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Scientific paper
ISSN 0351-9465, E-ISSN 2466-2585
https://doi.org/10.5937/zasmat2301048G
Zastita Materijala 64 (1)
48 – 57 (2023)

Ceramic rolls for rolling of steel foils

ABSTRACT

High hardening of the steel, which is caused by martensitic transformation through cold forming, leads to significant local elastic roll deformation (flattening). The rolling of strain-hardened steel requires higher rolling forces and higher torques, which result in high rolling force. Roll flattening can be reduced by using rolls made of a material with a significantly higher modulus of elasticity. The suitability of ceramic materials for the rolls of modern cold and hot rolling mills was examined. The rolling tests with silicon nitride rolls were carried out with a two-high rolling stand with coilers. The industrial applications of silicon nitride rolls in the rolling of thin steel foils in a 20-high Sendzimir mill consistently showed excellent applicability of this material. A review of conducted research has shown that the use of silicon nitride work rolls minimizes roll flattening and leads to a significant reduction in rolling force.

Keywords: *work rolls, flattening, strain-hardened steel, silicon nitride, Sendzimir mill*

1. INTRODUCTION

Depending on the chemical composition of the material, the cold forming of the austenitic stainless spring steels can cause the austenitic (fcc) phase to partially or completely change into a martensitic (bcc) phase. Martensite formation affects the mechanical properties of the material and the forming behavior as follows: while the tensile strength, yield stress and indentation hardness increase sharply, the elongation values such as uniform elongation and elongation at break only increase slightly. During a forming process, the power and labor requirements as well as the tool stress increase accordingly, resulting in a high system load. One effect of high rolling forces due to strong hardening is an increasing roll flattening of the work rolls in cold rolling mills, which can be reached in particular in the last stands of multi-stand tandem mills, where it can happen that only elastic deformations of the work rolls occur and no further deformation of the band is reached. During roll flattening, the contour in the contact area changes from the original circular shape to a curve with a smaller and no longer constant curvature (Fig. 1).

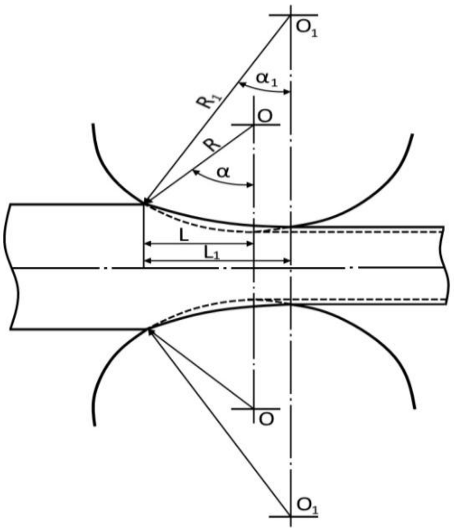

Figure 1. Roll flattening scheme: O - effective center of curvature of roll surface, O_1 - effective center of curvature of deformed roll surface, ***,*** *α - angle of contact, α_1 - angle of contact of deformed roll, R - radius of non-deformed roll, R_1 - radius of deformed roll, L - length of the deformation zone, L_1 - length of the deformation zone of deformed roll [1]*

Slika 1. Shema spljoštenja valjka: O - centar krivine površine valjka, O_1 - centar krivine deformisane površine valjka, α - ugao kontakta, α_1 - ugao kontakta deformisanog valjka, R - radijus nedeformisanog valjka, R_1 - radijus deformisanog valjka, L - dužina zone deformacije, L_1 - dužina zone deformacije deformisanog valjka [1]

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Paper received: 11. 07. 2022.
Paper accepted: 13. 09. 2022.
Paper is available on the website: www.idk.org.rs/journal

The main effects produced by roll flattening are [1-4]:

- Arc of roll contact is lengthened for the same draft when compared with a rigid roll
- Planes of entry and exit are shifted outward from the centreline of the rolls.

In order to keep rolling forces and roll flattening small, it makes sense to use small roll diameters in cold rolling. Another variable is the modulus of elasticity of the roll material. A high modulus of elasticity of the roll material immediately results in small flat spots on the roll.

Roll damage

The cold rolling of high-alloy chromium-nickel steels in a multi-stand tandem cold-rolling plant is characterized by high strain hardening, which is caused by the formation of martensite through the forming. The tougher rolling conditions can lead to roll damage such as cracking, shelling and roll breakage. A characteristic of the use of cold rolling rolls is the cyclic contact load, which can lead to damage to surface layers, even if the alternating stress is below the fatigue limit. The contact stresses in the presence of weak points in the microstructure, which have arisen due to manufacturing or use conditions, can lead to premature roll failure without pronounced traces of fatigue fractures [5]. Non-metallic inclusions, pores, microshrinkage, microcracks, accumulations of carbides, etc. can serve as the triggering factor of premature damage to surface layers or fracture [5-9].

The rolls examined in a four-stand tandem cold rolling mill were made of high-speed steel (HSS) (Table 1).

Table 1. Chemical composition of high-speed steels

Tabela 1. Hemijski sastav brzoreznih čelika

Steel	Chemical composition (%)								
	C	Si	Mn	P	S	Cr	Mo	V	W
S 6-5-2	0.86-0.94	≤0.45	≤0.40	≤0.030	≤0.030	3.80-4.50	4.70-5.20	1.70-2.00	6.00-6.70
S 6-5-3	1.17-1.27	≤0.45	≤0.40	≤0.030	≤0.030	3.80-4.50	4.70-5.20	2.70-3.20	6.00-6.70

Such rolls with a hardness of 62 to 66 HRC are primarily used in four-high and two-high wide and narrow strip rolling mills for hot and cold rolling of steel and non-ferrous metals. Carbide formation, which is primarily dependent on the chemical composition of the steel, can only be influenced to a very limited extent. Possibilities are given by the solidification rate and the degree of hot forming. The roll of HSS type S 6-5-2 is made by metallurgical melting process. The microstructure was further improved by controlling forging and heat treatment. Figure 2 shows a typical microstructure of forged steel, consisting of fine, tempered martensite and fractured carbide mesh. The small carbides are distributed in strips perpendicular to the forging direction and show less regularity in terms of distribution and greater scatter.

