Final report

for the IGF-project

Life time increase of tools for fine blanking operations by optimized tool materials and coating systems (InFiBlank)

research participants

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(☒ mutual report of all research participants)

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Place and date of issue | Name and signature of project manager

I. Summary

In order to improve the lifetime of blanking tools, the application of high quality steel, heat treatment and coatings has become an interesting issue for many European companies dealing with stamping, punching and blanking operations. Important trends such as longer life time, higher accuracy and higher complexity of the products are challenging and require more special materials and techniques.

The technological solutions to improve the existing processes are not obvious because of the amount of possibilities in available materials, heat and surface treatments for the envisaged industrial processes and applications. An in-depth research to understand the manufacturing processes with the consequence of an increased performance and lifetime of the tools as well as the opportunity of further optimization was the main goal of this project.

However, the ever increasing production rate and the use of high strength steel sheet can induce problems in the wear and fracture behavior of blanking tools with low lifetimes as a consequence. This project studied the tribological synergy of the substrate-heat treatment-surface relationship and their influence on life-time in heavy load conditions.

The project shows some specials regarding the conventional tool making. Many influences in the mechanical treatment of different tool materials can support the live time or can lead to very bad cutting results, that means for example you have loose particles or bad polished and compacted surfaces.

A preliminary study was performed on the cutting edges of special designed triangular punches made of several high alloyed steels which were heat treated in a conventional way and by deep cryogenic treatment after quenching. The influence of additional plasmanitriding treatments and coatings were investigated. After the research some demonstration tools were tested in industrial conditions to show the feasibility of certain selected combinations.

From results of the preliminary study it can be concluded that all the selected steel substrates performed well during blanking operations. The best results were found with the Vanadis 4 and 23 steel. A special coating could improve the adhesive wear of the reference steel 1.2379. in case of the PM steels the use of a coating is optional. Furthermore DCT treatment could improve the flaking and wear behaviour in both the lab scale and industrial tests. The surface preparation after EDM is found to have an important positive influence on the wear especially when the surface is blast and polished. The industrial blanking tests confirm the positive contribution of DCT on several sheet materials.

The goals of the project were achieved.

Content

II. Symbols

symbol	unit	relevance
s	mm	sheet thickness
t	s	time
T	°C	temperature
v	$m\ s^{-1}$	velocity

Abbreviations

symbol	relevance
DCT	deep cryogenic treatment
NHD	nitriding hardness depth

1 Topic of research

Life time increase of tools for fine blanking operations by optimized tool materials and coating systems.

2 Scientific and technical approach

The process of cutting (*Figure 1*) or stamping with a single punch uses a free blank holder. This method is shown on the left hand side. The process of fine blanking instead uses a compressed blank holder and counter forced ejector. This method is shown on the right hand side. In both cases, the punch movement draws the sheet metal over the cutting edge with a constant force Fs. The result of the cut is also shown: the die clearance in case of normal cutting is rather high. This generates an edge burr with a curved fracture surface; the borders of the punched hole and the sheet are not flat but deformed.

These burrs and deformation at the hole and the sheet does not appear when using a compression on the blank holder as in case of fine blanking. Here the blank holder consists of a guide plate equipped with beads or stingers (comparable to deep drawing beads) which is pressed against the sheet with a constant force FR. The clearance is also smaller than traditional stamping. The pressure and draw beads prevent the deformation of the sheet borders during punching. This action results in a nice and flat hole without burrs.

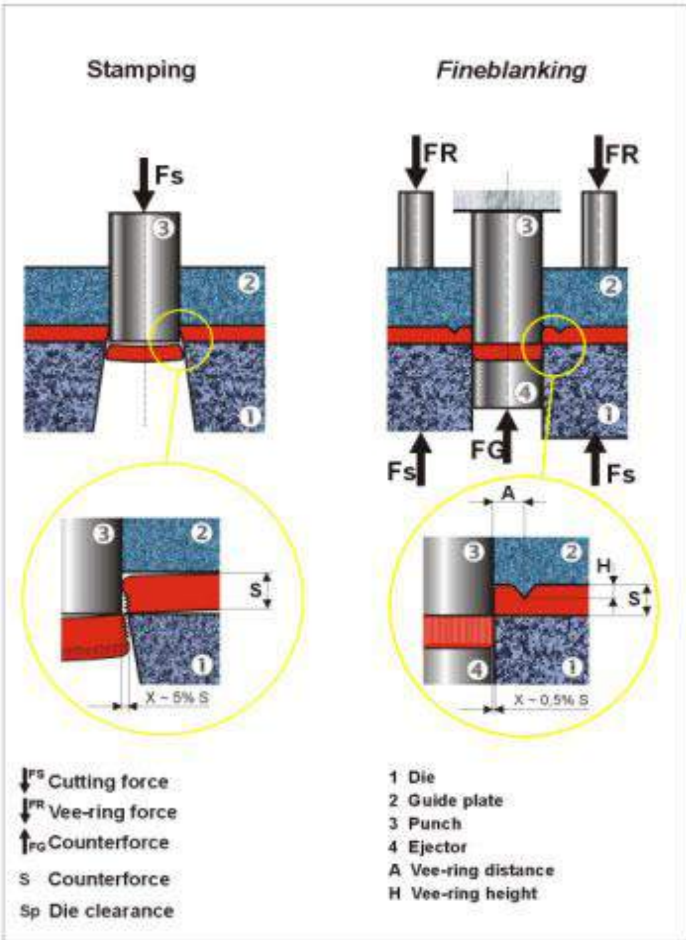


Figure 2-1: Differences between Cutting and Fine blanking

Within calculations of the mechanical and thermal stresses in tools, such as those for precision cutting of various materials in *Figure 2*, the occurrence of very high contact pressures and temperatures confirm at the cutting edge of the punch (point B). Several studies even assumed temperatures up to 600°C. The high mechanical loads in fine blanking operations lead to increased wear of the tools, especially the punch. (*Figure 3*) With increasing sheet thickness and strength of the sheet material the wear increases and therefore economic production often is impossible.

The specifications in fine blanking also pose increased demands on the active tool parts, especially at the cutting punch. Such requirements are:

- The small cutting gap requires very tight dimensional tolerances of the tools and tool guides.
- The tool surfaces have high surface pressures and temperatures can withstand contact.

The cutting zone is especially with thicker sheets for lubricants inaccessible. The lubricants have a very high pressure. Especially when cutting high-strength materials (> 450 N / mm ²) and thicknesses from 6 mm can therefore not be waived toxicologically harmful organochlorine compounds as an additive.

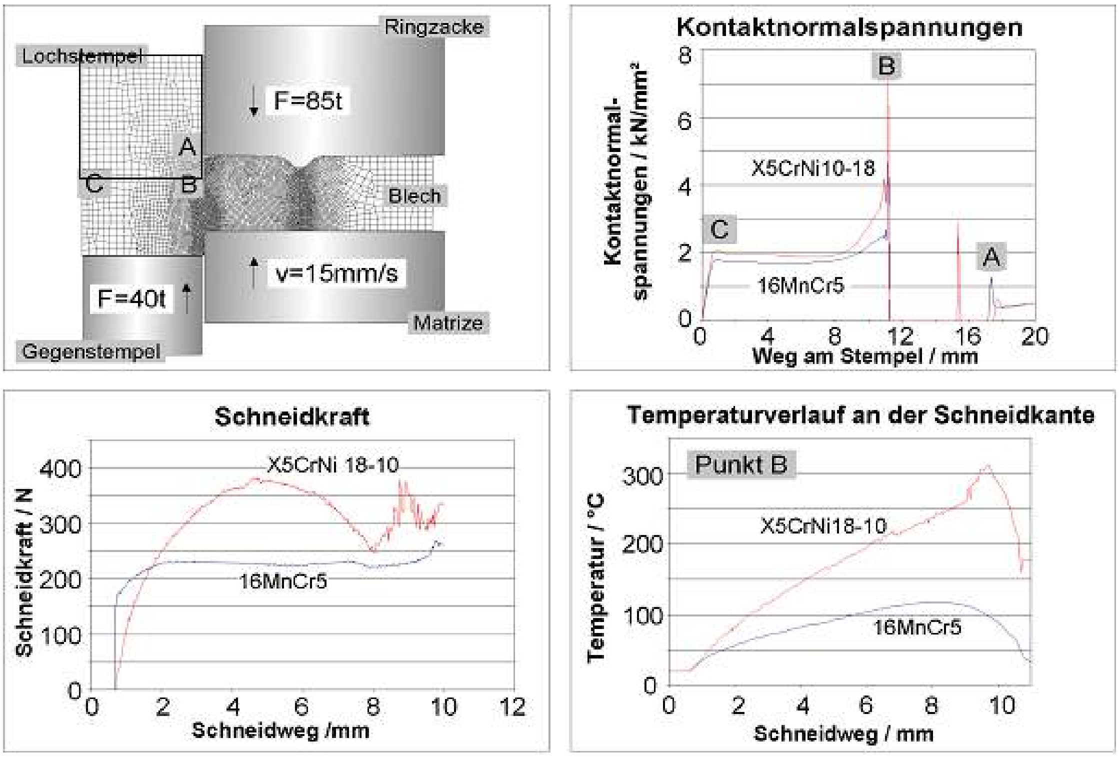


Figure 2-2: Calculation of the mechanical and thermal stresses of the tool for fine blanking of various materials. (Source: WZL, RWTH Aachen)

