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Modern materials for cast rolls of hot strip mills

ABSTRACT

The requirements for the work rolls for the various roll stands of hot strip mills are shown. The modern materials for cast rolls are analyzed and the operational performance of different types of rolls in different stands of the rolling mill is described. The trends in improvement of rolls performance were presented.

Keywords: *cast rolls, microstructure, martensit, carbide, mechanical properties*

1. ROLLS OPERATING CONDITIONS AND REQUIREMENTS FOR ROLLS

As tools in the rolling process, the rolls (Fig. 1) determine the quality of the rolled product, the productivity of the rolling mill and thus the price of the rolled products. The roll costs are 5-15% of the total costs of a hot or cold strip mill [1]. With the constantly increasing demands of the customers on the accuracy and surface quality of the rolled steel, the demands on the quality of the rolls are increasing.

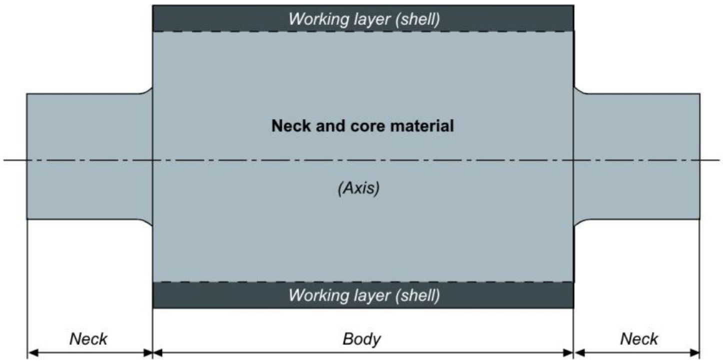

Figure 1. Scheme of a roll [2]

Slika 1. Šema valjka [2]

The choice of roll materials depends on the rolling conditions in a specific stand of a mill and depends on the following factors:

- rolling force
- torque
- temperature of the rolling stock
- rolling speed
- roll cooling
- coefficient of friction
- stand type (two-high or four-high stands)
- continuous or reversing rolling stands
- rolled material
- rolling program
- roll costs.

The operating conditions of the work rolls in roughing and finishing stands show great differences. In the roughing stands, the slabs with a thickness of 200-300 mm are rolled through a high reduction up to 15 or 50mm. In the roughing stands, the rolls are under high cyclical mechanical and thermal loads, which are associated with high rolling stock temperatures (~1200°C), large forming

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forces and a low rolling speed, which leads to a long contact time between the rolling stock and the rolls are connected. The surface temperature of a roughing roll can reach 650-700°C. Fire cracking on the roll surface is a reason to change rolls (Fig. 2).

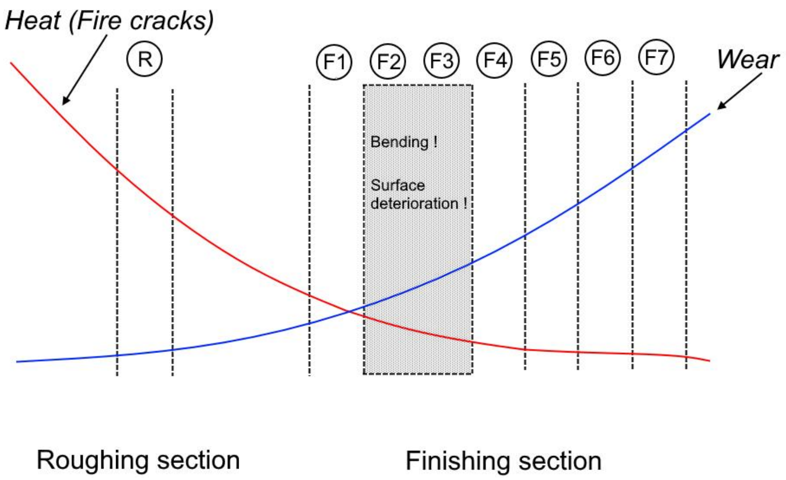

Figure 2. Influence of thermal and mechanical loads on work rolls in a hot strip mill

Slika 2. Uticaj termičkih i mehaničkih opterećenja na radne valjke u valjačkoj pruzi za toplo valjanje lima

In the last finishing stands, the thermal load is significantly lower due to the low rolling stock temperatures and short contact times between the rolling stock and the rolls. In the last roll stand, the temperature of the rolling stock can be around 700°C and this brings with it the increased mechanical loads on the rolls. In these stands, the rolls are primarily damaged by abrasive wear. A combination of the aforementioned loads can be seen in the intermediate stands. The work rolls are cooled with water or emulsion, which leads to intensive oxidation of the rolls surface.

