UDK 621.77.014.2:621.78
Professional article/Strokovni članek

ISSN 1580-2949
MTAEC9, 48(6)983(2014)

A MODIFIED HEAT TREATMENT TO IMPROVE THE PROPERTIES OF DOUBLE-LAYER CAST ROLLS

MODIFICIRANA TOPLOTNA OBDELAVA ZA IZBOLJŠANJE LASTNOSTI DVOPLASTNIH VALJEV ZA VROČE VALJANJE

Marko Sedlaček[1], Bojan Podgornik[1], Slobodan Milanović[2]
[1]Institute of Metals and Technology, Lepi pot 11, 1000 Ljubljana, Slovenia
[2]VALJI group, d. o. o., Slovenia
marko.sedlacek@imt.si

Prejem rokopisa – received: 2014-01-24; sprejem za objavo – accepted for publication: 2014-09-24

In practice, the wear resistance, lifetime and capability of components and tools to resist loading greatly depend on the residual stress field in the material. This is especially true for hot-rolling applications, which require rolls with hard, heat- and wear-resistant surfaces, a tough core and the proper compressive residual stress level to resist Hertzian cyclic loading. If the casting, heat treatment, cooling process and surface machining and grinding are not done properly, a very high and uneven tensile residual stress field may occur, causing a drop in the wear resistance, cracking or even fracture of the roll.
The aim of this investigation was to determine the impact of various heat treatments of double-layer cast rolls on the values and distribution of residual stresses in the rolls made from semi-high-speed steel with a high content of chromium (SHSS HCS). Using the hole-drilling method, the residual stress depth distribution was measured circumferentially and transversely on the double-layer cast roll surface after casting, heat treatment, turning and grinding. Furthermore, using different turning and grinding parameters (speed, feed), and heat-treatment parameters (temperature, time), the influence of these parameters on the residual stress level and the wear resistance of roll's outer layer were determined.

Keywords: residual stress, hot rolling, wear, machining, heat treatment

V praksi je odpornost proti obrabi, trajnostna doba in sposobnost komponent ter orodij, da se uprejo obremenitvi, močno odvisna od zaostalih napetosti v materialu. To še posebej velja za aplikacijo vročega valjanja, kjer se od valjev zahteva, da imajo trdo, toplotno in obrabno odporno površino, žilavo jedro in ustrezen nivo tlačnih zaostalih napetosti, ki so se sposobne upreti Hertzovem cikličnem utrujanju. Če so postopki litja, toplotne obdelave, proces ohlajanja, površinske obdelave in brušenja opravljeni nepravilno, lahko to privede do zelo visokih in neenakomernih nateznih zaostalih napetosti, kar povzroči padec odpornosti proti obrabi, razpoke ali celo lom valja.
Cilj raziskave je bil ugotoviti vpliv različnih toplotnih obdelav dvoslojno litih valjev na vrednosti in porazdelitve zaostalih napetosti v valjih, izdelanih iz hitroreznega jekla z visoko vsebnostjo kroma (SHSS HCS). Z uporabo metode vrtanja luknjice je bila izmerjena porazdelitev zaostalih napetosti z globino. Meritve so bile opravljene po obodu in prečno na površini dvoslojno litega valja po ulivanju, toplotnih obdelavah, struženju in brušenju. Poleg tega so bili z uporabo različnih parametrov struženja in brušenja (hitrost, pomik) ter parametrov toplotne obdelave (temperatura, čas) ugotovljeni vplivi teh parametrov na porazdelitev zaostalih napetosti in odpornost zunanje plasti valjev proti obrabi.

Ključne besede: zaostale napetosti, vroče valjanje, obraba, obdelava, toplotna obdelava

1 INTRODUCTION

With a heat treatment we alter the physical and, sometimes, the chemical properties of materials. These changes also result in a changed distribution of the residual stresses. In principle, residual stresses occur through changes in the volume of materials or constructions that are caused by thermal expansion, plastic deformation and/or phase transitions in the materials and technical systems. What is decisive for the appearance of residual stresses is that these sequential and/or local volume changes vary and volume changes of again varying magnitude are created in individual parts of the specimen.[1] Therefore, residual stresses arise in engineering components as part of their manufacturing by processes such as casting, turning, forming, rolling, welding or quenching operations.[2] Residual stresses are also introduced deliberately as part of surface-treatment procedures, such as shot-penning, cold expansion or nitriding, to produce surface compression.[3] A precise knowledge of the level of residual stresses that exist in engineering components is necessary in analysis and quality control as well as for an accurate prediction of the component's lifetime.[4–6] For example, the presence of compressive stresses is beneficial to a certain stress level, while tensile stresses can enhance the potential for failure in engineering components.[7] Specifically, in components operating at high temperatures, i.e., hot-rolling,[8] these stresses can increase the probability of creep failure.[9]

In order to achieve the requirements in terms of wear and temperature resistance, toughness and hardness rolls for hot-rolling are usually made as a double-layer construction by casting in two stages, first by centrifugal casting of an outer layer from a harder heat- and wear-resistant material, followed by conventional casting of a more ductile core material. During cooling, the core and surface layer cool down differently, causing a high tensile residual stress to appear in the roll material. If the heat-treatment and cooling process are not done properly, a very high and uneven tensile residual stress field may occur, causing cracking or fracture of the roll even before its use.[10,11] On the other hand, if the compressive residual stress is too low, the roll will not reach the expected lifetime in operation.[12] Another step in the roll's production, which also affects the level of residual stress, is machining and grinding of the roll's surface. And again, improper machining or grinding parameters (i.e., speed, feed, etc.), will cause an uncontrolled change in the residual stress,[13] which can also lead to surface failure or a drop in the surface wear resistance.

