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DESCRIPTION OF RESIDUAL STRESS DISTRIBUTION IN THE SURFACE LAYER AFTER HEAT TREATMENT AND SHOT PEENING

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Abstract
The stress distribution function in the surface layer is created as a result of using stress measurements on the surfaces of C45 steel samples after shot peening. Stresses were measured by X-ray diffraction with the use of the PSF-3M device from the Rigaku Company. For measuring residual stresses, subsequent layers of the top surface of the material were used as a basis, and these were obtained through electrochemical etching. The test results i.e. distance into the material, sample hardness, shot type, stress) were entered into the stepwise multiple regression program. A record of residual stresses was obtained in the form of the second-degree regression function of three independent variables with interactions. The obtained analytical form of the residual stress function was used in the FUNVAL3.EXE program to calculate the tabular values of stresses permeating into the material. For the analytical description of the stress distribution, the REGPOLY.EXE regression program was used, which creates a polynomial functional form of the residual stress distribution. The plot form of the residual stress distribution was obtained using the EXCEL Microsoft Office 2000 program.

Keywords: X-ray diffractometer; measurement of stresses; psi sine square method; metal crystal lattice; wave beam diffraction; pneumatic shot peening; multiple regression; planned experiment
Type of the work: research article

1. INTRODUCTION

Dynamic surface shot peening is a continuous process of changing the state of the surface layer consisting of plastic deformation and other processes accompanying this phenomenon, the most important of which are phase transformations. Shot peening is characterised by the formation of compressive residual stresses. The quantities determining the state of compressive stresses are: the value of maximum stresses, the depth of their deposition and the distribution in the hardened surface layer. Research on the shot peening process is relatively more widely and more often used for the selection and optimisation of technological parameters and for forecasting the obtained states of stresses and deformation.

An X-ray diffractometer of the PSF-3M type from the Rigaku Company (Japan) was used to measure stresses on the surface of the samples, using a chromium lamp, using the $\sin^2(\psi)$ method. The 40 × 40 mm amples, having a hardness of 30–50 HRC, were made of C45 steel. Four types of shot were used to harden the surface layer of the samples: cast steel shot SW170 with a diameter of 0.4 mm and SW330 with

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a diameter of 0.8 m and a hardness of 470 HV; and steel shot StD-03 with a diameter of 0.4 mm and StD-06 with a diameter of 0.6 mm and a hardness of 640 HV. The shot peening time of the sample was 120sec. The air pressure during peening was 0.45MPa. The depth of the hardened layer was in the order of 0.8 mm. The subsequent layers of the samples with the thickness of 0.04–0.06 mm were removed by an electrochemical method. The number of removed layers was in the range of 10–12. For the analytical description of the measurements of the residual stress distribution tests after heat treatment and shot peening, the multiple step regression program REGSTEP.EXE[1] was used (using the results the work of Mońka and Janowski [1]). The independent variables in the stress tests were: the depth of the hardened layer deposition d, the hardness of the HRC sample and the type of shot marked with successive natural numbers N (1, 2, 3, 4). Residual stresses σ MPa measured by X-ray diffraction were the dependent variable.

The test results (d, HRC, N, σ) were entered into the stepwise multiple regression program REGSTEP.EXE. In total, 128 experiments were carried out as part of the present study. The studies in the factor space ($d \in$ <0.0–0.8> mm, HRC $\in$ <25–50>, $N \in$ <1, 2, 3, 4>) were not performed according to the rules of the planned experiment [9], but were random. The residual stress distribution function σ, derived from the REGSTEP.EXE program, is a function of three second-degree independent variables with interactions. The obtained function σ is used to obtain the tabular distribution of stresses into the surface layer using the FUNVAL3.EXE[2] program. The REGPOLY.EXE[3] polynomial regression program was used for analytical recording of the tabular distribution of residual stresses. The EXCEL Microsoft Office 2000 program was used to graphically present the distribution of residual stresses in the form of a polynomial.

2. TEST METHOD OF RESIDUAL STRESS DISTRIBUTION AFTER HEAT TREATMENT AND SHOT PEENING

2.1. X-ray diffractometer

The PSF-3M X-ray diffractometer was used to study the distribution of residual stresses in the surface layer with a thickness of 0.8 mm [2], [,3],[12].

