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Pavel MACURA*, František FOJTÍK, Radim HALAMA**, Michal ŠOFER****

EXPERIMENTAL ANALYSIS OF ROLL BANDAGES FOR ROLLING MILLS

EXPERIMENTÁLNÍ ANALÝZA BANDÁŽÍ VÁLCŮ VÁLCOVACÍCH STOLIC

Abstract

The goal of the submitted paper is to introduce briefly results of experimental stress analysis which was focused on bandage of a back-up roll of rolling mill. Measurements have been carried out during technological process of manufacturing particular bandage roll as well as during running in the mill line. At first, residual stresses had been measured from previous heat-treating process and also after following press mounting on the roll. After press mounting a superposition, from the residual stresses and the stresses caused by press mounting, occurred. Stresses from the press mounting have been also numerically analyzed. Manufactured rolls were consecutively built into mill line and after particular time of running, residual stresses on the surface of bandage had been measured. For the purpose of comparison, we have also measured residual stresses on forged roll as well as on cracked bandage of broken out roll. Hole drilling method has been used for residual stress measurement.

Abstrakt

V příspěvku jsou stručně uvedeny výsledky experimentální analýzy napětí v bandáži opěrného válce válcovací stolice. Měření se prováděla jak v průběhu technologického procesu výroby bandážovaného válce, tak i při provozním nasazení ve válcovací trati. Nejdříve se měřila zbytková napětí po tepelném zpracování bandáže a pak po jejím nalisování na válec. Po nalisování došlo k superpozici zbytkových napětí a napětí od nalisování. Napětí od nalisování byla analyzována i početně. Vyrobené válce byly postupně zabudovány do válcovací tratě a po určité době provozu se měřily hodnoty zbytkových napětí na povrchu bandáže. Pro srovnání se měřilo zbytkové napětí i na kovaném válci. Rovněž se proměřila zbytková napětí v prasklé bandáži vyřazeného válce. K měření zbytkových napětí se použila odvrtávací metoda experimentální analýzy napětí.

1 INTRODUCTION

Rolls of rolling mills are often associated with high demands, which are often contradictious to each other. They must exhibit high strength and simultaneously high ductility in respect to fatigue loading. However, their surface must be very hard and resistant against contact fatigue. These requirements are satisfied by bandaged rolls, consisting of inner roll, made of ductile material, on

* prof. Ing. Pavel MACURA, DrSc., VŠB - Technical University of Ostrava, Faculty of Mechanical Engineering, Department of Mechanics of Materials, av. 17. listopadu 15, CZ-708 33 Ostrava-Poruba, (+420) 59 732 3598, pavel.macura@vsb.cz

** Ing. František FOJTÍK, Ph.D VŠB - Technical University of Ostrava, Faculty of Mechanical Engineering, Department of Mechanics of Materials, av. 17. listopadu 15, CZ-708 33 Ostrava-Poruba, (+420) 59 732 3292, frantisek.fojtik@vsb.cz

** doc. Ing. Radim HALAMA, Ph.D., VŠB - Technical University of Ostrava, Faculty of Mechanical Engineering, Department of Mechanics of Materials, av. 17. listopadu 15, CZ-708 33 Ostrava-Poruba, (+420) 59 732 1288, radim.halama@vsb.cz

** Ing. Michal ŠOFER, VŠB - Technical University of Ostrava, Faculty of Mechanical Engineering, Department of Mechanics of Materials, av. 17. listopadu 15, CZ-708 33 Ostrava-Poruba, (+420) 59 732 3290, michal.sofer.st@vsb.cz

which is pressed up abrasion resistant and appropriately heat-treated bandage. During manufacturing of this type of rolls, considerable residual stresses arise as a result of head-treating, as well as stresses from press mounting. Even though the stresses resulting from press mounting can be computed relatively easily, the computation of stresses due to heat-treating is non-trivial and, therefore the experimental measurements are very valuable. Experimental results referred to stress measurement on bandage after press mounting as well as after using bandaged rolls in mill line are also very valuable.

