rotor blades leads to a shift of the original level of compressing residual stresses towards tension.



## Application 3. Stress Condition Check in Aluminum Alloy Aircraft Wheel Hubs

Check was performed in the facilities of Moscow Institute for Steel & Alloys and Rubin AK OJSC, with participation of A.V. Lyutsau, Dr. Eng. Sc. A.V. Kotelkin, Dr. Phys. Math. Sc. A.D. Zvonkov, Dr. Eng. Sc. D.B. Matveev, Dr. Eng. Sc. Mozalev.

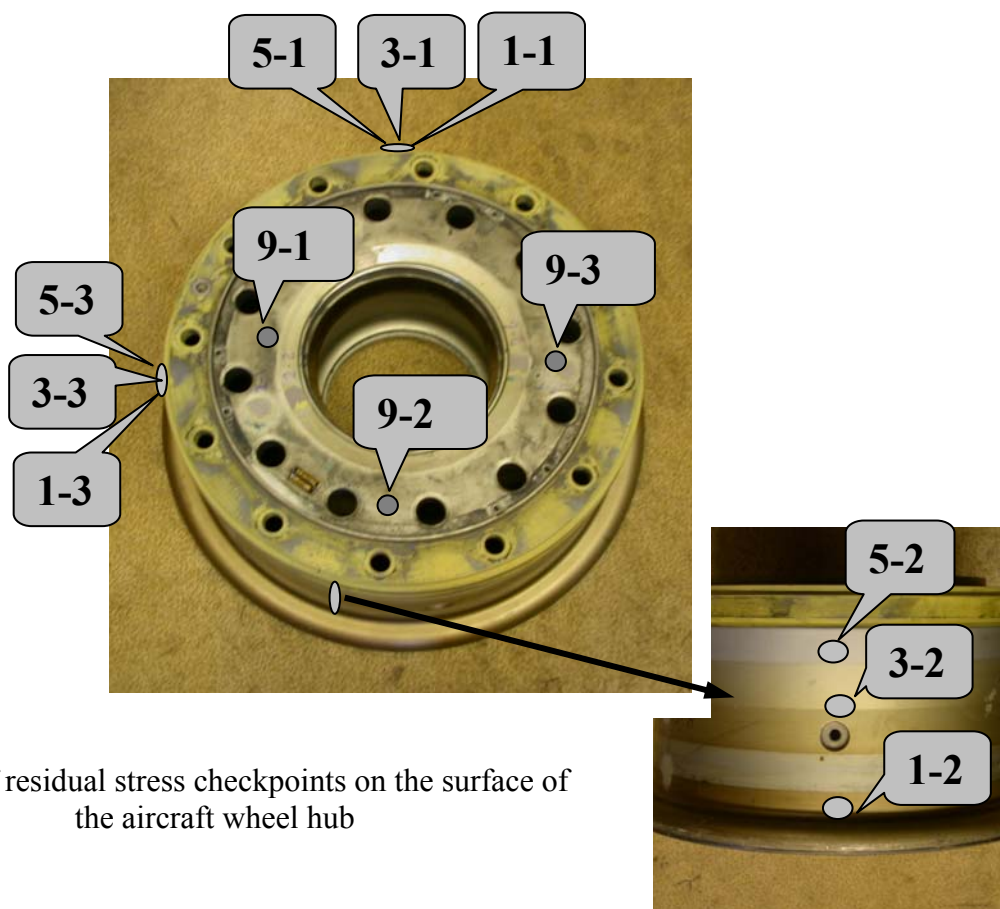
**Object of Check** – two used aircraft wheel hubs made of alloy AK-6, one with strengthened working surface, the other one without.

**Purpose of check** – determining the difference between the stresses condition of aircraft wheel hubs with strengthened versus non-strengthened working surface.

**Method used to assess stress condition**– « $\sin^2\psi$ » method.

**Radiation used** –  $\text{CrK}\alpha$ .

**Check points** – are depicted on the scheme.



Scheme of residual stress checkpoints on the surface of the aircraft wheel hub

**Stressed Condition Index** – in each checkpoint, two components of residual stresses were assessed: radial ( $\sigma_r$ ) and tangential ( $\sigma_t$ ).

### Results Obtained

The results of determining residual stresses on hub surfaces are given in tables 1 and 2. It follows from there that the strengthened hub had compressive residual stresses in all checkpoints while the non-strengthened – mostly tensile stresses shortening its life.

Table 1. Stresses on the Surface of Non-Strengthened Wheel

Checkpoint No.	$\sigma_{t\ t}$ , MPa	$\sigma_{z\ z}$ , MPa
1-1	-90	+90
1-2	-180	0
1-3	0	+130
3-1	+20	-85
3-2	+120	-65
3-3	-205	-55
5-1	+150	+30
5-2	+170	+30
5-3	0	+25
9-1	+130	-
9-2	+65	-
9-3	+50	-

Table 2. Stresses on the Surface of Strengthened Wheel

Checkpoint No.	$\sigma_t$ , MPa	$\sigma_z$ , MPa
1-1	-130	-330
1-2	-110	-200
1-3	-110	-370
3-1	-130	-190
3-2	-220	-310
3-3	-150	-370
5-1	-345	-370
5-2	-260	-320
5-3	-240	-370
9-1	-10	-
9-2	-70	-
9-3	-130	-

### Publications on the Subject

X-ray method of determining residual stresses in moldings and parts made of titanium, aluminum, nickel; and other alloys / Kotelkin A.V., Zvonkov A.D., Lyuttsau A.V., Matveev D.B., Kumakhov M.A., Ibraimov N.S. – In Collected Articles: Die forging: perspectives and development (collected science reviews) – GOU VPO «UGTU-UPI», 2005. – pp. 784-790. (In Russian)

# Application 4. Stress Condition Check of Aluminum Alloy Tank of Refueller ATZ-20

Check was performed at the premises of the Bykovo Aircraft Repair Workshop parking site, with participation of A.V. Lyuttsau, Dr. Eng. Sc. A.V. Kotelkin, Dr. Phys. Math. Sc. A.D. Zvonkov, Dr. Eng. Sc. V.S. Krasovsky.

**Object of Check** – tanks of refueller ATZ-20 of 20m<sup>3</sup> capacity made of aluminum alloy 5086.

**Purpose of Check** was to determine stress condition of empty refueller tank, and when the tank was filled – mean effective stress.



During measurement of refueller tank ARZ-20

**Method used to determine stress condition** – vertical exposure method.

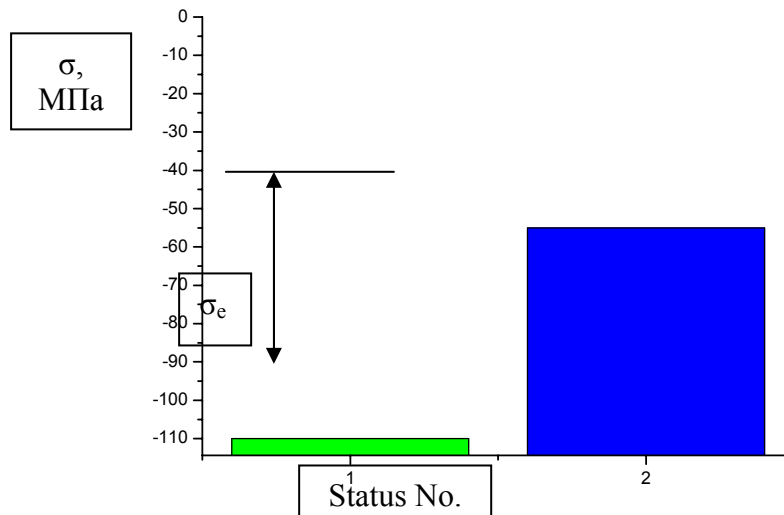
**Radiation used** – CrK $\alpha$ .

**Checkpoints** – in the most stressed tank part: around weld seam in the bottom.

**Stressed Condition Index** – since the requirement was to assess stress condition in each status of the tank on the whole, the stress condition index was selected as the mean stress of all checkpoints.

## Results Obtained

Before the tank was filled (status 1), mean stress made –110 MPa (mean standard sample deviation = 20 MPa), after it was filled (status 2): -55 MPa (mean standard sample deviation = 90 MPa). Consequently, the mean stress  $\sigma_e$  when the refueller tank is filled equals to +45 MPa (see the diagram).



## Publication on Subject

X-ray method of determining residual stresses in moldings and parts made of titanium, aluminum, nickel; and other alloys / Kotelkin A.V., Zvonkov A.D., Lyuttsau A.V., Matveev D.B., Kumakhov M.A., Ibraimov N.S. – In Collected Articles: Die forging: perspectives and development (collected science reviews) – GOU VPO «UGTU-UPI», 2005. – pp. 784-790. (In Russian)

## Application 5. Stress Condition Check of Chromium-Nickel Alloy Disks of Gas Turbine Engine

Check was performed at the premises of Salyut MMPP, with participation of A.V. Lyuttsau, Dr. Eng. Sc. A.V. Kotelkin, Dr. Phys. Math. Sc. A.D. Zvonkov, Dr. Eng. Sc. D.B. Matveev.



**Object of check** – six disks made of chromium-nickel alloy.

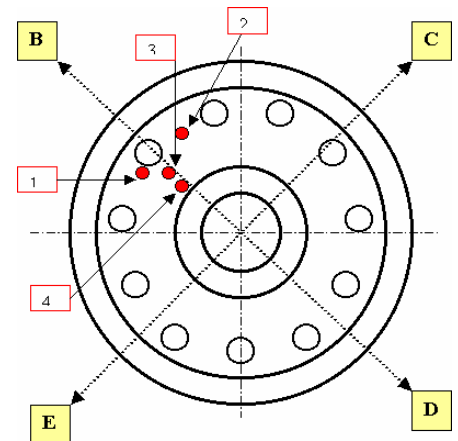
**Purpose of check** – was to determine influence of operation time on the stressed condition of strengthened disk surface.

**Method used to assess stress condition** – was the vertical exposure method.

**Radiation used** – CrK $\alpha$ .

**Checkpoints** – on one of the sides of strengthened flat of each disk, 8 checkpoints in four sectors, which directions coincide with symmetry axes. In each of B, C, D, and E

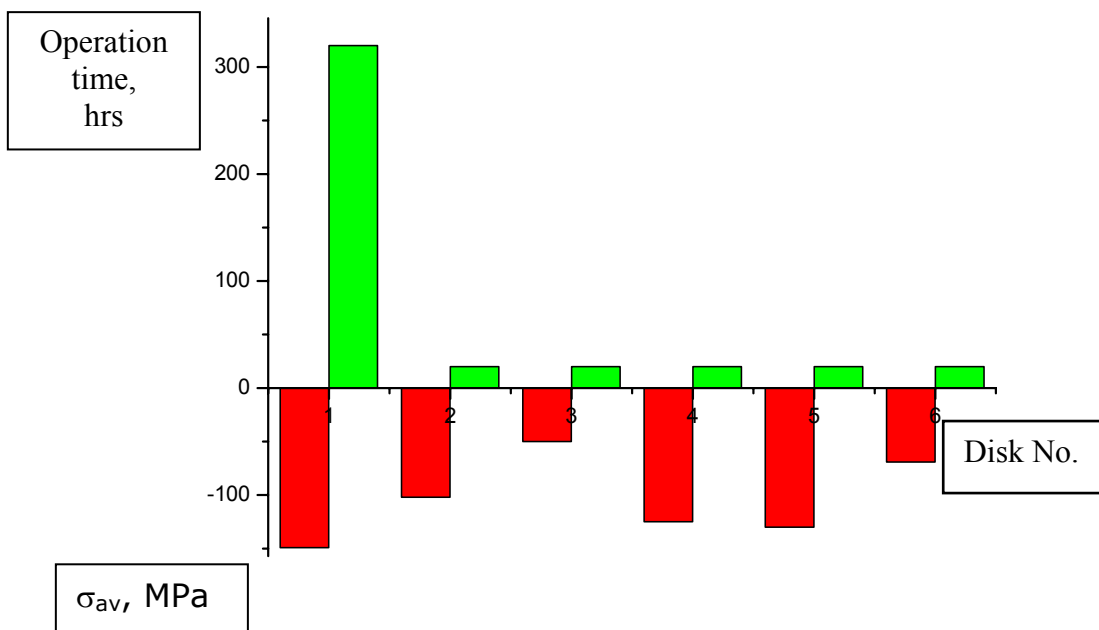
directions, on the disk part strengthened by surface plastic deformation, four measurements were performed: checkpoint 1 – next to the hole, 2 – between the holes, 3 – under the hole, 4 – under the hole, closer to the collar (see the schematic).