The aim of this investigation was to determine the impact of various heat treatments of double-layer cast rolls on the values and the distribution of residual stresses and wear resistance for the rolls made from semi-high-speed-steel with a high content of chromium (SHSS HCS) double-layer cast rolls. Using the hole-drilling method[13], the residual stress depth distribution was measured circumferentially and transversely on the roll surface after casting, heat treatment, turning and grinding. Furthermore, using different turning and grinding parameters (speed, feed), and heat-treatment parameters (temperature, time), the influence of these parameters on the residual stress level and the surface wear resistance were determined.

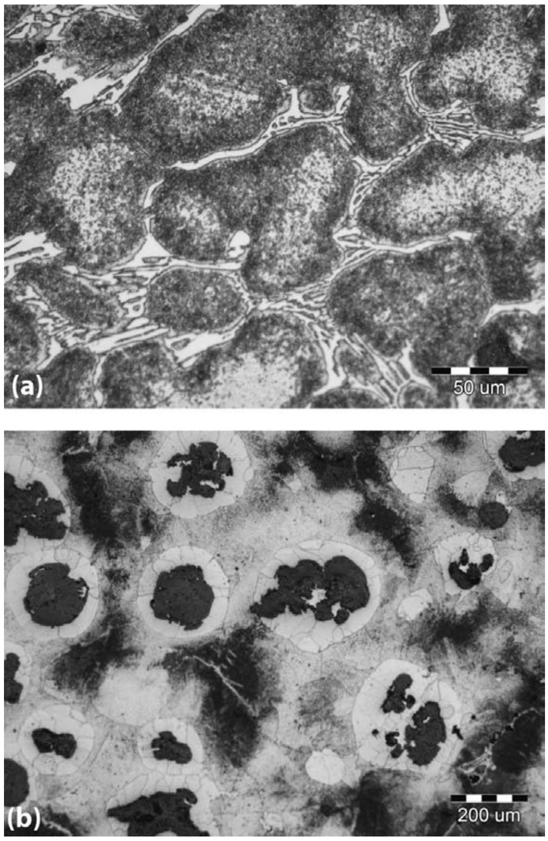

Figure 1: Microstructure of test rolls after casting: a) wear-resistant outer layer and b) core material
Slika 1: Mikrostruktura preizkusnega valja po litju: a) obrabno odporni zunanji plašč in b) jedro valja

2 EXPERIMENTAL

2.1 Test Material

The test specimens included in this investigation were double-layer hot strip mills (≈ 1030 mm × 4500 mm), with an outer wear-resistant layer made from cast steel with a high Cr content and core made from nodular cast iron. Because different micro-alloying elements can have an influence on the mechanical properties[14] the chemical composition was kept the same during this investigation. The chemical composition and microstructure after casting are shown in **Table 1** and **Figure 1**, respectively.

After casting, the test rolls were coarse ground, which removed the oxide layer and the casting that remained from the working surface and then heat treated in order to refine the surface layer's microstructure, and to obtain the proper surface hardness and residual stress distribution. The heat treatment consisted of hardening and multiple tempering, with three different tempering procedures included in this investigation, as shown in **Figure 2**. During the classical heat-treatment procedure the hardening from 970 °C is followed by three tempering stages at about 500 °C. In the modified heat treatment Mod1, aimed at reducing the roll's heat-treatment time, the tempering was reduced to just two stages (**Figure 2**). Finally, in heat treatment Mod2, used to investigate the effect of the hardening temperature on the

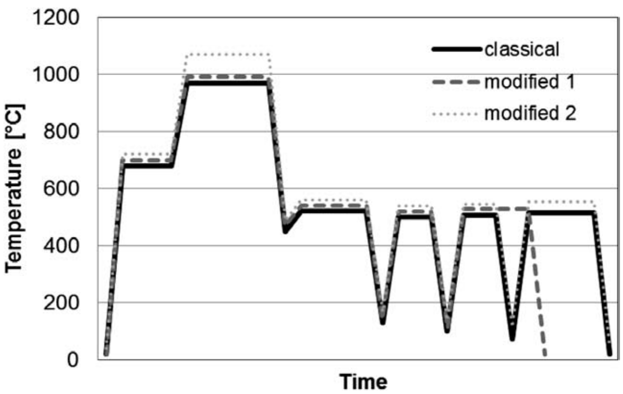

Figure 2: Heat-treatment procedures used in the investigation
Slika 2: Diagram poteka toplotnih obdelav

Table 1: Test rolls chemical composition (*x*/%) and hardness after casting
Tabela 1: Kemijska sestava (*x*/%) in trdota preizkusnega valja po litju

	C	Si	Mn	Cr	Ni	Mo	V	Hardness
Core	2.97	2.52	0.39	0.08	0.10	0.01	0.02	50 HRc
Outer layer	1.74	0.70	0.79	11.79	1.86	0.11	0.22	55 HRc

x – amount fraction/množinski delež

residual stress field, the hardening temperature was increased to 1070 °C and followed by a standard three-stage tempering procedure (**Figure 2**).