2 PROCEDURE AND RESULTS OF MEASUREMENTS

2.1 Method of measurement and evaluation

Semi-destructive hole-drilling method has been used for measurements of residual stresses. The method is based on measurement of released deformations in vicinity of drilled hole at inspected place. Released deformations were measured with rectangular strain gauge rosette of type *RY 61 – 1,5/120 S* made by *Hottinger*. Drilled holes in the centre of each rosette are 1.6 mm in diameter; the depth of all the drilled holes was 1.6 mm. A *RS200* device produced by *Vishay* was used for drilling; released deformations were measured with a static strain gauge apparatus *P 3500* with measured place switching option *SB 10* from the same producer. The hole can be drilled either continuously into full depth – in this case we evaluate average value of residual stresses through the depth, or stepwise, where we are able to evaluate the depth profile of residual stresses. Evaluating of residual stresses has been done according to mathematical relationships, published by Kirsch [1]. These relationships are the basis for methodology of evaluating residual stresses in articles [2], [3], [4] as well as for American standard ASTM – E837 – 08 [5]. Some examples of residual stresses´ measurement on metallurgical and engineering products are outlined in the article [6].

2.2 Bandage measuring after heat-treating

Measuring was carried out on standing bandage in four measuring places *R1, R2, R3,* and *R4*, whose location is displayed in Fig. 1

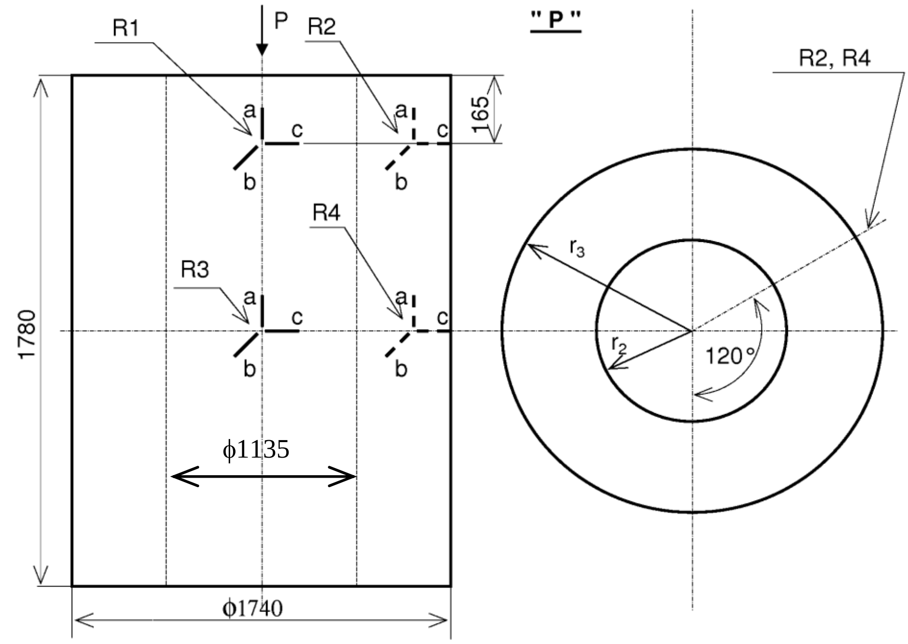


Fig. 1 Strain gauge rosette positions and strain gauges´ orientation.

Measurement results and evaluation after reaching the maximum depth are summarized in Tab. 1.

Values of measured released deformations from particular strain gauges of rosettes are mentioned first, following by evaluated principal stresses σ_1 and σ_2. Angle α is giving us the information about the direction of the algebraic larger principal stress σ_1 with regard to the strain gauge grid a direction. Stress $\sigma_a \equiv \sigma_o$ expresses the residual stress along the direction of bandage´s longitudinal axis. Residual stress $\sigma_c \equiv \sigma_t$ acts along the tangent to the bandage´s perimeter. In the last column are values of reduced residual stresses, calculated according to HMH hypothesis.

Tab. 1 Residual stresses on outer surface of bandage before press mounting.