A test sample with dimensions 40 mm × 40 mm is placed on the base of the instrument. The measurement zone on the sample is located in the central part of the sample. The diffractometer is equipped with two movable arms: one arm with a chromium X-ray lamp is used to set the angle of incidence ψ of the beam of X-ray waves on the surface of the sample, and the other arm with a transducer is used to process the reflected beam of X-ray waves, bent on the steel crystal lattice.

The X-ray method of measuring residual stresses is used for metals with a crystalline structure. Residual stresses are introduced into the surface layer of the object by heat treatment and shot peening, which causes displacements in the crystal lattice of the metal.

The stream of X-rays, after being reflected from the displaced crystal lattices, undergoes diffraction and is recorded in the transducer of the diffractometer [3], [12]. The image of the stream of X-ray waves after diffraction is shown in Fig. 1 [3]. For the subsequent angles of incidence ψ of the stream of X-ray waves on the surface of the object, the parameter 2Θ of the top of the diffraction profile is recorded. The deformation of the crystallographic lattice in the metal after heat treatment and shot peening, recorded during the measurement with a diffractometer, is calculated from the following relationships:

[1] REGSTEP.EXE; Institute of Manufacturing Technology, Warsaw University of Technology
[2] FUNVAL3.EXE; Institute of Manufacturing Technology, Warsaw University of Technology
[3] REGPOLY.EXE; Institute of Manufacturing Technology, Warsaw University of Technology

• Bragg's formula [3], [11], given by the following expression:

$$n\lambda = 2d_{hkl} \cdot \sin\Theta \tag{1}$$

where λ indicates the X-ray wave length (Ao), dhkl the distance between the planes of the crystal lattice of the metal and Θ the angle of incidence of the X-ray beam; and

• Hooke's law relating the deformations ε to a plane state of stresses σ, as follows:

$$\varepsilon_x = \varepsilon_y = \frac{\nu\sigma_y}{E} \tag{2}$$

where E indicates Young's modulus for the material (in megapascals) and ν the Poisson's ratio for the material.

From the quoted relationships in Eqs (1) and (2), the dependence for the calculation of residual stresses in the X-ray method using the $\sin^2\psi$ method was derived in the following formula:

$$\sigma_\Theta = \frac{E}{1+\upsilon} \cdot m \tag{3}$$

where m indicates the angular coefficient of a straight line approximating a set of points with the coordinates ($\sin^2\psi$, 2Θ) obtained from the measurements using the X-ray diffractometer.

An example of a test protocol [1] of the measurement of residual stresses using the X-ray diffractometer with an approximation line in coordinates ($\sin^2\psi$, 2Θ) is shown in Fig. 2.

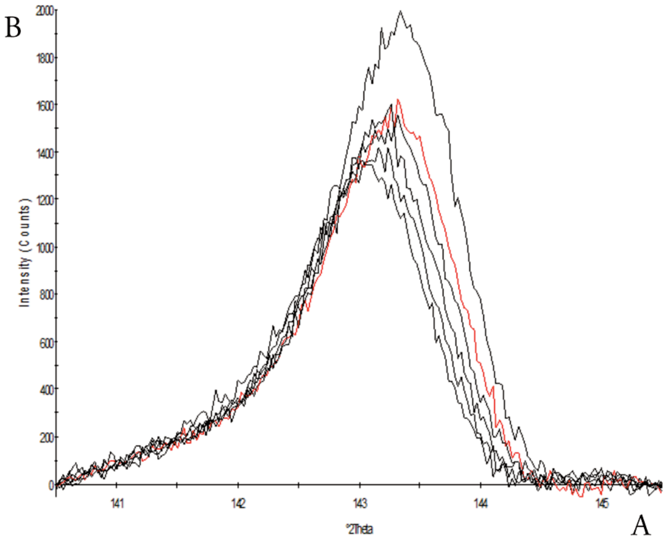


Figure 1. Profiles of diffraction lines obtained at different angles of incidence ψ of the beam of X-ray waves: (A) horizontal axis – angle 2Θ; and (B) vertical axis – intensity of X-ray diffraction.