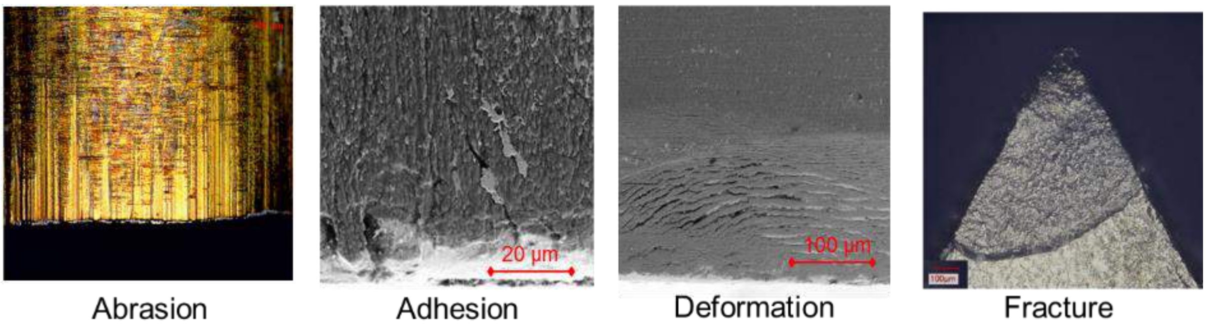


Figure 2-3: Wear mechanism on cutting tools. (Source: Fraunhofer IST, Fraunhofer IWU)

The operating range to perform defect-free fine blanking is determined by various factors, the most important influencing factors are:

- tribology (lubrication, surface roughness, punching velocity)
- tool material (hardness, toughness, wear resistance)
- punching machine (effectiveness, accuracy, stiffness)
- the die clearance
- tool geometry (cone form etc)
- sheet metal material (punchability, yield strength, strengthening index etc.)

3 Research objective and problem solution

Scientific and technical objectives:

- Increase of tool life especially for machining of high strength steels
- Better cutting quality
- Reduced adhesion of workpiece material (e.g. stainless steel, aluminium)
- Investigation of the influence of deep cryogenic treatments on the tool life

Solution approach:

- Optimization of tool material
  - → *Selection of the tool material*
  - → *Deep Cryogenic Treatment (DCT)*
- Coating development and optimization
  - → *Plasma nitriding treatments*
  - → *Use of novel wear-resistant coatings* → *CrXN* (X=Ti, Al, Si, V, W)
  - → *Wear analysis of the tools*
- Tool testing
  - → *Tool manufacturing*
  - → *Cutting tests on laboratory scale*
  - → *Cutting tests at industrial partners*

At the start, the project partners and the interested companies will characterize the fine blanking process as well as the tools and the available equipment to perform cutting and blanking tests on several metal sheet.

In addition, the coating parameters will be examined on reference samples. In this step Sirris will make a material selection of the base material (substrate) which can be involved in the project and which is suitable for coating with PVD techniques.

The heat treatment consists traditionally of a quenching step and a subsequent tempering treatment to set the proper hardness. Additionally to the quenching and tempering, a deep cryogenic treatment after quenching or after tempering depending on the steel quality will be considered as well. This treatment will be performed at industrial heat treating companies under supervision of Sirris. When the selection of materials and heat/cold treatment is determined, coating of test samples can be made in a next step.

Developing special PVD coating for blanking tools will then be the next topic. Several test samples will be coated at the Fraunhofer IST facilities. The tools will then be characterized in order to investigate the adhesion and homogeneity of the coating as well as the accuracy of the active tool parts. Based on the results and the properties of the different coatings, treatments and substrates a knowledge transfer to the industry will be organized.

The next step involves the coating of tools for small scale laboratory tests before real production tools are prepared for the practical cutting tests under production conditions. These tests will be performed at the Fraunhofer IWU facility. The purpose of the tests is to gain information on the performance of the coating/substrate combinations selected before. A final evaluation of the cutting experiments and a systematization of the experimental results will be prepared before a final report is made.

4 Results

4.1 WP1 Characterization of the fine-blanking process

In this WP detailed work conditions and requirements for fine blanking will be set up. The state of the art of commercial fine blanking and punching will be reported with the aim to describe the needed specifications and the desired properties of the tools for the fine blanking operation in industrial environments.

4.1.1 WP1.1 Requirements for fine blanking of high strength steel, stainless steel

The state of the art in industrial applications is the pressure of the market regarding tool costs and workpiece costs. These very strong materials like high strength steels or stainless steels can reduce the live up to 80% comparing to conventional steels. Especially for very fine geometries and long punches are still many unsolved problems. On the other side you want to produce always workpieces with no burr and without fracture zone so there is at the end no rework.

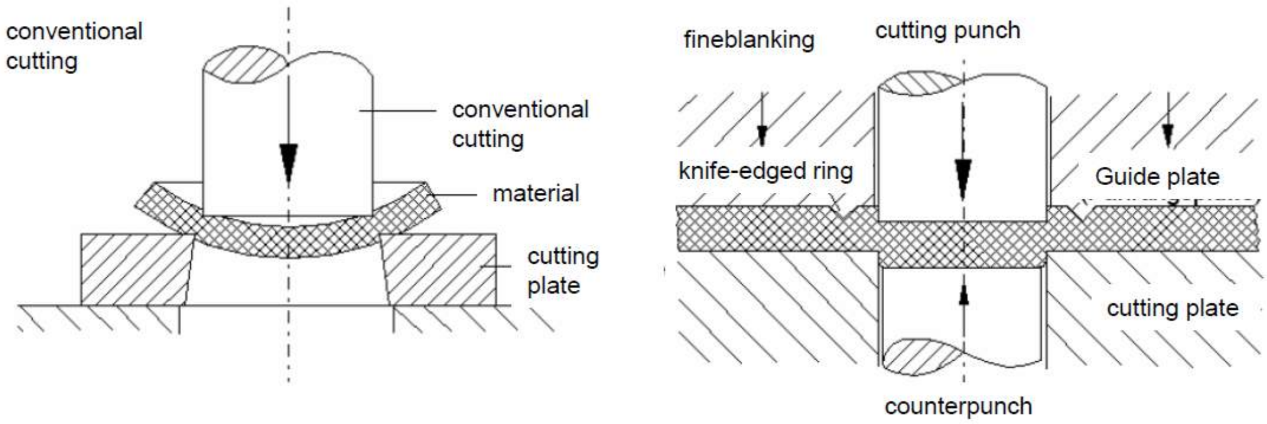


Figure 4-1: cutting technologies (left conventional cutting, right: fine blanking)

The fine cutting was developed in the 20s of the 20th century. A strong shear strain in the cutting area resulting in permanent plastic deformation. The formability of the material is in this case by shifting the state of stress in the print area is greatly increased. The tool elements clamp, opposite Temple and the V-shaped projection produce compressive stresses.

The tribological problem of fine blanking processes is the extreme increasing of stresses in surface areas. The shearing process creates a highly reactive surface, which contributes greatly to the formation of adhesions on the tool elements tends. Fine blanking represents an extreme example of tribological conditions in the cold forming or at the end it goes to temperatures up to 300°C.

The target of the project was with DCT-Treatment and optimized surfaces to provide the typical damages of a punch (*Figure 4-2*) and subsequently to have a much higher lifetime. A special target of the project is to provide the wear in the lateral zone. If the punch has finished the cut, he is going back in the basic position. Especially during the backstroke it comes to a hard contact between the punch surface and the cutted area. Very often is a broken punch due to the bad tribological situation in this moment. One possibility is to improve the tribological system with optimized fluids or coatings. On the other side, you can improve the material quality of the tools through a better heat treatment, so the punch cannot brake in this situation so easy.

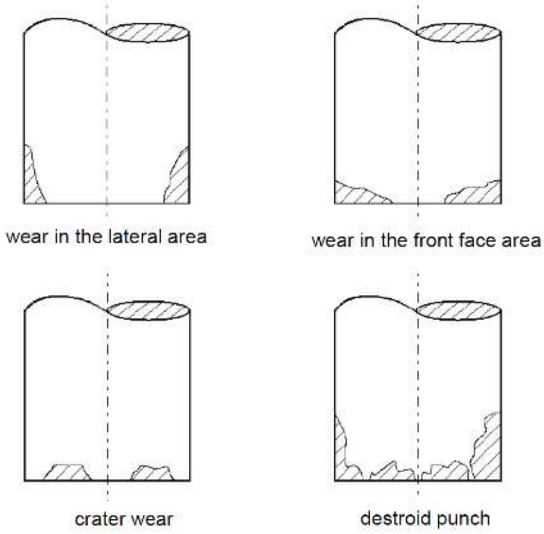


Figure 4-2: typical problems with punches and different damages

4.1.2 WP1.2 Definition of geometries for lab scale and industrial tests / material definition

For the lab scale tests in the facilities of the Fraunhofer IWU Chemnitz a special tool geometry was defined.To get useful results in a short time a very hard cutting regime with a small punch and a geometry with very sharp edges was defined (*Figure 4-3*). The test tool has three identical stamps (*Figure 4-4*) and an automatic feeder which allows continuous test series near to industrial applications with increasing temperature from stroke to stroke. For the cutting tests stainless steel with two thicknesses (0,8mm / 1,5mm) and DC04 with a thickness of 1,5mm was selected. During this project phase many basic materials from the involved material suppliers Böhler and Uddeholm with different heat treatments and coatings were tested. The details of the material selection for the tools are described in WP2.1 the test parameters in WP4.