The simultaneously acting cyclic bending, torsional and temperature change stresses as well as the frictional forces lead to special demands on the rolls. The most important requirements for shell of the work rolls in hot rolling mills are:

- high breaking strength
- high wear resistance
- high resistance to thermal fatigue
- insensitivity to stripping
- good surface finish
- sufficient biting.

The most important properties for the roll core and necks are the high bending strength and fatigue strength.

The requirements for the materials of work rolls change depending on the operating conditions. The best possible compromise between mechanical loads, tribological behavior between the rolls and the rolled material (coefficient of friction, adhesion, oxidation) and thermal shock resistance must always be achieved for different applications. The values of the above roll properties depend on the chemical composition of the roll material, the solidification conditions of the roll in the casting mold and the heat treatment [2,3].

2. MATERIALS OF CAST ROLLS

In recent years, the investigations of roll materials have been intensively supported by various simulation techniques. Roll materials are developed using Thermo Calc® software [4-7]. Numerous Finite Element calculation models have been developed and used successfully [8-15] to calculate the stresses that can arise during roll heat treatment and during elastic roll deformation with the introduction of rolling forces and torques.

Work rolls for the roughing stands

The roughing stands are mostly two-high stands, in which rolls are subjected to very high cyclic bending and thermal loads. Because of this, roll materials are needed that have high flexural and tensile strength values as well as high resistance to fire cracking and oxidation. A good grip is an unconditional requirement for the roll material. The composite cast rolls with a working layer (shell) made of chrome steel, HSS (High Speed Steel) or semi-HSS (semi-High Speed Steel) [3,5-7,16-20] and a core made of cast iron with nodular graphite meet these requirements. The rolls are manufactured using vertical or horizontal centrifugal casting processes [3,21]. Practical experience shows that the highest best performance values can be achieved with these rolls qualities.

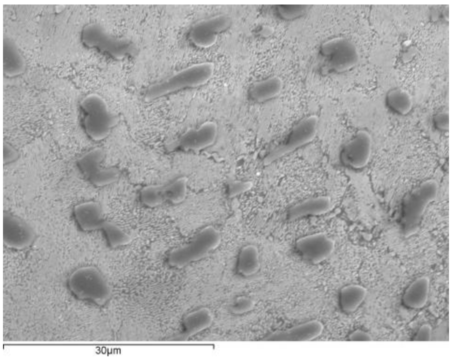

Figure 3. Microstructure in the working layer of an HSS roll (SEM)

Slika 3. Mikrostruktura spoljašnjeg radnog sloja HSS valjka (SEM)

The structure of chrome steel rolls consists of chromium-rich eutectic carbides of the type M_7C_3 (5-10%), which are present in the martensitic matrix. The rolls made of chrome steel have a hardness of 72-78 ShC and show no drop in hardness up to the final diameter and good oxidation resistance, which is associated with a high chromium content. The chrome steel cast rolls have excellent mechanical properties (tensile strength of 700-850 N/mm², bending strength of 1200-1400 N/mm²), high wear resistance and high resistance to fire cracking.

The structure of HSS rolls consists of tempered martensite and fine, evenly distributed primary and secondary carbides (7-10 wt.%), Figure 3.

The primary carbides are considered to be the carriers of the wear resistance, the secondary carbides provide the heat resistance (tempering resistance). Depending on the chemical composition and solidification rate of the HSS, different types of carbides can form: MC, M_2C, M_7C_3, M_6C and $M_{23}C_6$ [3-7, 22, 23]. These differ in terms of morphology, hardness, chemical composition and type of crystal lattice (Table 1) and result in very high wear resistance.

Some of the primary carbides are dissolved during austenitizing, whereby austenite becomes saturated with carbon and alloying elements. The vanadium-based MC carbides dissolve only partially (Fig. 4), as they have a higher dissolution temperature in austenite than the hardening temperature [25].