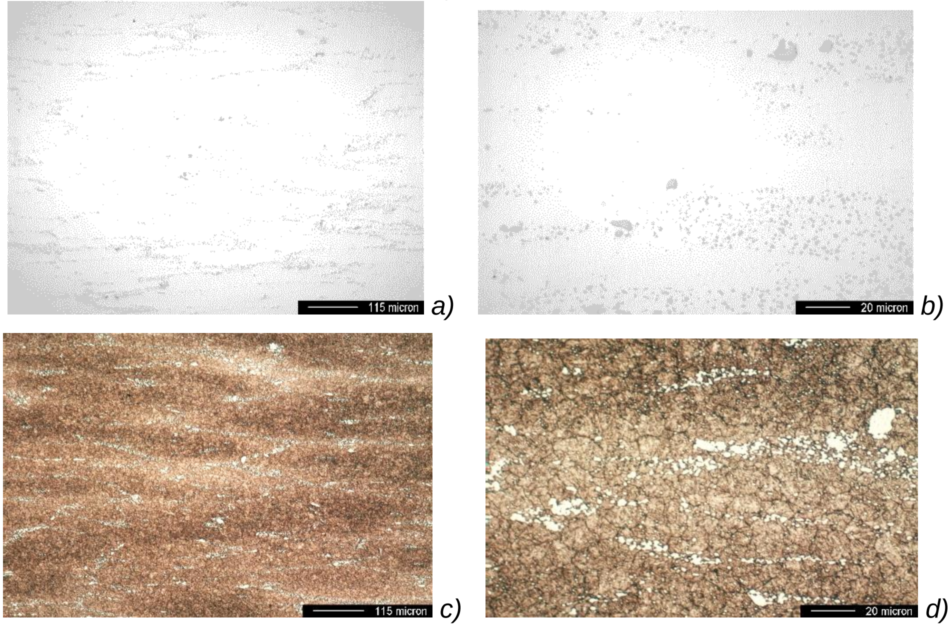


Figure 2. Microstructure of forged steel roll: a, c - overview; b, d - detail; (c, d - etched)

Slika 2. Mikrostruktura valjka od kovanog čelika: a, c - pregled; b, d - detalj; (c, d - nagrizano)

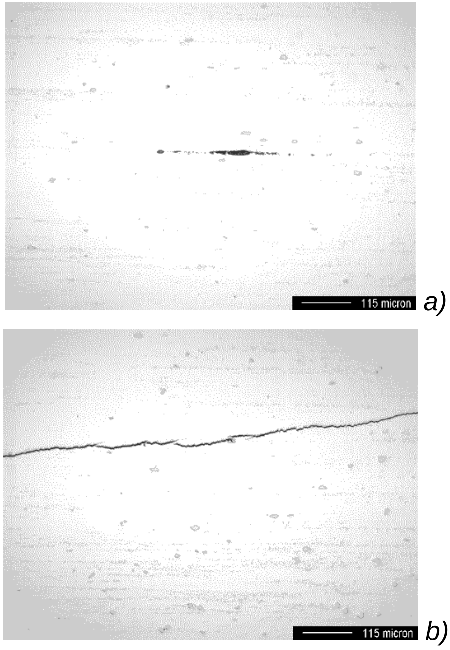


Figure 3. Structural defects in forged steel roll: a - broken non-metallic inclusion; b – crack

Slika 3. Greške u strukturi valjka od kovanog čelika: a - deformisani nemetalni uključak; b – pukotina

In the matrix of the roll, non-metallic inclusions were identified, which were formed and crushed by forging processes (Fig. 3a). In the case of cyclic mechanical loads, these could act as triggers for crack formation and lead to roll breakage. Figure 3b shows an identified crack in the steel matrix.

Although there are several different structural defects in metallic components that could act as potential triggers for crack formation and further destruction, practice has shown [8-10] that normally only one of them is the cause of component destruction. However, this does not exclude the possibility of further (micro)cracks at previous loads, which during co-growth and co-action with other types of structural defects in metals such as micro-cracks, pores, blisters, etc., could lead to the destruction of the component.

The S 6-5-3 type high-speed steel roll was manufactured by powder metallurgy (hot isostatic pressing). The result is an absolutely dense, completely homogeneous and segregation-free steel, which is then forged and heat-treated in the usual way. Solidification speed and block size can be decoupled using powder metallurgical processes, whereby extremely homogeneous carbide distributions and small carbide sizes can be achieved with large semi-finished product diameters [11]. The heat-treated microstructure contains very small, evenly distributed carbides in the tempered martensite matrix **(**Fig. 4) and gives the material very good wear resistance with high toughness.