**Stress Condition Index** – since the requirement was to assess stress condition in each operation of the part of the whole, the stress condition index selected was the mean stress of all checkpoints.

### Results Obtained

Residual stresses in disk checkpoints are very scattered both in terms of value and in terms of polarity: from  $-520$  MPa to  $+200$  MPa. This evidences large instability of the technological operation of disk flat strengthening.



The results obtained are given on the diagram. One can see that the first disk has the highest level of compressive stresses at the comparatively longest operation time while other disks at minimum operation time have the least level of compressive stresses. Consequently, depending on the quality of surface strengthening operation, the operation time affects differently on the change in the residual stresses level.

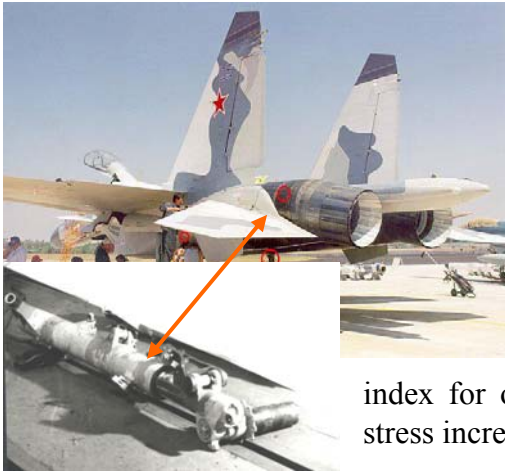
### **Publications on Subject**

X-ray method of determining residual stresses in moldings and parts made of titanium, aluminum, nickel; and other alloys / Kotelkin A.V., Zvonkov A.D., Lyuttsau A.V., Matveev D.B., Kumakhov M.A., Ibraimov N.S. – In Collected Articles: Die forging: perspectives and development (collected science reviews) – GOU VPO «UGTU-UPI», 2005. – pp. 784-790. (in Russian).

# Application 6. Stress Condition Check of Steel Landing Gear in Fighter SU-30MKI

Check was performed in the premises of Sukhogo OKB OJSC, with participation of A.V. Lyuttsau, Dr. Eng. Sc. A.V. Kotelkin, Dr. Phys. Math. Sc. A.D. Zvonkov, Dr. Eng. Sc. D.B. Matveev, Dr. Eng. Sc. A.A. Sannikov.

**Object of check** – four main landing gears: 1 – landing gear without operation time; 2,3,4 – landing gears with operation time: 642; 1166; 1175 times used, respectively.



**Purpose of check** – was to determine correlation between the stressed condition of landing gear and operation time.

**Method used to assess stressed condition**– was the vertical exposure method.

**Radiation used** – FeK $\alpha$ .

**Checkpoints** – 6 checkpoints close to weld seams.

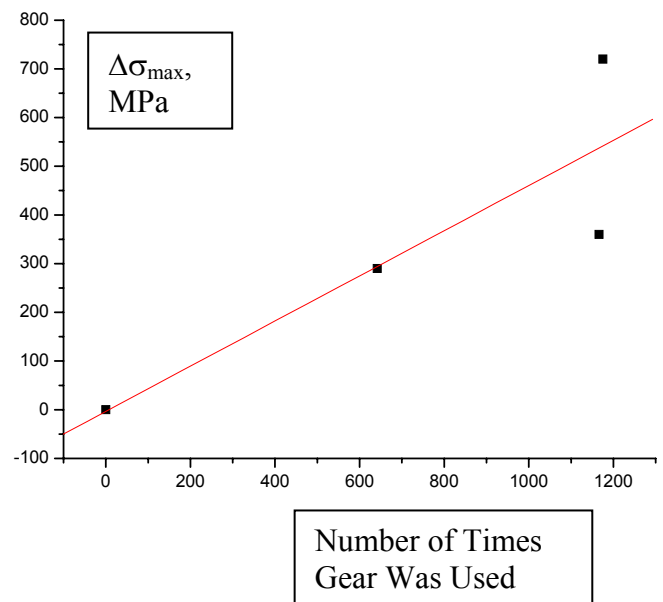
**Stress Condition Index** – residual stresses of the unused landing gear were taken as zero, the stress condition index for other landing gears was the maximum, among six checkpoints, stress increment  $\Delta\sigma_{max}$  (for subsequent calculation of remaining life).

## Results Obtained

The results obtained are given in the table. Correlation analysis between the stress condition of landing gear and its operation time shows good correlation between  $\Delta\sigma_{max}$  and number of times the gear was used (Pearson coefficient  $r$  equals to 0.73). Linear approximation of  $\Delta\sigma_{max}$  dependence on operation time is shown on the figure. It follows from the resultant functional dependence that landing gear operation leads to a shift of the original level of residual stresses towards tension.

Table  
Maximum Stress Increment for Each Gear and Pearson Coefficient

Gear No.	$\Delta\sigma_{max}$ , MPa	Number of Times Gear Was Used	$r$
1	0	0	0,87
2	290	642	
3	360	1166	
4	720	1175	

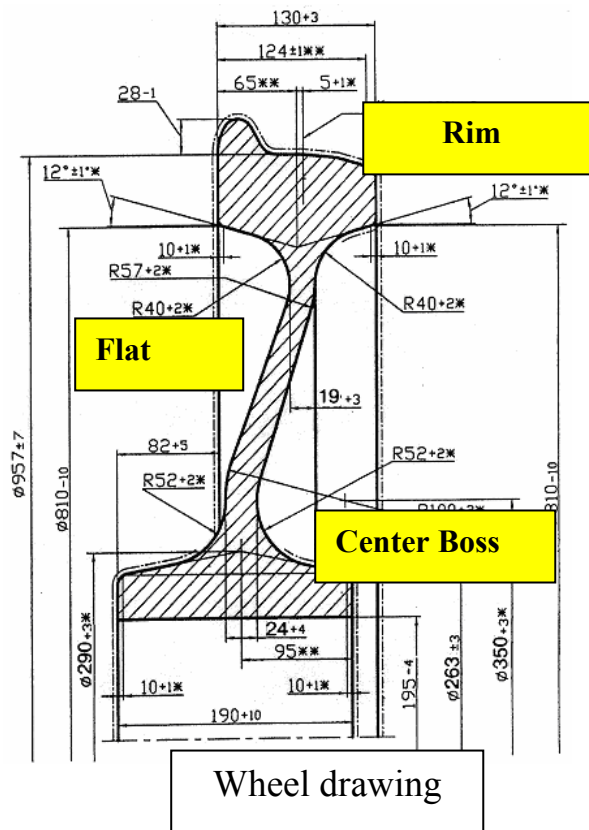


## Application 7. Stress Condition Check of Solid-Rolled Steel Railway Wheels

Check was performed at the premises of All-Russia Railways Transport Research Institute (VNIIZhT), with participation of Dr. Eng. Sc. A.V. Kotelkin, Dr. Phys. Math. Sc. A. D. Zvonkov, Dr. Eng. Sc. D.B. Matveev, A.V. Lyuttsau, S.L. Shitkin.

**Object of check** – solid-rolled wheel with standard cone-and-plate disk.

During wheel measurement



**Purpose of Check** – was to determine stress condition on the inner and outer sides of the wheel.

**Method used to assess stress condition** – « $\text{Sin}^2\psi$ » method.

**Radiation used** –  $\text{FeK}\alpha$ .

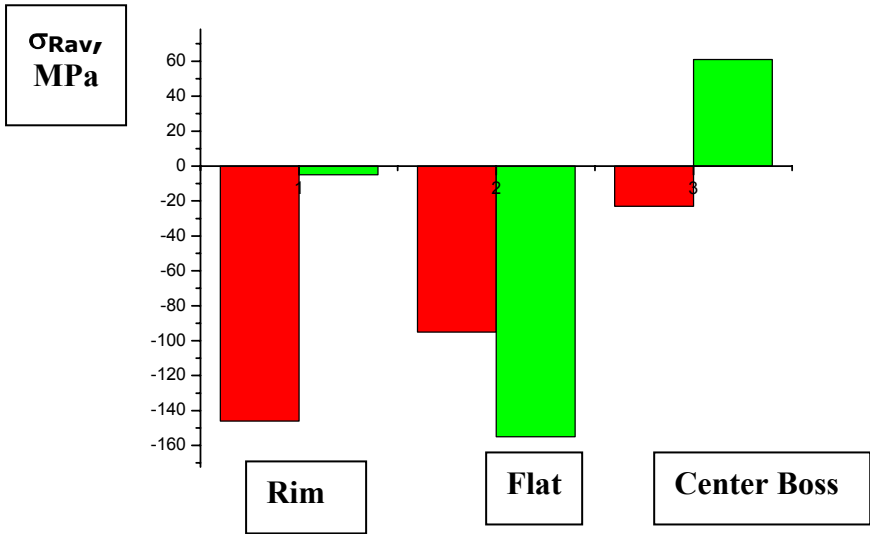
**Checkpoints** – 6 checkpoints on the rim; 10 checkpoints on the flat and 4 checkpoints on the center boss on each side of the wheel.

**Stress Condition Index** – was mean stress on the side in radial direction  $\sigma_{\text{Ray}}$ .

### Results Obtained

The results obtained are given on the diagram. On the diagram, red color marks residual stresses on the inner side, green color – on the outer side. On the inner side of the rim, rather large compressing stresses only are effective; on the outer side, the residual stresses are practically absent. On the flat, compressive residual stresses are higher on the outer side. On the center boss, the residual stresses of compression on the inner side and of tension on the outer side are observed.

Diagram of Residual  
Stresses Level On Different  
Wheel Sides



## Application 8. Stress Condition Check of the Locomotive Pinion Made of Steel 45XH

Check was performed in the premises of the Moscow Institute of Steel & Alloys, with participation of Dr. Eng. Sc. A.V. Kotelkin, Dr. Phys. Math. Sc. A.D. Zvonkov, Dr. Eng. Sc. D.B. Matveev, A.V. Lyuttsau, A.V. Shevchenko.



**Object of check** – a fragment of the locomotive pinion made of steel 45XH (Lyublino Foundry Mechanics Factory).

**Purpose of check** – was to assess the possibility of nondestructive quality control of pinions' thermal processing based on residual stresses.



**Method used to assess stress condition** – was «Sin<sup>2</sup>ψ» method.

**Radiation used** – FeK $\alpha$ .

**Checkpoints** – on the butt-end surface of pinion fragment, three checkpoints at the base of each of six teeth.

**Stress Condition Index** – in each checkpoint, residual stresses were determined in tangential (X) and radial (Y) directions.

### Results Obtained

The results obtained are summarized in the table.

Table  
Residual stresses in checkpoints in radial and tangential directions

Tooth No.	Checkpoint No.	Check Results	
		$\sigma_y$ , MPa	$\sigma_x$ , Mpa
1	1-1	-83	-115
	1-2	-1544	-119
	1-3	-574	+90
5	5-1	-16	-574
	5-2	-303	-349
	5-3	-264	-350
2	2-1	-40	-131
	2-2	-1081	-222
	2-3	-728	+53
6	6-1	-1085	-207
	6-2	-1149	-154
	6-3	-1206	+59
3	3-1	-368	+26
	3-2	-330	+30
	3-3	-109	-110
7	7-1	-673	-470
	7-2	-266	-57
	7-3	-580	+118
4	4-1	-692	+906
	4-2	-480	+263
	4-3	-490	-546

One can see from the results obtained that all radial residual stresses  $\sigma_y$  feature the nature of compression. At that, significant variation is observed: from -1544 MPa to -16 MPa.