Finally, the working surface of the rolls was machined to the final dimension and surface roughness using turning and fine-grinding operations. Different turning parameters, including rotation speed and feed, were used in this phase in order to investigate their effect on the residual stress distribution.

2.2 FEM modelling to determine the values and the distribution of the stresses in the rolls

Finite-element modelling, using Code Z-Set/ZéBuLoN[15], with a 2D finite-element model, was used to determine the values and the distribution of stresses in the operating rolls when loaded.

The finite-element computation assumes plane-strain conditions. This assumption is made in order to reduce the computational time. The mesh contains 16423 elements distributed as follows: the area beneath the contact is meshed using rectangular four-node elements, with a decreasing element size towards the vicinity of the contact region. The rest of the plate is discretized with a coarser mesh using triangular elements.

Friction at the contact interface is modelled using Coulomb friction with a coefficient of friction of 0.1. This is a typical value for a lubricated metal-to-metal contact in boundary lubrication. This approach is valid for a dry contact and for sliding surfaces separated by a very thin film of lubricant.

The boundary conditions for simulating reciprocating sliding were applied in two steps. Firstly, the cylinder is displaced in the vertical direction until a penetration depth of 5 μm was reached. This position was kept while an oscillatory stroke of 1.0 mm is applied to the flat. The top of the cylinder was constrained in the horizontal direction and the bottom of the flat in the vertical direction in order to avoid rigid body motion.

The material behaviour of the cylinder and the flat is assumed to obey a viscoplatic material law, as thoroughly described in,[16] in the framework of small deformations. The model accounts for isotropic and kinematic hardening. The material parameters were fitted in order to represent the viscoplastic behaviour of the used material. The selected material parameters are suitable for describing cyclic plasticity, but ratcheting is not taken into account.

The input data for a static analysis of the system are represented in **Table 2** with the nominal dimensions of

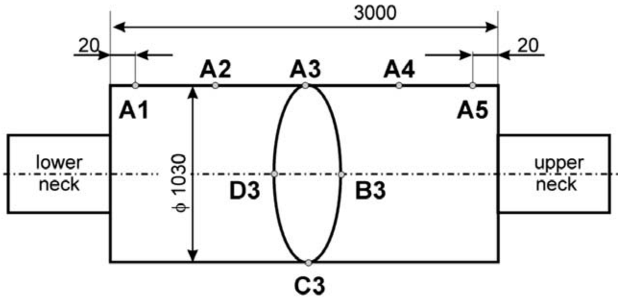

Figure 3: Location of the residual stress measuring points on the test roll surface
Slika 3: Mesta meritev zaostalih napetosti na površini valja

the cylinder and modulus $2.12 \cdot 10^5$ MPa and a plate with modulus $1 \cdot 10^5$ MPa.

For a realistic view of the stress distribution of the rolls for hot rolling, a system of sheet metal, working roller and supporting roller in the space was used.

2.3 Residual stress measurement

The residual stress values and the distribution in the roll's surface after different phases of the roll production were measured on a cleaned metallic surface using a HBM MTS3000 hole-drilling apparatus, with measuring points positioned circumferentially and longitudinally on the roll's surface, as shown in **Figure 3**. The hole-drilling method, being a semi-destructive method, is based on a measurement of the changes in the surface strain caused by stress relief when machining a shallow hole (≈ 1.8 mm × 0.5 mm) in the surface. The removal of the stressed material will result in the surrounding material needing to readjust its stress state to attain equilibrium, which reflects in the strain relief. A specially designed three-element strain-gauge rosette then measures the associated partial strain relief, which is used to calculate the residual stress field. The method is standardized and described in the ASTM E 837 standard.[17]

2.4 Tribological Testing

The tribological investigation, including the coefficient of friction and the wear rate, was focused on the wear-resistant surface layer of the test rolls, with the tests being performed on disc samples (≈ 20 mm × 8 mm) taken from the residual stress measurement positions (**Figure 3**). The disc samples were taken after the heat treatment of the test rolls, from three different depths: surface (0), 10 mm from the surface (10), and 20 mm from the surface (20), in order to determine the surface layer wear resistance as it becomes worn down or re-

Table 2: Load state of investigated rollers for hot steel rolling
Tabela 2: Obremenitveno stanje preiskovanega valja za vroče valjanje

Motor power (MW)	Rolling speed (m/min)	Load (MN)	Temp. (°C)	Diameter and roller length (mm)	Estimated production (t)	Sheet thickness (mm)
9.0	100	17.7–24.5	1100–1200	1032 × 1676	8000–12000	160–250

moved through the regrinding process. All the tests were performed under dry reciprocating sliding, with a hardened bearing steel ball (100Cr6; 62 HRc) loaded against the investigated material. The normal load was set to 33 N (p_H = 1.5 GPa) and the sliding speed to 0.1 m/s (s = 1 mm, f = 50 Hz). The first set of experiments was performed under room conditions (T = (20 ± 2) °C) and the second set at an elevated temperature of 80 °C. All the test samples were cleaned in ethanol and dried in air before the test, with the standard hardened 100Cr6 steel (62 HRc) used as a reference material.

