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WEAR MECHANISM FOR DEEP-WELLS DRILLING TOOLS

MEHANIZEM OBRABE ORODIJ ZA IZVEDBO GLOBOKIH VRTIN

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When drilling deep wells with a large diameter drill bit, it is important to ensure optimum progress with the cutting tool, effectively cutting or crushing the rock through which we are penetrating for as long as possible. When drilling a well, we encounter complex conditions at depth resulting from variables such as the strength of the rock, the load on the bit, the number of revolutions of the tool, significant temperature and pressure fluctuations and the material properties of the tools used in the drilling. The article shows how mechanisms develop due to the drilling parameters used and the complex drilling conditions, which lead to wear of the cutting unit and a decrease in efficiency. The influence of the aforementioned drilling conditions on the steel materials of the roller-cone drill bit, which is the tool we use to penetrate deeper, is reflected in the change in the material properties of the steels. These changes, which are explained in the article, lead to gradual fatigue and degradation of the materials. The wear mechanism of the cutting tool is composed of the different material properties of the steel from which the roller-cone drill bit is formed, the influence of sudden temperature changes on the steel materials and erosion processes on free, newly formed surfaces, which are the result of the erosion effect.

Keywords: erosion, carbide coating, temperature change, steel recrystallisation, material fatigue

Pri vrtanju globokih vrtin s kotalnimi dleti velikega premera je vodilo, da se z rezalnim orodjem zagotovi optimalen napredek ob čim daljšem efektivnem rezanju oziroma drobljenju kamnine skozi katero napredujemo. V toku vrtanja vrtine se v globini srečujemo s kompleksnimi pogoji, ki jih tvorijo spremenljivke kot so trdnost kamnine, obremenitev na kotalno dleto, število obratov orodja, izrazito nihanje temperature in tlaka ter materialne lastnosti orodij, ki jih v toku vrtanja uporabljamo. V članku prikazujemo kako se zaradi uporabljenih parametrov vrtanja in kompleksnih pogojev izvajanja vrtanja razvijajo mehanizmi, ki privedejo do obrabe rezalnega mehanizma in zmanjšanja učinkovitosti. Vpliv omenjenih pogojev vrtanja na jeklene materiale kotalnega dleta, ki predstavlja orodje s katerim napredujemo v globino, se odraža v spremembi materialnih lastnosti jekel. Zaradi teh sprememb, ki so pojasnjene v članku, pride do postopnega utrujanja in razpadanja materialov. Mehanizem obrabe rezalnega mehanizma je skupek različnih materialnih lastnosti jekel iz katerega je formirano kotalno dleto, vpliva naglih sprememb temperature na jeklene materiale in erozijskih procesov na proste novo formirane površine, ki so posledica erozijskega delovanja.

Ključne besede: erozija, karbidna obloga, sprememba temperature, prekristalizacija jekla, utrujanje materiala

1 INTRODUCTION

Carrying out complex deep-drilling operations requires the manufacture of accessories and tools that are sophisticated from the point of view of both mechanical engineering and metallurgical alloys. The tools used for deep drilling work under very unfavourable and variable conditions for the materials. One of the most stressed tools and equipment in deep-well drilling is the bit, which is used to penetrate the rock material. In addition to the physical stresses acting on the drill bit, drilling is also associated with an unfavourable and changing environment in which the cutting process takes place. There are strong temperature fluctuations. For this reason, the quality of the bit design and the materials used are crucial, as we want to drill as long a section of the well as possible with a single drill bit, because each manoeuvre to lift the drill bit out of the well and insert a new one is a time-consuming process, which increases the degree of instability of the well casing and thus a possible collapse.

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To ensure the longest-possible effective service life of the drill bit, it is important not only to use quality steel but also to choose the right drilling process to ensure even wear of the tool's cutting mechanism. Only if the cutting mechanism of the tool wears correctly and evenly can we drill efficiently without putting unnecessary dynamic stress on the other parts of the drilling rig.

In the case of drilling parameters or the drilling regime, we restrict ourselves to the direct factors that can be influenced during the drilling itself, namely: load on the bit, number of revolutions, torque and flushing of the drill bit area. We generally have no influence on the factor of the rock through which we are drilling, as it is determined by the geomechanical and geotechnical properties of the rock material. An improper choice of drilling parameters leads to improper wear and thus to failure of the drill bit in terms of good drilling progress.