The situation with tangential residual stresses  $\sigma_x$  is much worse: together with effective stresses they are responsible for crack formation at the teeth basis. There, along with compressive stresses, there are zones with tensile residual stresses as well. The variation in the data obtained is even greater than for residual stresses: from -574 MPa to +906 MPa. The variation in value obtained (1480 MPa) is comparable to the elastic limit of steel 45XH.

Such variation evidences imperfectness of the existent operation of teeth surface thermal processing.

## Application 9. Stress Condition Check of Steel Weld Seam in Nuclear Power Industry

Check was performed in the premises of a nuclear power plant, with participation of Dr. Phys. Math. Sc. A.D. Zvonkov, Dr. Eng. Sc. A.V. Kotelkin, Dr. Eng. Sc. M.B. Barikov.



During weld joint check

**Object of check** – weld joint made of structural steel.

**Purpose of check** – was to assess the possibility of nondestructive check of weld joints in nuclear power plant environment using portable x-ray diffractometer «Rikor».

**Method used to assess stress condition** – « $\text{Sin}^2\psi$ » method.

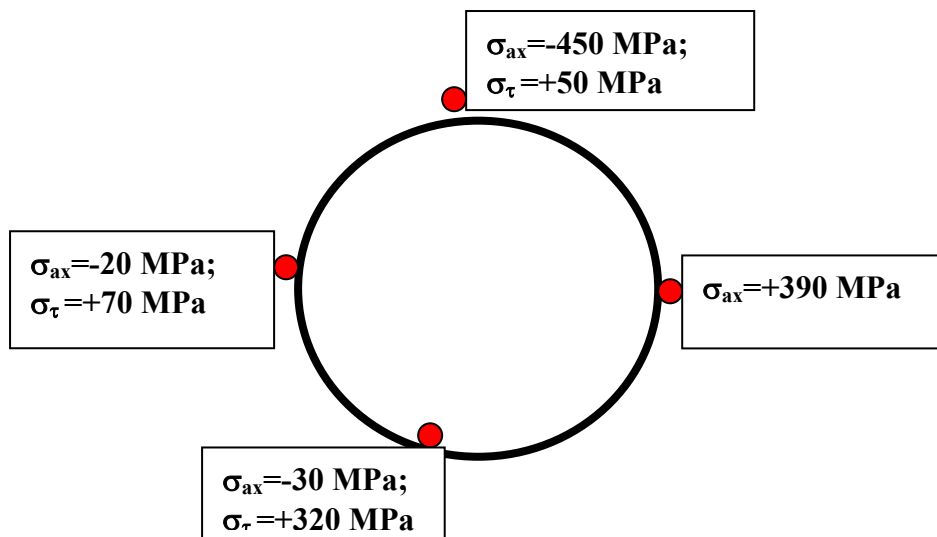
**Radiation used** –  $\text{FeK}\alpha$ .

**Check Points** – in the area of weld joint thermal impact.

**Stress Condition Index** – in each checkpoint, residual stresses were determined in tangential ( $\sigma_\tau$ ) and axial ( $\sigma_{ax}$ ) directions.

### Results Obtained

The results obtained for residual stresses in axial ( $\sigma_{ax}$ ) and tangential ( $\sigma_\tau$ ) directions in different weld joint checkpoints are given on the figure. The work done showed the possibility of nondestructive check of weld joints in nuclear power plant environment using portable x-ray diffractometer «Rikor»



# Application 10. Stress Condition Check of a Stainless Steel Fragment of Weld Joints in Nuclear Power Industry

Check was performed in the premises of IRO LLC, with participation of A.V. Lyuttsau, Dr. Eng. Sc. D.B. Matveev, Dr. Phys. Math. Sc. N.S. Ibraimov, Dr. Eng. Sc. V.G. Lyuttsau, A.A. Bolotokov

**Object of check** – a fragment of weld joint made of austenitic steel.

**Purpose of check** – was to assess stress condition of the weld joint fragment in the seam and thermally affected area.

**Method used to assess stress condition** – « $\text{Sin}^2\psi$ » method.

**Radiation used** –  $\text{CrK}\alpha$ .

**Check Points** – in the weld joint seam and thermally affected area.

**Stress Condition Index** – in each checkpoint, residual stresses were determined in axial direction.

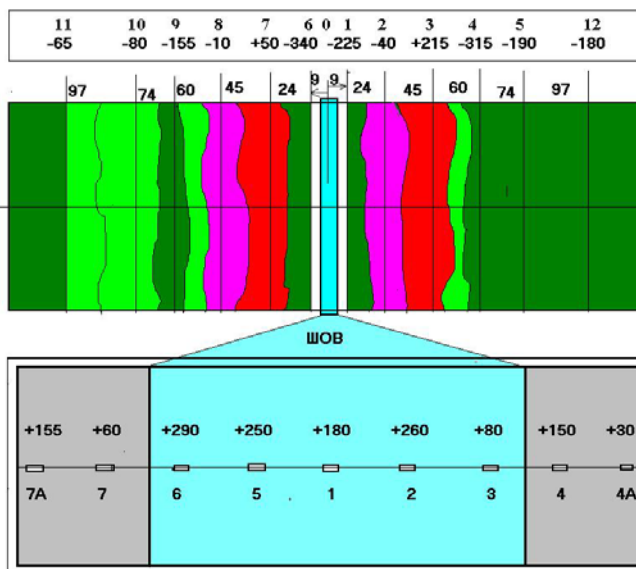
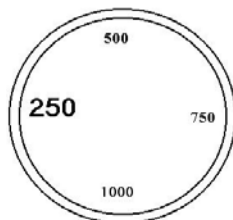


Measuring tube fragment made of steel 12X18H10T

## Results Obtained

Residual stresses are presented on the figure below, where checkpoint 0 is the middle of the seam, checkpoints 1 and 6 are 9 mm, checkpoints 2 and 7 are 24 mm, checkpoints 3 and 8 are 45 mm, checkpoints 4 and 9 are 60 mm, checkpoints 5 and 10 are 24 mm, checkpoints 6 and 11 are 97 mm from the middle of the seam. At the bottom of the figure, the residual stresses in the weld seam and closer than 9 mm from it are presented. These stresses were obtained with the help of polycapillary collimation system of 0.5 mm in diameter.

### Residual Stresses in the Weld Joint Vicinity

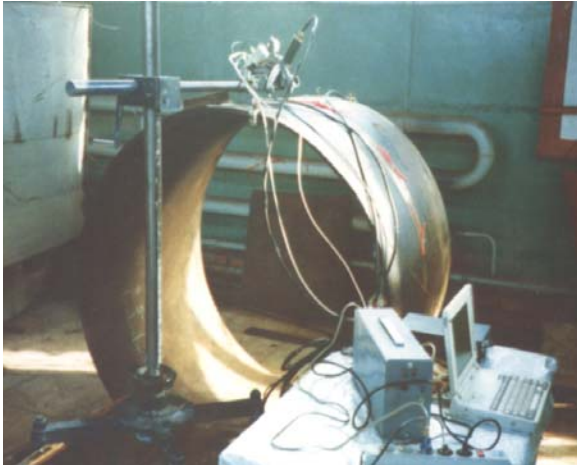


### Publications on the Subject

X-ray method of determining residual stresses in moldings and parts made of titanium, aluminum, nickel; and other alloys / Kotelkin A.V., Zvonkov A.D., Lyuttsau A.V., Matveev D.B., Kumakhov M.A., Ibraimov N.S. – In Collected Articles: Die forging: perspectives and development (collected science reviews) – GOU VPO «UGTU-UPI», 2005. – pp. 784-790. (in Russian).

# Application11. Stress Condition Check of Steel Gas-Line Weld Joint Fragment

Check was done in the premises of All-Russia Gas Research Institute (VNIIGAZ), with participation of Dr. Eng. Sc. A.V. Kotelkin, Dr. Phys. Math. Sc. A.D. Zvonkov, Dr. Eng. Sc. D.B. Matveev, A. V. Lyuttsau, Dr. Eng. Sc. V.N. Sereda



**Object of check** – a fragment of gas pipe weld joint.

**Purpose of check** – was to assess stress condition of weld joint in thermally affected area of the gas line fragment having the operation time of  $\tau_2=17$  years and that of gas line garment with operation time  $\tau_1 = 0$  years.

**Method used to assess stress condition** – vertical exposure method.

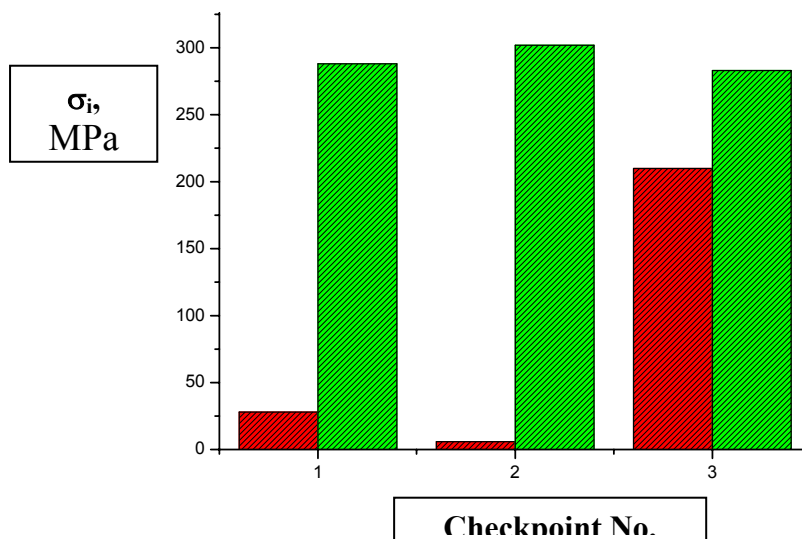
**Radiation used** –  $FeK\alpha$ .

**Check Points:** three checkpoints at different distances from the longitudinal weld seam.

**Stress Condition Index** –  $(\sigma_1 + \sigma_2)/3$ .

## Results Obtained

The diagram represents residual stresses read from checkpoints 1...3 in case of 0 years operation time (red color), and 17 years operation time (green color). The data obtained show that the original level of tensile residual stresses in the said checkpoints considerably grows after seventeen years of operation, to a greater extend – in the nearest to the weld seam checkpoint, and to a lesser extend – in the third checkpoint.



## Publications on the Subject

X-ray method of determining residual stresses in moldings and parts made of titanium, aluminum, nickel; and other alloys / Kotelkin A.V., Zvonkov A.D., Lyuttsau A.V., Matveev D.B., Kumakhov M.A., Ibraimov N.S. – In Collected Articles: Die forging: perspectives and development (collected science reviews) – GOU VPO «UGTU-UPI», 2005. – pp. 784-790. (in Russian).

## Application 12. Stress Condition Check of Steel Metal Columns of the Christ the Savior Cathedral

Check was performed during construction in Moscow of the largest Christ the Savior Cathedral (Synod Cathedral), with participation of A.V. Lyuttsau, Dr. Eng. Sc. A.V. Kotelkin, Dr. Phys. Math. Sc. A.D. Zvonkov, Dr. Eng. Sc. D.B. Matveev.

**Object of check** – four steel supporting columns in the ground floor of the Christ the Savior Cathedral (the Synod Cathedral).