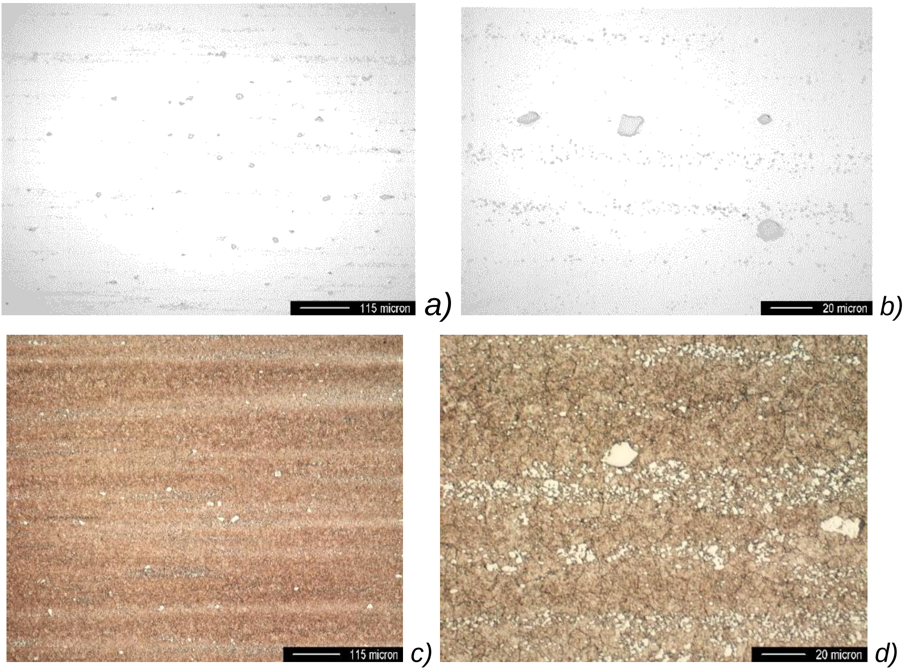


Figure 4. Microstructure of the powder metallurgy roll: a, c - overview, b, d - detail (c, d - etched)

Slika 4. Mikrostruktura valjka proizvedenog metalurgijom praha: a, c - pregled, b, d – detalj (c, d - nagrizano)

The powder metallurgical roll contains more carbides, which is associated with the higher carbon and vanadium content in the high-speed steel used. The carbides are much finer and more evenly distributed. This gives the material extraordinarily good wear resistance with maximum possible toughness. The HSS rolls retain both wear resistance and hardness down to the minimum diameter. The carbide size plays an important role in the propagation of an incipient crack in the matrix. The small carbides lead to frequent crack deflection or to the deceleration or stopping of the crack [12].

2. MATERIALS OF TECHNICAL CERAMICS

Although the high-speed steels have a significantly higher modulus of elasticity (220-240 GPa [13]) than conventional iron-based materials (190 to 210 GPa), the HSS rolls cannot avoid flattening. Significantly higher moduli of elasticity can only be achieved with other materials such as tungsten carbide [14] or high-performance ceramics. As tungsten prices have increased dramatically in recent years, this has led to significant cost increases for users of carbide products, which can contain up to 94% tungsten. The ceramic materials show some positive properties or combinations of properties that have not been achieved by other groups of materials (Fig. 5).

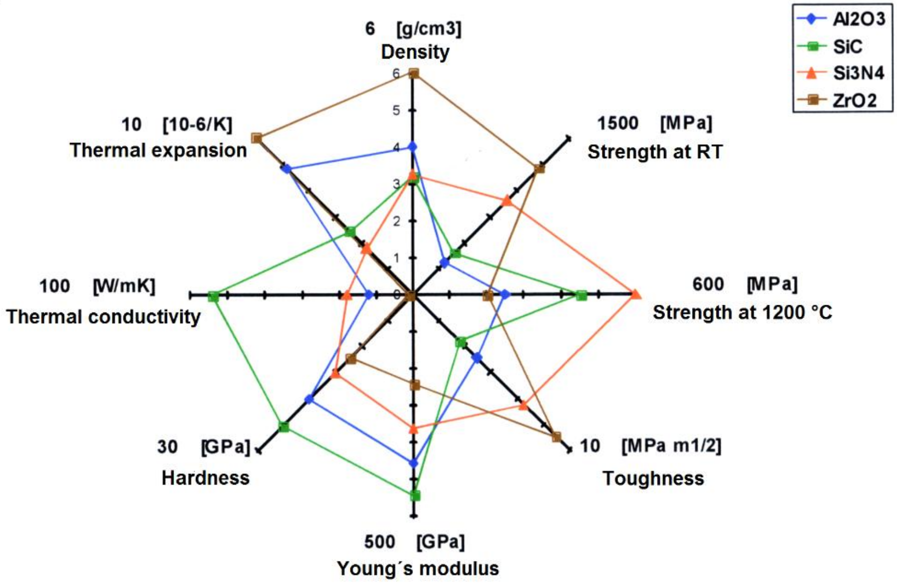


Figure 5. Comparison of the properties of high-performance ceramics [15]

Slika 5. Poređenje svojstava keramike visokih performansi [15]

The great interest in engineering ceramics is based on certain significant advantages compared to metallic materials, such as a significantly higher modulus of elasticity, higher strength, and a lower coefficient of thermal expansion. The reason for this lies in the type of bonding: ionic bonding (heteropolar bonding) dominates in oxide ceramics and atomic bonding (covalent bonding) in non-oxide ceramics. The other advantages of ceramic materials compared to metallic materials also include the significantly higher thermal shock resistance and resistance to temperature changes, which are associated with medium thermal conductivity and low thermal expansion of ceramic materials. Therefore, these materials could be considered suitable for the production of high-strength and thermally highly resilient components with special requirements for mechanical, physical and chemical properties. The impact, tensile and bending loads are undesirable for the ceramic components, which is associated with the low toughness of the ceramic.