Analyses of the changes in the steel materials of the drill bit after drilling provide detailed information about the wear mechanisms of the cutting mechanism for the bit.

In our study, we performed an in-depth analysis of the change in material properties of steel using an 8 ½" (215.9 mm) diameter roller-cone drill bit with IADC code 117 drilled with the correct parameters and a 6 1/8" (155.57 mm) diameter roller-cone drill bit with IADC code 136 drilled with inadequate drilling parameters.

The chosen drilling regime, taking into account the correct selection of the roller-cone drill bit for drilling through the rock material predicted by the geological analysis, represents the selection and adjustment of at least the following parameters:

- Weight on bit (WOB) [N/m]
- Number of revolutions of the bit [min^{-1}]
- Flushing fluid (mud) used

In very simplified terms, propulsion by drilling into the material can be represented by an axial load and a rotation or moment that is transmitted by the cutting tool to the material, in this case the rock, which is crushed by the forces acting in the axial and transverse directions (**Figure 1**).

When using the roller-cone drill bit, the mechanism of penetration into the material is more complex. The axial force is directed downwards in the vertical direction and the rotation of the rod is directed transversely to the vertical axis. This ensures the force on the tool and its rotation. The roller-cone drill bit, on the other hand, has a cutting mechanism in the form of rollers that are mounted slightly transverse to the vertical axis. Under the influence of the vertical rotation of the tool, the rollers rotate around their axis and ensure that the teeth of the roller, which form the cutting part of the bit, alternately come into contact with the material – the rock.

The theory of the tooth effect of a roller-cone drill bit was established by Cheatham,[1] who in his study determined the load on the tooth (wedge) required to penetrate the rock. In his model, he assumed that the rock under the tooth is isotropic and homogeneous. This was within the limits of the Mohr-Coulomb failure criterion theory. In 1965, Paul and Sikarskie[2] explained the effect of a roller-cone drill-bit tooth on the rock by the effect of a wedge-shaped wedge in the material, which then fails under load according to the Mohr-Coulomb failure criterion.

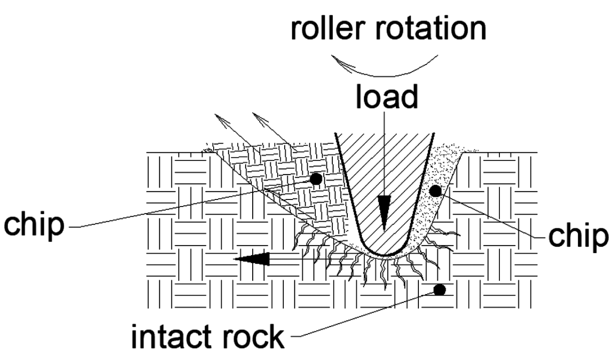

Figure 1: Advance of the tooth into the rock

Dutta[3] built on the theory of Paul and Sikarskie[2] by explaining the mechanism of material progression as the release of energy through crushing and fracturing. It was shown that the principle of rock fracture can be understood as the breaking of a brittle material, the fractures of which are the result of the action (load) of the cutting tool on the rock.

The accelerated wear of the cutting mechanism – the teeth – has the direct consequence of reducing the rate of penetration (ROP) of the drilling operation.

Studies have shown that the load on a single tooth of the bit acting on the rock is a function of the projected surface area of the tooth in contact with the rock, the depth of penetration of the tooth into the rock, and the mechanical properties of the rock.[4]

As the bit penetrates the rock, the chosen drilling regime, the mechanical properties of the drill bit and the mechanical properties of the rock lead to gradual wear of the bit teeth. The progressive wear is caused by the interaction of each tooth with the rock, which breaks and crumbles under the influence of the force, while at the same time the temperature in the tooth material increases due to its resistance and friction.[5–19]

Flushing the bottom area of the well and the drill bit with drilling fluid (mud) serves to effectively remove rock fragments from the bit area and to lower the temperature of the steel parts of the bit. The poisoning of the mud, which contains rock fragments around the individual segments of the bit, influences the secondary grinding of material that has not been effectively removed from the tooth area of the bit and on the erosive wear of the materials of the structural elements of the bit (the rollers) that do not come into contact with the rock.[20–23]

As part of our research, we analysed a series of roller-cone drill bits. We were particularly interested in the change in material properties in direct contact with the rock, i.e. the changes that occur when a tooth is pressed into the rock. In this paper we present the wear mechanism of a roller-cone drill bit with a cutting part consisting of teeth.

