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Rings for compound rolls of rolling mills

ABSTRACT

Modern materials for producing rings for compound rolls and their most important application properties are described. The advantages and disadvantages of rings made of cemented carbide, high-speed steel, ceramic materials and their damage mechanisms are analyzed. The structure of composite material rings made of cemented carbide/ iron-based alloys, HSS rings manufactured using powder metallurgy and melt metallurgy, and rings made of silicon nitride are described.

***Keywords**: ring, compound roll, cemented carbide, high-speed steel, silicon nitride, clamping system*

1. INTRODUCTION

The roll rings are the interchangeable components of the composite rolls that are used in the intermediate and finishing stands of wire and bar steel, light section and pipe rolling mills. The roll rings are mostly made of cemented carbide and high-speed steel. The rings made from such materials are usually manufactured using powder metallurgy processes (hot isostatic pressing). Depending on the operating conditions, the roll rings are manufactured with different properties. In order to adapt to the user's requirements, a number of material groups and material qualities have been developed that are used in the production of roll rings.

2. MATERIALS FOR ROLL RINGS

Cemented carbide

The roll rings are mostly made of cemented carbide (WC-Co). The tungsten carbide has absolute wettability with cobalt and the ability to assume a faceted shape in sintered cemented carbidealloys. The cemented carbide rings are used in hot and cold rolling. During hot rolling, the cemented carbide rings are used in:

- Wire rod finishing mills
- Wire rod intermediate mills
- Cantilevered stand mills for rounds and shapes
- Merchant bar mills – rounds, rebar, shapes
- Pinch rolls – guide rolls
- Roller entry guides

During cold rolling, the roll rings are used in:

- Cluster mill work rolls
- 2-Hi narrow strip mills
- Wire flattening and forming mills
- ERW tube mills
- Turks heads[1].

The rings can be made with or without a caliber. The use of cemented carbide rolls leads to [2]:

- Long caliber service life by significantly reducing wear, especially at high rolling speeds
- Higher dimensional accuracy and dimensional accuracy as well as surface quality of the rolling stock, especially in multi-core rolling mills
- Longer service life compared to conventional roll materials, which leads to fewer wear-related roll changes and a significant increase in productivity of the rolling mill
- Possibilities of producing high-quality thin cold strip due to insignificant roll flattening and low coefficient of friction.

The reliability and service life of the rings depend on the operating conditions in a particular rolling stand. Depending on these, the rings are made from alloys that differ in the WC/binding metal ratio. In these materials, the binding metal content can range from 4.5% to 31.5% and will determine the mechanical and thermo-physical

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properties of the cemented carbide, such as hardness, density, fracture toughness, compressive strength, modulus of elasticity, thermal conductivity, coefficient of thermal expansion, etc. strongly influenced. The required operational properties of the cemented carbide will be achieved through a desired compromise between the opposing properties such as hardness and toughness as well as the other important operational properties of the cemented carbide. The rings made from such materials have the following advantages:

- Homogeneous, segregation-free structures with carbides of a defined grain size evenly distributed in the basic structure
- Homogeneous properties
- Near-net-shape raw components.

The cyclical temperature changes and high mechanical roll loads in the slow-running front intermediate stands of the rolling mills can lead to the formation of so-called “orange peel” on the caliber surface as well as quite deep cracks beneath the surface. These often lead to breakage. In order to avoid such damage, the roll rings made of tough cemented carbides types are used in these rolling stands, which contain 25 - 30% binder and have a hardness of 78.0 – 81.0 HRA. The slightly lower hardness and wear resistance of these “soft” cemented carbide rings are offset by increased strength, toughness and thermal fatigue resistance. The roll rings made of slightly harder types of cemented carbides are used in a finishing block of the high-speed wire rolling mills [3, 4]:

- in the front rolling stands, roll rings with a hardness of 83.8 to 84.1 HRA are used (binder content 20 – 15%, respectively)
- in the middle rolling stands, rings with a hardness of 85.7 – 84.1 HRA and a binder content of approx. 15% are used
- the rear rolling stands are equipped with hard roll rings (87.2 – 88.3 HRA, binder content 10 – 8%, respectively).

When rolling ribbed reinforcing steel, cemented carbide alloys with 25 – 30% binder are used in the finishing block, which can withstand the notch effect of the grooves and have better mechanical machinability of the rings.

The rings made of cemented carbide grades (87.7 – 87 HRA) with a binder content of 8 – 10 % are also successfully used in sizing mills.

The cemented carbides roll rings have excellent wear resistance with uniform wear, which is associated with the high hardness of tungsten carbide grains and their uniform distribution in the microstructure. The Knoop hardness of the WC grains can vary between 2500 and 1000 depending on the crystal plane and direction [5]. The cemented carbides still have a sufficiently high hardness even at 1000 °C. The WC grain size influences the properties of the cemented carbide. The grain sizes of cemented carbide rolls are generally between 0.7 and 7.0 µm [1]. Coarse-grained WC powder is most commonly used for the production of roll rings. Although increasing grain size for a given binder content reduces wear resistance, it increases toughness. With regard to thermal fatigue, experience shows that a coarse grain tungsten carbide grain is superior to medium or fine grain grades. Therefore, larger grain sizes are very important in hot rolling. Finer grains, on the other hand, improve wear resistance and compressive strength and are therefore often used in the cold rolling process [1].

Compared to highly wear-resistant iron-based alloys (such as high-alloy hot-work steels, high-chromium steels, high-speed steels), the cemented carbides used in rolling mills have a significantly lower coefficient of thermal expansion of 5,3 – $8.2 \cdot 10^{-6}$ 1/K, which has a major influence on the fatigue strength of cemented carbide. The thermal expansion of the cemented carbide decreases with increasing tungsten carbide content and increases with increasing cobalt content.

The very high values of elastic modulus (420–630 GPa), hardness (78 – 89 HRA, and compressive strength (3000 – 4300 N/mm²), of the cemented carbide ensure high rigidity of the ring and enable its very high resistance to elastic deformation in the deformation zone, which leads to a significant reduction in ring flattening. This also enables higher reductions with the same rolling forces lies in improving the accuracy of the rolled product.