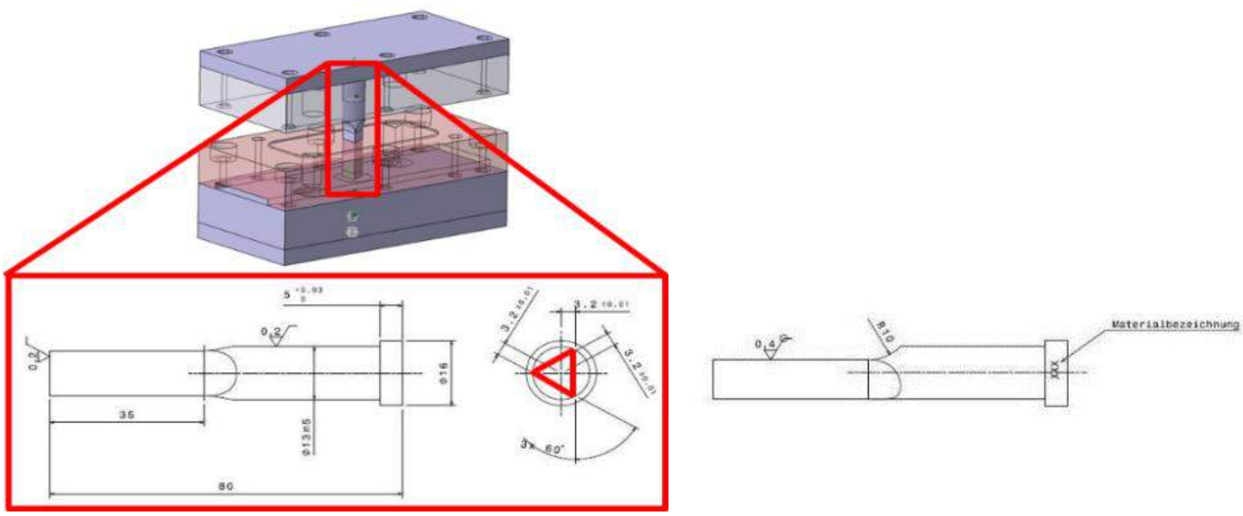


Figure 4-3: Tool geometry for lab scale tests, "Triangle-Punch"

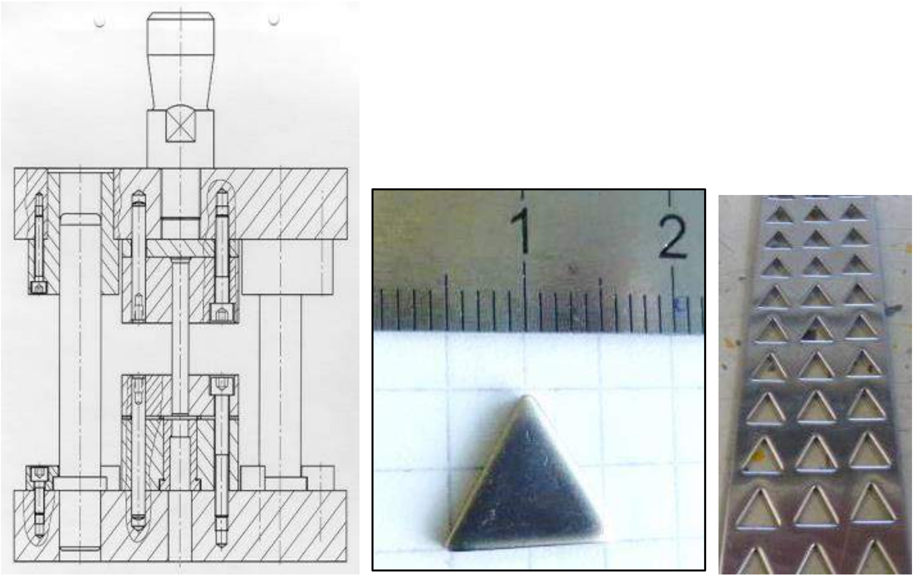


Figure 4-4: test tool at IWU Chemnitz/ size of cutted workpiece / cutted stripe-picture

For the industrial tests two tool geometries and cutting setups were defined.

The company “Karl Naumann GmbH”, which is a supplier for the clock industry near to Dresden, executed cutting tests with very strong stainless steel sheets with a thickness of 1.5mm for the manufacturing of gear parts (*Figure 4-5*). The geometry of the punch is very complex and the quality claims of the customers very hard. The tool costs are very high and a long lifetime is important for an efficient production. The production costs for one stamp are nearly 1.000€. After testing many different tool materials in previous works, the reference tool life is 4.000 pieces per stamp.

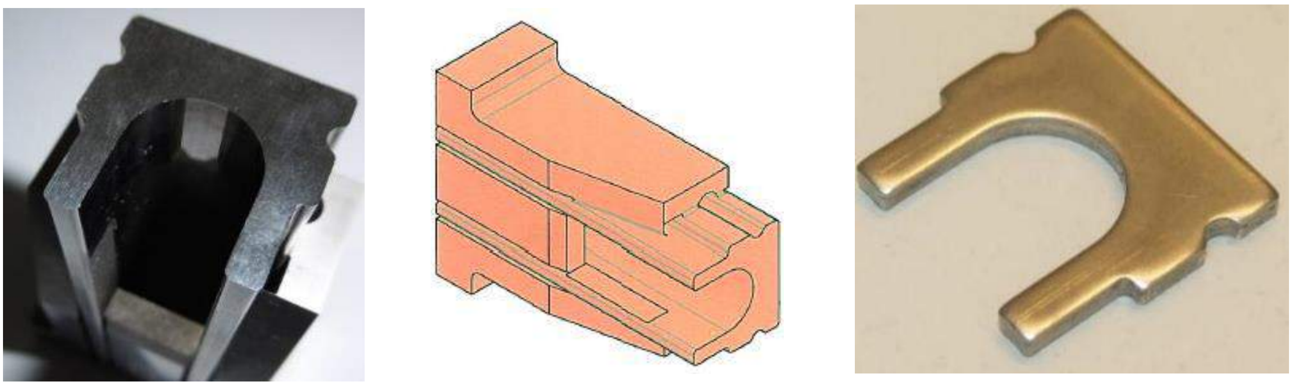


Figure 4-5: Tool geometry and work piece for blanking tests by company Karl Naumann GmbH, “gear folk”

Another industrial test application was a fine blanking process by the partner company “Meteor” from Zella-Mehlis. This company has a very long experience in the field of fine blanking. For the production of the gear part “Mitnehmer” high strength steel S 700MC in the thickness of 4.5mm has to be cut (*Figure 4-6*). The typical cutting power for this process was 1.300KN. Normally the company “Meteor” is able to cut with one punch nearly 8.000 pieces. Different tool materials from

Uddeholm like Unimax and Vanadis 4e were tested. More details of the selected cutting processes are described in WP5.

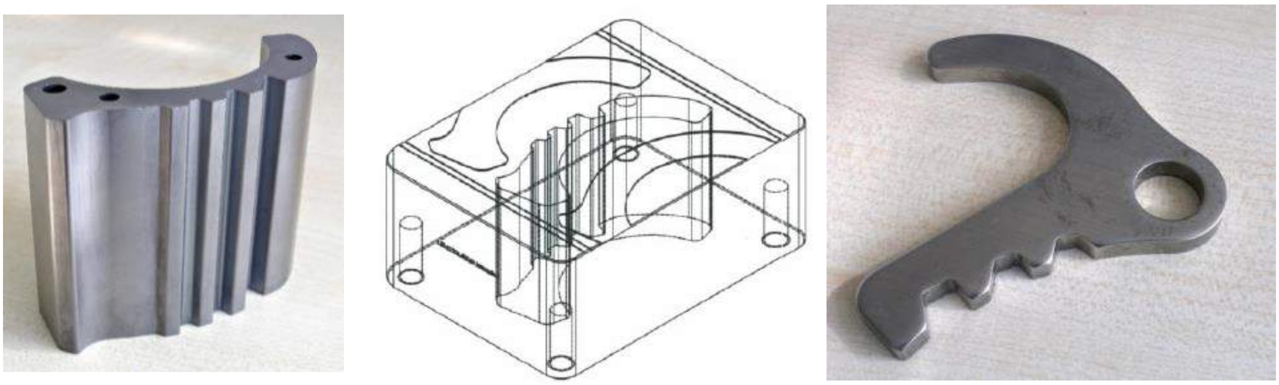


Figure 4-6: Tool geometry and work piece for fine blanking tests by company Meteor, "Mitnehmer"

4.1.3 WP1.3 Definition of wear characterisation tests / component quality determination

For wear analysis the following methods were used:

- First examination of wear mechanism was done with a digital microscope Keyence VHX-2000D in the magnification range from 20x – 1000x.
- A more detailed wear and element analysis was done by scanning electron microscopy (SEM, Leo 1530, Leo Electron Microscopy with EDX-System Oxford 7426).
- The geometry of the tools for lab scale tests ("Dreieckstempel") was measured by laser scanning before and after the tests.
- The surface roughness before the lab scale tests was detected by Hommel Tester
- Scratch tests were executed on flat uncoated steel samples (Revetest tip radius 200µm, 180 N constant force at 10 mm/min, length 4 mm)

4.2 WP2 Optimization of the tool material

The material selection and the subsequent heat/cold treatment of these materials is of upmost importance for the success of the final coating operation. In this part several tool materials used in industrial environment will be listed from WP1. Also new developed steel materials will be involved in this selection. The selected materials will be subjected to a combined heat and cold treatment to enhance hardness, toughness and stability. Finally characterization of the mechanical and structural properties will be performed and a well-defined selection of steel materials will be made for the laboratory tests. From the results obtained in WP3 and WP4 feedback will be given to optimize the substrate by adapting the heat or cold treatment.