Our investigations have shown [16] that the use of ceramic rolls, which have significantly higher Young's moduli than iron-based materials, can minimize the problem of rolls flattening. This possibility is based on the behaviour of ceramic materials under high line loads, which differs from the behaviour of metallic materials due to the type of bonding. Dislocation sliding, which enables plastic deformation in metallic materials, only occurs hypothetically in ceramic materials at high stresses, at which the breaking strength of the ceramic materials is already exceeded. At low and medium temperatures, mechanical loads are not reduced by plastic processes in the component. Dislocation-induced plasticity is almost entirely absent in ceramics. This is the basis for their high hardness and brittleness. Typical values for the fracture toughness of ceramics are in the range of 1 to 10 MPa and the total elongation at break is usually less than a few parts per thousand [17]. In the event of mechanical overload, the behaviour of ceramic materials is not determined by resilience and deformation, but rather by crack formation, crack growth and fracture.

Silicon nitride (Si_3N_4) occupies a promising position within the non-oxide ceramics, which compared to other technical ceramics shows significantly higher strength values at room and higher temperatures (see Figure 5). Compared to conventional iron-based materials, silicon nitride exhibits significantly higher values of hardness, Young's modulus and thermal conductivity, while at the same time having a lower coefficient of thermal expansion, lower density and excellent resistance to wear (Fig. 6).

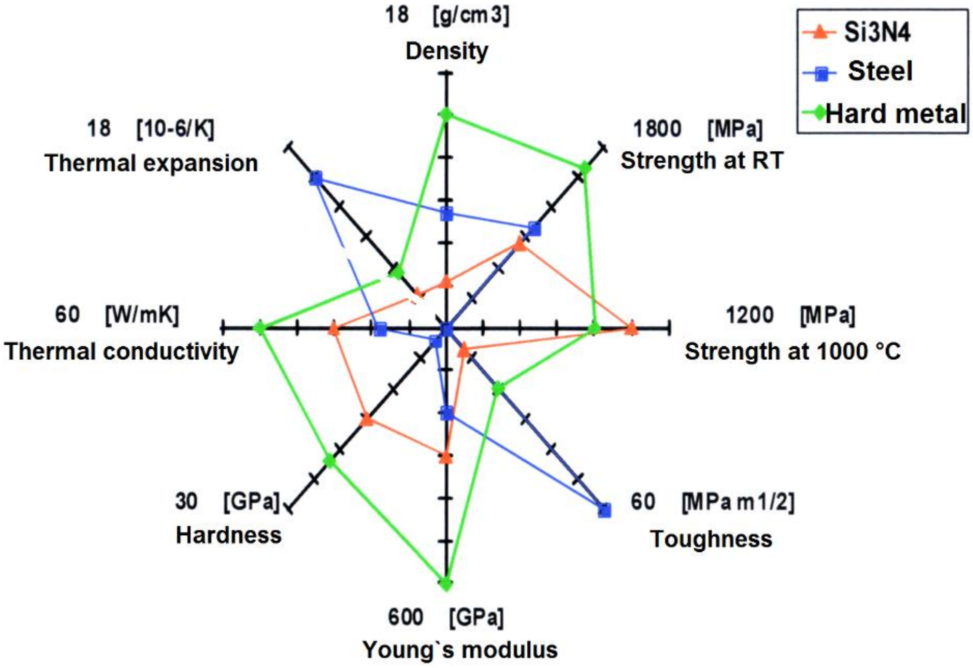


Figure 6. Comparison of properties of steel/ hard metal/ silicon nitride ceramic [15]

Slika 6. Poređenje svojstava čelika /tvrdog metala/ silicijum nitrid keramike [15]

3. SILICON NITRIDE ROLLS

The analysis of the most important application properties of modern high-performance ceramics showed that silicon nitride and alumina toughened zirconia (ATZ) can be considered as possible materials for the rolls of modern cold and hot rolling mills. The suitability of these materials was examined by upsetting cylinder samples made of steel, pure aluminium, copper, tungsten, molybdenum and Cu-Sn and Cu-Ag alloys with ceramic upsetting tracks (Ø50 x 30) made from the above-mentioned ceramic materials. The effect of the quality of the compression track, such as silicon nitride raw material quality (standard or high quality), manufacturing process (low-pressure sintering, gas-pressure sintering, hot isostatic pressing), surface condition (ground or polished surface), effect of the compression force used, compression tests with the above-mentioned metals and alloys are presented by us in [18-24].

Rolling tests with Si_3N_4/ steel compound rolls

The rolling tests with silicon nitride rolls were carried out with a two-roll stand with coilers [16]. The compound rolls used consisted of silicon nitride rings fixed to the steel shafts. With these rolls, steel wire of Ø 4.0 mm was cold-rolled to flat wire with a thickness of 0.6 mm or 0.8 mm (Fig. 9). The rolling forces were in the range from 10 kN to 117 kN.

In the hot rolling tests, the bars made of mild steel S235JR of Ø 6.0 mm or Ø 9.0 mm and a length of 500 mm were rolled flat to a final thickness of 1.42 or 3.16 mm (Fig. 10). The rolling temperature was 950 °C. The rolling forces used were around 10 kN. No signs of roll damage were found after the rolling tests.

Figure 9. Cold rolling test with Si_3N_4 compound rolls

Slika 9. Ispitivanje hladnog valjanja sa složenim valjcima Si_3N_4/ čelik

Figure 10. Hot rolling test with Si_3N_4/ steel compound rolls

Slika 10. Ispitivanje toplog valjanja sa složenim valjcima Si_3N_4/ čelik

The rolling tests carried out showed that a desired microstructure of the formed steel can be achieved with Si_3N_4 rolls without any problems. Figure 11 shows the microstructure development in austenitic steel wire during forming.