Place	ε_a	ε_b	ε_c	σ_1	σ_2	α	$\sigma_a \equiv \sigma_o$	$\sigma_c \equiv \sigma_t$	σ_{red}
-	μS	μS	μS	MPa	MPa	°	MPa	MPa	MPa
R1	94	116	107	-141	-160	-34	-147	-154	-152
R2	80	194	242	-193	-290	-11	-197	-286	-256
R3	124	125	105	-164	-180	114	-177	-166	-172
R4	144	215	206	-234	-290	-26	-245	-280	-267

2.3 Stress calculation after press mounting

Stress calculation after press mounting can be done on the basis of theory of thick-walled pressed up vessels. The graphical (Fig. 2) and numerical stress solution for real interference, which is equal to $\Delta r_2 = 0.65mm$, according to the dimensional report can be done by following way:

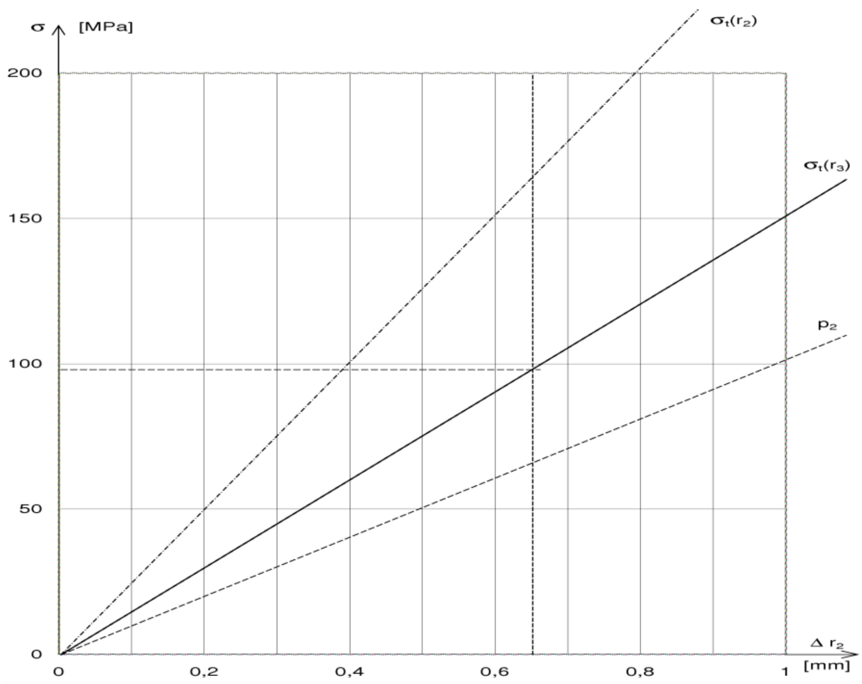


Fig. 2 Graphical dependency of stresses mentioned above in the bandage after press mounting and with particular interference Δr_2.

$$\sigma_t(r_3) = \frac{Er_2}{r_3^2}\Delta r_2 = \frac{2.10^5.567,5}{870^2}0,65 = 97,5MPa, \tag{1}$$

where $\sigma_t(r_3)$……. peripheral stress on bandage´s outer surface,

$$\sigma_t(r_2) = E\frac{r_3^2 + r_2^2}{2r_2r_3^2}\Delta r_2 = 251,2.0,65 = 163,3MPa, \tag{2}$$

where $\sigma_t(r_2)$……. peripheral stress on bandage´s inner surface, and

$$p_2 = E\frac{r_3^2 - r_2^2}{2r_2r_3^2}\Delta r_2 = 101,23.0,65 = 65,8MPa, \tag{3}$$

where p_2…….. compressive stress between bandage and roll.

2.4 Stress measurement after bandaging

After bandaging, the roll has been laid horizontally and the measurement of residual stresses had been realized close to the places, on which we have measured before bandaging. The measurement results are summarized in Tab. 2; the last measurement in place *N1* has been realized during stepwise drilling. Evaluated stress depth distribution under the surface is displayed by form of protocol in Fig. 3.

Tab. 2 Residual stresses on outer surface of bandage after press mounting

Place	ε_a	ε_b	ε_c	σ_1	σ_2	α	$\sigma_a \equiv \sigma_o$	$\sigma_c \equiv \sigma_t$	σ_{red}
-	μS	μS	μS	MPa	MPa	°	MPa	MPa	MPa
N1	137	64	6	-71	-144	86	-144	-71	-124
N2	163	132	122	-201	-226	76	-225	-202	-215
N3	145	160	-43	-24	-129	93	-128	-25	-118
N4	188	107	52	-142	-218	85	-218	-142	-192

2.5 Residual stresses in running rolls

Further measurement has been realized on roll with bandage after its twentieth mounting in rolling mill after rolling 702,000 tons of sheets (40,052 km). The roll has been re-grinded from diameter 1,738.82 mm onto 1,679.32 mm. After establishment, the roll has been even more re-grinded onto diameter of 1,675.57 mm. Fig. 4 displays locations and places, where the residual stresses were measured. The measurement was realized in plane, which included groove pin roll; measuring places *R3* and *R4* are located on the opposite side towards the places *R1* and *R2*.