4.2.1 WP2.1 Material selection for tools

The goal of this task was the selection of steel suitable for production of tooling for fine blanking of difficult to process materials like high strength steel, stainless steel sheet.

Both rolled tool steel qualities and powder metallurgical (PM) tool steel were involved in this selection. The selection criteria for the materials were: machinability, hardenability, toughness and hardness after tempering. Tempering at an elevated temperature is needed to guarantee the hardness stability after a coating operation is performed. The different materials were be characterized on their chemical composition, structure and mechanical properties in the delivered condition as well as after hardening (quenching and tempering at the desired hardness level) in task 2.2. Special attention were paid on the toughness measured by impact tests.

The two main tool steel producers were considered for the material selection. Based on a selection chart of the Uddeholm company with a semi quantitative indication of the wear and degradation properties of the available tool steel for cutting operations [Udd03], it could be stated that the powder metallurgy (PM) steels Vanadis 4E and Vanadis 23 have a high resistance against wear (both abrasive and adhesive) combined with a high resistance against cracking and plastic deformation. A third PM-steel called Vancron 40 was also considered as a suitable tool steel due to its high adhesive wear resistance despite the lower abrasive wear resistance, properties which are considered as important for punches.

In *Figure 4-7* from the Böhler company, the wear resistance is given as function of the toughness and ductility for tool steels produced by this steel manufacturer. Three curves are visible: the lower curve represents the conventional steels like 1.2379 (equivalent to K110 or Sverker 21), the middle curve representing the Electro-Slag Remelted steels (ESR) and finally the upper curve representing the powder metallurgical steels (PM). The aim was to choose two different types of steel on the highest curve. Therefore the tool steel S390 with relative low toughness and high wear resistance was chosen as well as the steel K890 with a lower wear resistance than S390 but with a higher toughness. As a reference K110 was taken which is equivalent to DIN 1.2379.

Figure 4-7: Performance of tool steels according to Böhler

4.2.2 WP2.2 Material hardening for basic performance

The goal of this task was the hardening of the selected materials in task 2.1. As stated a standard hardening cycle without DCT was performed on each material as a reference. This heat treatment procedure can be found in the literature [Str01, Wen02] or in the material specifications of the supplier [Udd03]. After hardening was done, an in-depth material characterization based on the mechanical properties (especially hardness and hardness distribution) and structural analysis were performed before the material is approved for further coating operations in task 3. The retained austenite in the steel was measured by the X-ray diffraction technique. It is known that this phase is an important parameter for stability. Austenite is namely formed together with martensite after hardening and quenching. The martensite transformation is however not always complete for most alloyed steels, so that untransformed austenite remains. This retained austenite has a lower hardness than martensite and is very unstable. Distorsion can occur when the steel is heated or during plastic deformation due to a sudden transformation of austenite into martensite. Deep cryogenic treatment is therefore needed to enhance the initial transformation of unstable, retained austenite into stable martensite. This treatment is not usual in the actual state of the art of the heat treater's practice.

The substrate for the punches was hardened in a conventional way as well as with a standard DCT cycle after quenching. The heat treatment cycle was tuned for each of the tool steel by the Ventec Heat Treatment Shop (Moorsele, Belgium) before DCT was applied. All the steel bars were treated in a vacuum furnace with gas quenching then shipped to the Nitrotechnics company (VBS in Tubize, Belgium) within 2 days (time delay) where the DCT cycle was applied.

After this DCT cycle the samples were sent back to the heat treating company for a final tempering treatment. In most cases the tool steel was tempered three times at high temperature (higher than 500°C).

Some of the conventional heat treatment (without DCT) was also performed by Aweba in Germany.

The standard DCT cycle was performed with the following parameters:
- Cooling speed: -2°C/min
- Maximum cooling temperature: -196 °C
- Holding time: 24 hours
- Heating speed: ca 1 °C/min

The cryogenic chamber (Type Cryotron) was a wet type of cooling chamber with a volume of ca 2 m^3 and directly connected to a liquid nitrogen tank (*Figure 4-8*).

Figure 4-8: Cryogenic chamber and liquid nitrogen tank for execution of DCT on materials

4.2.3 WP2.3 Material hardening for optimal performance

Based on the previous investigation on suitable tool materials for fine blanking, deep cryogenic treatments was added to the standard hardening cycle to reduce the retained austenite and increase the structural stability and hardness. After performing a frequently used cycle (no DCT cycle is actually standardized) the hardness and retained austenite was measured by the X-ray diffraction method. In literature it is stated that the best results with DCT is obtained after quenching and before tempering is done. However some exceptions to this rule exist depending on the steel alloy composition etc. The goal was to have the lowest retained austenite level, the highest hardness and toughness. The toughness was measured by impact tests (notched and unnotched).

For the new tool steel Vancron 40 a hardness diagram with different tempering temperatures was first established (*Figure 4-9*). For the other tool steel used in this project technical data f.i. [Pel04] was available in literature.

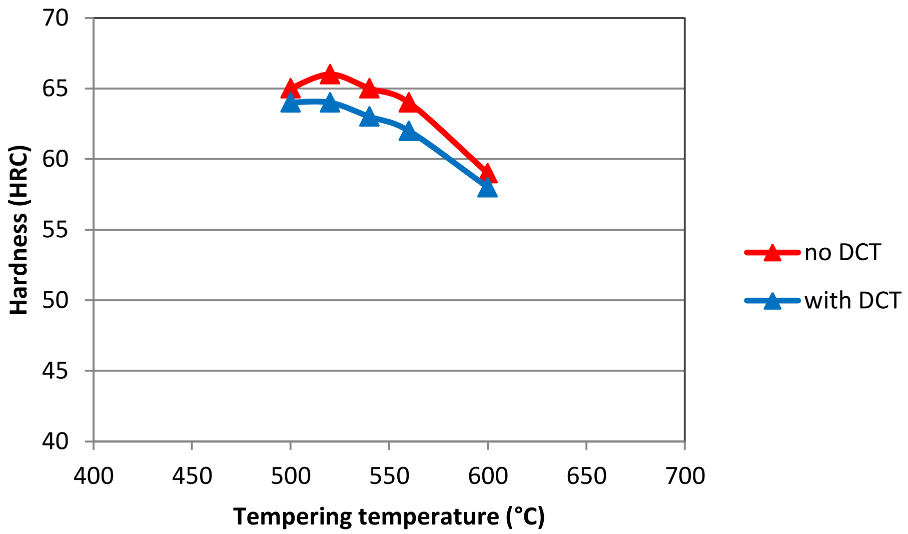


Figure 4-9: Tempering diagram of Vancron 40

The standard hardening cycle for tool steel has normally 3 tempering treatments after quenching. However since the DCT influences the tempering behavior the tempering heat treatment had to be adapted to obtain the same hardness. The selected hardness was 59+2 HRC.

The amount of retained austenite was measured by XRD method. *Figure 4-10* shows some results obtained after conventional hardening and DCT.

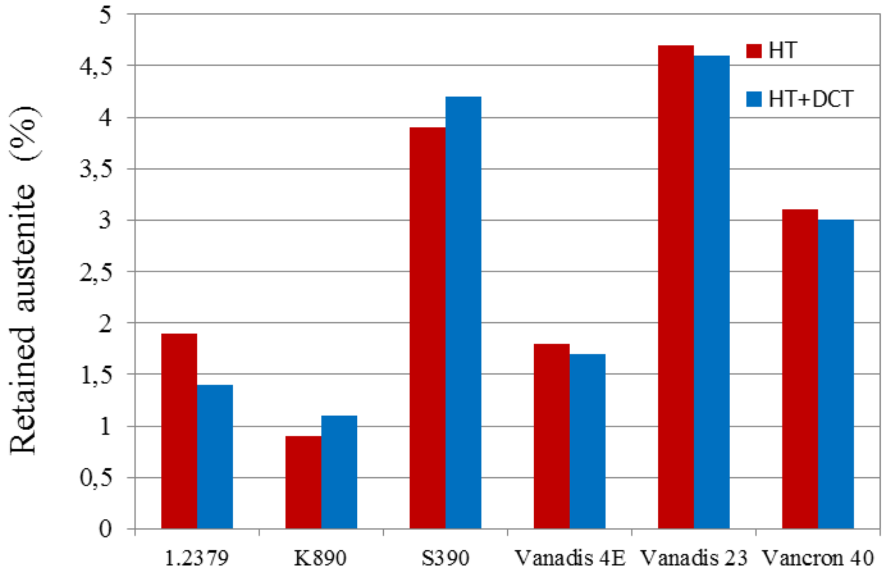


Figure 4-10: Retained austenite after heat treatment

From this figure it can be observed that the amount of retained austenite is quite low for most of the steel and that DCT only slightly reduces this amount. In some cases like S390 and K890 DCT even seems to increase the amount of retained austenite. However in most of the selected steels DCT is not reducing the retained austenite because of the extended tempering treatment after hardening.

The presence of special carbides due to the DCT was analyzed by SEM-EDX analysis. However this method could not reveal the special ‘eta’ carbides reported in literature [STRAT01; JUNG05]. These carbides are considered to influence the wear behavior in a positive way.

The fracture toughness of the samples was measured with standard V-notched and unnotched test samples (non-standard samples 7 x 10 x 55) on a Zwick 750 impact test machine at 20°C. The tests were performed on 3 types of tool steel. The purpose was to investigate the influence of DCT sometimes mentioned in literature on the toughness [Wen02]. The results showed no negative influence of DCT on notched and unnotched samples. The fracture surface of the steels on unnotched samples with and without DCT also showed no difference in morphology.