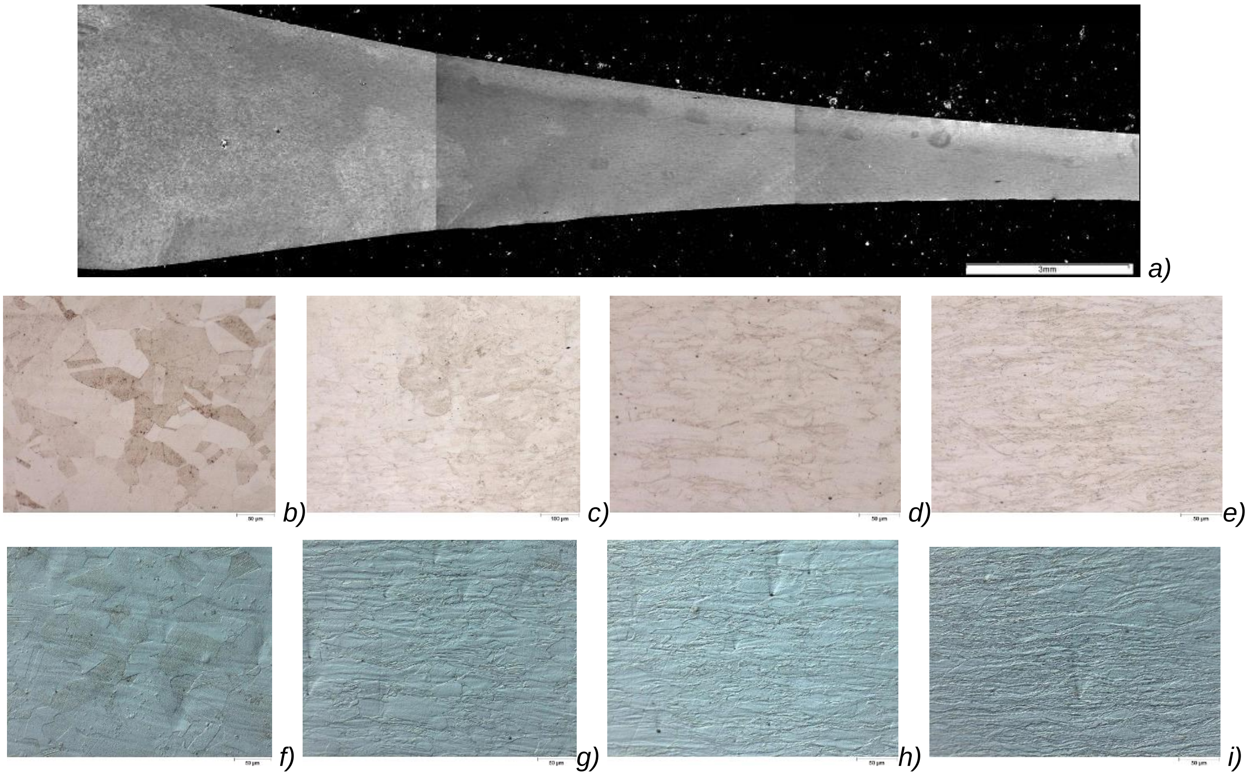


Figure 11. Development of microstructure in austenitic steel wire during forming (longitudinal sections, etched): a - overview; b to i - details; b to e - reflected light; f to i - polarized light

Slika 11. Razvoj mikrostrukture u austenitnoj čeličnoj žici tokom oblikovanja (uzdužni preseci, nagrizano): a - pregled; b do i - detalji; b do e - reflektirana svetlost; f do i - polarizovana svetlost

Rolling of steel foils in a 20-high Sendzimir mill

In contrast to the rolls of two and four-high mills, the work rolls of multi-high mills are practically not subjected to bending stresses due to the supporting effect of the intermediate rolls, but mainly to contact stresses. In a 20-high mill, each of the two work rolls is supported by two first-row intermediate rolls, which are supported by three second-row intermediate rolls located on four back-up rolls that transmit the rolling force to the rigid housing transferred [25]. There is a three-point contact between two larger and one smaller rolls. In the work roll, there is this three-point contact with the rolling stock and the two next largest back-up rolls and leads to a compressive stress state that avoids bending tensile stresses in the work roll. Such a scheme provides exceptional rigidity of the entire roll system and the almost complete absence of deflection of the work rolls. In 20-roll stands, a whole network of lateral forces is generated, which leads to radial roll stress [26, 27] (Fig. 12).

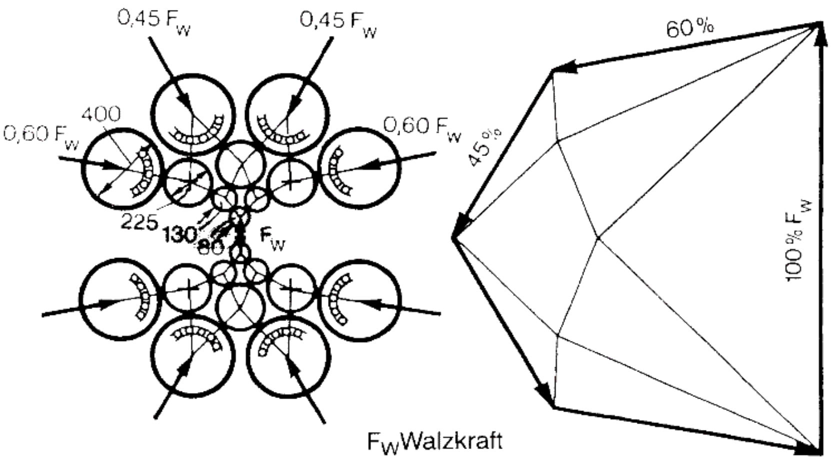
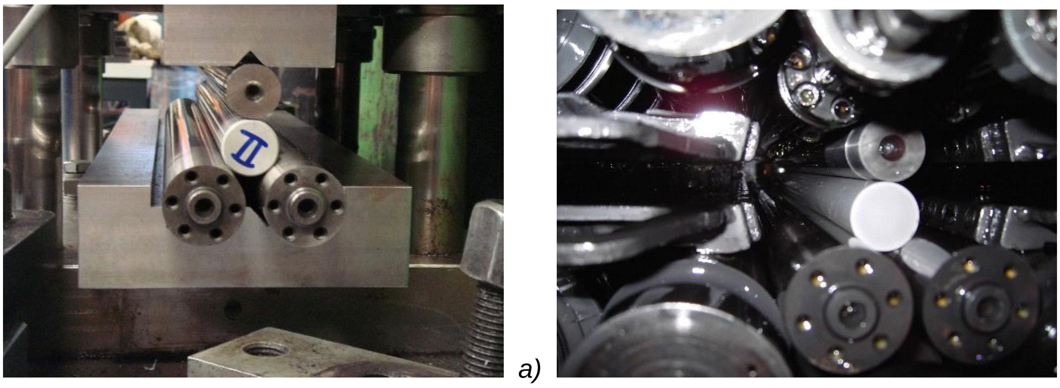