In our case, the cutting tools (teeth) investigated are steel teeth that have been protected with tungsten carbide in the area of the expected more intense wear.

The wear rate and wear mode of a roller-cone drill bit for drilling in soft rock was investigated:

- When using drilling parameters recommended by the bit manufacturer
- When using drilling parameters that deviate from the bit manufacturer's recommendations

In the first case, a roller-cone drill bit with the IADC code 117 was used and in the second case a roller-cone drill bit with the IADC code 136. Both bits are shown in **Figure 2**. The IADC code is a system for classifying bits according to their properties and their applicability in various soil and rock materials. The IADC classification is created by the International Association of Drilling Contractors (IADC).

Figure 2: Roller-cone bit IADC 136 (left), IADC 117 (right) – side and top view

The wear analysis of the tested roller-cone drill bits was performed to verify the type and degree of wear of the cutting mechanism of the teeth and rollers. Using metallurgical methods of material investigation, a detailed analysis of the damage to the materials was carried out to determine the causes of the damage and to understand the mechanism of damage expression to potentially gain new insights into modifications, e.g., to the drilling regime, tooth arrangement and geometry, flushing, etc., that could either increase the ROP or extend the effective life of the bit.

2 MATERIALS AND METHODS

After the drilling intervals, a comprehensive analysis of the steel materials of the bit was carried out with the following tests:

- the chemical composition of the tooth steel by flame spectroscopy with ICP–OES Agillent 720 and Agillent 720
- the composition of the carbide steel of the teeth of the bit using the XRF method (X-ray fluorescence spectrometry) with Thermo NITON XL3t
- examination of the cross-section of the teeth by electron microscopy using the EDS/SEM method (energy-dispersive X-ray spectroscopy/scanning electron microscopy) with Jeol JSM 5610
- determination of the deformation properties of the roller steel and the carbide coating in a dilatometer with Bähr DIL 801
- measurement of the Vickers hardness of the steel (100 g load) with a Shimadzu type M microhardness tester

The drilling parameters were monitored during the drilling process:

- rotational speed (min^{-1})
- rate of penetration (ROP)
- amount of drilling fluid

The drilling parameters were continuously monitored during the drilling process using a calibrated set of sensors, known as a drillometer in drilling technology. This device contains a series of sensors that measure the load on the drilling tool, the torque, the number of revolutions, etc.

The bit efficiency or bit wear rate was estimated from the drilling progress.

Figure 3 shows a cross-section through a worn tooth of a roller-cone drill bit with a reconstruction of the condition before the wear.

3 RESULTS

The chemical composition of the tooth steel is shown in **Table 1**.

Table 1: Chemical composition of tooth steel

Element	Unit	Result	
		117	136
C	*w*/%	0.145	0.17
Si	*w*/%	0.25	0.26
Mn	*w*/%	0.59	0.79
P	*w*/%	0.007	0.011
S	*w*/%	0.002	0.016
Cr	*w*/%	0.11	0.60
Ni	*w*/%	3.50	0.74
Cu	*w*/%	0.18	0.27
Mo	*w*/%	0.201	0.50
Fe	*w*/%	95.958	95.385