3 RESULTS AND DISCUSSION

3.1 Residual Stress

3.1.1 FEM modelling

Taking into account the actual rate of deformation of the sheet metal, the yield strength and the modulus of elasticity of the sheet metal, the supporting roller and the working roller, the FEM simulation of the spatial system showed that the maximum residual stress always occurs on the surface, the wear-resistant layer of the working cylinder (**Figure 4**). At the start of the rolling, when the temperature of the cartridge is high and the degree of deformation low, the maximum residual stress values of 450 MPa occur at a depth of ≈ 35 mm. With the cooling of the cartridge, increasing the degree of deformation and hardening of the transformed material, its strength increases. By increasing the strength of the material from 300 MPa to 500 MPa, the tension in the surface layer of the cylinder increases to 700–800 MPa, the maximum tensions are moved towards the surface to a depth of ≈ 20 mm. In the final stage of rolling, when the strength of the rolled material increases over 700 MPa, the maximum strength of 920 MPa occurs on the surface of the cylinder.

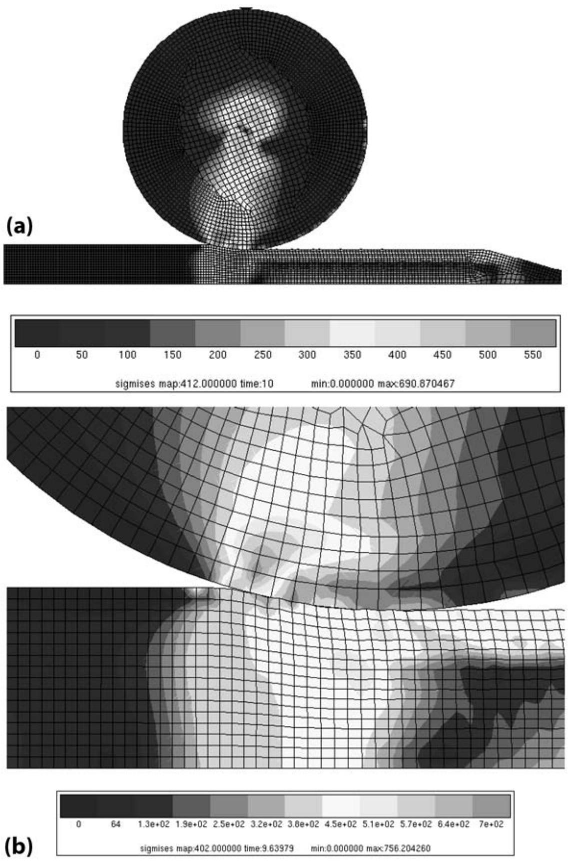

Figure 4: Stress field during sheet-metal hot rolling
Slika 4: Napetostno polje pri vročem valjanju pločevine

3.1.2 Casting

After casting, the test roll's surface is in the tensile stress state, with residual stresses being in the range of 500 MPa and a Vickers hardness of 635 HV_{10}. However, only a top layer of less than 100 μm shows a tensile residual stress, while the rest is in the compressive residual stress state, as shown in **Figure 5**. Not taking into account the very top layer residual stresses are compressive in the range of 350 MPa close to the roll's lower neck, which is positioned at the bottom of the casting pit during the casting. Towards the roll's upper neck the residual stress drops, reaching a value of about 175 MPa at the position 5, as shown in **Figure 6a**. The drop in the residual stress towards the upper neck is mostly due to the increased thickness of the outer layer, caused by the casting process of the core material. Circumferentially, the residual stress is higher in positions A and B, which were exposed to a faster cooling rate due to the absence of nearby rolls in the casting pit. However, the difference in the residual stress is in the range of 50 MPa (**Figure 6b**).

3.1.3 Coarse Grinding

Through coarse grinding the surface layers, including oxides, sand and the remains of the casting, are removed from the roll's working surface. However, the conditions of coarse grinding have a very large influence on the residual stress field, left in the surface layer after the grinding, as shown in **Figure 7**. In the case of dry grinding, the whole roll's surface is left with a very high tensile residual stress (400 MPa to 1000 MPa), which