Figure 12. Supporting forces in the 20-roll Sendzimir mill [27]

Slika 12. Potporne sile u Sendzimirovoj pruzi sa 20 valjaka [27]

The torque of the four intermediate rolls of the second row is transmitted over the entire length to all intermediate and wok rolls without any torsional deformation. This important feature is of great importance when selecting the material for the production of work rolls in multi-roll stands. When bending stresses occur, which can arise when the strip breaks, the rolls are often broken. The severe operating conditions of the rolls, characterized by a large length to diameter ratio, will be exacerbated by slippage of the strip along the surface of the work rolls and work rolls along the surface of the first intermediate rolls.

After the successfully passed pressure tests with a line load of 300 kN, 700 kN and 1350 kN in a test stand specially developed for this purpose (Fig. 13a) and with a line load of 400 kN and 700 kN in a 20-roll mill (holding time 15 to 20 min) (Fig. 13b) ceramic rolls were released for rolling stainless steel [16].



a) *b)*

Figure 13. Line load tests with a work roll made of Si_3N_4: a - in a test stand; b - in a 20-roll mill

Slika 13. Ispitivanja linijskim opterećenjem radnog valjka od Si_3N_4: a - u ispitnom postrojenju; b - u valjačkoj pruzi sa 20 valjaka

The Si_3N_4 rolls were used for rolling foils from austenitic and ferritic steels (Fig. 14).

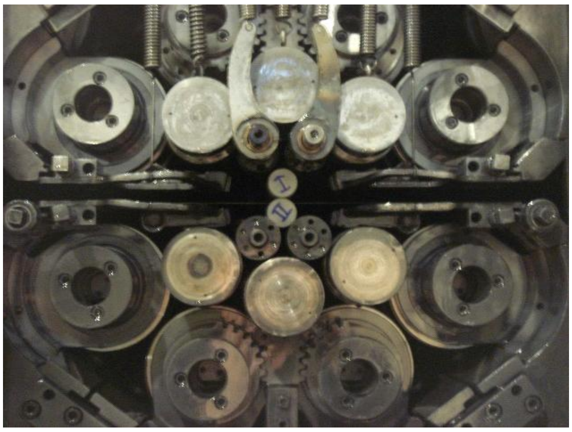
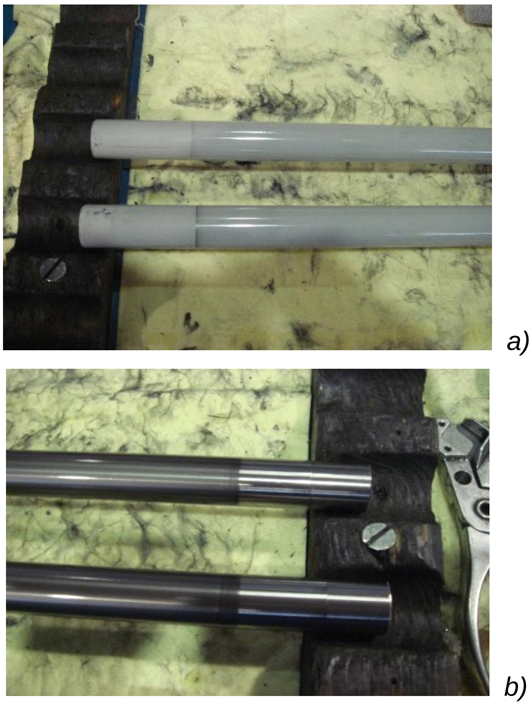


Figure 14. Arrangement of silicon nitride work rolls (I and II) in a Sendzimir mill [16]

Slika 14. Raspored radnih valjaka od silicijum nitrida (I i II) u Sendzimirovoj valjačkoj pruzi [16]

An austenitic steel was rolled in 7 passes from 0.30 mm to 0.050 mm with a tolerance of ± 3 µm [16]. The first 4 passes (from 0.30 to 0.090 mm) were made with Si_3N_4 rolls. Passes 5 to 7 (from 0.090 to 0.050 mm) were made with the steel rolls produced by powder metallurgy. The surface condition of ceramic rolls (roughness development) was monitored after each pass using a Perthometer M1 roughness measuring device. After each additional pass, the roll surface became smoother and smoother, which had a positive effect on the surface condition of the strip. The rolling time was approx. 15-35 minutes per pass with a total rolling time of approx. 3 hours. The whole rolling campaign ran smoothly and without incident.