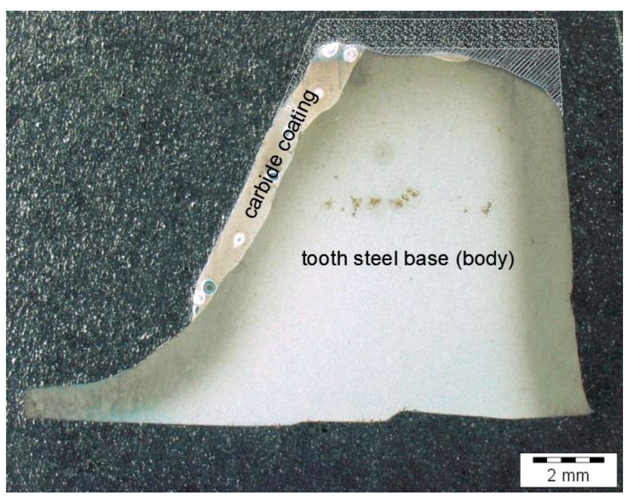

Figure 3: Cross-section of the tooth with reconstruction of the worn part

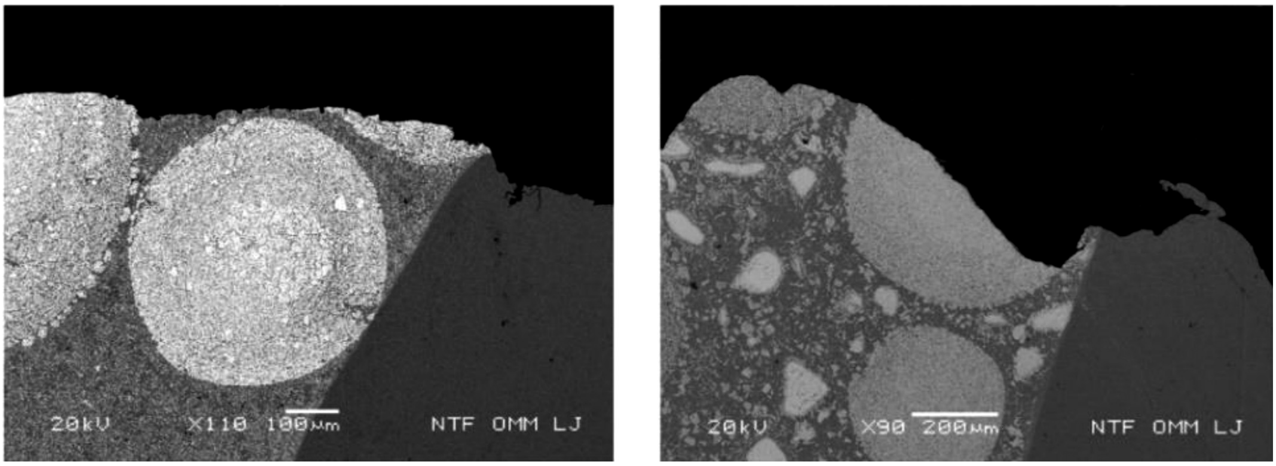

Figure 4: Carbide coating. The layer that protects the tooth surface from erosion (a) bit 136, b) bit 117)

Based on the results of the chemical analysis shown in **Table 1**, we have established that this is a tool steel for cold work with increased toughness.

The chemical composition of the tungsten carbide coating was also analysed using SEM. The carbide coating layer consists of an alloy with larger round Co-W grains (19.5–79.54 *w*/%) and a tungsten crumb embedded in the base (matrix), which consists mainly of Fe, Ni, W. The lighter colours are the alloys with larger Co-W grains (19.5–79.54 *w*/%). The lighter colours are the materials with the higher density and represent the tungsten particles in the Fe-Ni matrix (**Figure 4**).

The hard carbide coating of the tooth is clearly visible on the left-hand side of the two images (lighter colour tones), while the right-hand side of the two images shows the steel base of the roller-cone drill bit tooth.

Vickers microhardness measurements were carried out on the tooth cross-sections of the bits and on the carbide coating of the teeth of the two roller-cone bits.

It was found that bit 117 has a slightly higher hardness than the tooth itself, with hardnesses averaging between 380 HV and 328 HV. As expected, the hardnesses in the carbide coating are much higher, reaching up to 2200 HV.

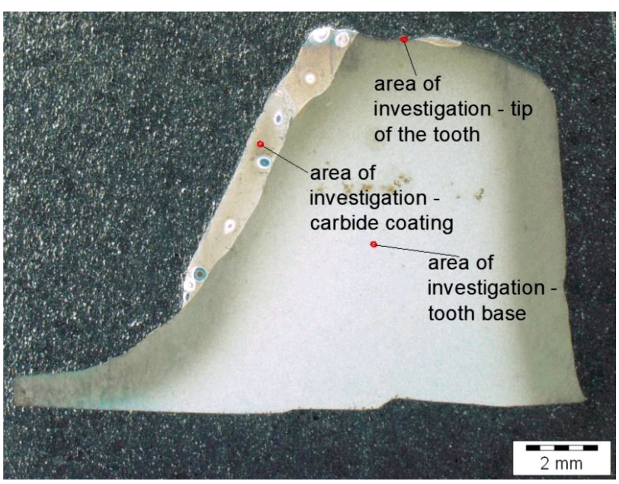

Figure 5: Vickers hardness testing areas

In bit 136, it was found that the upper part of the tooth, which is worn, has a slightly higher hardness of 594 HV than the centre part of the tooth, where the hardness averages 433 HV. As expected, the hardnesses in the carbide coating are higher and reach hardnesses of up to 1436 HV. **Figure 5** shows the areas of the Vickers hardness test on the cross-section of the tooth.