The main types of cemented carbide ring failure arewear,thermal fatigue, mechanical shear due to tangential stress, and corrosion. Ring wear is manifested in the sliding friction of the rolled metal on the surface of the caliber due to the different speed of their movement at the entrance and exit from the deformation zone. Small thermal fatigue cracks may appear on the roll work surface caused by the cyclic temperature changes. The service life of the rings in use is limited by the formation and growth of cracks. A low resistance of the cemented carbide to thermal fatigue is compensated for by the use of efficient cooling systems. Compared to iron-based alloys, the cemented carbide has twice the thermal conductivity (85 – 120 W/m·K) and the heat penetrates deeper into the rolls. The thermal conductivity of cobalt is 100 W/m·K. Rolls withcemented carbide rings must always be cooled during hot rolling and the cooling systems should have a built-in warning system coupled to a flying shear to allow the workpiece to be sheared in the event of a drop-in water pressure.This requires effective ring cooling to prevent heat transfer from the surface to the deeper areas of the composite roll. Intensive roll cooling is particularly required in the front rolling stands, where the rolling stock has a significantly higher temperature and the contact area of the roll and the rolling stock is larger than in the rear rolling stands. In the front rolling stands, the rolls rotate at a lower speed, which leads to a longer contact time between the roll and the rolling stock and thus promotes heat transfer. The resulting microcracks will slowly propagate from the surface into the depth of the ring. The crack surfaces are attacked by corrosion due to constant contact with the cooling water, which can lead to a decrease in the strength of the cemented carbide and can affect the wear resistance of cemented carbide rings [6-8]. Binder corrosion leads to a decrease in the bond between neighboring carbide grains, which promotes the spalling of individual carbides. The significant differences in the thermal expansion coefficients of WC ($5.4 \cdot 10^{-6}$ 1/K) and cobalt ($12.3 \cdot 10^{-6}$ 1/K) play an important role. The presence of large carbides in the structure or their accumulation can lead to a further accumulation of local stresses, which can lead to a weakening of the boundaries of the carbides and the binders. The individual carbide grains or grain agglomerates can therefore easily be detached or sheared off and can form a crater. The interaction of neighboring cracks can also lead to crater formation. The resulting hills can be sheared off. The detached WC grains that can enter the deformation zone will themselves have an abrasive effect. The effect of abrasive wear can also be enhanced by oxides of the rolled metal, which can enter the deformation zone. The separation of WC grains causes roughening of the caliber surfaces. As the rolls continues to operate, the crack formation in these damaged areas can be increased by diffusion processes and corrosion and can lead to ring breakage.The problem of roll fatigue is therefore purely a problem of crack growth. To reap the benefits of carbide rings, all surface cracks must be eliminated. Before the cracks on the caliber surface reach a depth of 1 – 1.5 mm, it should be regrinded [8]. A ground roll surface must be free of microcracks. The remaining cracks immediately begin to grow when the roll surface comes into contact with the hot rolling stock.

The quality of the cooling water is also very important for the successful use ofcemented carbide rings and the requirements for the cooling water are high. When the pH is high (about 8.5), the Co-binder has good corrosion resistance. A more acidic environment can lead to accelerated erosion of the cobalt binder. At pH below 7.5, cobalt alloys tend to electrochemical corrosion and the corrosion rate is very high. The rate of corrosion varies depending on the type of carbide and is generally inversely related to that of the binder content. The types of cemented carbide that contain nickel in the binder phase have a higher corrosion resistance than the types with a Co-binder [8]. The use of cemented carbide rings with binders containing chromium can minimize the corrosion rate.Multi-component cemented carbide grades such as WC-(Co-Ni) and WC-(Co-Ni-Cr) were developed, which have higher corrosion and temperature resistance [3, 4, 8-11]. Such materials are used at low pH values. Through a controlled pH value and the addition of calcium during the rolling process, the cemented carbide can be coated with a protective film of $CaWO_4$ and thus protected against corrosion [1].

In addition to the water flow, which can be from 10 to 50 m^3/h depending on the rolling stand, and the water pressure (from 2.8 to 5.5 baragain depending on the rolling stand) the purity and low ion content of water must be guaranteed, especially with regard to chlorides and sulfates [12]. The recommended water analyzes are (µg/L): chlorides 40 max, sulfates 75 max, nitrites/nitrates 2 max, $CaCO_3$ 200 max; suspended solids 80 max; total basicity 100 max; iron 25 max; pH 7.5 to 8.5 [3] or chlorides 40 max; sulfates 75 max; nitrates 3 max, $CaCO_3$ 400 max; suspended solids 80 max and pH value 8 to 8.5 [8].

Another factor for the successful use of tungsten carbide rings in rolling mills is the temperature of the cooling water. It should not be higher than 32 – 35°C [1] and should not exceed the ambient temperature by more than 6°C [3]. The difference between the temperature of the cooling water and the surface temperature of the ring should not be greater than 10°C [8] or 14°C according to [3]. The water jet should generally be approximately twice as large as the width of the caliber. In addition, attention should be paid to suitable cooling systems for sufficient cooling [1, 3, 8, 10].

A low fracture toughness of the cemented carbide (K_{1C} = 14.2 – 28.5$MPa \cdot \sqrt{m}$), which limits the shrinkage of the rings on the steel shafts, as well as a 10 – 50% lower impact resistance can limit the transmission of torque via springs and wedges in some cases [13].When rolling with the use of cemented carbide rings, excessive reductions and the increased coefficient of friction must be avoided, especially when rolling alloyed steels that are difficult to form. The optimal cross section of the cemented carbide ring must also be considered.

The calculation of the elastic deformations of roll rings and rolling shafts, especially in the fillet, with the introduction of high loads (rolling forces, torques) in the prestressed compound rolls as well as the stress distribution in their bodies during the rolling process are carried out using mathematical methods based on finite elements occurs [14, 15].The contact conditions are defined for the compound rolls and for the rolling stock and are simulated together with all rolling parameters. The software available makes it possible to determine the mechanical stress on rolls (stresses and deformations) based on the rolling parameters (rolling force, torque, contact surfaces, etc.).

The use of cemented carbide roll rings is characterized by its particular cost-effectiveness. Despite the significantly higher manufacturing and processing costs of the cemented carbide roll rings compared to conventional cast materials, their use in high-performance wire mills makes economic sense due to the significantly increasing campaign length [16-18]. The higher fatigue strength of the cemented carbide and the minimized wear meant that redressing could be reduced. Cemented carbide rings increase groove life by a factor of 10 in rolling special steel bar [19, 20] and have at least 15 times longer life than rings made from AISI D2 tool steel in rolling bar steel [21].

Cemented carbide composite materials

When producing cemented carbide composite materials, the melt of high-quality cast iron is cast around the inner surface of a cemented carbide ring (cast-in carbide or CIC-process) [22]. The cemented carbide binder (cobalt) that comes into contact with the melt is melted and dissolved in the penetrated cast iron. The cobalt is completely replaced by cast iron and only traces of cobalt are observed in the newly formed binder.

The WC particles are well wetted by cast iron melt, which stabilizes the formation process of the composite layer.The penetration depth is proportional to the overheating of the cast melt. The greatest depth of penetration is achieved when using alloys with the widest solidification interval. The alloys with the narrow or not wide enough solidification interval solidify very quickly and the poured melt does not penetrate into the hard metal. As a result – no connection of two materials. The penetration depth depends heavily on the casting temperature of the cast alloy.This must be at around 350°C above the melting point in order for penetration to occur, as the cemented carbide ring will act like a permanent mold and the solidification rate of the melt will be greatly accelerated, which prevents or greatly impairs the penetration of the melt.

The very fine WC particles that come into contact with the melt are partially dissolved. In the areas of the cast iron melt close to the bond, the new tungsten carbides are formed, which have a completely different morphology and sizes.In the area of the tungsten carbides formed, the matrix is depleted of carbon and a pearlite veil forms around tungsten carbide. Practical experience shows that both the tungsten carbides formed and the pearlite veil will not affect the strength of the composite or the overall performance of the rings. The investigations of the mechanical properties of the composite have shown that the composite material formed has a strong metallurgical bond. The graphitization of cast iron is not suppressed by small amounts of dissolved tungsten. The graphite precipitates are observed in the composite zone to a depth of approx. 700 µm.A comprehensive study of the microstructure is presentedin the separate article [23].