Table 1. Hardness and structure of carbides [24]
Tabela 1. Tvrdoća i kristalna struktura karbida [24]

Properties	Carbide type				
	MC	M_2C	M_6C	M_7C_3	$M_{23}C_6$
Hardness (HV)	2600-3000	1800	1500	1500	1200-1600
Crystal-lattice structure	FCC	hexagonal	FCC	hexagonal	cubic (complex)

The primary carbides, which are not dissolved during austenitizing, will have a decisive influence on the wear resistance of the HSS.

During tempering, the martensite, which is saturated with carbon and alloying elements, is separated into ca. 10^{16}-10^{18} 1/cm³ nanometer-sized (ca. 1x10x10 nm) secondary carbides [26]. These prevent the movement of dislocations (according to the Orowan mechanism) and thus strengthen the steel (secondary hardening). The type and amount of precipitated secondary carbides depends on the ratio of the content of alloying elements to carbon in the mixed crystal [26, 27]. The more carbon and alloying elements are dissolved in the martensite, the more secondary carbides are precipitated. Secondary hardening increases the hardness and thermal stability of the matrix. The strengthened martensitic matrix supports the hard and wear-resistant carbides and prevents them from tearing off the contact surface. The optimization of the matrix is reflected in an improvement in macroscopic properties such as fracture toughness (K_{1c}), which is used as an indicator of crack propagation. The K_{1c} values of developed HSS (tested according to ASTM-E 399 90) are over 30 MPa·m$^{1/2}$, which significantly exceeds the K_{1c} values of other roll materials [28].

The proportion of carbide in the structure of HSS rolls is roughly the same as in rolls made of chrome steel, but the HSS rolls have a significantly higher wear resistance. Compared to chrome rolls and Indefinite Chill Double Pour rolls (ICDP) (see below), HSS rolls show a 2 to 5 times longer service life. The higher performance of HSS rolls are associated with the special features of the microstructure, which has a hardness of 78-84 ShC and a tensile strength of around 900 N/mm² [25]. This is achieved through the presence of fine special carbides (primary and secondary carbides), which have a significantly higher hardness than M_7C_3 carbide, and the higher hardness of the strengthened matrix of tempered martensite. A major contribution to the performance of HSS rolls is made by their high resistance to fire cracking, which can be evaluated using the thermal shock index (TSI) [29].

$$TSI = \frac{(1-\mu)\cdot\lambda\cdot Rm}{E\cdot\alpha}, \qquad (1)$$

where:

λ - thermal conductivity; μ - Poisson's ratio; α - coefficient of thermal expansion; Rm - tensile strength; E - Modulus of elasticity.