Drill bit 117 was used to drill 610.7 m in sandstone with carbonate binder and a compressive strength of 30 MPa. The 117 drill bit was loaded during drilling in accordance with the manufacturer's recommendations. The drilling regime was as follows:

- RPM: 55 min^{-1}
- WOB: 40 kN

The rate of penetration (ROP) was 4.68 m/h.

Drill 136 drilled 87.89 m in carbonate mud with sandstone and limestone pools with compressive strengths between 25 MPa and 75 MPa. Bit 136 was not loaded during the drilling operation as per the manufacturer's recommendations due to the variable conditions. The drilling regime was as follows:

- RPM: 40 min^{-1}
- WOB: 35 kN

The rate of penetration (ROP) was 0.4 m/h.

When we noticed that the ROP had dropped drastically, even though we were drilling in the same rock material as the effective ROP, we removed the bit from the borehole and examined it for visual damage.

Examination of bit 117, which had been drilled over a longer interval and loaded according to the manufacturer's instructions, showed that damage in the form of wear of the bit-tooth material had occurred wherever the bit was not protected by a carbide coating. The material wear is due to the erosive effect of the drill cuttings, which contain a high proportion of silicate particles. The damage is reflected in the reduction in the dimensions of

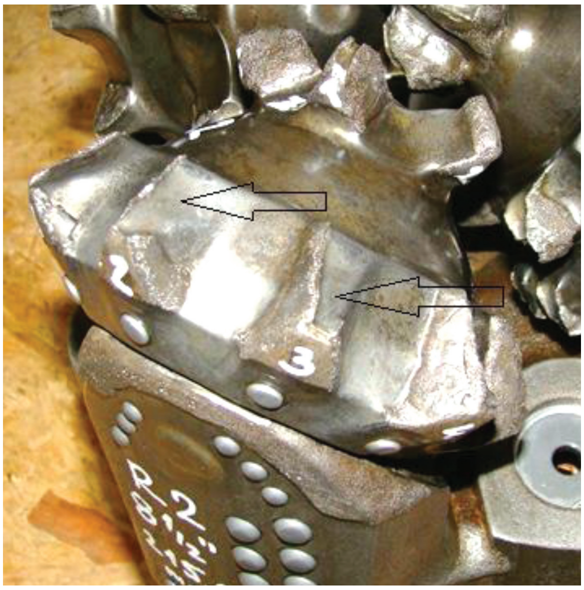

Figure 6: Overview of the characteristic wear of the teeth of a roller-cone drill bit 117

the tooth body and the formation of erosion channels on the top of the tooth (**Figure 6**).

After extracting and cleaning bit 136, damage or wear was mainly evident in the wear of the top of the teeth, which was evident on all the teeth of the bit. Some teeth were chipped, and some were even broken (**Figure 7**).

4 DISCUSSION

The mechanisms that act on the drilling tool during drilling are complex and can be roughly divided into the following loads and stresses:

- Stresses caused by the creation of the necessary conditions for rock crushing

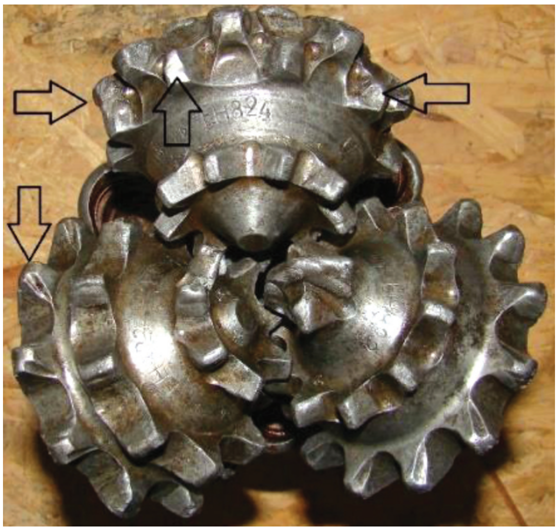

Figure 7: Overview of the characteristic wear of the teeth of a roller-cone drill bit 136