Vyhodnocení měření zbytkových napětí

Měřicí místo : N1 - Bandáž

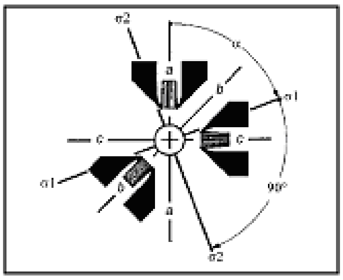
Průměr otvoru : 1,6 mm

Typ růžice : RY61 1,5/120S

Materiál : Bandážový

E : 2,10E+05

μ : 0,3



Z	Z/D	εa	εb	εc	σ1	σ2	α	σo	σt	σ red
mm		μS	μS	μS	MPa	MPa	°	MPa	MPa	MPa
0,254	0,050	37	31	19	-128,7	-202,8	99,2	-200,9	-130,6	177,7
0,508	0,100	80	45	17	-71,5	-181,5	86,8	-181,1	-71,8	158,3
0,762	0,149	110	59	14	-56,1	-165,5	88,2	-165,4	-56,2	145,8
1,016	0,199	124	64	15	-54,9	-152,9	87,1	-152,6	-55,2	134,1
1,27	0,249	136	66	1	-42,4	-147,9	88,9	-147,9	-42,5	131,9
1,524	0,299	137	64	6	-48,9	-144,6	86,7	-144,3	-49,2	127,4

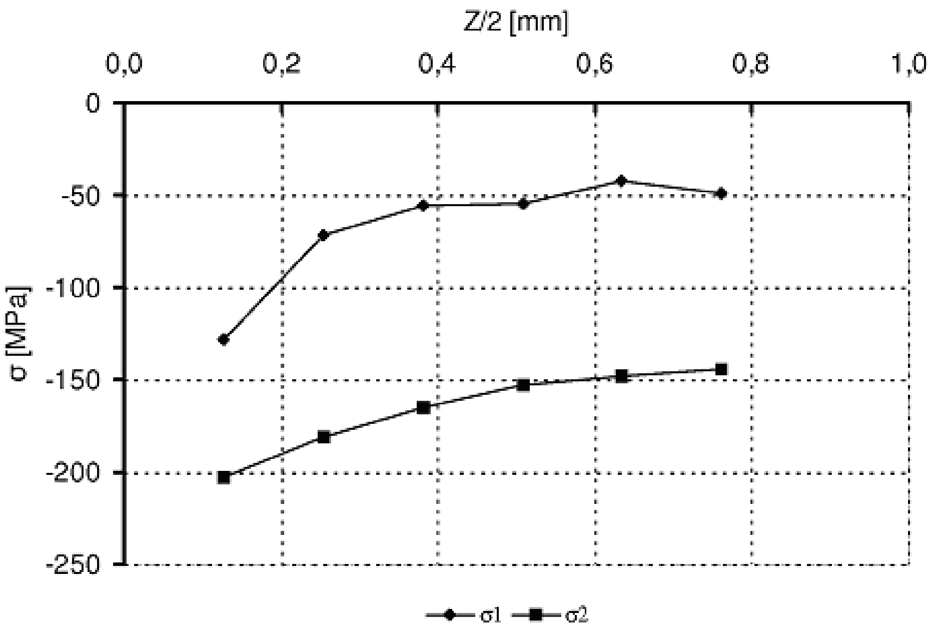


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Fig. 3 Resulting stresses below bandage´s outer surface after bandaging.