The printout (Fig. 2) shows:

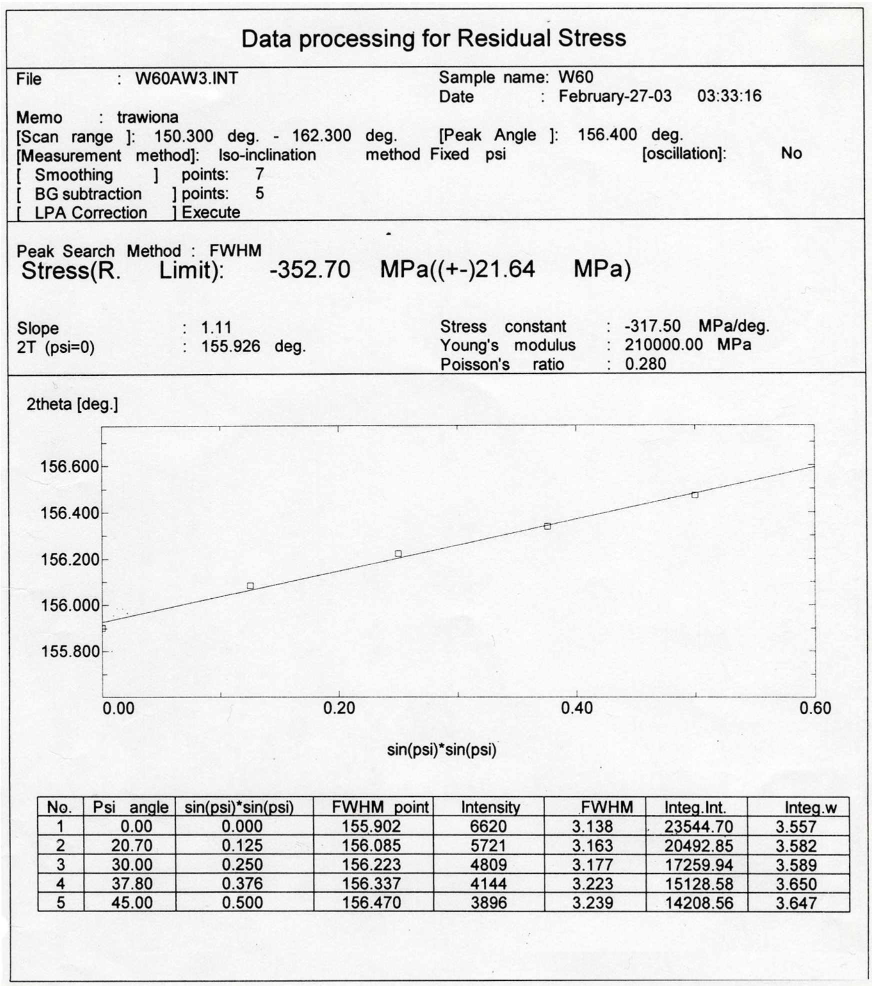
• the value of residual stresses σ_Θ = –35,270 Mpa for the material with the following properties:

· E = 210,000 MPa – Young's modulus, and

· ν = 0.280 – Poisson's ratio;

as well as,

- the approximation line in the coordinates: ($\sin^2\psi$, 2Θ), on which the slope factor m is read (Eq. (3)).



Data processing for Residual Stress

File : W60AW3.INT Sample name: W60
Date : February-27-03 03:33:16

Memo : trawiona
[Scan range]: 150.300 deg. - 162.300 deg. [Peak Angle]: 156.400 deg.
[Measurement method]: Iso-inclination method Fixed psi [oscillation]: No
[Smoothing] points: 7
[BG subtraction] points: 5
[LPA Correction] Execute

Peak Search Method : FWHM
Stress(R. Limit): -352.70 MPa((+-)21.64 MPa)

Slope : 1.11 Stress constant : -317.50 MPa/deg.
2T (psi=0) : 155.926 deg. Young's modulus : 210000.00 MPa
Poisson's ratio : 0.280

No.	Psi angle	sin(psi)*sin(psi)	FWHM point	Intensity	FWHM	Integ.Int.	Integ.w
1	0.00	0.000	155.902	6620	3.138	23544.70	3.557
2	20.70	0.125	156.085	5721	3.163	20492.85	3.582
3	30.00	0.250	156.223	4809	3.177	17259.94	3.589
4	37.80	0.376	156.337	4144	3.223	15128.58	3.650
5	45.00	0.500	156.470	3896	3.239	14208.56	3.647

Figure 2. Report on the measurement of residual stresses using the X-ray method, using the PSWF-3M device from the Rigaku Company: Young's modulus E = 210,000.0 MPa and Poisson's ratio ν = 0.280.