The development of cemented carbide composite materials has solved the problem of torque transmission. The tough and easy-to-machine ductile iron transfers the torque to the cemented carbide area of the rolling ring. This manufacturing process makes it possible to save around half of the expensive cemented carbide, which significantly reduces the manufacturing costs of the rings. The unique CIC (Cast-in-Carbide) ringsare successfully used in more than 100 rolling mills worldwide and have a service life up to 20 times longer than conventional cast rolls, which has a significant impact on downtime costs [12, 22]. In pipe rolling mills, the CIC rolls have a service life that is up to 40 times longer than conventional cast iron rolls, with excellent surface quality, tolerances and geometry of the rolled pipe [22].

In order to avoid a negative effect of the brittleness of the cemented carbide, cemented carbide/steel composite rings were developed [24]. The rings are manufactured as a material composite made of cemented carbide and Invar alloy using hot isostatic pressing. The composite materials have a comparable coefficient of thermal expansion, which corresponds to around two thirds of the HSS value, so that only low stresses occur in the composite.

Another material composite developed consists of cemented carbide, Invar alloy and tool steel. The resulting mechanical and thermal stresses are reduced by the Invar alloy, which serves as a buffer in this composite combination [25]. The rings can be shrunk or connected to the shafts using side or bore keys. The torque transmitted from the drive shaft to the steel area is transmitted over a large area to the integrated, wear-resistant cemented carbide ring via an Invar layer. Such rolls are used in cantilever middle mills, in flat rolling and in tube rolling.

High speed steel

Powder metallurgical process (PM process)

The roll rings made of high-speed steel (HSS) produced using powder metallurgy are successfully used in the rolling of steel profiles (wire and round steel, angle and special profiles). The areas of application of HSS roll rings depend on the operating conditions. When rolling wire and bars, the HSS roll rings are used in the intermediate stands and in the pre-finishing stands. When rolling reinforcing bars, the roll rings are used in the intermediate stands.

The HSS roll rings manufactured using powder metallurgy can be designed with or without a caliber [26]. The rings have a homogeneous, pore-free structure. The microstructure contains approximately 20% by volume of carbides with a size of 1 to 5 µm, which ensure exceptionally good wear resistance with the maximum possible toughness of the HSS. The carbide size plays an important role in the propagation of an emerging crack in the basic structure. The small carbides lead to frequent crack deflection or to delaying or stopping the crack. Despite a lower hardness (50 – 64 HRC) compared to carbide rings, HSS rings have a long service life and a uniform wear profile, which is associated with a fine-grained, segregation-free microstructure and evenly distributed, fine, globular-shaped VC carbides is. A high-volume fraction of these carbides leads to high wear resistance and service life of the rings. The HSS rings retain both hardness and wear resistance up to the minimum diameter. The modulus of elasticity of such steels is around 230 – 240GPa, which reduces roll flattening.

Although the powder metallurgy-produced HSS rings have a low thermal conductivity (26 W/m·K), they must be cooled intensively due to a higher thermal expansion coefficient ($11.6 \cdot 10^{-6}$ 1/K), which slows down thermal fatigue cracking.During hot rolling, a firmly adhering oxide layer forms on the ring surface (Figure 1, Table 1).

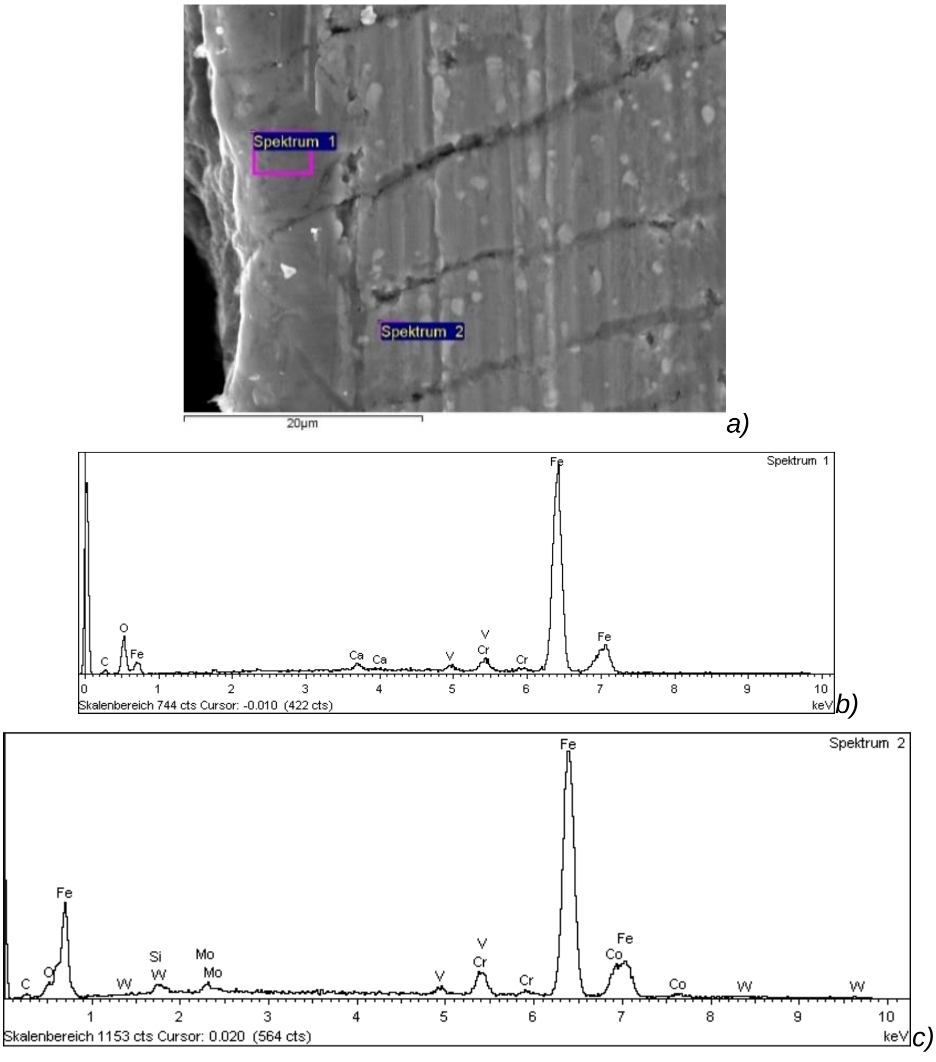


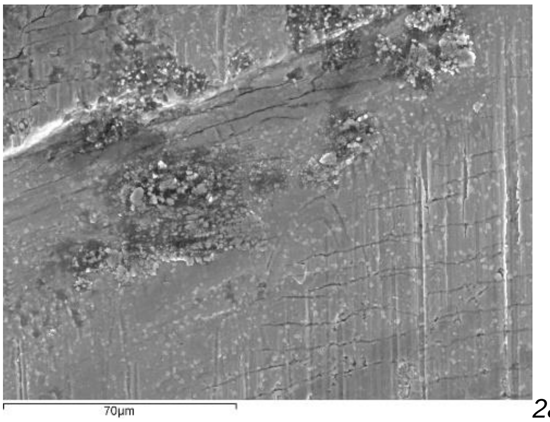
Figure 1. Oxide layer on the caliber surface: a – microstructure (SEM image)with the position of the EDX analysis; b – EDX analysis of the oxide layer; c – EDX analysis of the matrix

Table 1. EDX analysis of the caliber surface (mass%)

Spectrum	O	Si	Ca	V	Cr	Fe	Co	Mo	W	C	Total
1	10,43	-	0,91	1,12	2,52	81,62	-	-	-	3,40	100,00
2	1,97	0,50	-	0,86	3,98	76,20	8,90	2,38	1,79	3,42	100,00

The hard oxide layer protects the ring surface from intensive wear and acts as thermal insulation, which helps to reduce the contact temperature in the tribosystem "rolling stock - work roll" and leads to a reduction in heat transfer from the rolling stock to the rolls, which prevents or slows down the formation of thermal fatigue cracks on their surface. The stability of the oxide layer (formation and growth rate, thickness) depends on the chemical composition of the HSS. The improvement of the corrosion resistance of HSS and the formation of the desired iron oxide layer is achieved by a high chromium content in the steel (approx. 4.5 – 6%). Other elements that are crucial for corrosion resistance (molybdenum and nitrogen) will primarily increase the resistance to pitting corrosion.