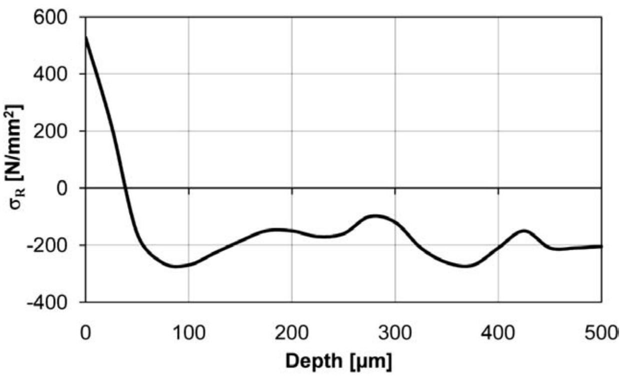

Figure 5: Residual stress depth distribution after casting (position A3)
Slika 5: Porazdelitev glavnih zaostalih napetosti po globini valja (mesto A3)

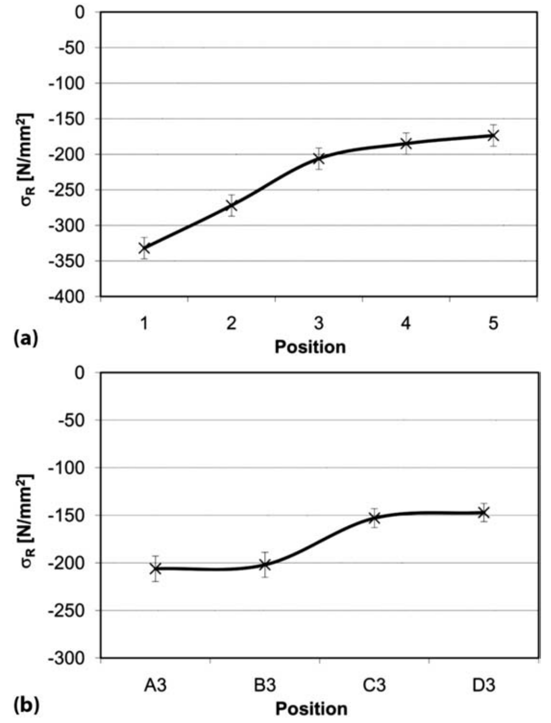

Figure 6: Residual stress level in the roll surface after casting: a) longitudinal and b) circumferential distributions

Slika 6: Vrednost zaostalih napetosti na površini valja: a) vzdolž valja in b) po obodu valja po fazi ulivanja

extends to a depth of about 1 mm. The use of water cooling results in a reduced tensile residual stress and a faster drop in stresses by depth (**Figure 7**). However, if the grinding feed is too high (100 mm/r; Water 1) the residual stress remains tensile over a depth of 500 μm. Only by reducing the grinding feed to an appropriate value (< 50 mm/r; Water 2) is the highly stressed surface layer of the material thinner than 300 μm, as shown in **Figure 7**. A high tensile residual stress extended over a great depth needs to be avoided in order to prevent the roll's surface cracking, or even the fracture of the roll.

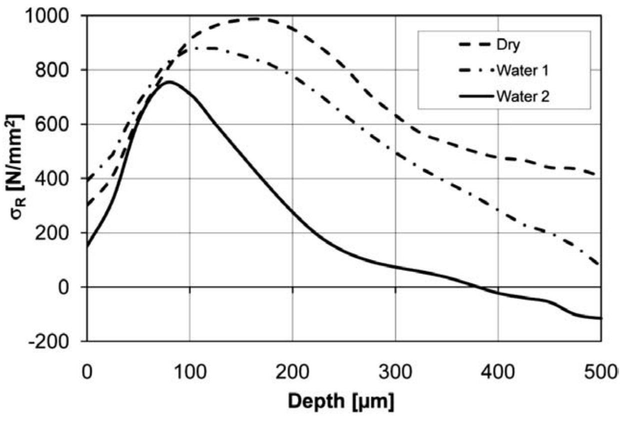

Figure 7: Influence of coarse grinding conditions on the residual stress depth distribution

Slika 7: Vpliv razmer pri brušenju na porazdelitev zaostalih napetosti po globini

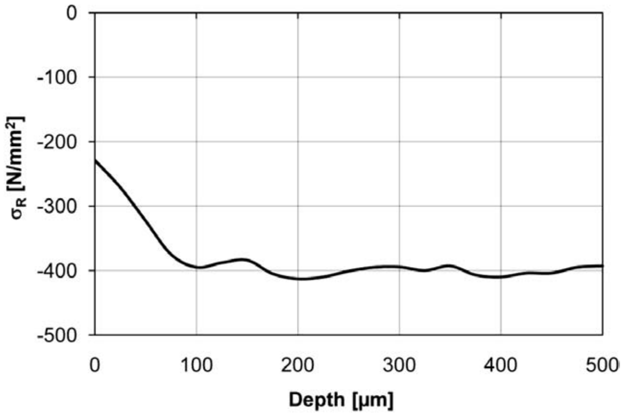

Figure 8: Residual stress depth distribution after classical heat treatment (position A3)

Slika 8: Porazdelitev zaostalih napetosti po globini po osnovni toplotni obdelavi (mesto A3)

3.1.4 Heat treatment

The results for the residual stress distribution after the classical and modified heat treatment are shown in **Figures 8** to **10**. After the heat treatment the surface of the test rolls was found to have a very homogeneous compressive residual stress already from the top surface, as shown in **Figure 8**. In the case of the classical heat