**Purpose of check** – was to assess stress condition of the supporting metal columns.

**Method used to assess stress condition** – vertical exposure method.

**Radiation used** –  $FeK\alpha$ .

**Check Points** – column base.

**Stress Condition Index** –  $\sigma = (\sigma_1 + \sigma_2)/3$ .



### Results Obtained

Check has revealed that three columns were loaded equally. The fourth column was somewhat unloaded as regards other columns.



Columns

# Application 13. Stress Condition Check of Steel Elements of Bridges

Upon request from Gormost FGUP, the Krymsky and Borodinsky Bridges across the Moscow River were checked with participation of A.V. Lyutsau, Dr. Eng. Sc. A.V. Kotelkin, Dr. Phys. Math. Sc. A.D. Zvonkov, Dr. Eng. Sc. D.B. Matveev, Dr. Eng. Sc. N.I. Potapov.

**Object of check** – load-bearing chains and ties of the Krymsky Bridge, structural elements of the Borodinsky Bridge.

## The Krymsky Bridge Check

### Load-Bearing Chain



### Tie

## The Borodinsky Bridge Check



**Purpose of check** – was to assess stress condition of the structural elements of bridges.

**Method used to assess stress condition** – vertical exposure method.

**Radiation Used** – FeK $\alpha$

**Checkpoints** – the most stressed points in the structural elements of bridges.

**Stress Condition Index** –  $\sigma = (\sigma_1 + \sigma_2)/3$ .

### **Results Obtained**

**Stress check of the load-bearing chains, ties of the Krymsky Bridge in Moscow revealed the necessity of repair operations.**

## Application 14. Physical Metallurgy Expertise of the Haulage Steel Rope of Lift No. 4 in the Ostankino TV Tower After Fire

The expertise was performed at the Moscow State University of Steel and Alloys (Technological University) BPO GOY upon request of the RF General Public Prosecutor Office, with participation of Dr. Eng. Sc. A.V. Kotelkin, Dr. Phys. Math. Sc. A.D. Zvonkov, A.V. Lyuttsau, Dr. Eng. Sc. D.B. Matveev, Dr. Phys. Sc. Yu. N. Parkhomeko

**Object of check** – two fragments of the haulage rope of lift No. 4: fragment №1 without evident traces of high-temperature impact, and fragment №2 with noticeable traces of high-temperature impact.

**Purpose of check** – to assess rope strength and nature of destruction

### Results Obtained

Portable x-ray diffractometer of «Rikor» Series established change under the temperature impact in the condition of rope metal from hard-drawn (after manufacture) into thermally processed. This, together with other analyses, this enabled establishing the reason for rope destruction – it resulted from sort-time creepage under the action of high temperature and bears plastic nature.



# Application 15. Comparison of Residual Stress Values Obtained by XRD Method Using «RIKOR» Series Instrument Versus DAVIDENKOV Method<sup>1</sup>

Comparison was done in the premises of Moscow Institute of Steel and Alloys and Salyut NPO, with participation of A.V. Lyuttsau, Dr. Eng. Sc. A.V. Kotelkin, Dr. Phys. Math. Sc. A.D. Zvonkov, Dr. Eng. Sc. D.B. Matveev, Dr. Chem. Sc. N.S. Merkulova.

Out of a fragment of a disk made of chromium – nickel alloy, two samples were cut. The scheme of measurements to be done with «Rikor» Series Instruments for the samples prepared for the analysis to be done by the Davidenkov method is given in figure 1.

Scheme of Measurements with «Rikor»  
Of Samples Prepared for the Davidenkov Method

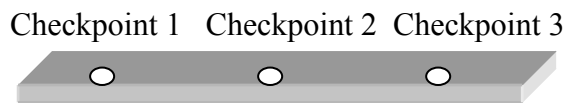


Fig.1

Thereafter, samples were handed over to N.S. Merkulova, Salut NPO, for stress analysis following the Davidenkov method using POVKON TENZOR plant. The resulting values of stresses along thickness  $h$  of the samples obtained at the POVKON TENZOR plant P (Davidenkov method) are given on fig.2 (sample 1) and fig. 3 (sample 2). Straight lines D and E limit the interval of residual stress values obtained using « Rikor » Series instrument. Curves B and C show distribution of residual stresses in the surface in case of consecutive removal with etching of the previous surface layer, which distribution was obtained following the Davidenkov method.

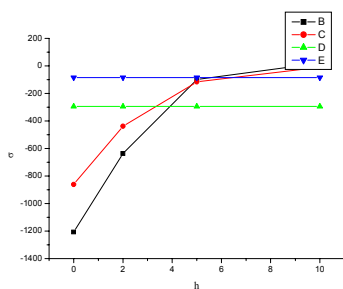


Fig.2

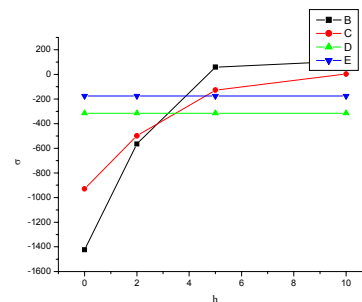


Fig.3

Almost one-hundred percent correspondence between two methods by mean residual stress values is noted at a depth of four microns (according to Davidenkov:-225 MPa, according to XRD method:-229 MPa). Since for alloy EP741, the depth of half x-rays attenuation varies within 4-6 microns, the match of the results obtained by the two methods, based on the mean value, can be assessed as ideal.

<sup>1</sup> Method of layer-by-layer chemical etching of one side of beam with a predeformed end. The Indentor mounted on the free end of the beam, based on the beam curvature, determines the residual stress value depending on the depth of the etched layer. It is widely used in aviation industry. It is a destructive method of checking (can be done only on samples).

## Application 16. Stress Condition Check of Al<sub>2</sub>O<sub>3</sub> Polycrystals (Polycor)

Check was done in the premises of the Moscow Institute of Steel and Alloys with participation of A.B. Lyuttsau, Dr. Eng. Sc. A.V. Kotelkin, Dr. Phys. Math. Sc. A.D. Zvonkov, Dr. Eng. Sc. D.B. Matveev.

**Object of check** – 4 samples of rectangular Al<sub>2</sub>O<sub>3</sub> polycrystalline (polycor) plates.

**Purpose of check** - was to determine residual stresses in the samples.

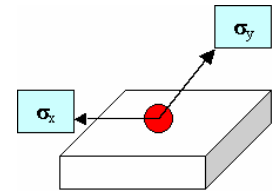
**Method used to assess stress condition** – «Sin<sup>2</sup>ψ» method.

**Radiation used** – CrKα., indices HKL: {234}, peak in the area of Θ=68°.

**Check Points** – one checkpoint in the center of sample.

**Stress Condition Index** – in each checkpoint, the residual stresses were determined in two mutually perpendicular directions:  $\sigma_x$  and  $\sigma_y$ . Elastic constants used in the calculation were: the Young module - 380000 MPa, the Poisson coefficient - 0.3.

**Method used to assess stress condition** – «Sin<sup>2</sup>ψ» method.



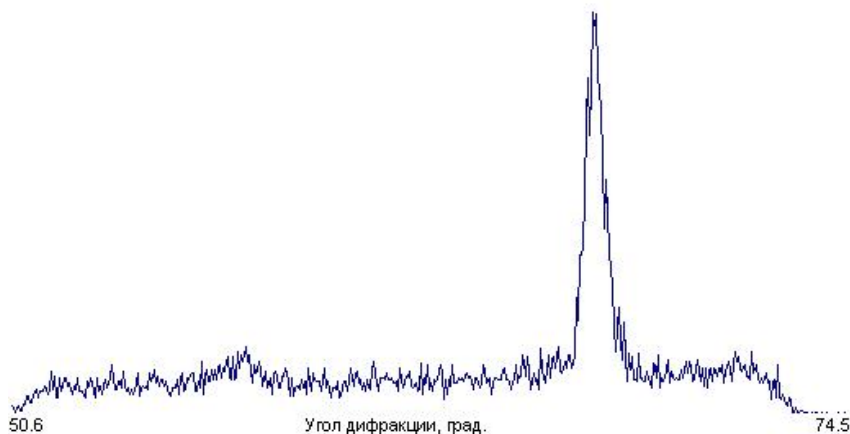
### Results Obtained

The results are given in the table.

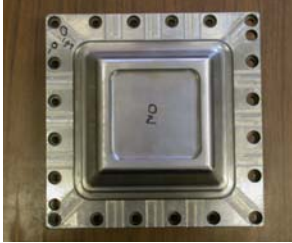
Table

Sample No.	$\sigma_x$ , MPa	$\sigma_y$ , MPa
1	-1130	-945
2	-1540	-1045
3	-610	-300
4	+80	-960

An example of sample diffractogram



## Application 17. Stress Condition Check of Chisels Made of Steel 40X13 and Bronze OCS-555



Chisels, Intercross LLC, were checked at the premises of the Moscow Institute of Steel and Alloys with participation of A.V. Lyuttsau, Dr. Eng. Sc. A.V. Kotelkin, Dr. Phys. Math. Sc. A.D. Zvonkov, Dr. Eng. Sc. D.B. Matveev



### Object of check -

1. A new puanson made of steel 40X13.
2. A chisel having the operation time of about 300000 cycles within the temperature range of 20 ... 200 degrees C at 0 to 8 atmospheres pressure.
3. A chisel made of bronze OCS-555 with operation time of about 300000 cycles within the temperature range of 20...200 degrees C at 0 to 8 atmospheres pressure.

**Purpose of check** – was to determine residual stresses of chisels.

**Method used to assess stress condition** – « $\text{Sin}^2\psi$ » method.

**Radiation used** -  $\text{FeK}\alpha$ , angle of diffraction  $\Theta=55.7^\circ$ .

**Checkpoints** – in the area of chisel fins.

**Stress Condition Index** – since it was required to assess the stress condition of chisel in the vicinity of fins on the whole, the stress condition index was selected as the mean stress of all checkpoints.

### Results Obtained

Mean stress on the fins of new chisel No.1 makes  $-240$  MPa.

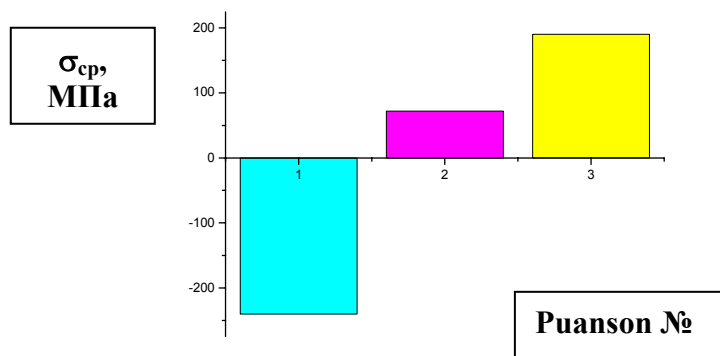
Mean stress on the fins of chisel No. 2 makes  $+72$  MPa.

Mean stress on the finds of chisel No.3 without cracks makes  $+190$  MPa.

As a result of operation impacts, residual stresses on the fins of the chisel made of steel 40X13 change their polarity (from compression  $-240$  MPa to tension  $+72$  MPa). For the chisel made of bronze, the tensile stresses are even higher. Residual tensile stresses impose over effective tensile stresses leading, in the excess of the elasticity limit, to cracking.

### Publications on the Subject

X-ray method of determining residual stresses in moldings and parts made of titanium, aluminum, nickel;



and other alloys / Kotelkin A.V., Zvonkov A.D., Lyuttsau A.V., Matveev D.B., Kumakhov M.A., Ibraimov N.S. – In Collected Articles: Die forging: perspectives and development (collected science reviews) – GOU VPO «UGTU-UPI», 2005. – pp. 784-790. (in Russian).