2.2. Station for electrochemical removal of material layers

In order to obtain the results of measuring residual stresses in the surface layer as a function of the distance *d* mm from the shot peened surface, a station for removing material layers using the electrochemical method was developed [1], [4]. The adopted parameters of the electrochemical process allowed for the removal of a layer with a thickness of 0.04–0.06 mm in one etching cycle. Ten to twelve cycles of layer removal were performed. Measurements of residual stresses σ were carried out using the X-ray diffraction method on the successive obtained surfaces. The distance between the successive layers was determined by using as a basis an average of the measurements of sample thickness obtained following the etching cycle.

2.3. Research materials

The tests of the shot peening process were carried out on samples that were heat treated (hardened and tempered at different temperatures to obtain different values of HRC hardness) and subjected to the pneumatic shot peening process [1]. The samples were divided into six groups as a function of hardness (HRC):
(1) HRC samples ∈ <25, 30>, (2) HRC samples ∈ <30, 35>, (3) HRC samples ∈ <35, 40>, (4) HRC samples ∈ <40, 45>, (5) HRC samples ∈ <45, 50> and (6) HRC samples ∈ (<50).

The samples were subjected to pneumatic shot peening with the following parameters:

- four types of shot, marked with the numbers of the *N* set (1, 2, 3, 4):
  - 1 – SW170 cast steel shot, granulation 0.4 mm, hardness 470 HV,
  - 2 – SW330 cast steel shot, granulation 0.8 mm, hardness 470 HV,
  - 2 – StD-03 steel shot, granulation 0.4 mm, hardness 640 HV, and
  - 2 – Std-06 steel shot, granulation 0.6 mm, hardness 640 HV;
- constant air pressure $p = 0.45$ MPa,
- shot peening time $t = 120$ s,
- 100% shot peened surface coverage, and
- the sample was rotating.

The shot peening process [8] was performed using the PEEN-IMP device, a patented station (patent PL204718), shown in Fig. 3.

Figure 3. PEEN-IMP device for pneumatic peening (patent PL204718).

2.4. Test results

The test results are summarised in Table 1. A total of 128 experiments were carried out. The independent variables are:

- deposition depth of residual stresses $x_1 \in <0. \div 0.8>$,
- material hardness $x_2 \in <25 \div 50>$, and
- the type of shot used marked $x_3 \in <1, 2, 3, 4>$.

The dependent variable is the residual stress σ MPa.

The selected test measurements of stresses for the shot N = 1, 2, 3, 4 are summarised in Table 1.

Table 1. Measurements of stresses σ MPa as a function of distance d mm from the surface.

Lp	**Distance from the surface d mm**	**Hardness HRC**	**Steel shot N 1,2,3,4**	**Stresses σ MPa**
1	0.000	35	1	–506.37
2	0.079	35	1	–465.59
3	0.127	35	1	–390.06
4	0.194	35	1	–397.08
5	0.241	35	1	–244.17
6	0.299	35	1	–209.32
7	0.399	35	1	–232.61
8	0.456	35	1	–172.24
...				
25	0.000	30	2	–448.40
26	0.046	30	2	–540.25
27	0.106	30	2	–571.50
28	0.150	30	2	–547.69
29	0.210	30	2	–527.38
30	0.258	30	2	–514.13
31	0.315	30	2	–427.26
32	0.340	30	2	–354.94
33	0.396	30	2	–305.50
...				
70	0.000	45	3	–682.34
71	0.051	45	3	–602.13
72	0.111	45	3	–615.84
73	0.191	45	3	–552.10
74	0.206	45	3	–395.75
75	0.227	45	3	–259.79
76	0.340	45	3	–249.39
77	0.393	45	3	–293.09
78	0.419	45	3	–195.22
...				
120	0.000	50	4	–643.16
121	0.116	50	4	–737.91
122	0.166	50	4	–745.57
123	0.220	50	4	–509.45
124	0.284	50	4	–394.01
125	0.347	50	4	–432.17
126	0.401	50	4	–321.01
127	0.462	50	4	–254.92
128	0.565	50	4	–261.30

where 0.000 indicates the free surface of the sample.

The meddle in the stresses measured on the surface of the samples after heat treatment were:
- hardness in the range of 25–30 HRC, stresses – б = –22 MPa;
- hardness in the range of 35–40 HRC, stresses – б = –28 MPa; and
- hardness in the range of 45–50 HRC, stresses – б = –145 MPa.