Figure 2 shows the surface of a powder metallurgically manufactured HSS rolling ring after use with thermal fatigue cracks and areas of corrosion.



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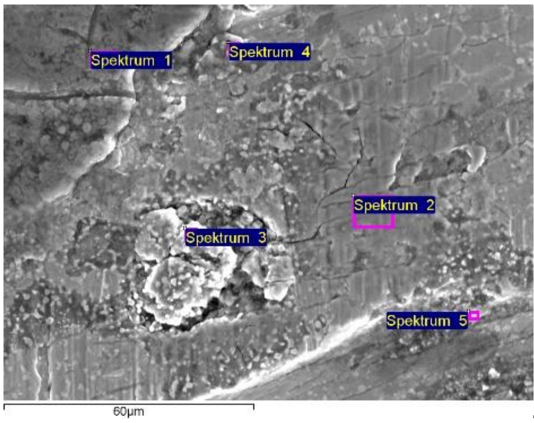

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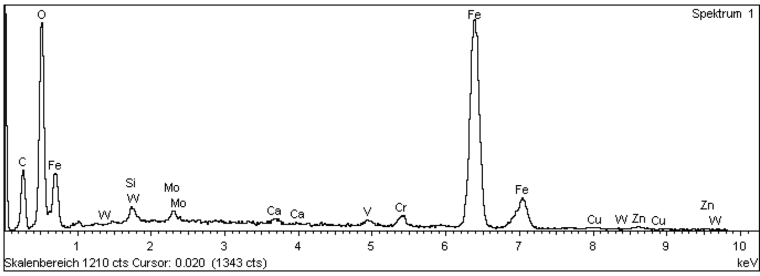

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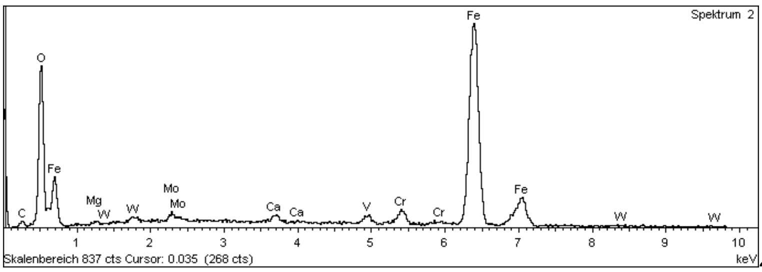

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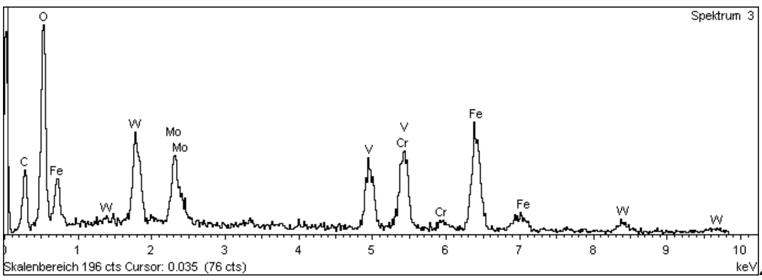

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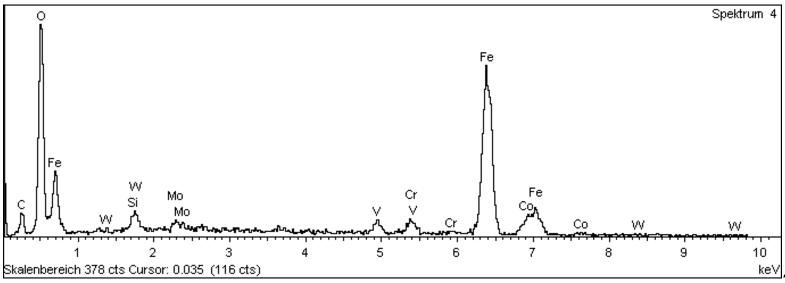

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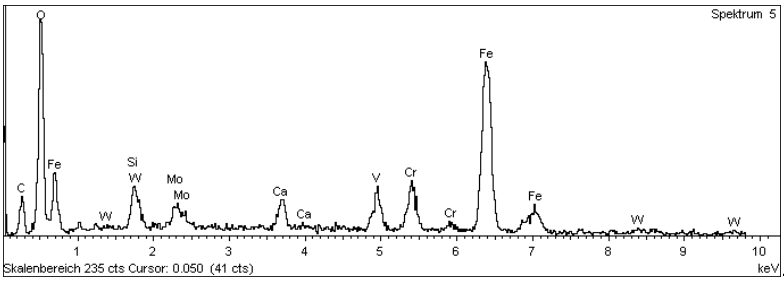
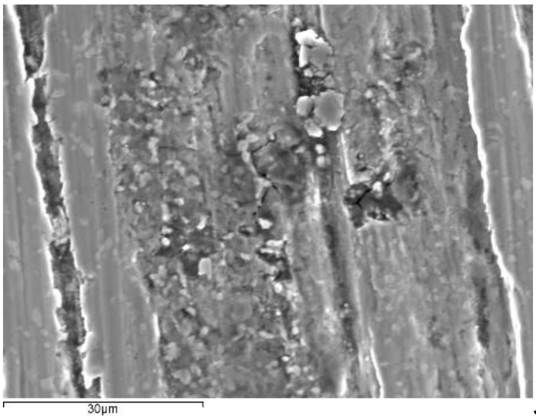


2g)

Figure 2. Thermal fatigue cracks with corrosion areas of an HSS rolling ring: a –surface appearance(SEM image);b – detail with the location of the EDX analysis; c, d, e, f, g – EDX analyzes of the matrix (c, d, f) and MC mixed carbide (e, g)

The corrosion attacks both the matrix and the carbides. The oxidation of carbides under cyclical action of dynamic and thermal loads can lead to the formation of cracks on their surface. This facilitates the carbide decomposition or detachment from the matrix. The calcium identified comes from the water used for ring cooling. Metallographic investigations in the areas of the resulting thermal fatigue cracks showed that their edges are heavily oxidized (Figure 3).