## Application 18. Stress Condition Check of a Cast Iron Forming Roll Fragment

Check was done at the premises of IRO LLC with participation of A.V. Lyuttsau, Dr. Eng. Sc. A.V. Kotelkin, Dr. Phys. Math. Sc. A.D. Zvonkov, Dr. Eng. Sc. D.B. Matveev, Dr. Phys. Math. Sc. N.S. Ibraimov, A.A. Bolotokov

**Object of check** – a forming roll fragment made of gray cast iron with a surface layer of white cast iron.

**Purpose of check** – was to determine residual stresses of the fragment.

**Method used to assess stressed condition** – « $\text{Sin}^2\psi$ » method.

**Radiation used** –  $\text{CrK}\alpha$ .

**Checkpoints** – the first checkpoint is on the working surface of the iron forming, the second – in the surface layer of white cast iron close to the working surface, the third one – in the gray cast iron layer far from the working surface.



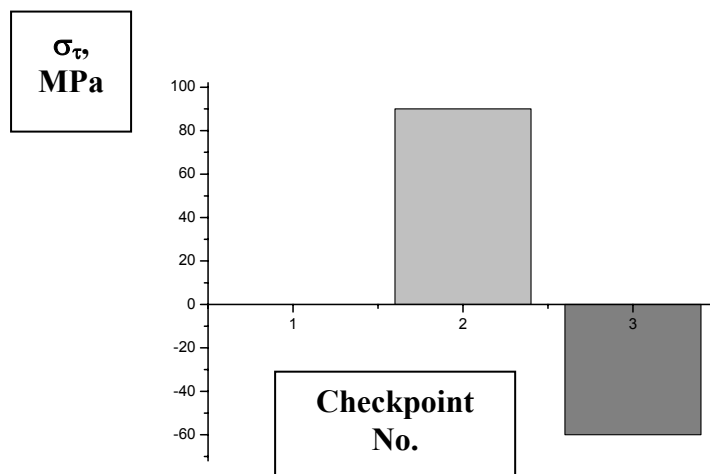
**Stress Condition Index** – in each zone, residual stresses in tangential direction were determined.

**Method used to assess stress condition** – « $\text{Sin}^2\psi$ » method.

### Results Obtained

On the working surface of the forming roll (checkpoint 1) the obtained level of residual stresses is close to nil.

In the tangential direction, in the surface layer of white cast iron (checkpoint 2), tensile stress was observed (+90 MPa); further, in the gray cast iron layer (checkpoint 3), there were compressive stresses (-60MPa).



### Publications on the Subject

X-ray method of determining residual stresses in moldings and parts made of titanium, aluminum, nickel; and other alloys / Kotelkin A.V., Zvonkov A.D., Lyuttsau A.V., Matveev D.B., Kumakhov M.A., Ibraimov N.S. – In Collected Articles: Die forging: perspectives and development (collected science reviews) – GOU VPO «UGTU-UPI», 2005. – pp. 784-790. (in Russian).

# Application 19. Stress Condition Check in Steel ShKh15 Steel Round Billets

Check was done at the premises of the Moscow Institute for Steel and Alloys with participation of A.V. Lyuttsau, Dr. Eng. Sc. A.V. Kotelkin, Dr. Phys. Math. Sc. A.D. Zvonkov, Dr. Eng. Sc. D.B. Matveev, D.B. Dubrovin

**Object of check** – four billets for fabrication of ball-bearing rings made of steel ShKh15, two had scale on the surface, the other two were free of scale.

**Purpose of Check** – was to determine residual stresses of billets.

**Method used to assess stress condition** – «Sin<sup>2</sup>ψ» method.

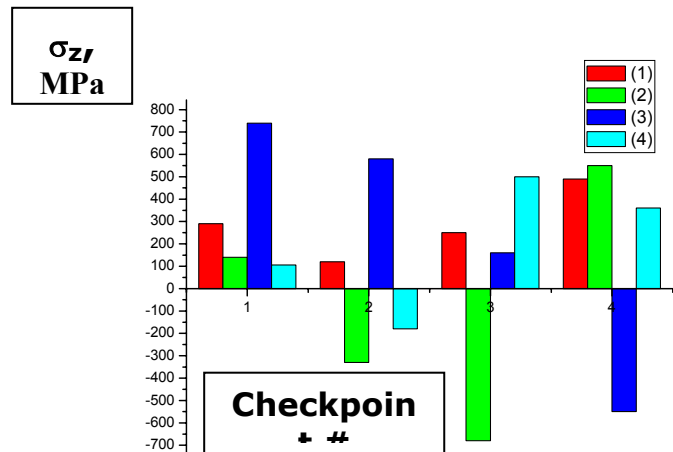
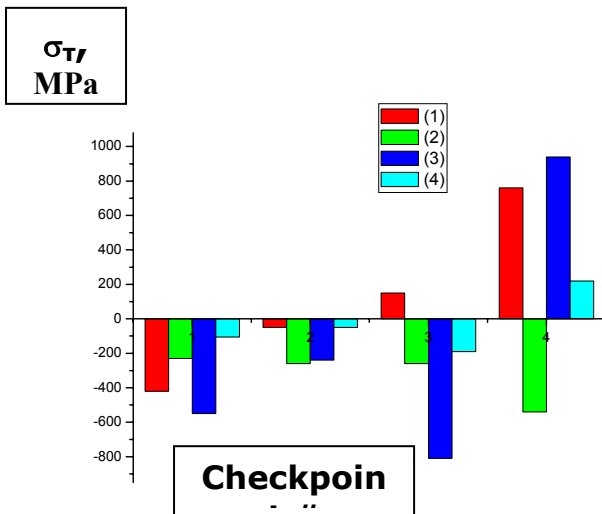
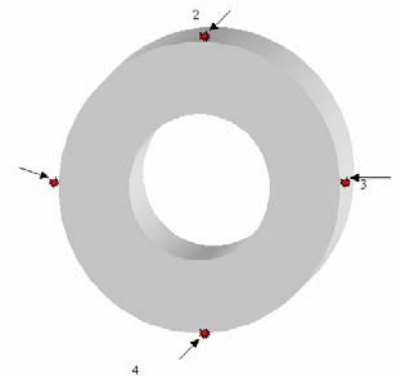
**Radiation used** – FeKα.

**Stress Condition Index** – in each zone, residual stresses were determined in axial (z) and tangential (τ) directions.

## Results Obtained

The inspection results are given in respective bar carts (samples 1, 2, 3, and 4 are marked with red, green, blue, and light blue color, respectively).

Scheme of Measurements



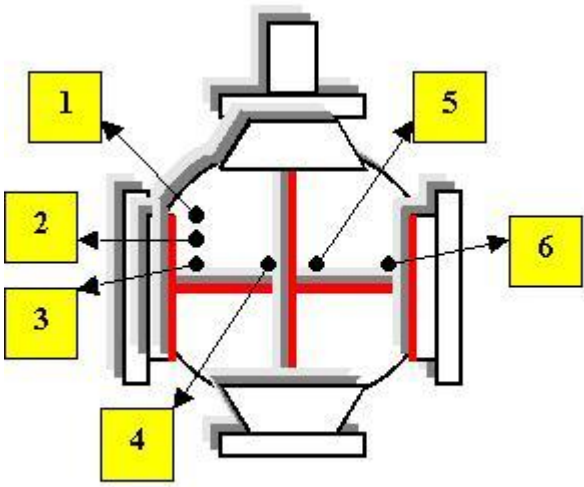
Stresses in axial direction do not ultimately render much influence on ovality of billet since those are partially eased in the course of tube cutting into rings.

Much greater influence on ovality is rendered by residual stresses. The data obtained show that in tangential directions billets 1, 3, and 4 reveal residual stresses of different polarity, which may lead to their ovality during their further processing.

## Publications on the Subject Matter

X-ray method of determining residual stresses in moldings and parts made of titanium, aluminum, nickel; and other alloys / Kotelkin A.V., Zvonkov A.D., Lyuttsau A.V., Matveev D.B., Kumakhov M.A., Ibraimov N.S. – In Collected Articles: Die forging: perspectives and development (collected science reviews) – GOU VPO «UGTU-UPI», 2005. – pp. 784-790. (In Russian).

# Application 20. Stress Condition Check of Steel Body of Borsig DU - 700 Crane Made of Steel 17G1S After Repair



Check was performed in the facilities one of engineering factories with participation of Dr. Eng. Sc. A.V. Kotelkin, Dr. Phys. Math. Sc. A.D. Zvonkov, Dr. Eng. Sc. A.A. Bogatov

**Object of check** – body of Borsig DU-700 Crane made of steel 17G1S after repair.

**Purpose of check** – was to assess stress condition of DU-700 crane after repair and tests as well as determining the effective stress during test.

**Method used to assess stress condition** – vertical exposure technique.

**Radiation used** –  $FeK\alpha$ .

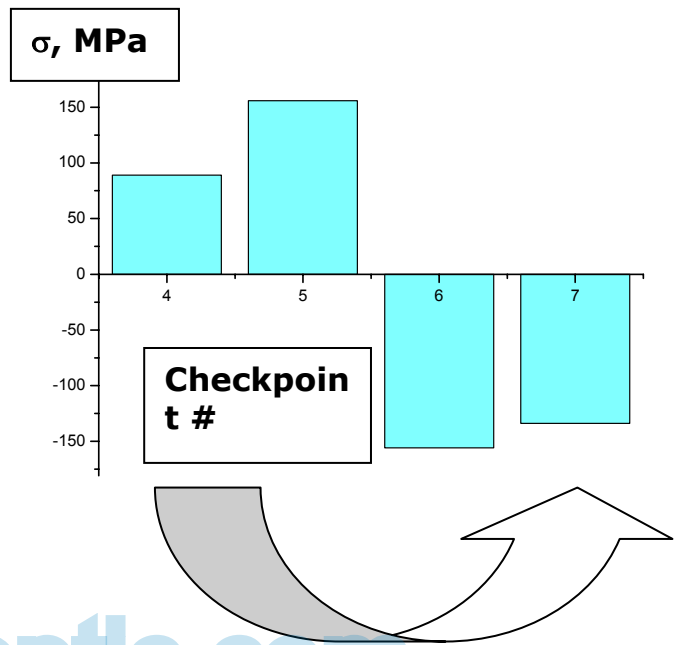
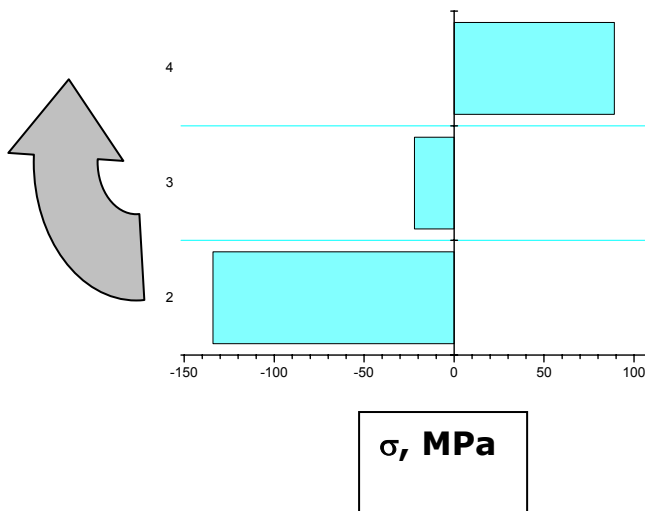
**Check Points** – seven checkpoints in the vicinity of welded seams (on the schematic, the welded seams are marked with red color).