The test results (d, HRC, N, σ) (Table 1) were entered into the REGSTEP.EXE stepwise multiple regression program. The program creates the σ MPa second-degree polynomial function of three independent variables (layer depth d, material hardness HRC and shot type N).

3. RESIDUAL STRESS FUNCTIONS OF THREE VARIABLES IN A MULTIPLE REGRESSION PROGRAM

The REGSTEP.EXE stepwise multiple regression program makes it possible to create many regression functions:
- linear,
- linear exponentials with the e base,
- second-degree non-linear, where the number of independent variables is one to four, and
- the listed functions may have variables written in natural or logarithm form.

The form of the regression function is related to the number of experiments entered into the REGSTEP.EXE program. For three independent variables with interactions, the minimum number of experiments entered into the program is 10 [9]. The second-degree regression function created by the program for three independent variables with interactions is as follows:

$$y = c_0 + c_1 \cdot x_1 + c_2 \cdot x_2 + c_3 \cdot x_3 + c_5 \cdot x_1 \cdot x_2 + c_6 \cdot x_1 \cdot x_3 + c_7 \cdot x_2 \cdot x_3 + \\ + c_8 \cdot x_1^2 + c_9 \cdot x_2^2 + c_{10} \cdot x_3^2 \quad (4)$$

where c_0, c_1, c_2, c_3, c_4, c_5, c_6, c_7, c_8, c_9 and c_{10} are coefficients calculated by the program.

The c_4 coefficient determines the y independent variable, has the value c_4 = 1 and is not printed by the program.

After entering the data (Table 1) into the REGSTEP.EXE program, the coefficients of the regression function (Table 2) and their statistical evaluation were obtained using the Student's t-test (T-VALUE). Regression coefficients are written in exponential format (E).

Table 2. Coefficients of the regression function calculated by the program for the results of measurements.

	Variable number	**Regression coefficient**	**Std. Error of reg. coeff.**	**Computed T-value**
(c_1)	1	–0.845537E+02	303.47275	–0.279
(c_7)	7	–0.865059E+01	1.82461	–4.741
(c_6)	6	0.259431E+02	52.86755	0.491
(c_2)	2	–0.109254E+03	26.07856	–4.189
(c_{10})	10	0.798438E+02	14.47331	5.517
(c_9)	9	0.160997E+01	0.35632	4.518

(c_3)	3	–0.114981E+03	60.96822	–1.886
(c_5)	5	0.138582e+02	7.15698	1.936
(c_8)	8	0.493962E+03	288.88644	1.710
(c_0)		0.168799E+04		

For example, in Table 3, the results of the last (ninth) step of the statistical evaluation of the obtained regression function are presented.

Table 3. Statistical evaluation of the obtained regression function using the statistical parameters R^2 (the square of the multiple correlation coefficient) and F (Snedecor's test).

STEP 9
VARIABLE ENTERED..... 8
(FORCED VARIABLE)
SUM OF SQUARES REDUCED IN THIS STEP.... 18743.844
PROPORTION REDUCED IN THIS STEP........ 0.006
CUMULATIVE SUM OF SQUARES REDUCED...... 2162765.250
CUMULATIVE PROPORTION REDUCED.......... 0.741 OF 2919265.000
FOR 9 VARIABLES ENTERED
MULTIPLE CORRELATION COEFFICIENT... 0.861
(ADJUSTED FOR D.F.)........... 0.851
SQUARE MULTIPLE CORRELATION COEFFICIENT ⊠ 0.741
F-VALUE FOR ANALYSIS OF VARIANCE... 37.483
STANDARD ERROR OF ESTIMATE......... 80.069
(ADJUSTED FOR D.F.)........... 82.716

The REGSTEP.EXE program is based on IBM subprograms [7]. The more important components'in Table 3 have the following equivalents:

- SQUARE MULTIPLE CORRELATION COEFFICIENT = 0.741 (R^2 = 0.741 – multiple correlation coefficient)
- F-VALUE FOR ANALYSIS OF VARIANCE... 37.483 (F Snedecor's test = 37.483).
- T-VALUE – Student's t-test for regression function coefficients marked: 1, 2, 3, 5, 6, 7, 8, 9, 10
- REGRESSION COEFFICIENT – coefficients of the regression function (1, 2, 3, 5, 6, 7, 8, 9, 10)