The material properties of the rolls have had a significant influence on the rolling process. Due to the high modulus of elasticity of silicon nitride, minimal roll flattening was achieved and two passes were saved in further rolling tests. The foils made of stainless ferritic and austenitic steels were rolled in 5 passes from 0.100 mm to 0.025 mm with a tolerance of ± 2 µm. Due to the minimal elastic deformation of the work rolls, the required rolling forces were reduced by approx. 40-50 % and the wear behavior of the rolls was clearly superior to the steel rolls otherwise used, which were produced using powder metallurgy. No damage such as adhesions, wear and tear or breakouts were found on the roll surfaces and the rolls remained operational for further use (Fig. 15a). The surfaces of the powder-metallurgically manufactured rolls were covered by an adhesive skin and must be ground and polished again before they can be used again (Fig. 15b).



a)

b)

Figure 15. Surface of the Si_3N_4 work rolls (a) and powder metallurgy rolls (b) after use

Slika 15. Površina radnih valjaka od Si_3N_4 (a) i valjaka proizvedenih metalurgijom praha (b) nakon upotrebe

The results obtained [16, 18-24] were used as a basis for further optimization of the rolling process in 20-roll stands [28-34].

4. SUMMARY

The ceramic work rolls have proven themselves extremely well when rolling stainless steel foils. The use of Si_3N_4 rolls minimizes roll flattening, which leads to a significant reduction in rolling force (approx. 40-50 %) compared to rolling with rolls manufactured using powder metallurgy. With high strain hardening of the rolled steel, silicon nitride offers a reduction in the number of passes and the possibility of achieving thinner strip gauges. There is no need to change the rolls after each pass, as is the case with powder-metallurgically manufactured steel rolls, since no adhesions form. The effects of ceramic rolls on the rolling process allow for a significant reduction in total rolling time and significant energy savings. The excellent wear properties of Si_3N_4 rolls lead to a significant improvement in the surface condition of the rolled product. The use of high-performance ceramic work rolls, which can be designed as singlematerial or compound rolls (Si_3N_4 ring/ steel axis), is highly efficient and offers great optimization potential.

5. REFERENCES

[1] A.P.Grudev (2001) Theory of Rolling. 2nd Edition, Intermet Engineering, Moscow.

[2] R.Kopp, H.Wiegels (1998) Introduction to Forming Technology, Publ. Augustinus Bookstore, Aachen, Germany.

[3] The Making, Shaping and Treating of Steel®. Flat Products Volume (2014) V.B.Ginzburg (Ed.). 11th Edition. Association of the Iron & Steel Technology (AIST), Warrendale, PA, USA.

[4] G.S.Nikitin (2009) Theory of Continuous Longitudinal Rolling. Baumans University, Moscow.

[5] V.P.Polukhin, V.A.Nikolaev, M.A.Tylkin, P.T. Shulman, V.A Masol, S.P.Efimenko, V.I.Dunaevsky, G.I.Valchuk, M.Ya.Belkin, A.S.Venzhega (1976) Reliability and durability of cold rolling mill rolls. 2nd Edition, Metallurgy, Moscow.

[6] Y.Ohkomori, I.Kitagawa, R.Shinozuka, T.Toriyama, K.Matsuda, Y.Murakami (1990) Effects of Nonmetallic Inclusions and Small Surface Pits on the Fatigue Strength of a High Strength Steel at Two Hardness Levels. 31th Mechanical Working and Steel Processing, Chicago (1989), Vol. XXVII, The Iron & Steel Society Inc., Warrendale, PA, USA, p. 41-49.

[7] H.J.Böhmer (1994) Decisive for Rolling Fatigue: Structural Weaknesses. Materials Testing, 36(1-2), 16-20.

[8] V.Goryany, O.Myronova, E.Schubrikoff, J.Buch, F.Stein (2018) Non-metallic inclusions and fatigue strength of steel 34CrNiMo6. Materials Testing, 60(10), 1004-1012.

[9] O.Myronova, V.Goryany (2021) Influence of non-metallic inclusions on the destruction of mechanically loaded steel products. Zaštita Materijala, 62(2),113-125.

[10] O.Myronova (2020) Influence of Various Structural Micro-Defects on the Fracture of Cyclically Stressed Components Revisited. Materials Testing, 62(4), 429-433.

[11] E.Matthaei-Schulz, A.Schulz, S.Spangel, K.Busch, H. Vetters (2003) Image analytical comparison of carbides in forged tools steels produced as ingot, by spray forming or by powder metallurgy. HTM - Härterei-Technische Mitteilungen, 58(6), 314-321.

[12] A.Schulz, V.Uhlenwinkel, C.Bertrand, C Escher, R. Kohlmann, A.Kulmburg, M.C.Montero-Pascual, R.Rabitsch, R.Schneider, D.Stocci, D.Viale (2005) Spray-compacted high-alloy tool steels - production and properties. HTM - Härterei-Technische Mitteilungen, 60(2), 87-95.

[13] A.V.Semichastnaya, F.I.Aleshkin (1973) Influence of temperature on the modulus of elasticity of high-speed and die steels. Metal Science and Heat Treatment of Metals, 3, 56-57.

[14] E.L.Klaphake, W.H.Rakoff (2002) Tungsten Carbide Rolls. In: Rolls for the Metallworking Industry. G.E.Lee (Ed.). A Publication of the Iron & Steel Society, Warrendale, PA, USA, p. 93-129.

[15] G.Wötting, H.Drachsler (2004) Ceramic rolling tools made of silicon nitride for the production of wire, tube and strip. Symposium Ceramics for rolling technology, 17-18 March, Neuwied, Germany.

[16] V.Goryany, P.J.Mauk, J.Giersbach (2011) Ceramic Working Rolls for Rolling of Thin Sheet Foils in a 20-Roll Sendzimir Mill. Materials Testing, (53)10, 643-648.