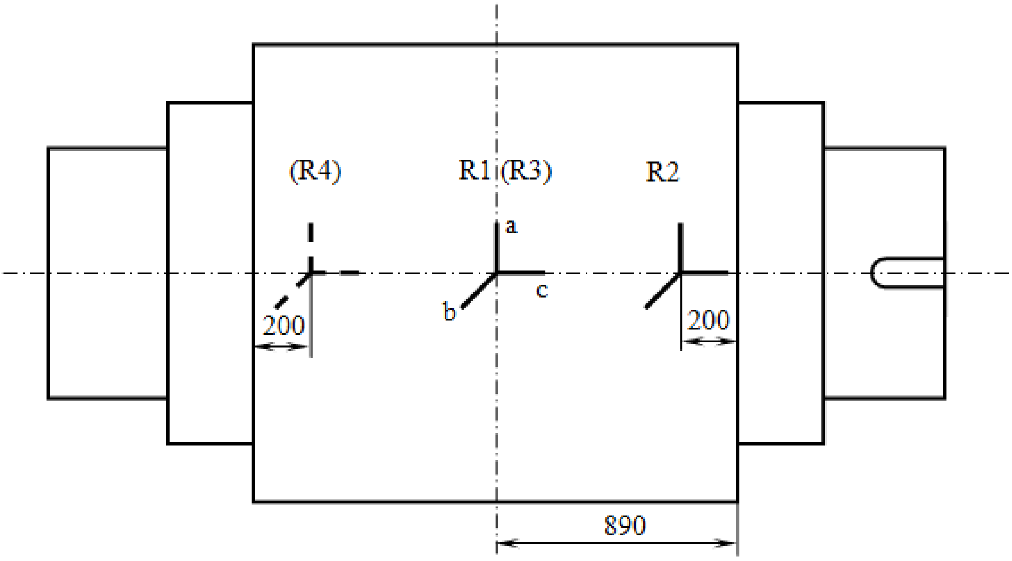
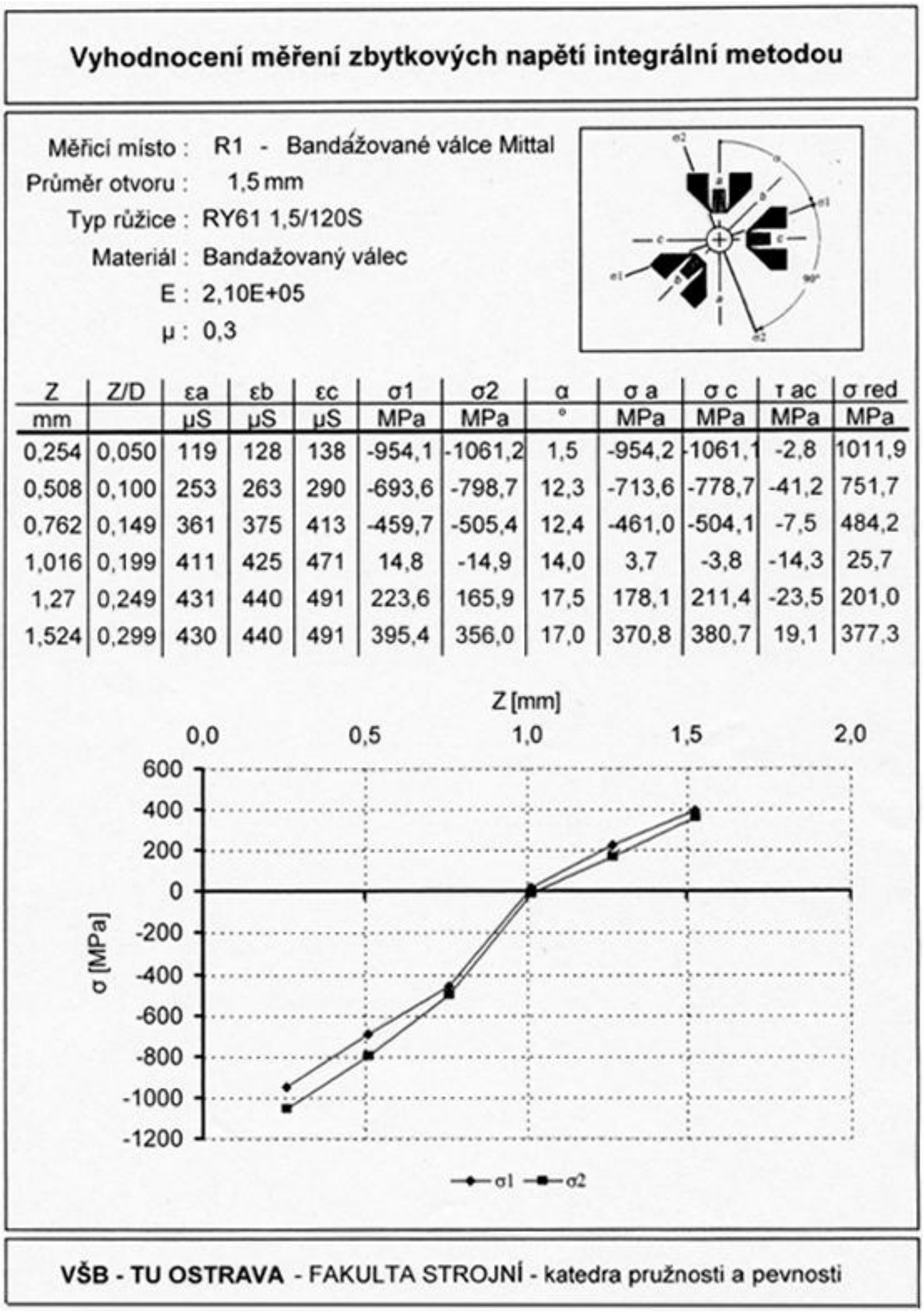