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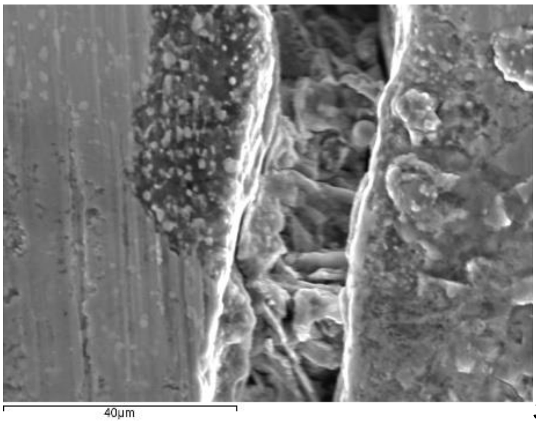

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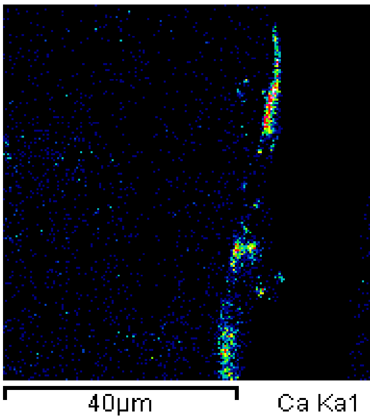

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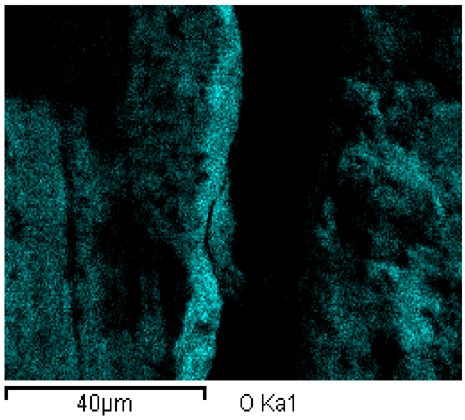

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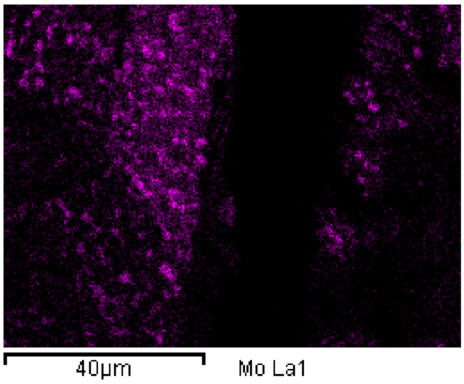

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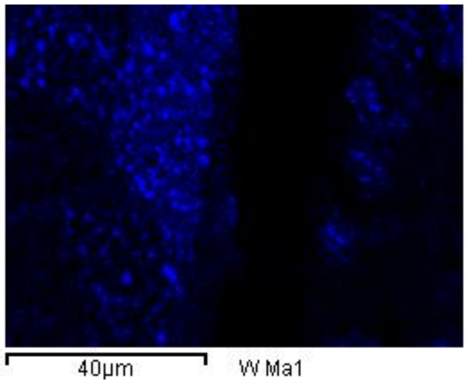

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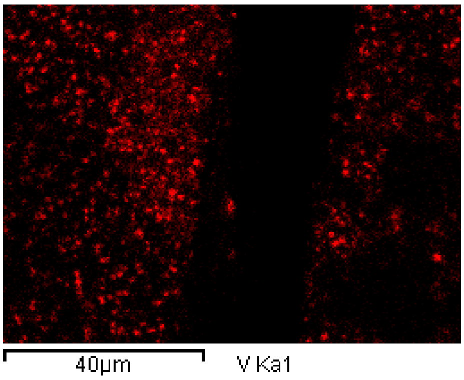
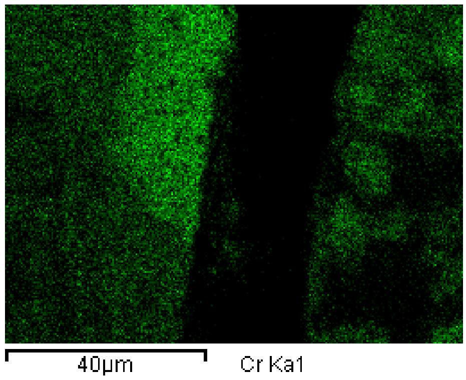


3g)



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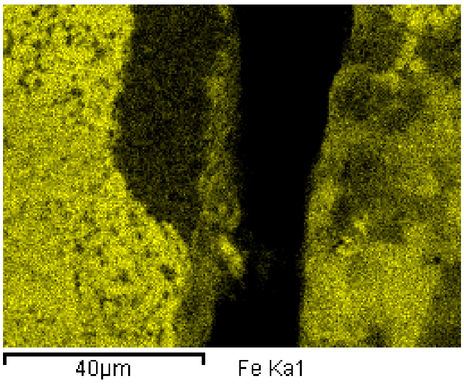

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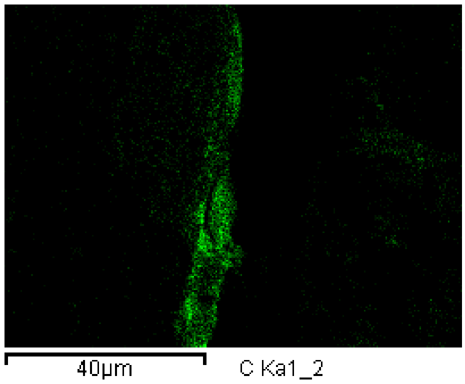
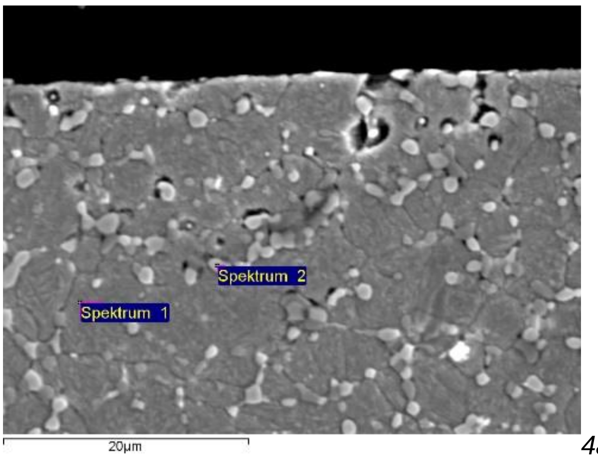


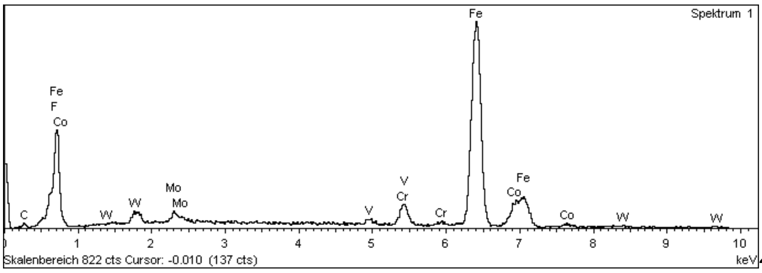
3k)

Figure 3. Element distribution in the area of a crack: a – microstructure(SEM image);b – microstructure detail; c, d, e, f, g, h, j, k– mapping

Since the martensitic matrix of HSS is softer than VC carbide, if the ring is used for too long (or depending on the type of steel being rolled), it can be washed out (Figure 4).