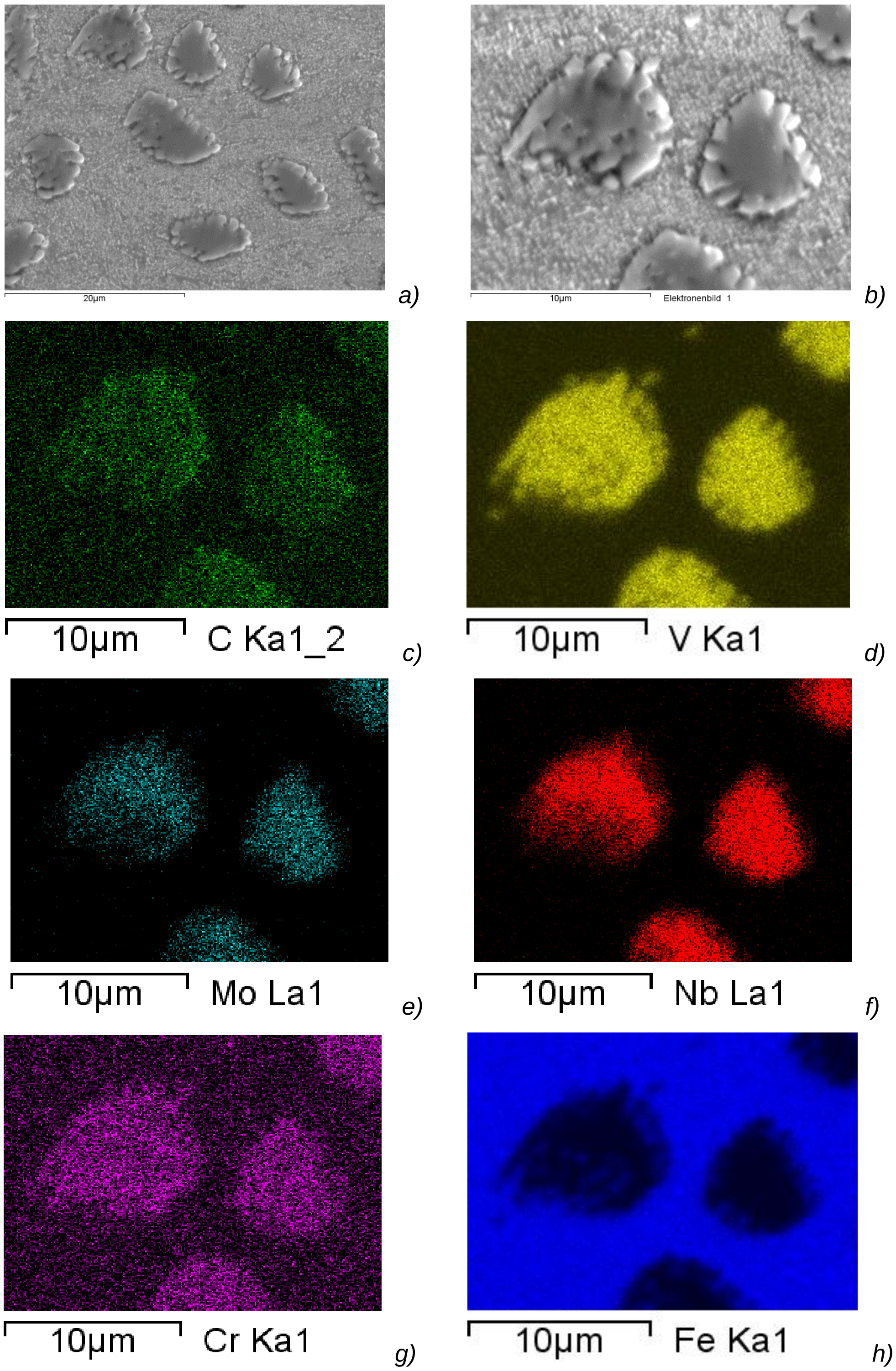

Figure 4. Partially dissolved MC carbides (SEM): a - overview image (3000:1), b - detail (6000:1) and EDX mapping to determine the element distribution (c - h) [25]

Slika 4. Delimično rastvoreni MC karbidi (SEM): a - pregledna slika (3000:1), b - detalj (6000:1) i EDX mapiranje za određivanje raspodele elemenata (c - h) [25]

The thermal shock index values indicate that compared to the other roll materials, such as chromium iron and ICDP rolls, HSS rolls have a significantly better resistance to thermal fatigue (Table 2).

Table 2. Thermal shock index of different roll materials [30,31]

Tabela 2. Indeks termo šoka različitih materijala za valjke [30,31]

Roll grade	HSS	HCrI	ICDP
Thermal shock index (W/m)	5737 5545	3919	3003 3515

Fire cracking is initiated when the roll surface temperature in the roll gap exceeds a critical limit temperature. Table 3 lists the limit temperatures for the various roll materials. These were calculated for the work rolls with a diameter of 800 mm, strip temperature 1020°C, rolling speed 1.5 m/s, contact time 0.044s, pass reduction 11mm and roll temperature 60°C [32].

Table 3. Comparison of the limit temperatures of HSS, HCr and ICDP rolls

Tabela 3. Poređenje graničnih temperatura HSS, HCr i ICDP valjaka

Parameter	HSS	HCr	ICDP
Roll surface temperature in roll gap (°C)	542	551	563
Limit temperature (°C)	545	483	382

The results presented agree with practical experience, according to which the material stability against fire cracking increases from ICDP to HSS:

ICDP → chromium iron → chromium steel → HSS *(2)*

Compared to conventional HSS rolls, the semi-HSS rolls contain lower levels of carbon (<0.9%) and carbide-forming alloying elements. This leads to a reduction in the carbide content of up to 4-6 wt.%. Due to this, the semi-HSS rolls show excellent biting as well as high strength and toughness values. The hardness of 72 to 78ShC and the application properties of HSS rolls mentioned above lead to successful use in roughing stands.

Work rolls for the finishing trains

In the first stands of the finishing trains (F1-F3 or F1-F4), both the chromium iron and the HSS rolls described above are used, with the last one having a 2 up to 4 times higher performance.