Fig. 4 Measuring places of residual stresses on supporting rolls.

Tab. 3 Evaluated residual stresses in supporting rolls.

Place	σ_1 [MPa]	σ_2 [MPa]	α [°]	σ_a [MPa]	σ_t [MPa]	σ_r [MPa]
R1	-763	-808	17	-767	-804	-787
R2	-742	-1088	-11	-754	-1076	-963
R3	168	83	23	155	95	146
R4	-790	-850	-18	-795	-844	-821
R5	-691	-817	-2	-692	-817	-762

Residual stresses can be affected by grinding before measurement itself; therefore we managed an additional measurement of residual stresses on another forged roll after reestablishment from rolling mill before any grinding. The measuring place (*R5*) is at distance of 340 mm from edge of working surface. Because drilling and measuring have been realized progressively in six steps, it is possible to evaluate the results either from final values of released deformations according to [2] or from progressively measured values of released deformations according to [4]. In both the cases the validity of Hook´s law is expected. Residual stresses can achieve yield limit for high values of contact stresses in contact region between working and back-up rolls. This fact is, by the way, proven in presented results. Results, evaluated according to [2] are in Tab 3; a protocol with results from progressive measurement and evaluation according to [4] is displayed in Fig. 5.



Vyhodnocení měření zbytkových napětí integrální metodou

Měřicí místo : R1 - Bandážované válce Mittal
Průměr otvoru : 1,5 mm
Typ růžice : RY61 1,5/120S
Materiál : Bandažovaný válec
E : 2,10E+05
μ : 0,3

Z	Z/D	εa	εb	εc	σ1	σ2	α	σ a	σ c	τ ac	σ red
mm		μS	μS	μS	MPa	MPa	°	MPa	MPa	MPa	MPa
0,254	0,050	119	128	138	-954,1	-1061,2	1,5	-954,2	-1061,1	-2,8	1011,9
0,508	0,100	253	263	290	-693,6	-798,7	12,3	-713,6	-778,7	-41,2	751,7
0,762	0,149	361	375	413	-459,7	-505,4	12,4	-461,0	-504,1	-7,5	484,2
1,016	0,199	411	425	471	14,8	-14,9	14,0	3,7	-3,8	-14,3	25,7
1,27	0,249	431	440	491	223,6	165,9	17,5	178,1	211,4	-23,5	201,0
1,524	0,299	430	440	491	395,4	356,0	17,0	370,8	380,7	19,1	377,3

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Fig. 5 Resulting stresses below outer surface of bandage after working conditions.

2.6 Residual stress measurement on cracked bandage

In the case of the second bandaged roll, which was employed, the bandage disrupted in consequence of grinding relatively large subsurface bubble before his deployment into service. In cracked and halved bandage the stresses caused by press mounting relaxed in contrast to residual stresses induced by high contact stresses between bandage and working roll. Between bandage and core of the roll, the residual stresses are still present. Location of measured places and their marking are displayed in Fig. 6.