In literature [Wen02; Law06; Vei07] most of the reported wear tests are performed on a small lab scale. In this project the aim and focus was directed towards both lab scale and industrial punch tests (see below). However in order to confirm some wear data it was necessary to use an additional lab test. The scratch test was chosen to compare the abrasive behavior of some tool steels involved in this study.

Figure 4-11 shows some SEM images of the scratches and *Figure 4-12* gives the penetration depth after scratching measured by a Perthen roughness measurement. It can be seen that the reference steel has the lowest resistance followed by Vancron 40. Furthermore the DCT seems not to favor the abrasive resistance of most of the tool steel. In the case of Vancron 40 a crack formation was found after DCT.

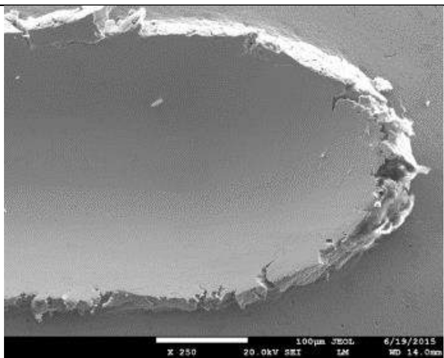
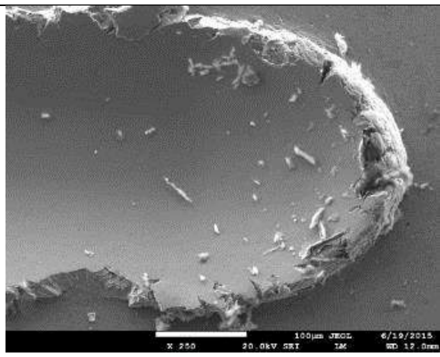
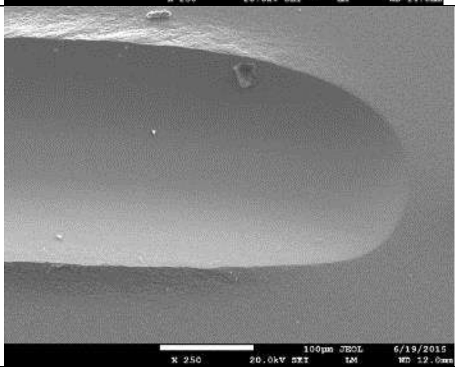
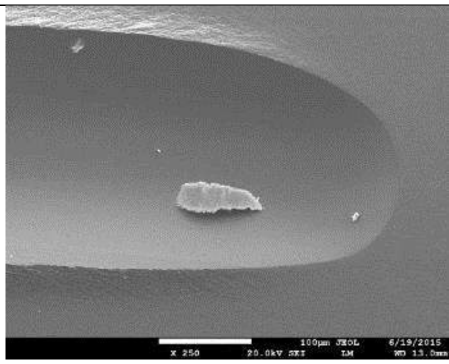
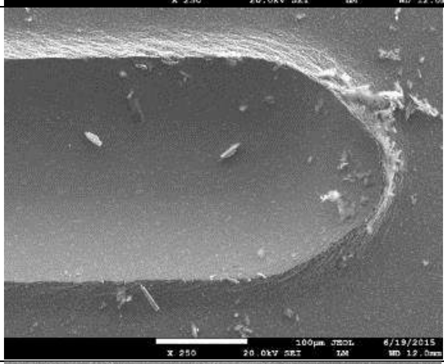
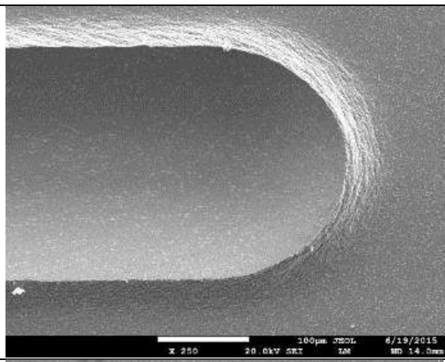
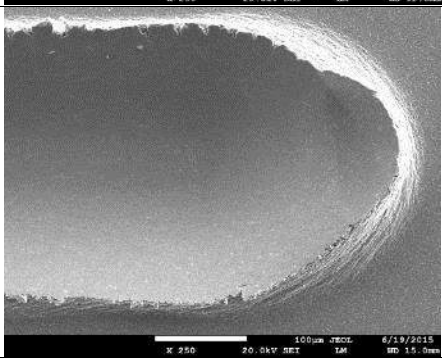
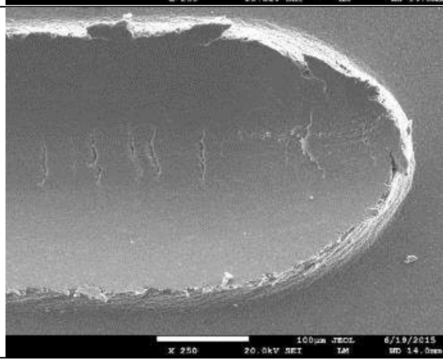
Material	CONVENTIONAL	DCT TREATED
1.2379		
Vanadis 4 E		
Vanadis 23		
Vancron 40		

Fig 4-11: SEM images of the surface after scratch tests on flat uncoated samples

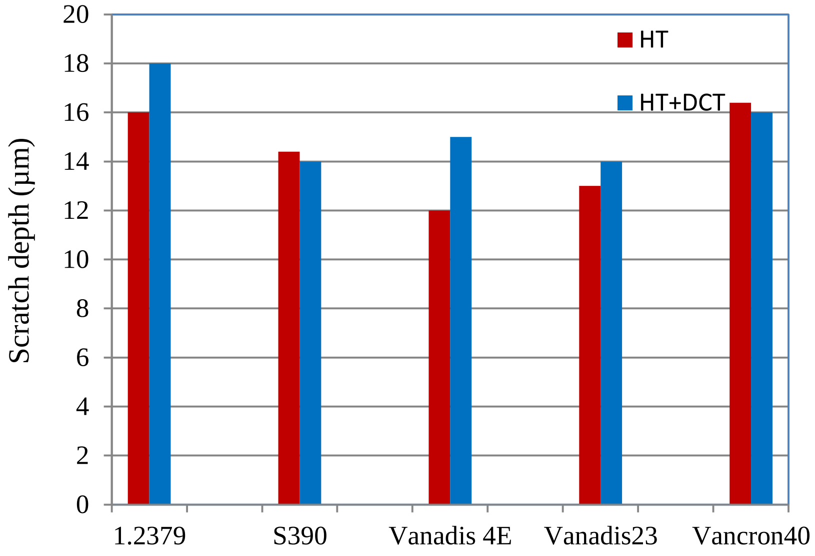


Fig 4-12: Results of scratch tests on flat samples

4.3 WP3 Coating development for fine blanking tools.

The coating development starts with the coating of reference samples and the determination of the coating properties on it. In iterative loops the coating properties shall be optimized. In the next step test and production tools will be coated with the best coating procedures. After cutting tests in WP 4 and WP 5 a detailed wear analysis will give information for further coating optimization.

4.3.1 WP3.1 Coating of reference samples

Objectives: The goal of this task was the coating of reference samples made from the materials selected in task 2.1 with and without deep cryogenic treatments from task 2.2 and task 2.3. Based on previous research projects and the characterization of the fine-blanking process in WP 1 suitable coating systems were selected. The coatings were applied by PVD (DC and pulse magnetron-sputtering) processes. The coating parameters were varied to optimize the coating properties concerning adhesion, hardness, wear resistance, coefficient of friction. To increase the adhesion and load bearing capacity of the coatings a plasmanitriding process was adapted to the selected materials. Of particular importance was the preservation of the material properties after deep cryogenic treatments.

State of the art of coatings for blanking operations:

For the most cutting and blanking operations tool coatings are indispensable in industrial production. Today hard coatings for wear reduction like TiN, TiCN, TiAlN and CrAlN are well established. The consequence of increasing productivity and product quality requirements is the need of an increase in the performance of tool coatings. Particularly, the trend to operate under dry conditions, high speed cutting, cutting of hard materials, and machining of lightweight materials is still a challenge for tools and coatings. The preparation of high performance coatings requires the application of deposition processes with high plasma activation, e.g. plasma enhanced sputtering. One way to increase the capability of tool coatings is the realization of coating systems consisting of different layers or phases in one coating with different materials and properties. Interesting for such combinations are especially TiAlN and CrAlN hard coatings, which are widely used in tool industry. Commonly they are prepared by PVD techniques like arc evaporation or magnetron sputtering. Typical micro hardness values of such hard coatings are in the range of 25-30 GPa.

In spite of the considerable progress in coating quality achieved in the last years, there are still a lot of approaches to improve the performance of TiAlN and CrAlN based coatings. So variations of the deposition process parameters can influence the density, crystallite size and orientation of such coatings [Bab07; Bou07]. Furthermore the coating properties, oxidation resistance and high temperature behavior can be markedly influenced by incorporating additional elements like Cr, Y, Si or by creation of multilayer systems [Vel09; Bar05]. Here also the superhard nanocomposite coatings consisting of transition metal nitride nanocrystallites "glued together" by thin amorphous layers [Vep05; Jia06; Vep08; Rav07] shall be mentioned. Another solution approach is the incorporation of W or V which are forming Magnelli-Phases at elevated temperatures which can decrease friction. Especially the effect of V is reported in the literature [Lew04; Mue00]

Solution approach:

In the present project the coating development was focused on CrN based coatings which were modified with Al, Ti, Si and V. Coatings modified with Ti, Al and Si were prepared by reactive sputter deposition especially using the pulsed sputter deposition mode, coatings modified with V, W and Ti were prepared by DC reactive sputter deposition.