- Stresses that act on the drilling tool due to the conditions in the well

The loads caused by creating the necessary conditions for rock crushing include:

- Axial load to generate the force under the influence of which the cutting mechanism penetrates the rock
- Transverse forces caused by the rotation of the drilling tool

The result of these loads is the generation of stresses in the rock and in the cutting tool itself. The friction of the teeth against the rock increases the temperatures and mechanical fatigue of the materials.

Stresses acting on the drilling tool due to the conditions in the well include the following:

- Abrasive flow of rock particles in the drilling fluid (mud) created during rock crushing when the cutting mechanism of the bit is pressed and rotated
- Rapid cooling of the highly heated cutting components of the roller-cone drill bit, which have heated up due to the rotation and turning of the roller

The result of the above mechanisms is the formation of mechanical material erosion due to the erosive effect of rock particles in the drilling fluid (mud) and the rapid heating and cooling of individual surfaces of the teeth that have been in contact with the rock.

The monitoring of the drilling performance and the drilling regime shows that the roller-cone drill bit 117 was loaded in accordance with the recommendations, which stipulate a bit load in the range of 40 kN to 200 kN. The load on the bit during drilling did not exceed 50 kN.

The failure of the carbide coating on the top of the teeth of the roller-cone drill bit 117 is due to the difference in strength and thermal expansion properties between the carbide material that forms the lining (protection) of the tooth body and the steel material of the tooth body. The carbide coating material is welded to the steel base of the teeth of the bit. During the drilling process, the teeth of the bit that come into contact with the rock to be crushed are strongly heated and then cooled by the flushing medium that flows around the teeth as they rotate around the roller axis. The different expansion or elasticity properties of the material, as actually observed during the tests in the low-temperature dilatometer, lead to the formation and progression of cracks between the two materials.

The latter led to a failure of the carbide coating. The failure of the carbide coating led to a new open surface of the steel tooth material, over which the flushing medium, which contained a large amount of siliceous abrasive components, flowed. The abrasive components eroded the newly opened surfaces at the tooth tips and caused erosion channels and thus the loss of the steel tooth material.

Although the carbide coating on the tooth tips and edges is more resistant to erosion, it is brittle and gradually disintegrates under the influence of the load on the

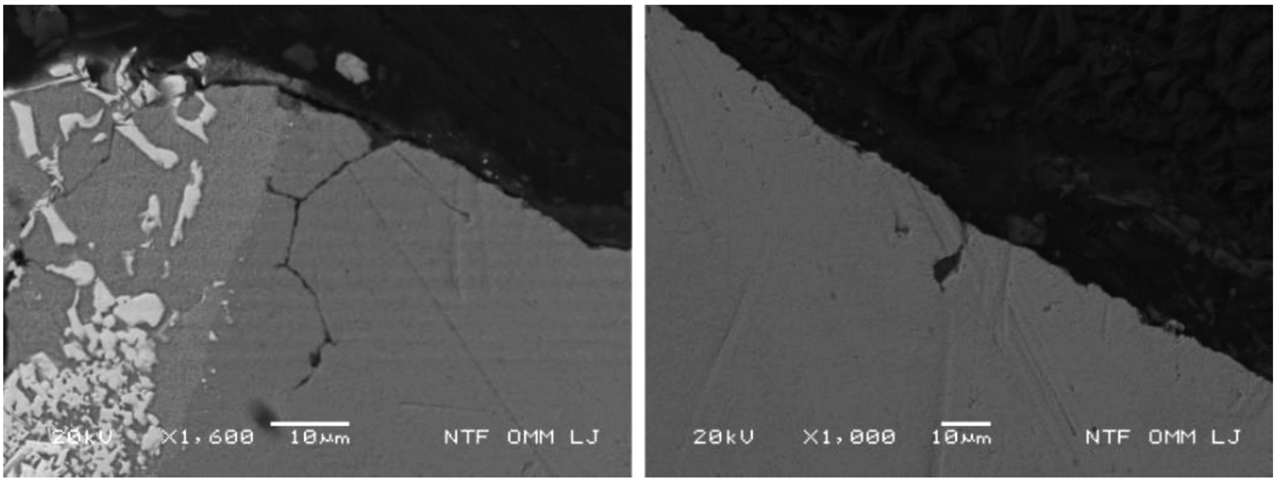

Figure 8: a) Microcracks at the interface between the carbide coating and the tooth steel, b) erosion channel

bit and the associated pressure and shear in contact with the rock, which leads to heating and cooling of the materials during drilling.