The regression function has the computational form:

$$\left.\begin{aligned} y = {} & 0.168799\text{E}+04+\text{-}0.845537\text{E}+02\cdot x_1+\text{-}0.109254\text{E}+03\cdot x_2+-0.114981\text{E}+03\cdot x_3+ \\ & 0.138582\text{e}+02\cdot x_1\cdot x_2+0.259431\text{E}+02\cdot x_1\cdot x_3+-0.865059\text{E}+01\cdot x_2\cdot x_3+ \\ & +0.493962\text{E}+03\cdot x_1^2+0.160997\text{E}+01\cdot x_2^2+0.798438\text{E}+02\cdot x_3^2 \end{aligned}\right\} \quad (5)$$

The functional form in Eq. (5) allows the calculation of the values of residual stresses in the factor space determined for the values of the variables:

$$\left.\begin{array}{l} x_1(depth \quad d \in <0.0-0.8> \text{ mm} \\ x_2(hardness \quad HRC) \in <25-50> \\ x_3(shot\ N) \in <1, 2, 3, 4> \end{array}\right\} \qquad (6)$$

4. PROGRAM FOR CALCULATING THE TABULAR DISTRIBUTION OF RESIDUAL STRESSES

The polynomial regression function in Eq. (5) makes it possible to calculate the value of residual stresses into the material σ for the assumed parameters of the factor space in Eq. (6) [5], [10], [11]. For practical purposes, the universal FUNVAL3.EXE program was developed, which, for the assumed values of the coefficients of the regression function and the values of three independent variables (x_1, x_2, x_3), calculates the value of the function in Eq. (5).

Table 4 presents the results of the calculations employed for ascertaining the tabular distribution of residual stresses as a function of every 0.10-mm change in the X_1 depth extending into the surface layer.

Table 4. Values of residual stresses σ as a function of changing the X_1 depth extending into the surface layer calculated by the FUNVAL3.EXE program.

Type of function - NATURAL -N-		
Values of Bi coefficients in the calculated function		
B0= 0.1688E+04, B1= –0.8455E+02, B2= –0.1093E+03,		
B3= –0.1150E+03		
B12= 0.1386E+02, B13= 0.2594E+02, B23= –0.8651E+01,		
B11= 0.4940E+03, B22= 0.1610E+01, B33= 0.7984E+02		
NUMBER OF POINTS N = 8		
Values of X_1, X_2, X_3 variables at set points		
X_1	X_2	X_3
0.000	35.0000	1.0000
0.1000	35.0000	1.0000
0.2000	35.0000	1.0000
0.3000	35.0000	1.0000
0.4000	35.0000	1.0000
0.5000	35.0000	1.0000
0.6000	35.0000	1.0000
0.7000	35.0000	1.0000
0.8000	35.0000	1.0000

Xi depth and Yi function values at set points		
No.	Xi	Yi
1	0.000	–501.1677
2	0.1000	–454.0123
3	0.2000	–396.5508
4	0.3000	–329.2101
5	0.4000	–251.9901
6	0.5000	–164.8909
7	0.6000	–67.9124
8	0.7000	38.9453
9	0.8000	155.6822

5. ANALYTICAL RECORD OF RESIDUAL STRESS DISTRIBUTION

The distribution of residual stresses shown in the tabular form (Table 4) is additionally presented in the analytical notation. The polynomial regression program REGPOLY.EXE developed on IBM subprograms was used to record the analytical tabular distribution of residual stresses (Table 4) [7]. The program for the tabular stress distribution generates successive polynomial regression functions of one variable, until the moment when the next added monomial does not improve the accuracy of the calculation of the value of the entire polynomial.

As a result of the calculations of the REGPOLY.EXE program, the second-degree polynomial describing the distribution of residual stresses in the surface layer was obtained. The second-degree function takes the following form:

$$y = \mathrm{a}_o + \mathrm{a}_1 \cdot x + a_2 \cdot x^2 \qquad (7)$$

The constants in the polynomial in Eq. (7) have the following values:

$a_0 = -0.50159 \times 10^3$, $a_1 = 0.42643 \times 10^3$ and $a_2 = 0.49396 \times 10^3$.