The mechanical properties at room temperature and after tempering were investigated and compared with the corresponding features and data for pure TiAlN coatings. The coating development started with the coating of conventional high speed steel (1.3343). Afterwards the best coatings were deposited on the steel substrates from task 2. In the next step the coating adhesion was optimized by additional plasma nitriding treatments.

Deposition of Ti, Al and Si modified CrN coatings on high speed steel:

The modified coatings were prepared using a CemeCon CC800/9 sputtering system (CemeCon AG, Würselen, Germany). The deposition processes consisted of five main steps: (i) heating (ii) Ar ion etching for substrate cleaning; (iii) sputter deposition of an adhesion improving layer by increasing the reactive gas flow gradually and increasing the target power up to maximum values; and (iv) gradually increasing the substrate bias up to the maximum selected bias value; and finally (v) the deposition of the modified CrN coating under constant process conditions. In the deposition steps (iii), (iv) and (v), different metal targets can be combined. With this method the variation of coating composition could be easily performed by applying different power to the targets. The structure of the coatings could be assumed to be nanolayered. Due to the rotation of the samples through the coating chamber and different coating deposition conditions in front of the different target materials this should result in an interrupted grain growth and therefore a fine grained and nanostructured respectively nanolayered coating. The total coating thickness was approximately 3-5 µm.

Typical process parameters are summarized as:

- Targets: TiAl (50:50), Cr (purity 99.9 %), Si (purity 99.99 %),
- Target power: TiAl 5 kW, Cr (3 kW), Si (1 kW), SiC (3 kW)
- Target mode: d.c. or pulsed d.c.
- Reactive gas: nitrogen (N2); Gas flows: Ar: 200–300 sccm; N2: 200–300 sccm
- Total gas pressure: approximately 0.5 Pa
- Substrate potential (d.c.): varied from −30 to −120 V,
- Process temperature approx. 350 °C

As substrate material for the first coating experiments polished steel substrates, e.g. high speed steel (1.3343) as well as Si wafers were used. The substrates were fixed at sample holders and coated in two-fold rotation. *Figure 4-13* schematically shows a schematic illustration and a cross section of the process chamber and the different sample positions. Position “plate” means the sample was clamped to a plate in the center of the satellite.

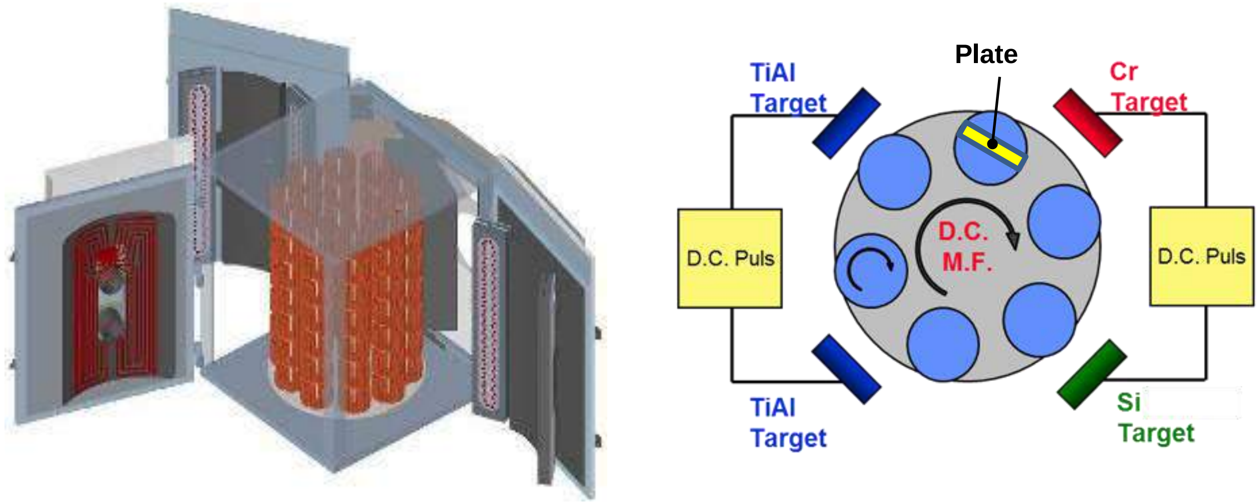


Figure 4-13: Schematic illustration of the magnetron sputter machine CC800/9 from Cemecon.

<u>Deposition of V and W modified CrN coatings on high speed steel:</u>

Another way to improve the coating properties of CrN especially hardness and tribological properties at higher temperatures is doping with vanadium, tungsten or titanium. CrN, CrVN, CrWN and CrTiN coatings were prepared by reactive d.c. magnetron sputtering in the unbalanced mode using a HTC 1000/4 (ABS) coater (Hauzer Techno Coating, Venlo, The Netherlands). The process chamber has a volume of 1 m^3. Typical deposition parameters and schematic illustration are shown in *Figure 4-14*. Targets made of chromium and the different doping metals (vanadium, tungsten, titanium) have been used for composing different coating systems, where the target power for chromium was constant 3 or 6 kW and variable for the doping elements depending on the requested metal content. The resulting deposition rates vary from 0.6 to 1.8 µm/h.

After a plasma etching step, using argon as process gas, an adhesive layer of chromium was deposited using 2 targets. The top layer was formed with additional nitrogen in the process atmosphere. The fraction of doping elements in the considered coatings was adjusted while controlling the power of the additional metallic targets. As reference coatings CrN, VN and WN were deposited.

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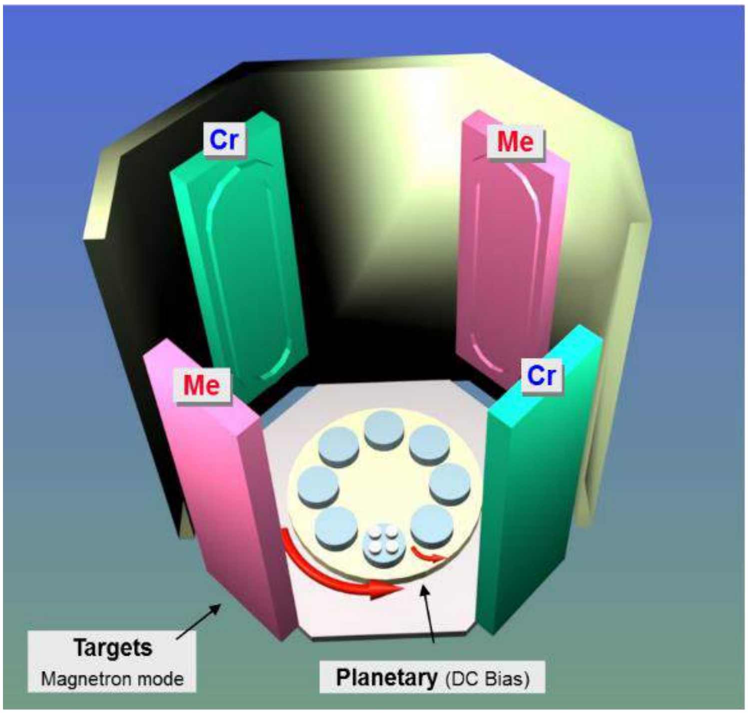


Targets

- **Cr + Me** (Me = V, W, Ti)

Target power

- Cr: 3 or 6 kW
- Me: variable, depending on requested Me content

Deposition parameters:

- U_b = - 100 V / - 400 V
- Coil current up 6 A (2 x)
- Sputter gas: Ar + N
- N_2 content: ≤ 50 %
- Sputter gas pressure: 0.3 Pa
- T_S = 100 - 450°C without additional heating
- Deposition rate: 0.6 – 1.8 µm/h

Figure 4-14: Schematic illustration of the magnetron sputter machine Hauzer HTC 1000 from Hauzer Techno Coating.

Optimization of the plasma nitriding treatment

Plasma nitriding can increase the hardness and wear resistance of tool steels for different applications. Plasma nitriding allows the synthesis of specific compound layers (gamma'-phase, Fe_4N; epsilon-phase, $Fe_{2-3}N$; and mixed gamma'-epsilon-phase) [He07]. The layers created during the plasma diffusion treatment offer mechanical support to hard coatings, so that the danger of the so called eggshell effect on soft substrates is reduced [Kli04]. The hardness can decrease gradually from the hard coating to the softer base material. There again nitriding normally decreases the ductility and crack resistance of the tool surface especially in the case of high alloyed steels like in this project. The material properties after nitriding depends on the process parameters (mainly temperature, time, ratio of N_2/H_2 in the process gas) but also on the type and amount of each alloying element. That is the reason why the nitriding treatment has to be adapted to the different materials selected in WP 2.

The Objectives of the optimization of the plasma nitriding treatment were:

- Increased coating adhesion and load bearing capacity
- No reduction in crack resistance of the base material
- Investigation of the influence of DCT on the nitriding result and vice versa

Small samples from the materials selected in WP 2 with and without DCT were plasmanitrided with a pulse plasma machine PP40/400x800 2135 (*Figure 4-15*) with the following parameters:

- Treatment time: 4 /16 h
- Used gases : 5 / 10% N_2, remaining quantity H_2
- Temperature: 520°C
- Pressure: 350 Pa
- Voltage: 500 V
- Pulse/pause ratio: 100/500 µs/µs.

Figure 4-15: Pulse plasma machine PP40/400x800 2135 (Plateg).