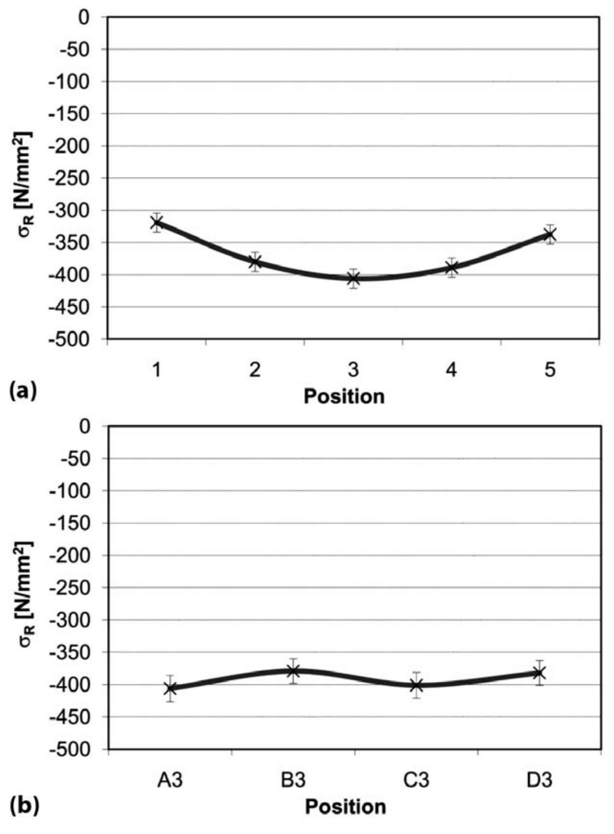

Figure 9: Residual stress distribution in the roll surface after classical heat treatment: a) longitudinal and b) circumferential distributions

Slika 9: Porazdelitev zaostalih napetosti na površini valja po osnovni toplotni obdelavi: a) vzdolžno in b) po obodu treatment, the surface of the rolls showed a hardness of about 660 HV_{10} and a compressive residual stress in the range from 320 MPa to 400 MPa. The highest residual stress was found in the middle of the test roll, which is then gradually reduced towards the roll's necks, as shown in **Figure 9a**. Circumferentially, the residual stress is very equally distributed around the roll (**Figure 3**), with the difference being in the range of 10 % (**Figure 9b**). A modification of the heat treatment, aimed at reducing the roll's heat-treatment time, resulted in an increased surface hardness (≈ 710 HV_{10}) and a residual stress level. However, the highest residual stress values of about 470 MPa are still located in the middle of the test roll, and the lowest ones (≈ 390 MPa) near the roll's necks, as shown in **Figure 10a**. On the other hand, an increase in the hardening temperature has an even larger effect (**Figure 10b**). By increasing the hardening temperature from 970 °C to 1070 °C the maximum compressive residual stress located in the middle of the roll increased to ≈ 575 MPa and at the roll's necks to about 430 MPa.

3.1.5 Turning

It is well known that machining operations influence the surface integrity and introduce an additional residual stress in the machined surface.[18,19] In order to evaluate this effect, different turning parameters were used in this

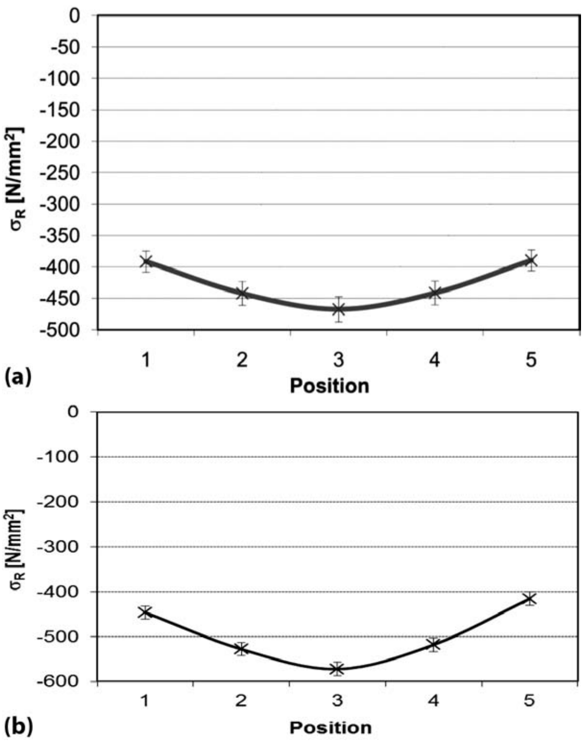

Figure 10: Surface residual stress distribution along the roll length after: a) reduced tempering phase – Mod1 and b) increased hardening temperature – Mod2

Slika 10: Porazdelitev zaostalih napetosti na površini valja po: a) skrajšani fazi popuščanja – Mod1 in b) povišani temperaturi kaljenja – Mod2