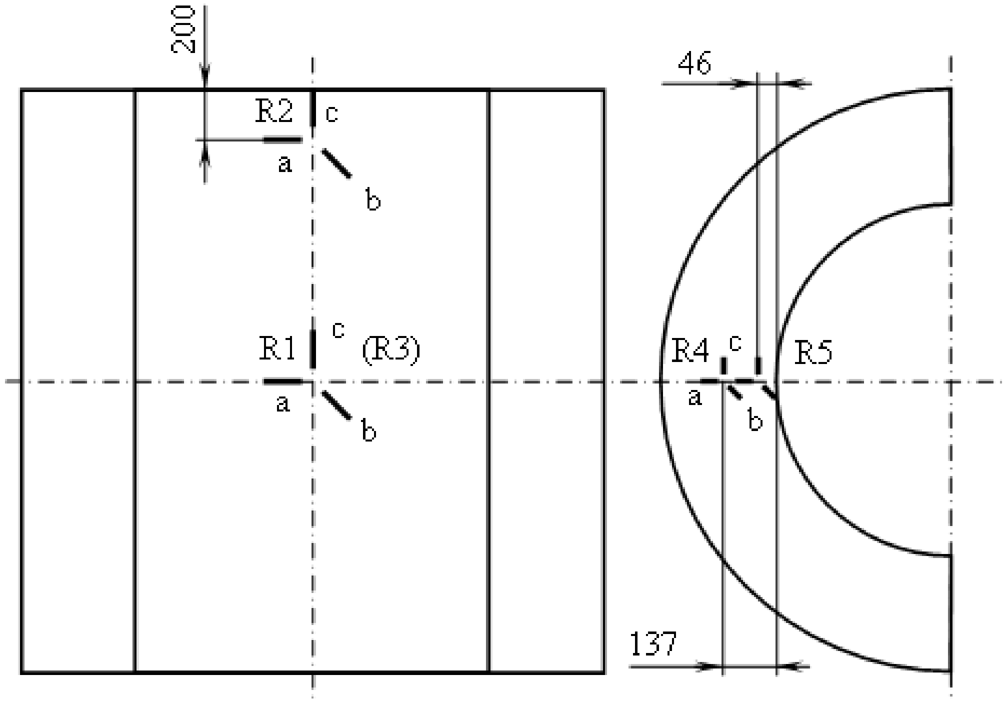


Fig. 6 Location of places of measurement on cracked bandage.

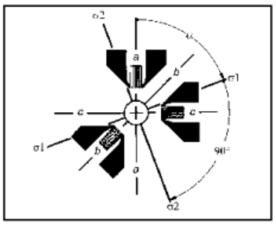
The measurement has been realized during progressive drilling of the hole. Evaluated residual stresses, which were calculated from released deformations related to the final depth, are listed in Tab. 4. Protocol with results from progressive measurement in place *R1* is displayed in Fig. 7.

Tab. 4 Residual stresses in cracked bandage.

Place	ε_a	ε_b	ε_c	σ_1	σ_2	α	$\sigma_a \equiv \sigma_o$	$\sigma_c \equiv \sigma_t$	σ_{red}
-	μS	μS	μS	MPa	MPa	°	MPa	MPa	MPa
R1	44	102	117	-111	-154	-15	-115	-160	-145
R2	128	91	185	-223	-311	33	-249	-285	-278
R3	398	191	-8	-207	-458	89	-458	-207	-398
R4	166	108	46	-144	-218	91	-218	-144	-192
R5	-3	51	25	8	-45	-35	-10	-27	-49

Vyhodnocení měření zbytkových napětí integrální metodou

Měřicí místo : R1 - Prasklá bandáž Mittal
Průměr otvoru : 1,5 mm
Typ růžice : RY61 1,5/120S
Materiál : bandážový
E : 2,10E+05
μ : 0,3