4.3.2 WP3.2 Determination of coating properties on reference samples

The goal of this task was the evaluation of the properties of the coating systems on the different treated tool materials from WP 2. Standardized procedures for coating characterization were used (Rockwell indentation test, micro hardness measurement, calo wear test). The preparation of cross sections allowed the investigation of the microstructure of the coatings and the tool material by optical and scanning electron microscopy (SEM). The coating composition was examined by electron probe micro analysis (EPMA).

<u>Coating properties of CrTiAlN and CrTiAlSiN compared to TiAlN:</u>

The indentation hardness and the Young's modulus of the coatings on HSS substrates were measured by a Fischerscope H100 commercial instrument. The hardness and Young's modulus were derived from load vs. indentation depth curves. The indentation depth was around 220 nm. Abrasive wear rates of the coatings on HSS substrates were determined with the ball cratering test operating with an alumina suspension. To quantify the results, the volume of the crater ground into the coating was divided by the normal load and the track length of the rotating ball [Tau98; Bew00]. The unit used for abrasive wear of our coatings is 10−15 m^3/Nm. The coating adhesion was determined by Rockwell (HRC) indenter tests. Furthermore the morphology of the coatings on silicon substrates could be verified with cross section images by scanning electron microscopy (SEM, Leo 1530, Leo Electron Microscopy). With microprobe measurements (EPMA, Cameca SX100) the chemical composition of the coatings on silicon substrates was determined. Tempering experiments were carried out with coated HSS samples under ambient atmosphere. The samples were arranged in a furnace (GPC 1300, Carbolite) and exposed to different temperatures (700 °C, 800 °C, 900 °C, 1000 °C) in each case for 30 min, followed by different coating characterization methods.

The morphology of the TiAlN reference coating prepared with pulsed magnetron sputter technique with a substrate bias gradient (from −30 V to−100 V d.c.) could be examined by a SEM cross section image. At a substrate bias value of approximately −60 V a change from columnar growth to a dense featureless structure took place (*Figure 4-16a*). CrTiAlN (*Figure 4-16b*) and CrTiAlSiN (*Figure 4-16c*) coatings, prepared with a substrate bias gradient from −30 V to −120 V show a comparable morphology. For low bias values a columnar growth structure is predominant and at a certain bias value the morphology changes to more glassy-like.

The chemical composition of the coatings was derived by EPMA. Typical compositions are:

- TiAlN [at:%]: Ti : 24,6; Al : 24,2; N : 51,1
- CrTiAlN [at:%]: Cr : 19,6; Ti : 14,8; Al : 14,8; N : 50,7
- CrTiAlSiN [at:%]: Cr : 24,1; Ti : 11,6; Al : 12,0; N : 50,7; Si : 1,5

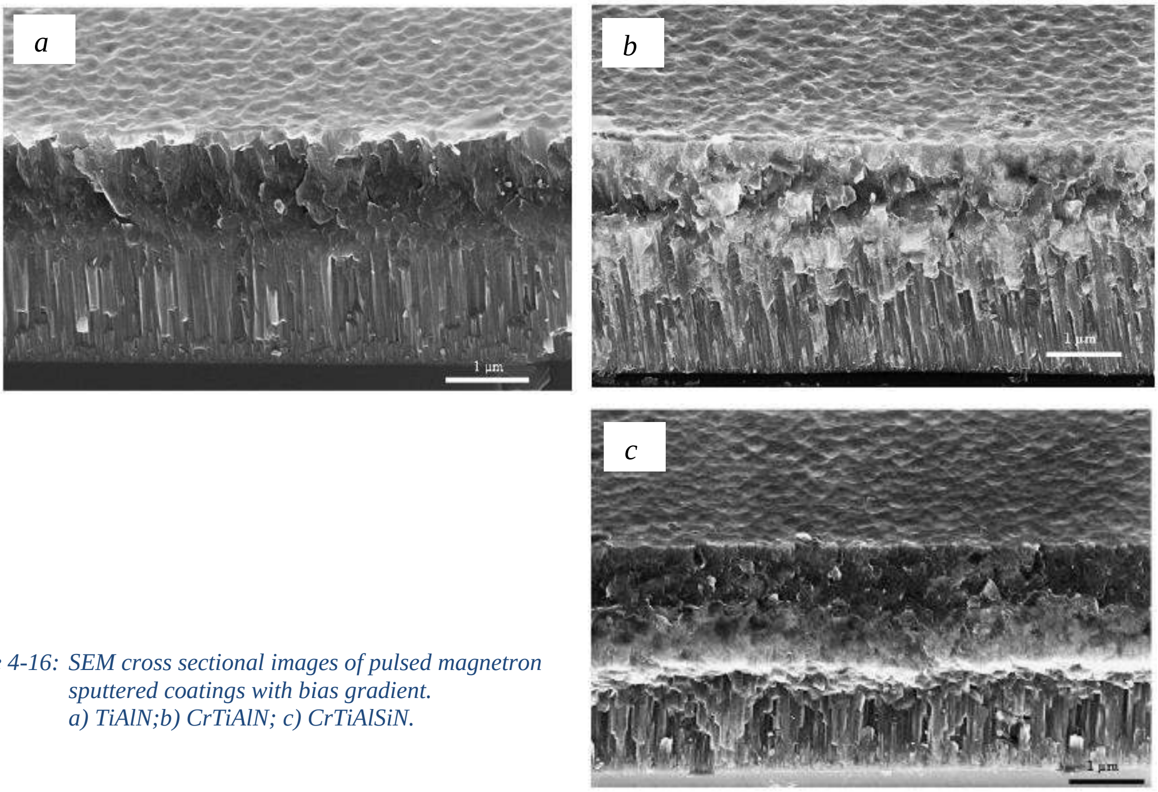


Figure 4-16: SEM cross sectional images of pulsed magnetron sputtered coatings with bias gradient. a) TiAlN;b) CrTiAlN; c) CrTiAlSiN.

Regarding the indentation hardness of the coatings (*Figure 4-17*), there is no significant difference. One can detect a hardness increase with increasing substrate bias values. Only for low bias values of −30 V the hardness of the CrTiAlSiN coatings was lower compared to CrTiAlN.and TiAlN coatings. Two more CrTiAlSiN coatings with −90 V substrate bias with slightly different Si content were also deposited. One coating had a slightly reduced Si content of about 1.2 at.% and an indentation hardness of 42 GPa. Another one had about 2.4 at.% Si content and an indentation hardness of 33 GPa. The hardness of the coatings was significantly affected by the Si content. Relative low Si contents <2 at.% seemed to sustain a high coating hardness for the regarded deposition conditions. However, it's noteworthy that for all coatings the coating indentation hardness reaches 40 GPa for substrate bias values in the range of −120 V. Another interesting property of the coatings is the abrasive wear rate also shown in *Figure 3-4*. The wear rates generally decrease with increasing bias values and the wear rates of the modified coatings are in the same range or slightly lower compared to TiAlN coatings, but at high bias values in the region of −120 V equivalent to high coating hardness only the wear rate of TiAlN coatings increase. This could be correlated to higher intrinsic stress of TiAlN coatings indicated by an inferior coating adhesion, e.g. in Rockwell adhesion tests (see *Figure 4-18*). High stress could lead to flaking of small pieces of coating material under the wear of the abrasive slurry resulting in a higher abrasive wear rate.

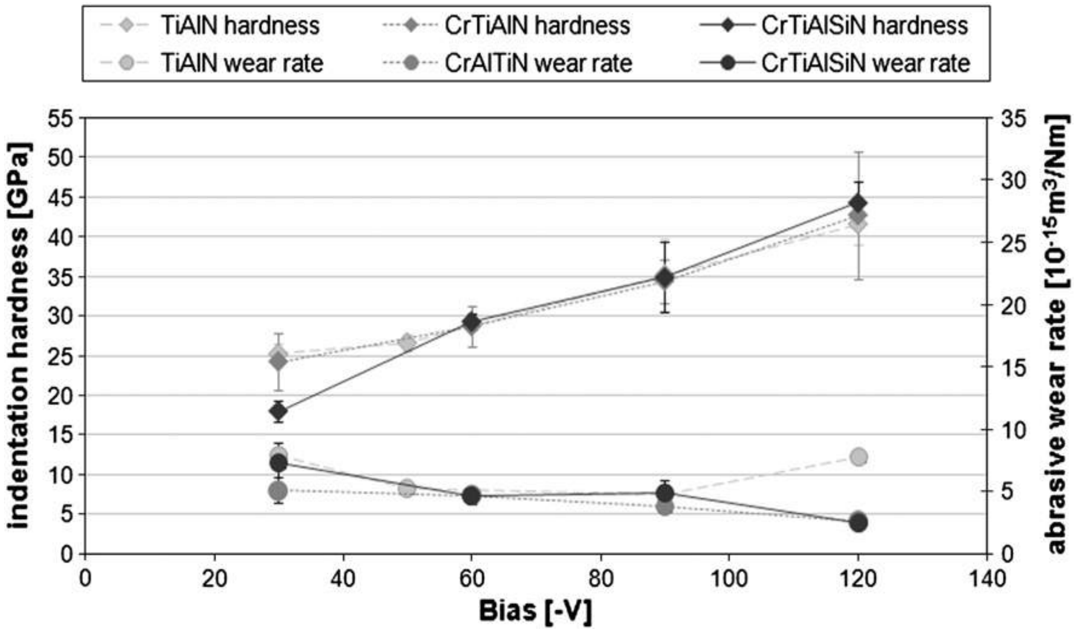


Figure 4-17: Coating hardness and abrasive wear rate vs. the applied substrate bias of Ti, Al and Si modified CrN coatings.