We were unable to determine with certainty the temperature at the tip of the tooth, which just penetrates the rock and shatters it. However, our experiments have shown the following:

- the microhardness experiments have shown that the hardness of the material is constant over the entire cross-section of the tooth, i.e., there are no microstructural changes in the tooth steel
- the deformation properties of the steel and the carbide coating are characterised at temperatures above 100 °C
- during rapid heating and cooling, microcracks form at the interface between the tooth steel and the carbide coating
- drilling fluid, which contains micron-sized abrasive rock particles, penetrates the resulting cracks and spreads them through erosion
- in the area where the carbide coating does not serve as erosion protection, the drilling fluid containing crushed rock particles eroded the tooth steel, creating erosion channels

Figure 8a shows microcracks at the interface between the carbide coating and the steel base, while **Figure 8b** shows an example of a micro-erosion channel in the steel of a tooth.

When monitoring the execution and the drilling regime, it can be determined that the roller-cone drill bit 136 was not loaded in accordance with the recommendations, which stipulate a bit load in the range of 15 kN to 27 kN. The load on the bit during drilling was 30–40 kN. This is due to the very different geological composition of the area. It can therefore be concluded that the bit was overloaded and the number of revolutions was too low. As a result, the drilling progress decreased after 87.89 m of the drilled interval.

Examination of the macroscopic image showed that the tooth tips were exposed to high temperatures and loads.

Figure 9 shows the tooth tip that was in contact with the rock. The colour of the steel changes from top to bottom and ranges from shades of blue at the point of contact between the rock and steel to shades of brown, the brightness of which varies from top to bottom.

In the sequence of exploitation, i.e., during drilling, large thermomechanical alternating and impact stresses occurred, which caused material hardening at the surface, where the stresses were greatest, due to uneven and random sudden cooling with drilling fluid. The microstructure of the material in the alternating zone is martensite.

To determine the area of temperature influence, the cross-section of the tooth was examined using a scanning electron microscope (SEM). The working surface of the tooth, which was in contact with the rock, is shown in **Figure 10**.

The change is noticeable on two levels:

- change up to a thickness of 36 µm

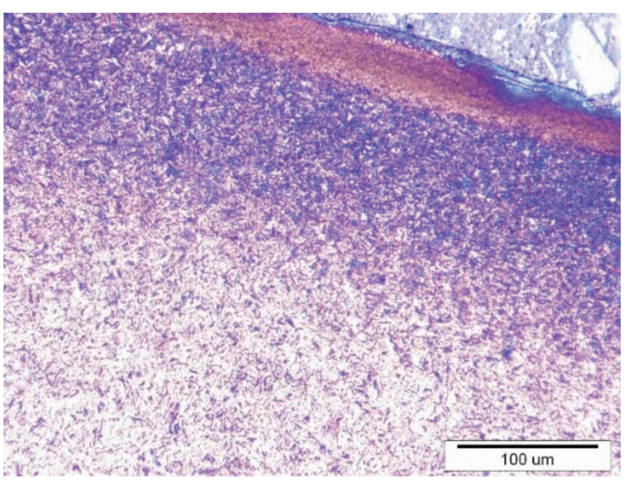

Figure 9: Top of the tooth of the roller-cone drill bit 136

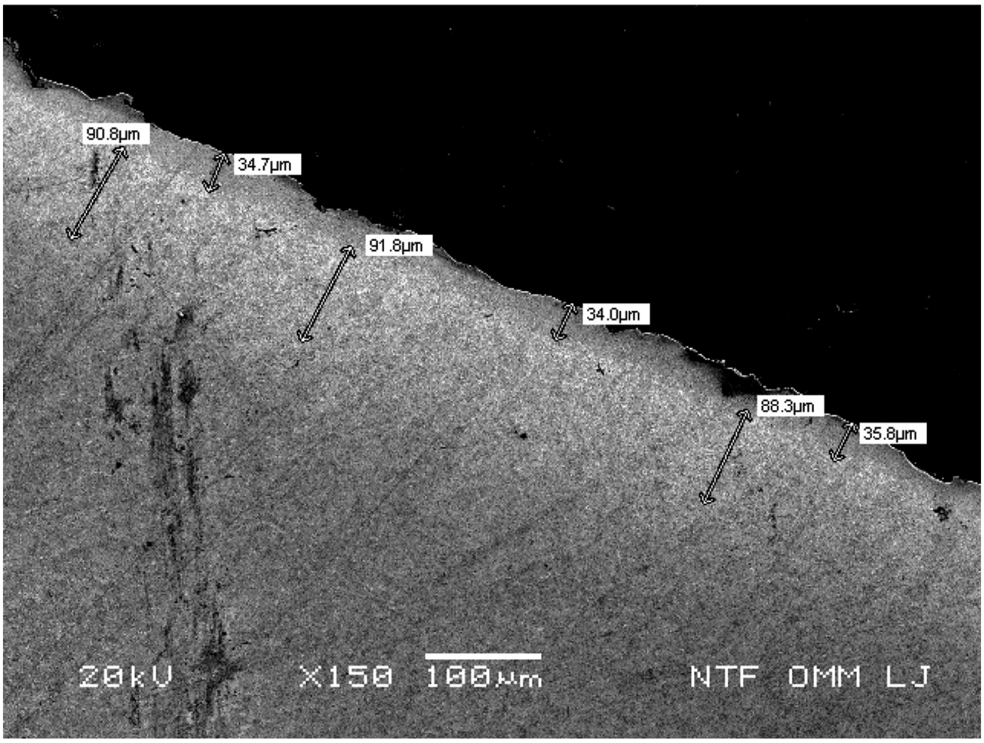

Figure 10: Temperature-influenced area of the tooth of the roller-cone drill bit 136

- still noticeable change from 32 to 92 µm

The change in the crystal structure of the steel of the tooth is due to:

- relatively high temperatures and mechanical stresses that occurred during drilling, when the tip of the tooth was in contact with the rock
- the strong cooling of the hot tooth during rotation around the roller axis and the pouring of cold flushing fluid
- overloading of the teeth during rock crushing due to excessive weight on the bit and excessive dwell time of the tooth in contact with the rock due to insufficient rotational speed

The consequence of such a drilling regime is an increase in the temperature of the material at the tip of the teeth, which, in combination with the load, leads to a hardening of the material at the edge of the teeth. As a result, the hardness of the steel at this point increased. The measured Vickers hardness was on average approximately 160 HV higher than the hardness of the steel material in the centre of the tooth.

Due to the influence of the intensive cooling with the drilling fluid, the process of microstructural changes in the steel only took place up to a depth of 92 μm into the tooth body. Such changes were only observed on the upper surface of the teeth, while on the flanks of the teeth, which were not in contact with the rock, these changes were not observed. The structure of the material corresponds to the structure of martensite.

Due to the influence of intense temperature fluctuations, there were also differences between the expansion coefficients of the steel of the tooth and the carbide coating. For this reason, when these two materials came into contact due to temperature fluctuations, there was an increase in internal stresses, which led to the formation and propagation of cracks and consequently to the detachment of the carbide coating from the steel base of the teeth.

5 CONCLUSION

It can be concluded from the above that the correct selection of a roller-cone drill bit for an individual rock type with the correct and recommended drilling regime (load on the bit, RPM, drilling fluid, etc.) has a major influence on the wear mechanism of the roller-cone drill bit and thus on the extension or shortening of the effective service life of the bit.

Development in terms of material improvement can be in the direction of developing gradient materials that make up the more stressed parts of the drill bit.

An ideal roller-cone drill bit should have a tough tooth core and a very hard and abrasion-resistant surface. The bond between these two materials must be continuous and coherent so that there are no significant differences between the material properties. Such a tooth construction could be achieved by welding different materials from the same family in layers (e.g., different composition of the carbide coating), which would differ in toughness and abrasion resistance depending on the distance from the tooth centre.

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