Z	Z/D	εa	εb	εc	σ1	σ2	α	σ a	σ c	τ ac	σ red
mm		μS	μS	μS	MPa	MPa	°	MPa	MPa	MPa	MPa
0,254	0,050	28	44	50	-237,8	-373,9	-12,2	-243,9	-367,8	28,2	327,7
0,508	0,100	40	75	83	-13,4	-119,5	-16,1	-28,4	-104,5	36,9	113,4
0,782	0,153	50	91	102	-15,5	-30,6	-15,0	-21,0	-25,2	-7,2	26,5
1,016	0,199	53	100	115	21,7	-4,2	-13,7	21,2	-3,8	-3,3	24,1
1,27	0,249	50	102	118	84,1	68,9	-14,0	79,8	73,2	6,8	77,6
1,524	0,299	44	102	117	132,7	88,3	-15,3	116,7	104,3	21,3	117,0

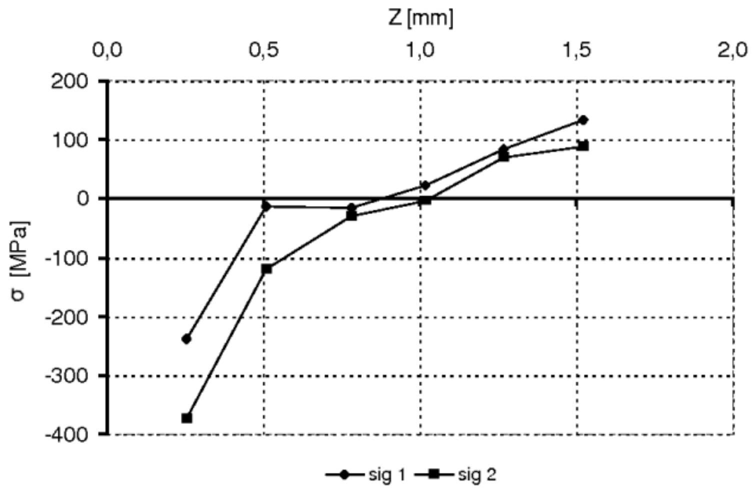


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Fig. 7 Resulting stresses below outer surface of bandage after working conditions.

3 CONCLUSIONS

Although the number of measured places was relatively small due to economic reasons, it is possible to deduce specific interesting conclusions.

1) Even though the bandage is rotationally symmetric, the distribution of residual stresses after heat-treatment isn´t uniform, see table 1. In the vertical cross section between the places *R1* - *R3* the peripheral residual stresses σ_t reach values about 160 MPa, while in cross section between the places *R2* – *R4* they reach values about 280 MPa. The stresses are in both cases compressive.

2) The change of peripheral stress on the outer bandage´s perimeter should be, according to theoretical calculations, equal to 97.5 Mpa; real measured variations of stress in peripheral as well as

axial direction are stated in Tab. 5. The change of peripheral stress near the edge of bandage is more than 80 MPa. This is caused by particular shape of inner roll, which isn´t cylindrical but specially formed with aim to reach the smallest change of axial stress after press mounting. The change of axial stress is, according to Tab. 5, very small.

Tab. 5 Differences of axial and peripheral stresses in bandage after press mounting

Place	*R1*	*R2*	*R3*	*R4*
$\Delta\ \sigma_{o1}$ [MPa]	3	14	49	27
$\Delta\ \sigma_{t1}$ [MPa]	83	84	141	138

3) The principal stresses on the surface remain compressive after bandaging.

4) High contact stresses between working and back-up rolls, which are present during rolling, are apparently caused by high compressive residual stresses, which can in outer surface layers reach the yield limit of bandage´s material; this fact is evident from Tab. 3 and Fig. 5.

5) High gradients of residual stresses are present below bandage´s surface. In particular depth, compressive residual stresses are changing to tensile values, see Fig. 5.

6) The distribution of residual stresses along outer bandage´s perimeter can be significantly irregular, see results of measurement in place *R3* (Tab. 3).

7) Roll´s surface grinding after his employment in rolling mill isn´t affected by relatively high values of compressive residual stresses. See Tab. 3 – measuring place *R5* which contains a comparison of measurements between bandaged and forged roll.

8) The residual stresses are present even in cracked bandage and in particular depth, they are changing to tensile values, see Fig. 6.

The results of measurements are valuable benefits for engineers and manufacturers of bandaged rolls; they also allow us to compare them with theoretical solutions related to this problem.

Acknowledgements

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