The notation of the residual stress distribution function is as follows:

$$\sigma = -0.50159 \cdot 10^3 + 0.42643 \cdot 10^3 \cdot x + 0.49396 \cdot 10^3 \cdot x^2 \quad \text{[MPa]} \qquad (8)$$

The EXCEL Microsoft Office 2000 program was used to obtain a graphic form of the tabular distribution of residual stresses (Table 4). The stress distribution diagram is shown in Fig 4.

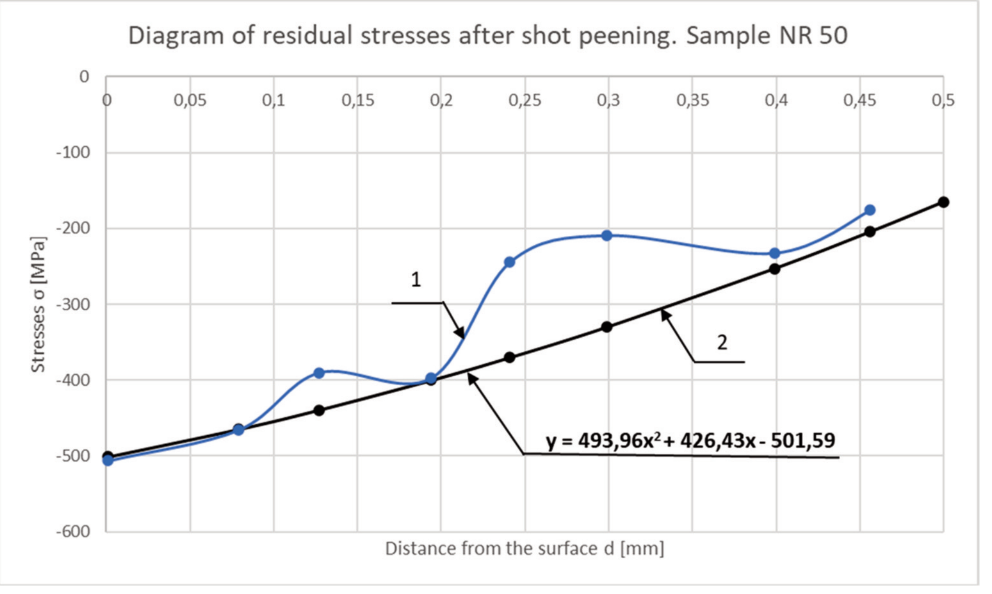


Figure 4: Graph of residual stress distribution in the sample after shot peening:

- sample NR50 (HRC, 35 MPa), shot N = 1,
- curve 1 – measured distribution of residual stresses, to a depth of 0.5 mm,
- curve 2 – distribution of residual stresses created by REGSTEP.EXE, represented by the equation: $y = 493,96x^2 + 426,43x \_ 501,59$.

Curve 1 (Fig. 4) presents the values of the residual stresses σ MPa measured by the $\sin^2 \Theta$ method using a diffractometer. Curve 2 represents the average value obtained by the REGSTEP.EXE stepwise multiple regression program. The presented curve 2 with the fixed parameters of the shot peening process allows an estimation of the distribution of residual stresses in the hardened surface layer.

6. SUMMARY AND CONCLUSIONS

A total of 128 experiments involving the measurement of residual stresses performed on the C45 steel samples after heat treatment and shot peening [8] were used to determine the form of the regression function of three independent variables (depth extending into the material, hardness of the C45 steel (HRC) and shot in the shot peening process). The REGSTEP.EXE stepwise multiple regression program was used. The test samples were shot peened on both sides in a device for pneumatic shot peening [1]. An X-ray diffractometer was used to measure the stresses. The successive layers of material 0.04–0.06 mm thick were removed from the samples by electrochemical etching. The FUNVAL3.EXE function value program was used to obtain a tabular distribution of residual stresses into the material. The REGPOLY.EXE polynomial regression program was used to record the analytical distribution of residual stresses into the material. The results of the obtained calculations satisfactorily reproduce distributions of stresses in the surface layer, which is confirmed by the following statistical parameters: R^2 (squared multiple correlation coefficient), Fisher's Snedecor test and Student's t-tests for regression function coefficients. The obtained regression function allows for the initial determination of shot peening parameters, and is recommended for obtaining the value of residual stresses in the surface layer.

The number of laborious experiments needed for determining the regression function of three independent variables can be reduced by applying the rules of the planned experiment [9].

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