The structure of cast chrome rolls consists of chromium-rich, eutectic carbides of the M_7C_3 type (20-30%), which are present in the martensitic matrix. The cast chrome rolls have a hardness of 75-80 ShC and constant rolling behavior up to the final diameter, as well as good oxidation resistance. The tensile strength of such rolls is 600-700 N/mm² and the bending strength is 900-1000 N/mm². A high yield strength at elevated temperatures reduces plastic deformation of the roll working layer under cyclic loads and increases fatigue resistance. This leads to a better surface quality of the rolled product and increases roll life. The cast chrome rolls do not show any drop in hardness, which leads to a significant increase in wear resistance compared to conventional indefinite chill rolls (ca. 1.5 to 2 times). The cast chrome rolls are manufactured as compound castings. Cast iron with nodular graphite is used as the core material.

In the last finishing stands (F4-F6 or F5-F7) of several hot strip mills, the Indefinite Chill Double Pour rolls (ICDP) with a hardness of 73-79 ShC and 78-84 ShC are used. Today, ICDP rolls are mostly manufactured using vertical or horizontal centrifugal casting processes. Cast iron with spheroidal graphite is used as the core material, cast iron with lamellar graphite is rarely used. The microstructure of ICDP rolls consists of a bainitic/ martensitic matrix, M_3C carbides (35-40%) of a ledeburitic structure and free graphite. ICDP rolls show a relatively small drop in hardness within the working layer and ensure high strip quality, but only offer a limited service life. Due to the frequent roll changes, the ICDP rolls are a bottleneck for the rolling mill, since the work rolls in the front rolling stands remain operational for a long time. The forced interruption of production to change rolls reduces the production efficiency of the rolling mill.

The use of conventional HSS rolls in these stands, which have a 4 to 5 times higher wear resistance compared to ICDP rolls [33], is due to the low resistance to cobbles, sticking and inferior crack resistance very limited [34].

In order to eliminate the disadvantages of the above materials, the ICDP rolls were developed, which were additionally alloyed with molybdenum, vanadium, tungsten, niobium and titanium (so-called ICDP-enhanced). The development strategy was to introduce the fine secondary carbides (MC), as in HSS, into the matrix of ICDP rolls made of tempered martensite and eutectic M_3C carbides (20-30%) and was intensively pursued [18, 34-38]. This resulted in a qualitative improvement in the wear resistance of the ICDP rolls, but hopes for a breakthrough in roll performance anticipated in the field were not met. An increase in performance of about 10-20% [39, 40] (18-26% according to [41, 42], 20-50% according to [33]) was registered compared to conventional ICDP rolls, which roll consumers was considered insufficient. In the front finishing stands (F1-F3) where the HSS rolls are used, the roll capacity between cuts is 5000-10000 t, which compares to the capacity of ICDP rolls (1500-2000 t) in the last finishing stands (F4-F7) exceeded several times [33].

A further improvement of ICDP rolls was achieved using thermal analysis [43]. It was found that ICDP rolls can perform optimally when the content of free graphite in the matrix is between 2 and 4% by volume and the graphite is distributed homogeneously over the entire cross-section of the working layer [44]. The control of the graphite content was achieved through the targeted use of inoculant. The optimization of the graphite content has increased the roll capacity by about 18-26% [41,42], but has not solved the problem in the last finishing stands.

As an alternative and promising solution to the problem, the development of graphitized HSS has been intensively studied and developed [28,40,45-51]. The aim of these investigations was to combine the advantages of ICDP and HSS rolls, i.e. to enable the precipitation of free graphite in addition to the primary and secondary carbides that are embedded in the martensitic matrix (Fig. 5).

Figure 5. Microstructure graphitized HSS [50]

Slika 5. Mikrostruktura grafitiziranog HSS [50]

The free graphite, which acts as a lubricant between the roll and the rolling stock [33,52], prevents adhesion between the friction partners and the sticking of the strip to the roll surface, which is particularly important for the work rolls in the last finishing stands. In the rolls made of graphitized HSS, the graphite content ranges from 2 to 5%. The graphite precipitates are about 10-50 µm in size [40]. In order to adapt to the relevant operating conditions, the required carbide and graphite proportions in HSS rolling can be achieved through the chemical composition and the heat treatment. With the use of rolls made of graphitized HSS in various rolling mills, a significantly increased performance was achieved.