**Stress Condition Index** –  $\sigma = (\sigma_1 + \sigma_2)/3$ .

## Results Obtained

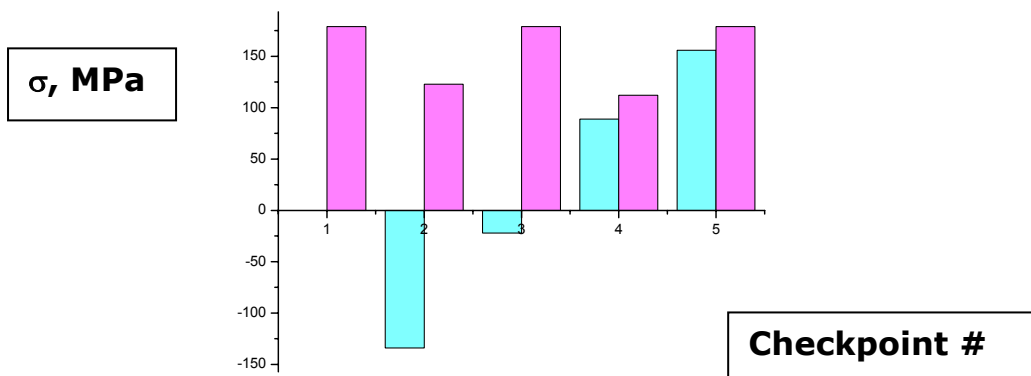
Stress condition of the crane body that occurred when a branch tube was welded thereto is observed in checkpoints 2, 3 and 4 (one fourth part of the vertical seam). The bottom left bar chart shows that as one moves from checkpoint 2 to checkpoint 4, polarity of residual stresses changes from compression to tensile. The same picture is true for half of the horizontal welded seam (checkpoints 4...7) connecting the top and bottom parts of the crane body. Checkpoints 4 and 5 (fourth part of the welded seam) are characterized by tensile residual stresses, checkpoints 6 and 7 (the other fourth part of the welded seam) – by compression ones.

**Checkpoint t #**

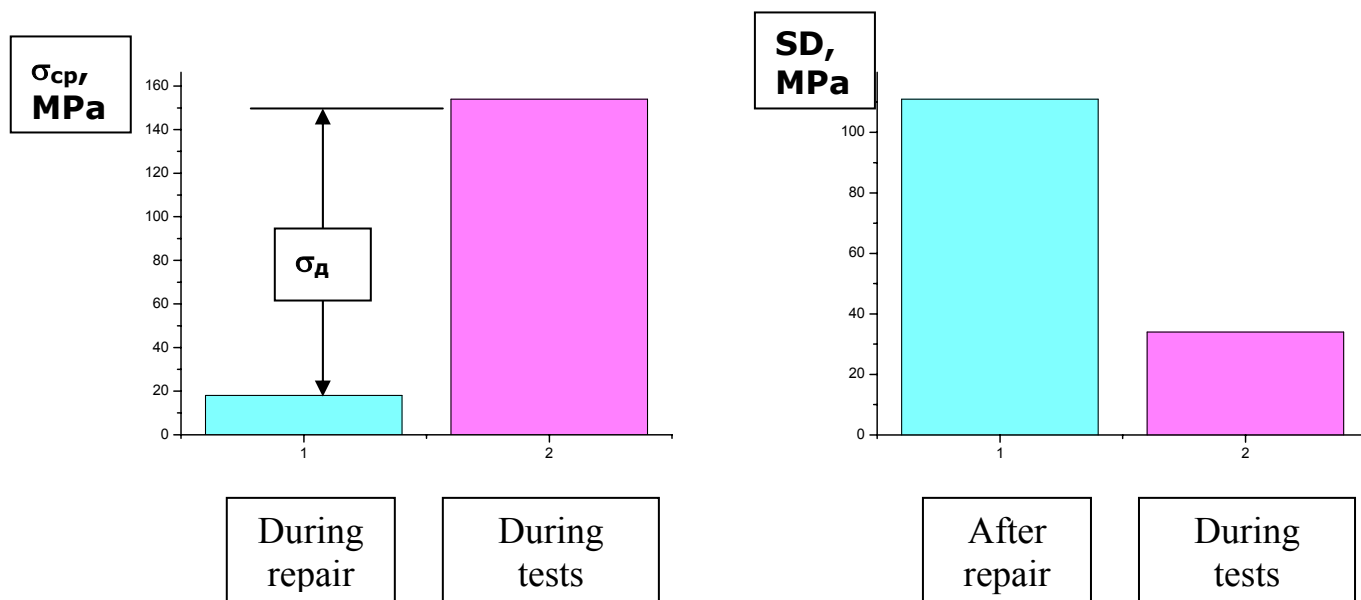


The resultant asymmetrical nature of residual stresses distribution relative to main axes **by tensile stresses** (the compression zone and the tensile zone) may cause distortion of the geometrical sizes of the body and welded branch tubes during crane repair.

After stress condition inspection of the crane body after repair, the body was checked in the course of its testing by internal pressure of 75 **Atm**. The residual stresses in checkpoints at the time of testing are marked with purple color in the bar chart below.



Based on the data obtained, mean stresses  $\sigma_{av}$  and standard deviation after repair and during tests were found out (see the bar charts below см. нижние гистограммы), which allowed determining mean effective stress  $\sigma_{ef} = 136$  MPa. Under the action of internal pressure, data scattering falls down (see the bar chart of standard deviations SD),



The internal pressure (75 Bar) levels irregularity of the stressed condition in the crane body. The influence of residual stresses' asymmetrical action may be pronounced during operation of this crane, particularly in checkpoint 5.

## Application 21. Stress Condition Check of Gas-Turbine Disks Made of Chromium-Nickel Alloy After Assembly

Check was performed in the facilities of Salute MMPP factory with participation of A.V. Lyutsau, Dr. Eng. Sc. A.V. Kotelkin, Dr. Phys. Math. Sc. A.D. Zvonkov, Dr. Eng. Sc. D.B. Matveev.



**Object of check** – a disk made of chromium – nickel alloy.

**Purpose of check** – determining stress condition of the disk after assembly

**Method used to assess stress condition** – vertical exposure technique

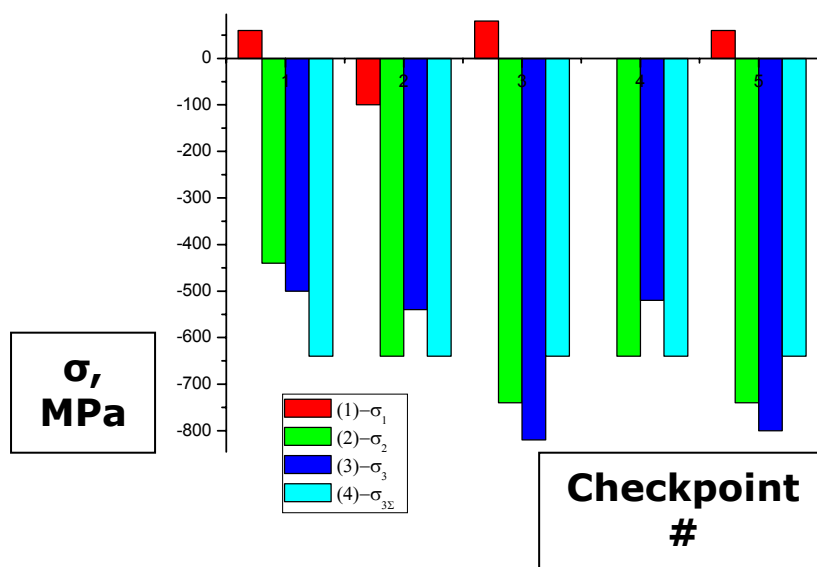
**Radiation used** – CrK $\alpha$ .

**Check Points** – on one side of the disk flat, measurements were performed in 5 checkpoints in one sector (checkpoint 1 – next to the hole, 2 – between the holes, 3 – under the hole, 4 – under the hole, closer to the ledge, 5 – next to the ledge).

**Stress Condition Index** –  $\sigma = (\sigma_1 + \sigma_2)/3$ .

### Results Obtained

The results obtained are shown on the bar chart. On the bar chart red color marks residual stresses ( $\sigma_1$ ) by checkpoints, green color – stresses after assembly ( $\sigma_2$ ), blue color – assembly stresses ( $\sigma_3$ ) in each checkpoint, light blue color – mean assembly stress ( $\sigma_{3\Sigma}$ ), the standard deviation being 160 MPa. The data obtained demonstrates that none of stresses exceed the elasticity limit of the material:  $\sigma_{0.2} > 900$  MPa, but are characterized by considerable scattering.



## Application 22. Check of Stress Condition Anisotropy in Aluminum Sheet

Check was performed at the premises of IRO with participation of A.V. Lyutsau, Dr. Eng. Sc. A.V. Kotelkin, Dr. Phys. Math. Sc. A.D. Zvonkov, Dr. Eng. Sc. D.B. Matveev.

**Object of check** – an aluminum alloy sample having an artificial concentrator in the form of a crack on the butt end.

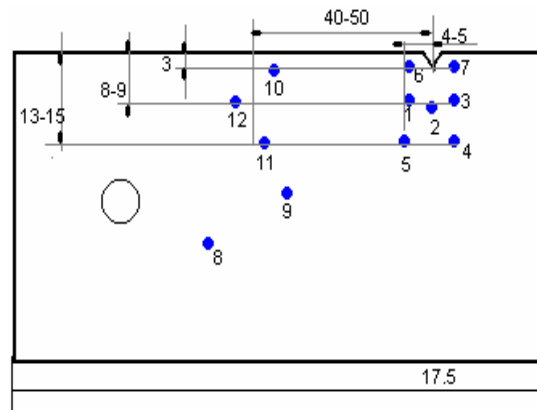
**Purpose of check** – determining stress condition anisotropy in aluminum alloy sample having a concentrator

**Method used to assess stress condition** – « $\sin^2\psi$ » method.

**Radiation used** –  $\text{CrK}\alpha$ .

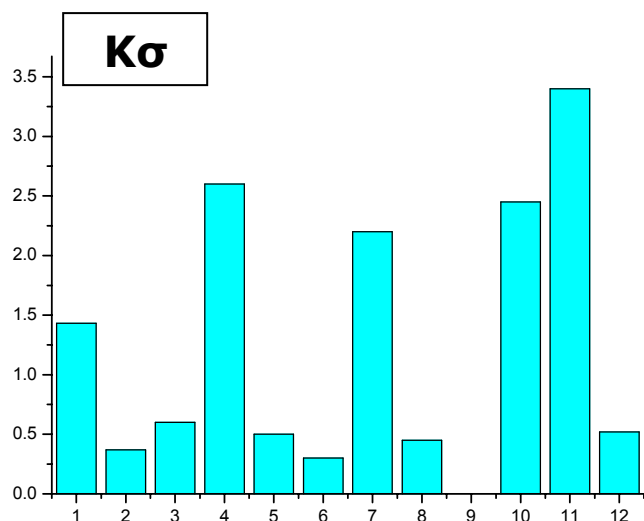
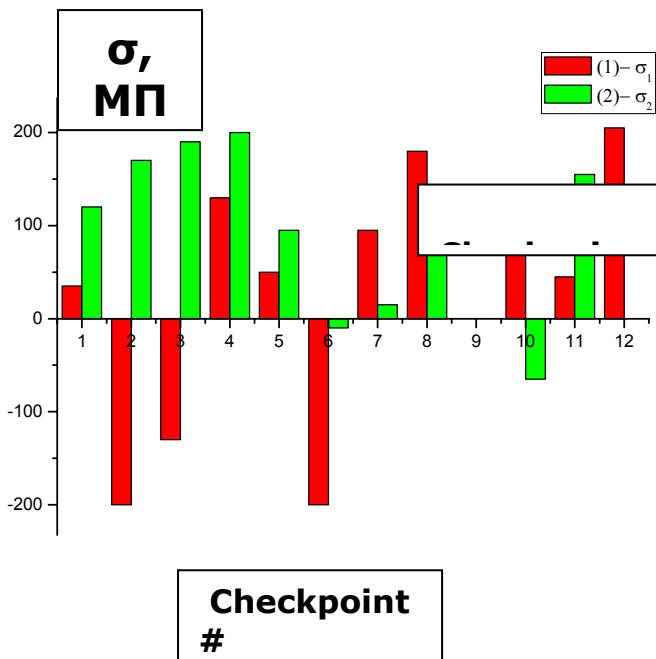
**Check Points** – shown on the schematic.