4a)



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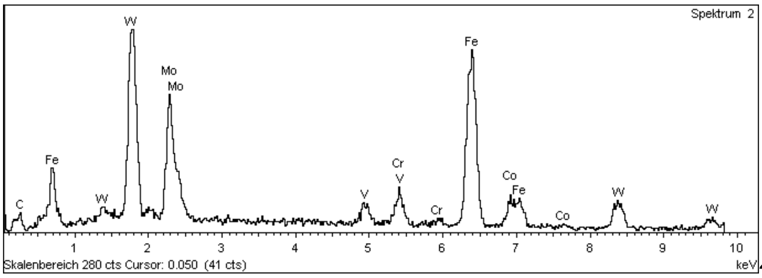


4c)

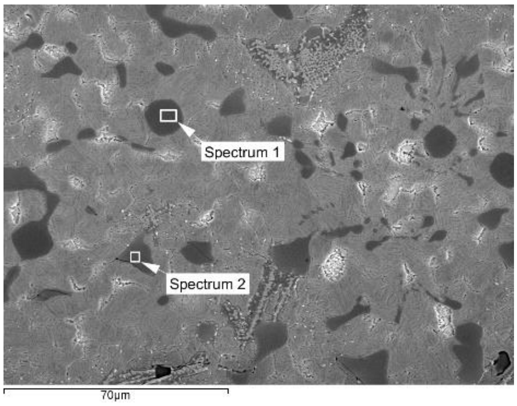
Figure 4. PM steel ring after use (cross section): a – location of the EDX analysis(SEM image);b –matrix; c – MC mixed carbide

This will compromise the mechanical support of the carbides and facilitate carbide separation from the ring surface. The roughness of the caliber is affected and the formation of cracks in the ring body is promoted.

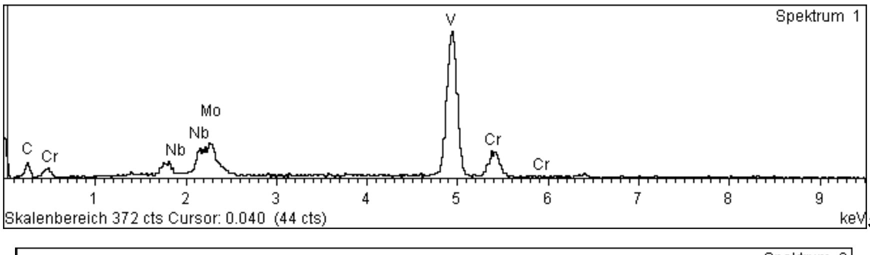
HSS cast materials

The manufacturing processes described above are energy and cost intensive. Nowadays, cheaper rolled rings that can be manufactured using the casting method are in demand on the market. These are also used effectively with the shorter campaign length. In order to meet the requested requirements of users, ring manufacturers have developed HSS casting grades that are alloyed with different combinations and contents of carbide-forming elements such as Cr, Mo, V, W, Nb and Ti. Depending on the chemical composition and heat treatment parameters, the hardness of the HSS rings varies from 60 to 64 HRC.The microstructure of these materials consists of tempered martensite with a high proportion of embedded primary and secondary carbides and exhibits higher wear resistance even at higher surface temperatures.

Figure 5 shows the structure of a ring made of V-Mo-Cr-W-Nb alloyed HSS casting quality that was developed by us in recent years [27, 28].



5a)



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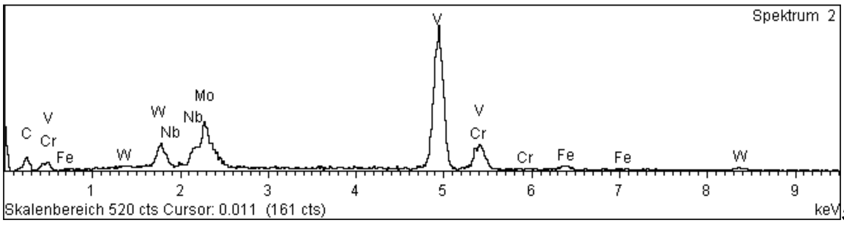

5c)

Figure 5. Microstructure of an HSS ring: a – overview with the location of the EDX analysis (SEM image), b, c – EDX analyzes of MC carbides

The optimal contents of alloying elements and structural components used were determined using ThermoCalc software. In thermodynamic equilibrium, the developed alloy contains approximately 26% by volume of carbides. The majority (approx. 10.4% by volume) is made up of type MC carbides. A high-volume content of VC carbide in the matrix is desirable. The VC carbides have a high hardness (2800 –3000 HV), which is not reduced even at higher temperatures [29], which leads to a high reduction in wear.The morphology of eutectic carbides is influenced by the cooling rate. At high cooling rates, the eutectic does not form a closed network. The very fine MC carbides – mainly VC – are present everywhere in the structure and are homogeneously distributed. A homogeneous arrangement of primary MC carbides was achieved by the fact that the first nucleation sites precipitate out in the melt. The formation and growth of MC carbide is facilitated at these nucleation sites. The primary, face-centered cubic VC carbide contains small amounts of molybdenum, chromium, tungsten and niobium. After the heat treatment (hardening and tempering), the microstructure has a tempered martensite, globular-shaped primary carbides that were not dissolved during the heat treatment and contribute significantly to the good resistance of the material to abrasive wear. When tempering HSS, 10^{16} to 10^{18} 1/cm³ of fine (about 1 x 10 x 10 nm) secondary carbides precipitate from the martensite [30], which is saturated with carbon and alloy elements, which prevent the movement of dislocations according to the Orowan mechanism and thus harden the steel (secondary hardening). The residual austenite remaining as a result of incomplete martensitic transformation acts as a carbon source for secondary carbide formation during tempering. The secondary carbides increase the room temperature and hot hardness, tempering resistance and the thermal stability of the matrix. A secondary hardness maximum corresponds to the maximum crystal lattice strain as a result of the maximum density of the precipitated hardening phases. By increasing the strength of the matrix, the mechanical support of the carbides is increased and prevents them from tearing off from the contact surface.

After heat treatment, such rings have a uniform hardness of 66 to 67 HRC across the cross section and can be re-set several times until the minimum diameter is reached. The tensile strength of the material is 980 MPa. The compressive strength and fatigue strength of the developed HSS are approximately 480 MPa and 3430 MPa, respectively. The manufactured rings were clamped onto roll shafts made of steel [31]. Each roll was equipped with two HSS rings and the manufactured composite rolls were delivered to a rolling mill. The rolls were used in the 10^{th} roll stand of a steel bar rolling mill for rolling high-carbon steel (final diameter 8.5 mm). Figure 6shows the surface of an HSS ring after use.

Figure 6. Surface of an HSS ring after use [27, 28]

After use, the developed HSS rings show uniform surface wear and a dwell time in the roll stand that is desired from user. No fire cracks were registered on the work surfaces.

The developed HSS was also used for the production of rings for the Kocks block.

Compared to cemented carbide rings, the cast HSS roll rings have a lower risk of breakage and therefore a higher safety of the rolling process. The high-speed steels therefore represent a reliable and cost-effective choice of material.

Ceramic materials

As tungsten prices have risen dramatically in recent years, this has led to significant cost increases for users of cemented carbide products, which can contain up to 96% tungsten. This situation stimulates the search for new material science and technological solutions.

Although the high-speed steels have a significantly higher modulus of elasticity (230 – 240 GPa) than conventional iron-based materials (190 – 210 GPa), the HSS rolls cannot avoid flattening. Significantly higher elastic moduli can only be achieved with other materials such as high-performance ceramics. The ceramic materials have some positive properties or combinations of properties that are not achieved by other material groups. The great interest in ceramic materials is based on certain significant advantages compared to metallic materials, such as significantly higher stiffness (elastic modulus), higher strength, a lower coefficient of thermal expansion and very high wear resistance. The further advantages of ceramic materials compared to metallic materials include the significantly higher resistance to temperature changes, which are associated with medium thermal conductivity and low coefficient of thermal expansionof ceramic materials (Figure 7).