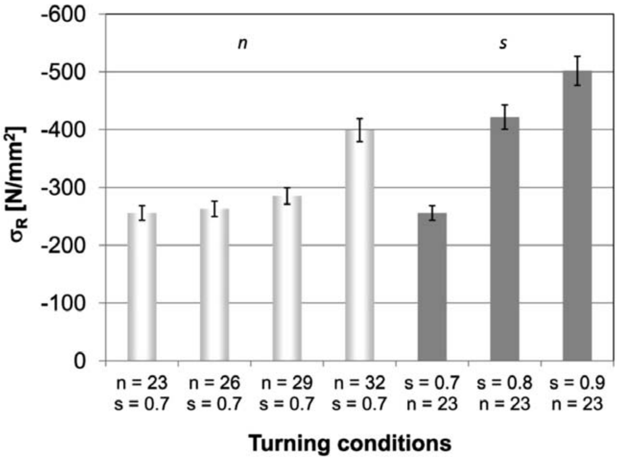

Figure 11: Influence of turning conditions (rotation speed and feed) on the residual stress value in position 3

Slika 11: Vpliv parametrov struženja (vrtilna hitrost in pomik) na vrednosti zaostalih napetosti v plašču valja v točki 3

step of the investigation, including four rotation speeds, *n* ((23, 26, 29 and 32) r/min) and three feed rates, *s* ((0.7, 0.8 and 0.9) mm/r). The residual stress-measurement results are shown in **Figure 10**.

After removing 2 mm of material the compressive residual stress in the middle of the test roll (position 3), heat treated according to the classical procedure (**Figure 2**), was in the range of 250 MPa, when using "standard" turning conditions (n = 23 r/min, s = 0.7 mm/r). Increasing the rotation speed to 26, 29 and 32 r/min, which is equal to a machining time reduction of (13, 26 and 39) %, also results in a compressive residual stress increase of 2.9 %, 11.6 % and 60.3 %, respectively. On the other hand, increasing the feed rate has an even greater influence, with feeding rates of 0.8 mm/r and 0.9 mm/r increasing the residual stress to 420 MPa (64.9 %) and 500 MPa (96.3 %), respectively (**Figure 11**).

3.2 Tribological Properties

Tribological properties of the wear-resistant surface layer of the test rolls were found to be very uniform along the roll surface, in both the circumferential and longitudinal directions. After a conventional heat treatment the surface layer of the roll displayed an average friction of 0.96 and a wear rate of 1.1×10^{-6} mm³/Nm, when tested under room conditions. Compared to through-hardened 100Cr6 steel, high chromium cast steel shows a slightly higher friction, but an up to 30 % lower wear rate. In terms of depth, the wear resistance and the friction of the investigated material remained constant over the depth of 20 mm, as shown in **Figure 12a**. The higher testing temperature (80 °C) led to a reduced friction (≈ 0.93) as well as α lower wear rate (≈ 0.7×10^{-6} mm³/(N m)), which was up to three times lower than that measured for the reference 100Cr6 steel. However, at the elevated testing temperature the wear resistance of the roll samples taken from greater depths

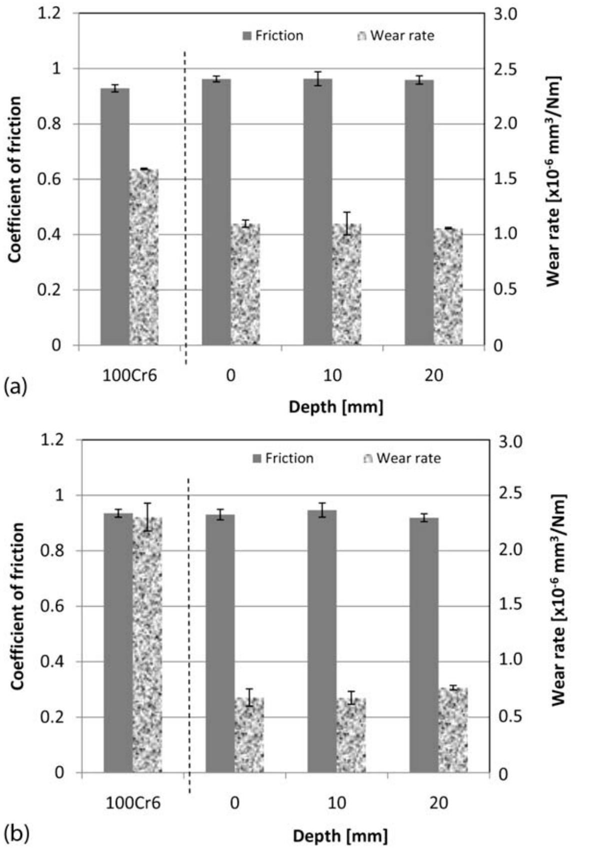

Figure 12: Average friction and wear rate for the high-Cr cast steel samples taken from different depths of the roll's surface layer: a) tested at room conditions and b) at 80 °C

Slika 12: Povprečen koeficient trenja in stopnja obrabe jekla z višjo vsebnostjo Cr, vzetega na različnih globinah od površine valja, preizkušenega pri: a) sobni temperaturi, b) pri temperaturi 80 °C

(20 mm) was reduced by up to 15 %, as shown in **Figure 12b**. By using modified/shortened rolls the heat treatment, which resulted in an increased compressive residual stress level, the wear resistance of the high Cr cast steel surface layer was also increased by ≈ 10 %.