**Stress Condition Index** – in each checkpoint, two components of residual stresses were assessed: across rolling ( $\sigma_1$ ) and along rolling ( $\sigma_2$ ), a well as stress condition anisotropy index  $K_\sigma = (|\sigma_2 - \sigma_{cp}|) / (|\sigma_1 - \sigma_{cp}|)$ .



### Results Obtained

The residual stresses obtained in checkpoints across and along rolling are given on the left bar chart, the stress condition anisotropy index  $K_\sigma$  – on the right. Mean values along directions for the whole sample make  $\sigma_{1cp} = 30$  MPa and  $\sigma_{2av} = 91$  MPa. It is evident from the data presented that stress condition in this sample is characterized by high level of anisotropy.



## Application 23. Stress Condition Check in the Defective Steel Sheet Area

Check was performed at the premises of Moscow Institute of Steel and Alloys (MISiS) with participation of Dr. Eng. Sc. A.V. Kotelkin, Dr. Phys. Math. Sc. A.D. Zvonkov, Dr. Eng. Sc. D.B. Matveev, Dr. Eng. Sc. A.V. Dub.

**Object of check** – sample №1 cut out from 4.4mm-thick hot-rolled steel sheet (the defect being skin); sample №2 cut out from 1.2mm-thick cold-rolled steel sheet (the defect being skin), and sample №3 cut out from 0.5mm-thick cold-rolled steel sheet (the defect being bulged-in sinter).

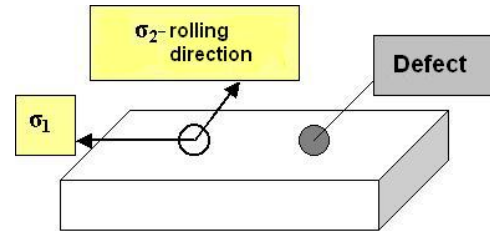
**Purpose of check** – determining stress condition in the defective area of steel sheet

**Method used to assess stress condition** – « $\sin^2\psi$ » method.

**Radiation used** –  $FeK\alpha$

**Check Points** – are shown on the schematic

**Stress Condition Index** – in each checkpoint, two components of residual stresses were assessed: across rolling ( $\sigma_1$ ) and along rolling ( $\sigma_2$ ).



### Results Obtained

Stress condition obtained for defect-free and defective surfaces of samples is presented as respective bar charts.

For the hot-rolled sample, residual stresses on the skin drift towards compression in both

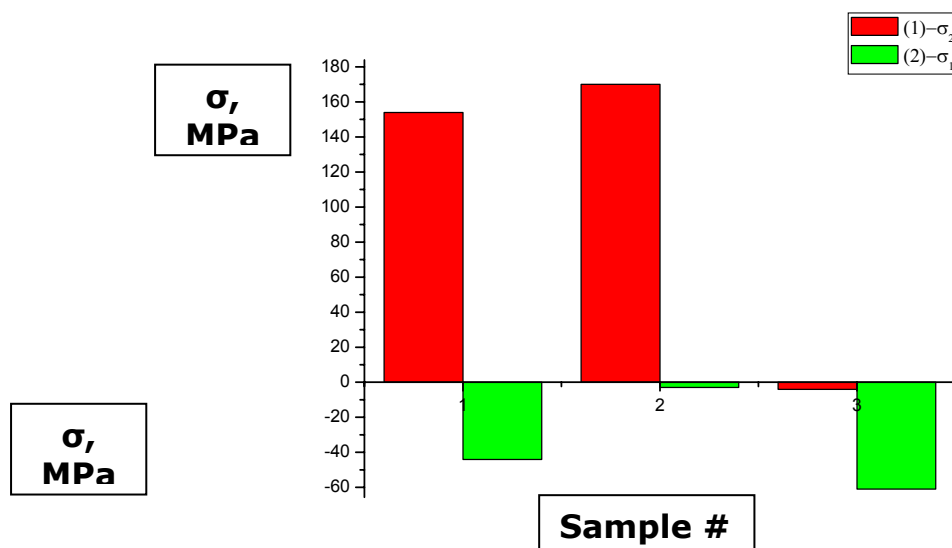
rolling and cross-rolling directions, the stress condition nature remaining the same.

For the 1.2mm-thick cold-rolled sample, the same picture as above is observed.

For the 0.5mm-thick cold-rolled sample, residual stress in rolling direction have the same features as above while compression residual stress in cross-rolling direction fell down to zero on the bulged-in sinter of the sample.

To a first approximation, the following nature of stressed condition in skin and bulged-in sinter types of defects relative to the stressed condition on the defect-free surface can be assumed – the stress condition pattern in defects is close to compression.

Stress Condition of Defect-Free Surface

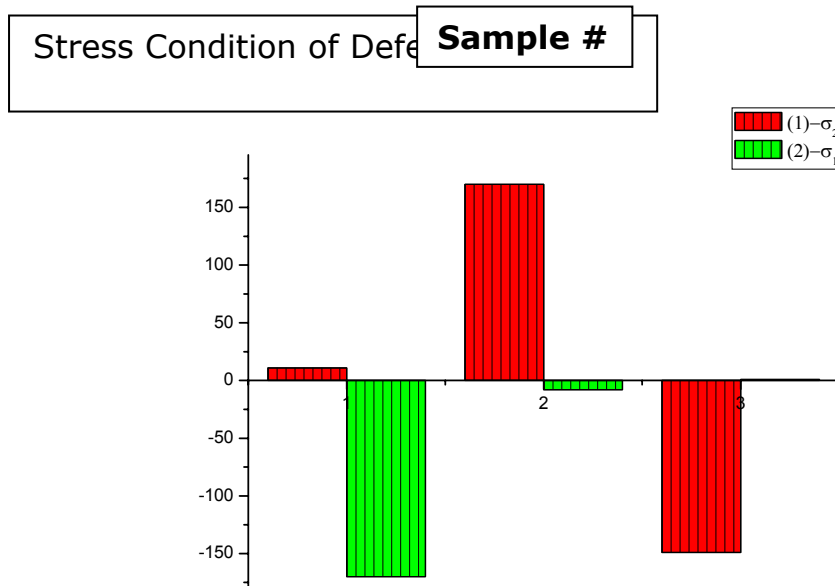


## Application 24.

### Comparison of Residual Stresses Obtained Through X-ray Analysis with «RIKOR» Series Instrument Versus Those Obtained Through Stain Measurement Method

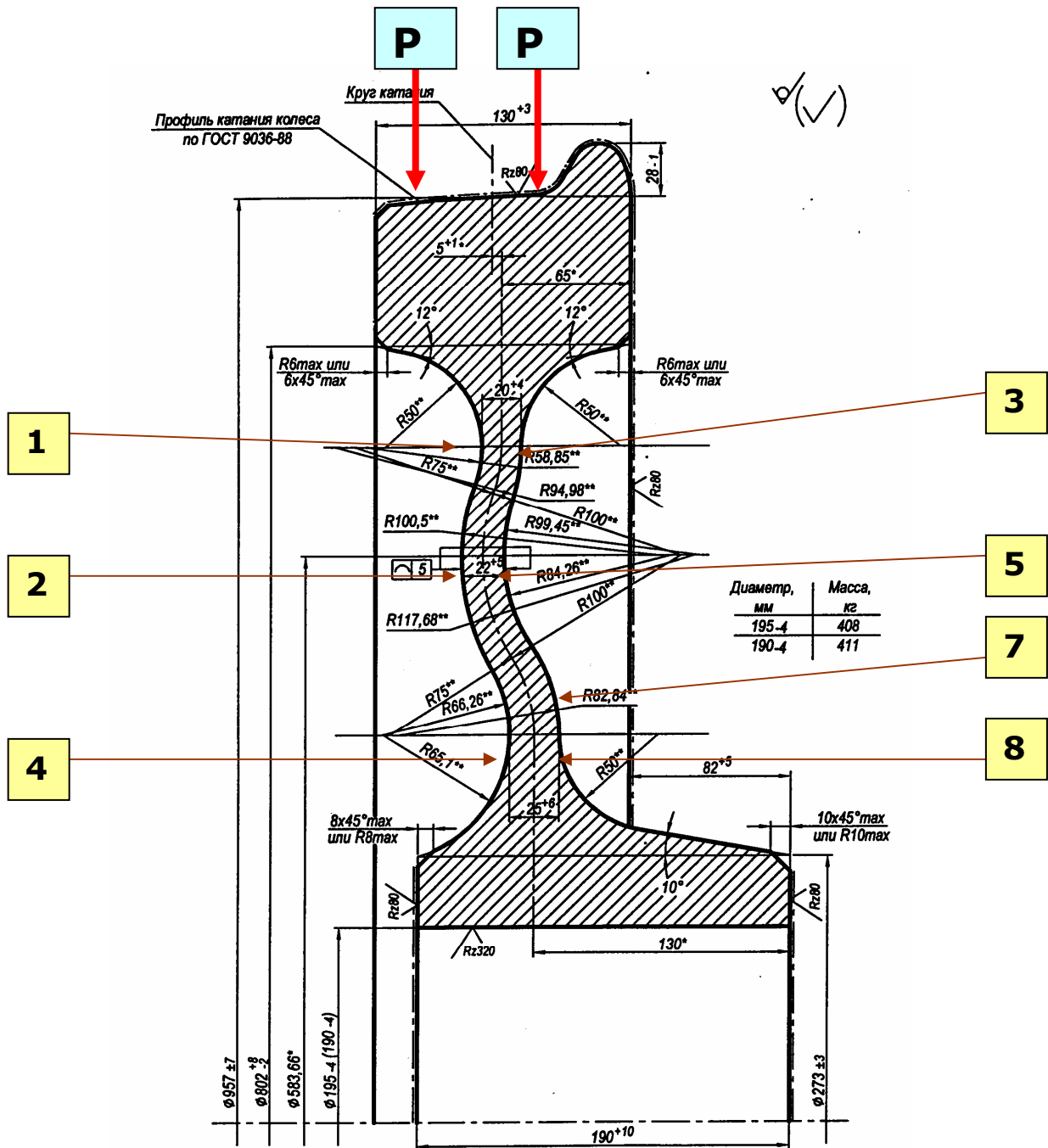
Comparison was performed in the facilities of VNUUZhT Railroad Research Institute and IRO with participation of Dr. Eng. Sc. A.V. Kotelkin, Dr. Phys. Math. Sc. A.D. Zvonkov, Dr. Eng. Sc. D.B. Matveev, A.V. Lyutsau, S.L., Shishkin, Dr. Eng. Sc. A.S. Razumov.

Comparison was carried out on solid-rolled wheel with a curvilinear disk, along the radius of which strain sensors were glued. The wheel was subjected to step-by-step action of static load: 20, 40, and 70 tons in different points of rolling surface,



$P_1$  and  $P_2$  (see the schematic). The points of measurement by different methods are marked with brown arrows on the schematic. Stresses were determined in radial direction.

Wheel Loading and Measurement Scheme



The results of determining stresses by different methods on the inner and outer wheel surfaces are given in tables 1 and 2.