[17] R.Danzer, T.Lube, P.Supancic, R.Damani (2008) Fracture of Ceramics. Advanced Engineering Materials, 10(4), 275-298.

[18] V.Goryany, P.J.Mauk, C.Eckardt (2008) Investigation of new Ceramic Materials for Rolls and other Components of Rolling Technology. XXVII Deformation Colloquium, 08.-11.03.2008, Planneralm, Austria.

[19] P.J.Mauk (2009) Rolling technical aspects and requirements. In: Ceramic Rolls. A.Kailer (Ed.). Proceedings of Symposium Ceramics for rolling technology, 28-29 July, Neuwied, Germany, Fraunhofer Press, Stuttgart, p. 113-130.

[20] P.J.Mauk (2009) Hot and cold rolling with ceramic materials. Steel 2009, Opportunities and prospects. International Annual Steel Conference, 12 November, Düsseldorf, Germany.

[21] V.Goryany, P.J.Mauk, C.Eckardt (2010) Investigation on the Ceramic Materials for Rolls and other Components of Rolling. MP Materials Testing, 52(1-2), 100-106.

[22] V.Goryany, R.Wagner (2011) Materials for Rolls and other Components for Hot Rolling. Materials Testing, 53(11-12), 748-757.

[23] V.Goryany, M.Hinnemann, O.Myronova (2017) Warm upsetting tests with cylindrical molybdenum and wolfram samples. Rosov pinn 2017. 3rd regional roundtable: refractory, process industry, nanotechnology and nanomedicine. June 1-2, 2017. Mountain Avala, Belgrade, Serbia.

[24] V.Goryany, M.Hinnemann, O.Myronova (2017) Warm upsetting tests with cylindrical molybdenum and wolfram samples. Zaštita Materijala, 58(4), 498-502.

[25] W.B.Laycock, A.Sendzimir (2002) Sendzimir Mill Rolls. In: Rolls for the Metallworking Industry. G.E.Lee (Ed.). A Publication of the Iron & Steel Society, Warrendale, PA, USA, p. 201- 211.

[26] V.P.Polukhin, V.K.Tutynin (1969) Inter-roll pressure in a 20-roll stand. Izvestiya vuzov. Chernaya metallurgiya, 5, 79-82.

[27] M.Espenhahn, G.Giermann, W.Bald, H.Römmen (1988) Modernization of a cold rolling mill for high-alloy Si strips. Stahl und Eisen, 108(18), 853-859.

[28] C.Overhagen, R.Braun, P.J.Mauk, Y.Lan, J. Giersbach (2012) Cold Rolling on High-Strength Stainless Steel Foils with Ceramic SiN Work Rolls. Steel Research International, Special Edition: 14th International Conference Metal Forming, Sept. 16-19, Krakow, Poland, p.67-70.

[29] C.Overhagen, P.J.Mauk (2012) Cold Rolling of Metal Foils by Means of Ceramic Rolls. AISTech 2012, 7-10 May, Atlanta, Ga, USA.

[30] C.Overhagen, P.J.Mauk (2013) Cold Rolling of Metal Foils by Means of Ceramic Rolls. Iron & Steel Technology, (10)2, 97-104.

[31] C.Overhagen, P.J.Mauk (2013) Ceramic materials for rolls and rolling tools in hot and cold rolling. Steel 2013, Steel in Motion. International Annual Steel Conference, 28 November, Düsseldorf, Germany.

[32] C.Overhagen, P.J.Mauk (2014) Ceramic materials for rolls and rolling tools in hot and cold rolling. Stahl und Eisen, 134(5), 53-59.

[33] C.Overhagen, P.J.Mauk (2014) A Model for Strip Profile and Roll Crown During Flat Rolling in Hot and Cold Mills With Special Emphasis on Innovative Work Roll Materials. AISTech 2014, 5-8 May, Indianapolis, Ind., USA.

[34] C.Overhagen, P.J.Mauk (2015) A Model for Strip Profile and Roll Crown During Flat Rolling in Hot and Cold Mills With Special Emphasis on Innovative Work Roll Materials. Iron & Steel Technology, 12(2), 72-79.

IZVOD

KERAMIČKI VALJCI ZA VALJANJE ČELIČNIH FOLIJA

Visoko očvršćavanje čelika, koje je uzrokovano martenzitnom transformacijom kroz hladno oblikovanje, dovodi do značajne lokalne elastične deformacije valjaka (spljoštenja). Valjanje čelika očvrščenog deformacijom zahteva veće sile valjanja i veće obrtne momente, što rezultira visoko opterećenje valjačke pruge. Spljoštenost valjaka može se smanjiti upotrebom valjaka od materijala sa znatno većim modulom elastičnosti. Ispitivana je pogodnost keramičkih materijala za valjke savremenih hladnih i toplih valjaonica. Laboratorijska ispitivanja valjanja sa valjcima od silicijumnitrida vršena su na valjačkoj pruzi sa dva valjaka. Industrijska primena valjaka od silicijumnitrida u valjanju tankih čeličnih folija u Sendzimirovoj valjačkoj pruzi konstantno pokazivala odličnu primenljivost ovog materijala. Pregled sprovedenih istraživanja je pokazao da upotreba radnih valjaka od silicijumnitrida minimizira spljoštenje valjaka i dovodi do značajnog smanjenja sile valjanja.

Ključne reči: *radni valjci, spljoštenje, očvrščenje deformacijom, silicijumnitrid, Sendzimirova pruga*

Naučni rad
Rad primljen: 11. 07. 2022.
Rad prihvaćen: 13. 09. 2022.
Rad je dostupan na sajtu: www.idk.org.rs/casopis

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