4 CONCLUSIONS

After casting the tensile stress field is generated in the uppermost surface layer (≈ 0.1 mm) of the roll. At larger depths the residual stress field is compressive, with the value being dependent on the conditions in the casting pit. The surfaces exposed to faster cooling rates will experience higher residual stress values.

Coarse grinding, if not carried out properly and under controlled conditions, will cause the formation of a very high tensile residual stress in the roll surface, which may extend to depths well above 500 µm, thus creating a high risk of surface cracking or roll fracture.

The heat treatment uniforms the residual stress field in the roll's surface. The maximum values in the range of 400 MPa are located in the middle of the roll and are then gradually reduced towards the roll's necks. The reduced heat-treatment time will result in an increased residual stress level and an improved wear resistance.

The turning parameters have a considerable influence on the roll's compressive residual stress field. An increase in the turning speed of up to 40 % gives a residual stress increase of about 60 %. On the other hand, the turning feed has an even larger effect, with an increase from 0.7 mm/r to 0.9 mm/r (≈ 30 %), giving a residual stress increase of almost 100 %.

Under the investigated conditions the wear resistance of the high-chromium cast steel layer was found to be superior than hardened 100Cr6 steel, especially at elevated temperature. Furthermore, the wear resistance of the roll's top layer was very uniform over the whole roll surface, while it shows a slight reduction with depth.

Acknowledgements

The present work was a part of the EUREKA E!3932 – ROPTIM project "Production technology optimization for rolls from Semi High Speed Steel", financially supported by the Ministry of Higher Education, Science and Technology, Republic of Slovenia (Contr. no.: 3211-07-000149).

5 REFERENCES

[1] B. Kämpfe, E. Auerswald, Determination of Residual Stresses in Microsystems Using X-ray Diffraction, Materials week 2000, Munich, Germany, 2000

[2] C. Achmus, FEM-Calculations of residual stress, 8. Germanspeaking ABAQUS – user meeting, Hannover, Germany, 1996, 55–63

[3] L. Vergani, Mechanics of materials, McGraw Hill, 2001, 456 p. (in Italian)

[4] M. D'Acunto, Characterization of residual stress and roughness of steel components, Proceedings of 3rd AIMETA Int. Tribology Conference, Salerno, Italy, 2002

[5] G. A. Webster, Role of residual stress in engineering applications, Mater. Sci. Forum, 347–349 (**2000**), 1–11

[6] J. Grum, A review of the influence of grinding conditions on resulting residual stresses after induction surface hardening and grinding, J. Mat. Proc. Technology, 114 (**2001**), 212–226

[7] S. Way, Pitting due to rolling contact, J. Applied Mech., 2 (**1935**), 49–61

[8] J. Ondrouskova, M. Pohanka, B. Vervaet, Heat-flux computation from measured-temperature histories during hot rolling, Mater. Tehnol., 47 (**2013**) 1, 85–87

[9] S. Hossain, M. R. Daymond, C. E. Truman, D. J. Smith, Prediction and measurement of residual stresses in quenched stainless-steel spheres, Mater. Sci. Eng., A373 (**2004**), 339–349

[10] F. A. Kandil, J. D. Lord, A. T. Fry, P. V. Grant, A review of residual stress measurement methods, NPL Report MATC(A)04, UK, 2001

[11] B. Podgornik, J. Vižintin, F. Kopač, Application of hole-drilling method in practice, Mat. Sci. Forum, 524–525 (**2006**), 555–560

[12] A. K. Datta, G. Das, P. K. De, P. Ramachandrarao, M. Mukhopadhyaya, Finite element modeling of rolling process and optimization of process parameters, Mat. Sci. Eng., A426 (**2006**), 11–20

[13] B. Podgornik, J. Vižintin, S. Milanović, Production technology optimization for rollers from Semi High Speed Steel – E!3932 ROPTIM project report, University of Ljubljana, Ljubljana, 2008

[14] M. Pellizzari, Thermodynamic modeling for the alloy design of high speed steels and high chromium cast irons, Mater. Tehnol., 44 (**2010**) 3, 121–127

[15] Z-Set/ZéBuLoN Version 8.4, Northwest Numerics, Seattle, USA, www.nwnumerics.com

[16] J. L. Chaboche, Constitutive equations for cyclic plasticity and cyclic viscoplasticity, International Journal of Plasticity, 5 (**1989**), 247–302

[17] ASTM E837-01, Determining residual stresses by the hole drilling strain-gage method, ASTM International, West Conshohocken, PA, 2001

[18] D. Bajić, B. Lela, G. Cukor, Examination and modelling of the influence of cutting parameters on the cutting force and the surface roughness in longitudinal turning, Strojniški vestnik – Journal of Mechanical Engineering, 54 (**2008**) 5, 322–333

[19] G. Totten, M. Howes, T. Inoue, Handbook of Residual Stress and Deformation of Steel, ASM International, 2002, 499