Table 1  
Stresses Determined by Different Method on the Inner Surface of Wheel

P, ton	Method	Checkpoint #			
		3	5	7	8
20	X-ray	-70	-70	-30	-30
	Strain measurement	-43	-114	0	0
40	X-ray	-150	-210	-60	-50
	Strain measurement	-85	-226	0	0
70	X-ray	-200	-330	-50	-60
	Strain measurement	-144	-390	0	0
	X-ray	-0	-110	+40	+40

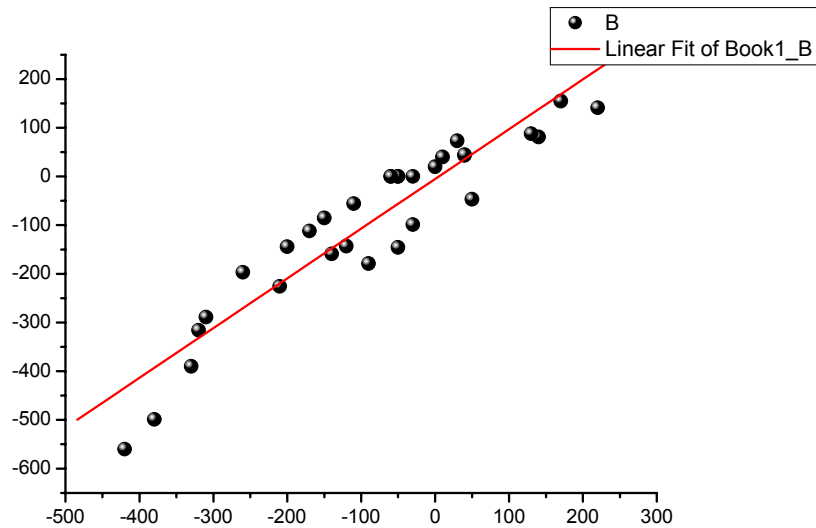
<b>P</b> <b>2</b>	<b>20</b>	<b>Strain measurement</b>	<b>+20</b>	<b>-56</b>	<b>+43</b>	<b>+45</b>
	<b>40</b>	<b>X-ray</b>	<b>+10</b>	<b>-170</b>	<b>+140</b>	<b>+130</b>
		<b>Strain measurement</b>	<b>+40</b>	<b>-112</b>	<b>+81</b>	<b>+88</b>
	<b>70</b>	<b>X-ray</b>	<b>+30</b>	<b>-260</b>	<b>+220</b>	<b>+170</b>
		<b>Strain measurement</b>	<b>+73</b>	<b>-197</b>	<b>+141</b>	<b>+155</b>

Table 2

Stresses Determined by Different Method on the Outer Surface of Wheel 1

<b>P, τ</b>		<b>Method</b>	<b>Checkpoint #</b>		
			<b>1</b>	<b>2</b>	<b>4</b>
<b>P</b> <b>1</b>	<b>20</b>	<b>X-ray</b>	+50		
		<b>Strain measurement</b>	<b>-47</b>		
	<b>40</b>	<b>X-ray</b>	-30		
		<b>Strain measurement</b>	<b>-99</b>		
	<b>70</b>	<b>X-ray</b>	-90		
		<b>Strain measurement</b>	<b>-179</b>		
<b>P</b> <b>2</b>	<b>20</b>	<b>X-ray</b>	-140		-50
		<b>Strain measurement</b>	<b>-159</b>		<b>-146</b>
	<b>40</b>	<b>X-ray</b>	-320		-310
		<b>Strain measurement</b>	<b>-316</b>		<b>-289</b>
	<b>70</b>	<b>X-ray</b>	-420		-380
		<b>Strain measurement</b>	<b>-560</b>		<b>-499</b>

The resultant from correlation analysis Pearson coefficient equals to 0.94 and evidences high correlation between the radial stresses obtained by strain measurement method ( $\sigma_R^T$ ) and by x-ray method ( $\sigma_R^{Xr}$ ), the statistical sample being  $N = 34$ .

$\sigma_R^T$  $\sigma_R^{Xr}$ 

Graphically, the correlation of radial stresses obtained by the strain measurement and x-ray methods is given in the figure. Linear approximation of these data (red straight line) allowed representing the analytical correlation between  $\sigma_R^{Xr}$  and  $\sigma_R^T$  as:

$$\sigma_R^T = -5.06 + 1.02\sigma_R^{Xr}.$$

## **Application 25.**

### **Comparison of Stress Determining Techniques**

Stress determining techniques were compared at the premises of MISiS and IRO with participation of Dr. Eng. Sc. A.V. Kotelkin, Dr. Phys. Math. Sc. A.D. Zvonkov, Dr. Eng. Sc. D.B. Matveev, A.V. Lyutsau.

For comparison, two direct nondestructive inspection techniques were selected: X-ray method and strain measurement; two direct destructive techniques: holographic technique and layer-by-layer etch removal technique (such as Davidenkov method); also three indirect techniques: magnetic technique (for example, Barkhausen noise analysis), electric (for example, amplitude phase-frequency characteristics), and acoustic.

This study was carried out with the help of PRINN software. The program was chosen for its open structure, rather than randomly, which enables flexible modifications to the strategy of examining different stress analysis techniques, hence, selection of the optimum option.

The following parameters were chosen as stress analysis assessment criteria:

- **direct technique**, meaning assessment of stresses in MPa ( $\text{kg}/\text{mm}^2$ ), in contrast to indirect assessment (for example, through taring at uniaxial stretching of samples);
- **nondestructive inspection**;
- **no surface preparation**;
- **determining residual stresses (RS)** ;
- **surface shape**, allowing inspection;
- **directional RS** – a criterion showing the possibility (impossibility) of determining residual stresses in a direction;
- **metals** – a criterion answering the question of what types of metals can be assessed by the technique;
- **on site** – the ability of carrying out inspection on site.

The results obtained are shown in Table 1. The left column shows the stress analysis techniques under investigation.

Other columns contain information concerning criteria. The top line of each column reads the description of criterion; below the criterion level is shown. In our case, to assess the importance of criteria, three levels were used: the most important (Bmax), usual (Omax), and neutral (N). Index "max" indicates that the parameter tends to its maximum value.

Weight shares of each criterion for all techniques were established based on own experience and analysis of literature.

The following criteria were determined as the most important: direct method, nondestructive inspection, and determining RS.

Table 1

## Efficiency of Different Stress Analysis Techniques

<i>Criteria:</i>	Direct Method	Non-Destructive Inspection	No Surface Preparation	Determining RS	Surface Shape	Directional RS	Metals	On Site	<b>Efficiency, %</b>
<i>Levels:</i>	<b>B<sub>max</sub></b>	<b>B<sub>max</sub></b>	<b>O<sub>max</sub></b>	<b>O<sub>max</sub></b>	<b>O<sub>max</sub></b>	<b>B<sub>max</sub></b>	<b>O<sub>max</sub></b>	<b>O<sub>max</sub></b>	
<b><u>Techniques</u></b> X-ray	100	100	1	100	80	100	100	100	<b>85</b>
<b>Layer-by-layer etch removal</b>	100	1	1	100	20	100	100	1	<b>48</b>
<b>Strain measurement</b>	100	100	1	1	60	100	100	100	<b>54</b>
<b>Holographic</b>	100	1	100	10	70	100	100	100	<b>58</b>
<b>Magnetic</b>	1	100	100	10	100	1	40	100	<b>47</b>
<b>Acoustic</b>	1	100	100	10	90	1	100	100	<b>47</b>
<b>Electric</b>	1	100	1	100	90	50	100	100	<b>54</b>

The outcome of efficiency calculation is given in the last column of table 1. It follows from the results obtained that efficiency of the x-ray technique (82%) is 1.5 - 2 time higher than other stress analysis techniques (47 - 58%).

# Application 26

## Estimating Remaining Life of Parts and assembly Units in Various Machines

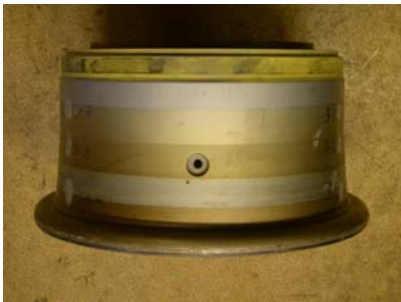
Remaining life was determined at the premises of MISA with participation of Dr. Eng. Sc. A.V. Kotelkin, Dr. Phys. Math. Sc. A.D. Zvonkov, Dr. Eng. Sc. D.B. Matveev, A.V. Lyutsau.

Following the method of determining residual stresses and newly developed method of estimating service life (Patent RU №2215280), service life was estimated for parts and assembly units of various machines.

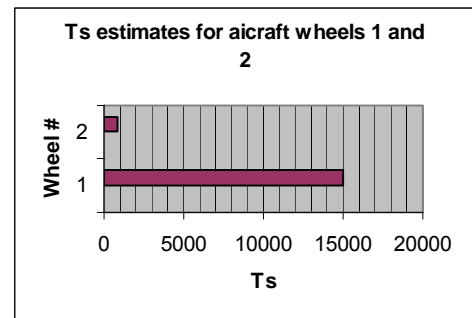
The efficiency of the method was demonstrated by the examples of calculating service and residual life of aircraft wheel hubs; bearing propeller blade longerons in MI-8 helicopter; gas-turbine engine disks; landing gear of SU-30MKI fighters; gas-line pipes.

### AIRCRAFT WHEEL HUBS

Two aircraft wheel hubs made of aluminum alloy AK-6 were inspected. The checkpoints were along hub.



Hub 1 has maximum stress of -190 MPa, hub 2 had the maximum stress of +95 MPa. As a result of calculation, service life time ( $T_s$ ) diagram was plotted. The relative error of ultimate life calculation amounted to 2% approximately.



approximately.

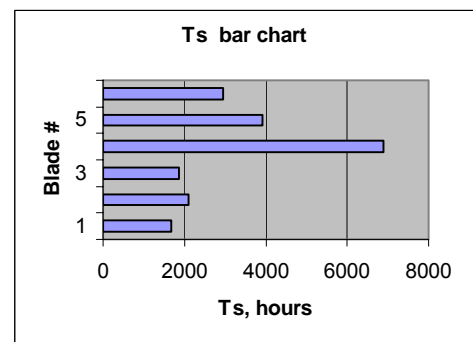
### HELICOPTER BLADES

Using portable x-ray diffractometer, six helicopter blades were examined, each having its own operation time. Their design life equals to 2000 hours in flight.



Application of the newly developed method allowed determining  $T_s$  for each blade (fig.4.3 and 4.4). As a result, blade 1 has residual

life time  $T_r = -319$  hours, blade 2 has  $T_r = 105$  hours, blade 3 has  $T_r = -141$  hours, blade 4 has  $T_r = 4897$  hours, blade 5 has  $T_r = 1922$  hours, blade 6 has  $T_r = 941$  hours.



## GAS-TURBINE ENGINE DISKS

Using portable x-ray diffractometer, three gas-turbine engine disks were analyzed, each having its own operation time. Their design life equals to 800 hours in operation. Application of the newly developed method allowed determining  $T_s$  for each disk (fig.5.1 and 5.2). As a result, disk 1 that has not been in operation has  $T_r = 0$  hours, disk 2 has  $T_r = 38$  hours (defect during manufacture), disk 3 has  $T_r = 752$  hours.

## LANDING GEAR

Using portable x-ray diffractometer, three landing gear sets were analyzed, each having its own operation time, and one landing gear set without any operation time. Their design life equals to 600 times of use. With the help of the developed method,  $K_V$  and  $T_s$  were determined for each landing gear set (fig. 7.1). As a result, landing gear 1 will operate longer than the design life by 40 times of use, landing gear 2 – 1234 times of use, landing gear 3 – 1225 times of use.

## GAS-LINE PIPE FRAGMENTS

Using portable x-ray diffractometer, residual life  $P_0$  was estimated for a gas-line pipe fragment having the operation time of 17 years. The first stage of determining the level of residual stresses was performed for the gas-line pipe fragment with 0-years operation time. The selected for assessment checkpoints were close to the longitudinal welded seam in each fragment. The results of calculation following the developed residual life assessment method are given in table 1.

Table 1

**Residual Life Calculation for Gas-Line Pipe Fragments**

Checkpoint #	$\sigma_{i1}$ , MPa	$\tau_1$ , year	$\sigma_{i2}$ , MPa	$\tau_2$ , year	$V_i$ , MPa/year	$T_s$ , year	$T_r$ , year
1	28		288		15.3		
2	6	0	302	17	17.4	16.9	-0.1
3	210		283		4.3		