In a medium-wide strip mill, the work rolls made of graphitized HSS showed a performance increase by a factor of 2.3 compared to ICDP, combined with a significantly improved surface of the final rolled product. In addition to the increase in performance, the roll abrasion between uses was reduced from ca. 0.4 mm to ca. 0.2 mm (in diameter) [48,50,51].

Work rolls made of graphitized HSS used in the 5th stand of a wide strip mill have shown a 1.8 times higher performance compared to ICDP-enhanced rolls [33,47,49]. The roll surface abrasion was reduced from about 0.39 mm to about 0.15 mm.

According to [41,42], the work rolls made of graphitized HSS show a significant increase in performance when used in a 7-stand wide strip mill. Compared to ICDP, the roll capacity increased to 160% in the 4th stand, to 154% in the 5th stand and to 47% in the 6th stand.

The developed grades of graphitized HSS have the potential to achieve better synchronization of roll changes in the last and front stands and to save significant costs. Nowadays ICDP, ICDP-enhanced and graphitized HSS rolls are used in the last finishing stands.

Core materials for compound cast rolls

Cast iron with nodular graphite (Fig. 6) is used as the core material for composite rolls, which ensures the necessary strength of the core and shell.

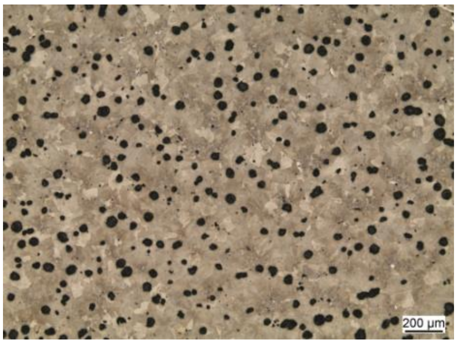

Figure 6. Cast iron with nodular graphite for core of compound rolls [8]

Slika 6. Liveno gvožđe sa nodularnim grafitom za jezgro kompozitnog valjka [8]

The mechanical properties of the nodular iron core materials are in the range of 615-625 N/mm² (tensile strength) and 820-1090 N/mm² (bending strength). The fatigue strength (10^7 rotating bending load changes) is approx. 150 N/mm². The transition zone between the shell and the core is very narrow and free from non-metallic inclusions, cavities, micropores and accumulations of large carbides (carbide inhomogeneity), Fig. 7.

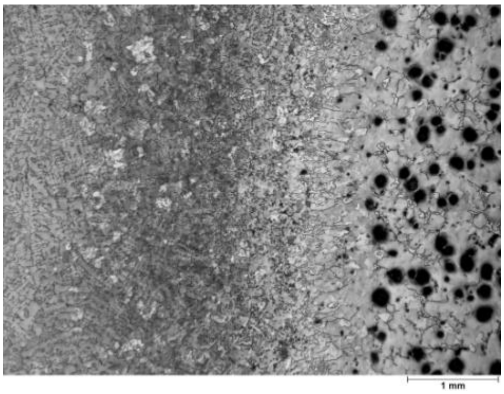

Figure 7. Microstructure in the transition zone of an HSS roll [28]

Slika 7. Mikrostruktura prelazne zone HSS valjka [28]

In recent years, the requirements for the quality of the necks have increased significantly, which is associated with a tendency to minimize the number of passes during rolling and the corresponding increase in the rolling forces used. The higher strength properties are achieved by means of a higher nickel content (1.0-1.1%). A higher elongation of the neck material (>1%), which has been requested more and more frequently by rolls users in recent times, is achieved through the use of modern inoculants.

3. CONCLUSION

The ever-increasing customer requirements with regard to strength properties, thickness and dimensional accuracy and the surface quality of the final rolled product are accompanied by a corresponding tightening of the roll application conditions and the increasing demands of the steel industry on the quality of the rolling mill rolls. In order to meet these conditions, continuous development and optimization of the materials for rolls and the roll manufacturing process is required.

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IZVOD

SAVREMENI MATERIJALI ZA LIVENE VALJKE U VALJAONICAMA ZA TOPLO VALJANJE LIMOVA

Prikazani su zahtevi za radne valjke različitih stanova valjačkih pruga za toplo valjanje lima. Analizirani su savremeni materijali za livene valjke i opisane su operativne performanse različitih vrsta valjaka u različitim stanovima valjačkih pruga. Predstavljeni su trendovi u poboljšanju performansi valjaka.

Ključne reči: *liveni valjci, mikrostruktura, martenzit, karbid, mehanička svojstva*

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