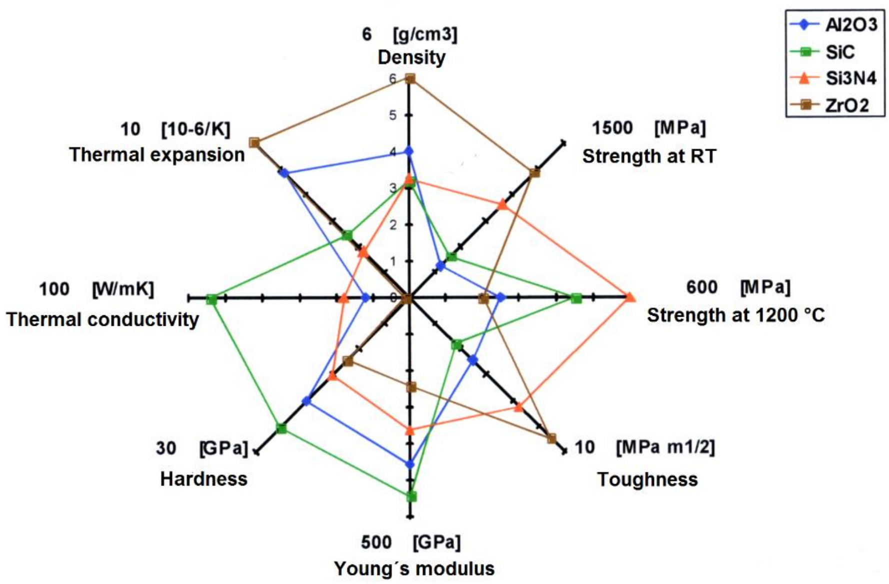

Figure 7. Comparison of the properties of high-performance ceramics [32]

Applications in rolling technology require ceramic materials that, in addition to high hardness and wear resistance, have high strength and crack toughness even at high temperatures. These materials must also have sufficient chemical resistance, in particular sufficiently high oxidation and corrosion resistance. These requirements are well met by many ceramic materials. In recent years, the suitability of technical ceramics as materials for rolls and other components of rolling technology has been intensively investigated. The ceramic rings for wire and bar rolls were made from silicon nitride (Si_3N_4), silicon carbide (SiC) and alumina-toughened zirconia (ATZ) and were used in rolling various types of steel. The last two ceramic types showed no measurable wear, but there were edge fractures, a fracture through the entire ring due to roll clamping, and edge fractures along the entire caliber [33]. The best results were achieved with silicon nitride. The Si_3N_4 composite rolls showed very little wear (max. height difference when comparing new and used calibers approx. 200 µm) and no cracks or breaks.

Silicon nitride occupies a promising position within non-oxide ceramics because it has a combination of many advantageous properties compared to other technical ceramics. Significantly higher strength values at room and higher temperatures as well as crack toughness lead to the long service life of Si_3N_4 composite rolls. This is associated with the unique needle-like or stalk-like structure of the fine-grained and evenly distributed Si_3N_4 grains and their mutual arrangement (Figure 8).

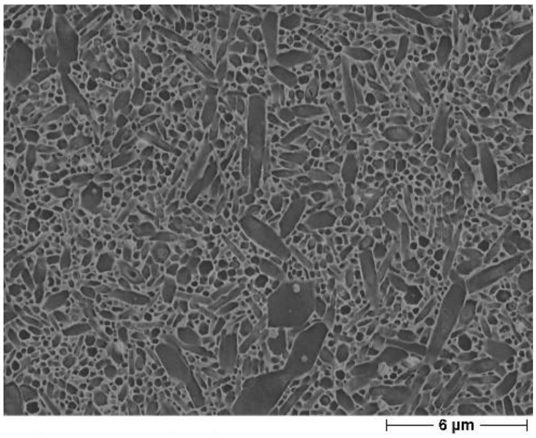

Figure 8. SEM image of a Si_3N_4 material (plasma-etched) [34]

As the Si_3N_4 starting powder is densified, the metastable α-Si_3N_4 modification transforms into the stable β-Si_3N_4 modification. The Si_3N_4 grains grow anisotropically to form needles with a hexagonal cross section. The main growth direction coincides with the c-direction of the Si_3N_4 crystal lattice. Since the starting powders are essentially globular, a texture-free structure of needle-shaped Si_3N_4 grains is formed when green bodies are sintered. The fineness and uniformity of the Si_3N_4 grains are important aspects for strength and high abrasive wear resistance [34]. The excellent high temperature properties of silicon nitride are related to the covalent bond. The excellent wear properties of Si_3N_4 rings lead to a smoothing of the roll surface and a significant improvement in the surface condition of the rolled product. We first observed this effect when rolling thin steel foils made of austenitic and ferritic steels in a 20-roll Sendzimir mill [35].The average wear rate is $2 \cdot 10^{-10}$ m per ring revolution, which corresponds to a surface loss of about 0.6 µm per rolled ton. Based on the typical service life of conventional cemented carbide rolls of 500 tons of rolled wire, this results in a "noticeable" wear of about 300 µm [36]. Si_3N_4 rolling rings used in Kocks blocks also show no damage after use [37].

Compared to hard metals and steels, the use of silicon nitride results in reduction of frictional forces, lower abrasive wear and no adhesion of rolled metal, which is associated with the non-metallic bonding type in ceramics. The high hardness (15 GPa), elastic modulus (300 – 320 GPa) and compressive strength (3000 MPa) prevent roll flattening in the roll gap and enable the accuracy of the rolled product to be increased.Due to its thermal properties, particularly as a result of its low coefficient of thermal expansion (approx. $3 \cdot 10^{-6}$ 1/K), silicon nitride has excellent resistance to temperature changes.

Good resistance of silicon nitride to oxidation and corrosionis an advantage when used at high temperatures. However, the coolant (water) can penetrate into the pores that can form during ring production and increase their growth through stress corrosion, which can lead to a reduction in the strength of the silicon nitride. Depending on the quality of the starting material and the manufacturing process used, Si_3N_4 products have different surface porosities. As can be clearly seen from Figure 9, the production of Si_3N_4 products with increasing sintering pressure (gas pressure: 100 bar, hot isostatic pressing: 2000 bar) and high quality of the starting material results in material structures with fewer pores and can ensure better resistance to stress corrosion.

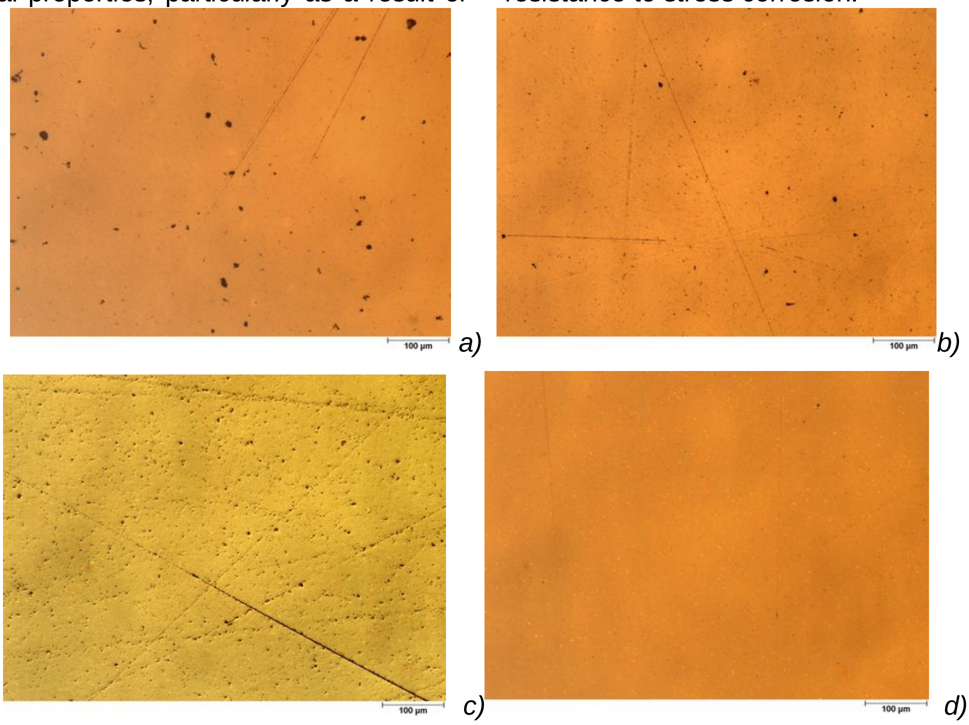

Figure 9. Micrographs of gas pressure sintered (left) and hot isostatically pressed (right) silicon nitride of standard quality (a, b) and high quality (c, d)

Corrosion occurs between Si_3N_4 grains. The grain boundary phase is often less stable than the grains and is triggered by corrosion processes deep into the interior of the structure, while the grains remain stable. Therefore, the grain boundary phase generally determines the corrosion stability of these ceramics. The Si_3N_4 grains can then easily detach from the working surface of the ring, which can lead to the formation of microcavities. Mechanically caused structural damage can intensify the corrosive attack. If a corrosive attack occurs with superimposed abrasive wear, the corrosion rate can increase significantly. As a material for forming tools, silicon nitride has great chemical stability.

Ceramic tools are successfully used as guide rolls in hot rolling. The guide rolls guide the running wire strand exactly into the rolling gap and prevent the oval wire strand from tilting in a round rolling caliber. Significant forces arise which are caused by the high forming strength of the materials being processed. The service life of Si_3N_4 guide rolls is on average 15 times longer [38].The Si_3N_4 pinch rolls, which guide and brake the wire end, have shown extremely low wear when rolling wire with a final dimension of 5.5 mm [33]. After eight times the service life of the steel rings, the wear depth was in the range of 90 µm, which was the end of the service life [37].

Silicon nitride rings are already routine in individual areas of rolling mills. Compared to standard materials –cemented carbide and steel – ceramic forming tools bring significantly greater efficiency to the production process. Production costs can be reduced without major modifications to production facilities. The economic advantage for the user results from the increased service life, depending on the application, by a factor of 10 to 15 [38].

Silicon nitride is a well-suited material for the production of rings. A comprehensive overview of the studies we have carried out in recent years can be found in [39].

Ring clamping systems

Various types of radial and axial mechanical clamping systems have been developed and used for clamping rolled rings. The load on cemented carbides and silicon nitride rings caused by the radial clamping pressure of a clamping system and by centrifugal force during the rolling process was examined [40]. The calculation results for a rolling ring made of cemented carbide have shown that there are tangential tensile stresses on the outer edge, which become even greater at high speeds and are often the cause of rolling ring fractures when clamped radially. Centrifugal forces that occur at high rolling speeds counteract the effective radial tension and impair the transferable torque. Calculations have shown that this effect is less pronounced when the mass density of the tool is lower [40, 41]. The lower density of the silicon nitride causes significantly smaller centrifugal stresses than with a cemented carbide ring at the same internal clamping pressure. This is of great importance for the transferable torque during rolling, especially for finished wire blocks, where there are very high final rolling speeds of up to 120 m/s.

When using ceramic tools, it must be noted that these materials cannot withstand tensile loads and the smallest tensile stresses lead to the destruction of the tool. Axial hydraulic clamping systems are used to clamp rolled rings. Various types of such tensioning systems have been developed that transmit mechanical tension through hydraulically generated preload. The absence of stress concentrators on the cement carbide ring prevents ring destruction due to the occurrence of critical bending and tensile stresses. This is achieved by using a sliding fit of the rings on the shaft with subsequent fixation using a special clamping device that creates compressive stresses along the roll axis [42]. The roll rings can be clamped with an axial pressure of 2000 bar [31]. To clamp the roll rings on the rolling shaft, this is expanded hydraulically via the ring piston and the resulting gap is closed without play using the patented wedge ring system. After the hydraulic pressure is removed, the high clamping force generated by the expansion of the rolling shaft is safely mechanically maintained via the wedge ring. To change the rings, the user relaxes the composite rolls, the roll rings are changed and tightened again. The hydraulic clamping system with a lower axial pressure of 1500 to 2000 bar can ensure rolling ring tensioning through a shaft expansion of 0.5 mm [43]. Using a hydraulic nut, a high axial contact pressure of up to 4000 bar can be generated, which ensures appropriate torque transmission and prevents the roll rings from slipping [44].

With the clamping systems mentioned above, radial clamping forces, which lead to an increased risk of breakage and reduced service life, are completely avoided. The clamping system is therefore of central importance for operational safety. In addition to secure rolling ring fastening, clamping systems also achieve an increase in production and further cost savings.

CONCLUSIONS

Depending on the operating conditions, the type of steel being rolled and the campaign length, the roll rings made from the available materials (cemented carbide, high-speed steel) can be used successfully to achieve the economic efficiency of the rolling process. The development of composite materials (cemented carbide/cast iron, cemented carbide/steel) has solved the problem of torque transmission and made it possible to save expensive cemented carbide and significantly reduce the production costs of rolled rings.

The ceramic materials offer high potential for use as ring materials for hot and cold rolling mills. This is due to their higher hardness and rigidity, coupled with lower density compared to steel or cemented carbide materials, which makes it easier to solve many rolling problems that are limited by the properties of steel or cemented carbide rings. The application of silicon nitride in the production of rolled rings and their successful use in different operating conditions has shown that there is significant potential for expensive but durable materials that have several advantages. When producing hot-rolled wire, roll rings made of silicon nitride offer advantages over conventional rings made of cemented carbide or steel and can be used as an alternative to cemented carbide. Substitution of cemented carbide with silicon nitride plays an important role given the likely future resource scarcity of tungsten.

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IZVOD

PRSTENOVI ZA SLOŽENE VALJKE VALJAONICA

Opisani su savremeni materijali za proizvodnju prstenova za kompozitne valjke i njihova najvažnija svojstva. Analizirane su prednosti i nedostaci prstenova izrađenihod tvrdog metala, brzoreznog čelika, keramičkih materijala i mehanizmi njihovog oštećenja. Dalje, predstavljeni su zahtjevi za vodu za hlađenje prstenova. Opisanaje struktura prstenova od kompozitnih materijala izrađenih od tvrdog metala i legura na bazi željeza, brzoreznog čelika, prstenova proizvedenih metalurgijom praha i metalurgijom rastopljenog metala te prstenova izrađenih od silicijum nitrida.

Ključne reči: *prsten, složeni valjak, tvrdi metal, brzorezni čelik, silicijum nitrid, steznisistem*

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