However, beside the mechanical properties at room temperature, the behavior of the coating properties at elevated temperatures in ambient atmosphere may be important especially for fine blanking tool applications. The coated samples were heated in ambient atmosphere in a furnace each for half an hour at 700 °C, 800 °C and finally 900 °C followed by subsequent cooling and a measurement of hardness and Young's modulus. The results of mechanical characterization of the coatings before (as deposited) and after the tempering test procedure up to 900 °C are summarized in *Table 4-1*. The coating thickness was not changed after the tempering tests. On the other hand for the mechanical properties significant changes were revealed. The indentation hardness of TiAlN coatings decreased to values in the range of 13 GPa, independent of the hardness of as deposited coatings. For the CrTiAlN coatings there was also a decrease of hardness, but in contrast to TiAlN to clearly higher values of approximately 20 GPa. The coatings with an additional Si content revealed a different behavior. The CrTiAlSiN coating deposited with −120 V bias shows also lower indentation hardness after tempering procedure of around 25 GPa. Remarkable was the behavior of the CrTiAlSiN coating deposited with −30 V bias. After the tempering procedure the coating hardness increased from 18 GPa as deposited to 26 GPa. Due to these results it could be suggested that for every special compound respectively coating composition a typical hardness range after tempering at elevated temperatures exists, independent from the as deposited coating hardness. In the literature the superior thermal behavior of Si modified hard coatings is already described [Rav07] and hardness increase of TiAlSiN coatings at elevated temperatures was reported in [Ven03]. But remarkable are these effects at relative low Si (≤2 at.%) contents in combination with relative high Cr (about 20 at.%) contents in combination with the used deposition technique.

Due to the high hardness and thermal stability as well as the good coating adhesion CrTiAlSiN was selected for coating the optimized materials from WP 2.

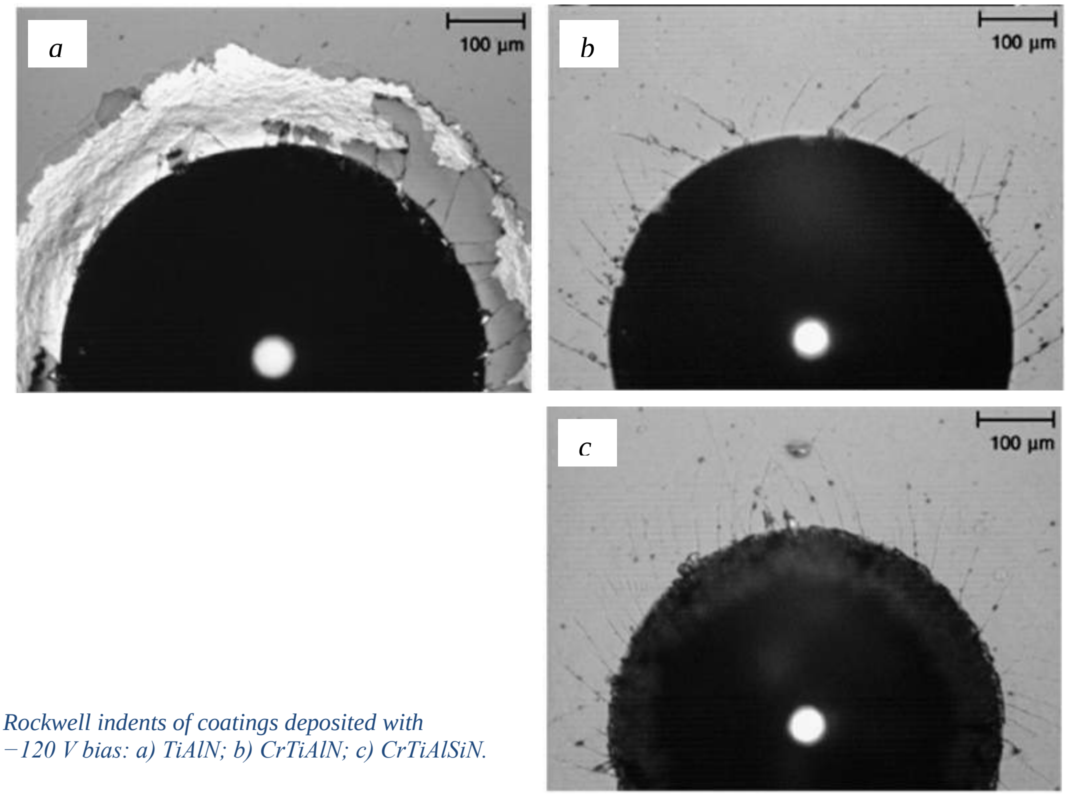


Figure 4-18: Rockwell indents of coatings deposited with −120 V bias: a) TiAlN; b) CrTiAlN; c) CrTiAlSiN.

Coating	Substrate bias [−V]	As deposited		After tempering	
		Coating thickness [µm]	Ind. Hardness [GPa]	Coating thickness [µm]	Ind. Hardness [GPa]
TiAlN	50	3,4	26,4	3,3	13,0
	120	2,6	41,6	2,6	12,8
CrTiAlN	30	2,8	24,2	2,9	18,5
	120	3,2	42,7	3,2	20,3
CrTiAlSiN	30	2,4	18,0	2,4	26,7
	120	2,9	44,3	2,9	25,0

Table 4-1: Properties of TiAlN, CrTiAlN and CrTiAlSiN coatings as deposited and after tempering procedure (half an hour for 700 °C, 800 °C and finally 900 °C).

Coating properties of V, W and Ti modified CrN coatings:

The chemical composition of the coatings was derived by EPMA. Typical compositions are:

- Nitrogen: 32 - 49 at. %
- Vanadium: 10 - 30 at. %
- Tungsten: 16 - 23 at. %
- Titanium: 9 - 12 at. %

- Chromium: balanced

The doping elements showed a strong influence on the growth structure of the coatings. A comparison between coatings which were deposited with a DC substrate bias of - 200 V and a target power of 6 kW on the chromium targets is shown in *Figure 4-19*. Under the same conditions deposited CrN has a columnar structure, tungsten promotes finer columns, vanadium and titanium causes rather amorphous structures. In all cases an increasing bias caused a cumulative amorphous structure.

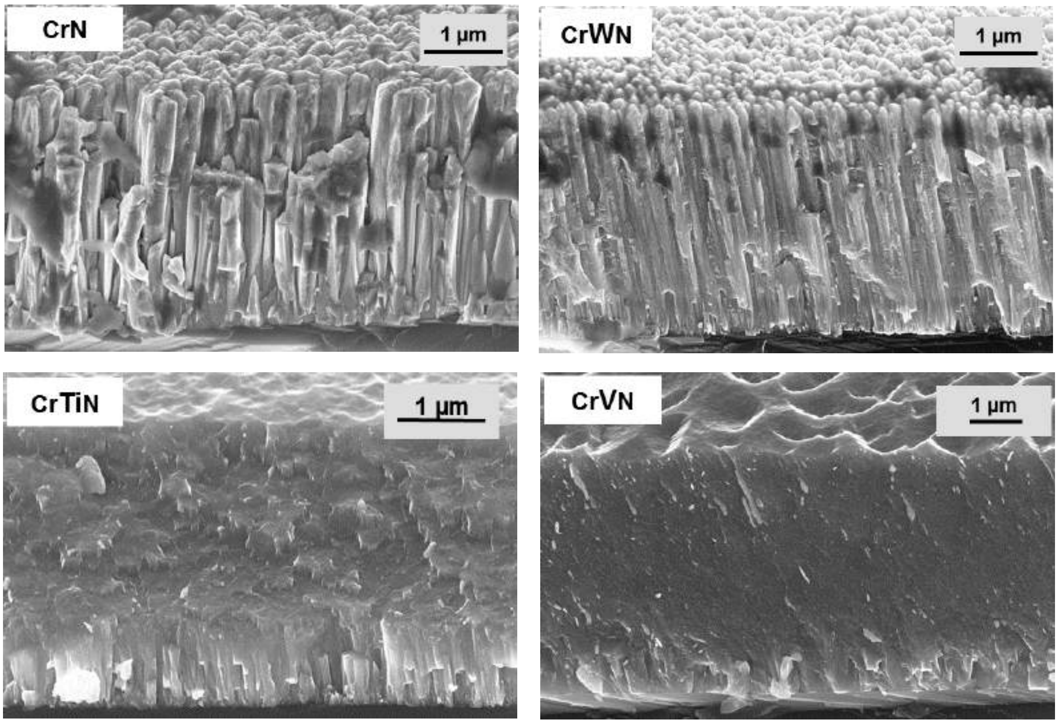


Figure 4-19: SEM cross sectional images of different magnetron sputtered coatings, DC substrate bias – 200 V, Cr 6 kW.

For all of the doping elements a significant increase in hardness was noted, with only minor differences between the elements. *Figure 4-20* shows the influence of the doping elements and the applied negative substrate bias voltage on the hardness. The toughness, on the other hand, dropped. This revealed itself in the results of scratch test in the reduced critical loads at which cracks and flaking occurred in the coating. This was most marked with tungsten doping, least with vanadium doping. The best abrasive wear resistance at room temperature could be achieved by doping with vanadium, worst by doping with tungsten. A similar favourable influence of vanadium on the sliding wear resistance, the critical load as well as the coefficient of friction was reported in [Mue00] for TiAlN-VN coatings.

An annealing of 2 hours in air at elevated temperatures has a significant influence on the whole layer structure. At 600°C in the CrN coating cracks were clearly visible. EDX measurements, done by scanning electron microscopy on grinded calottes, indicate the diffusion of nitrogen in the chromium adhesion layer and a loss of nitrogen in the top layer. At higher temperatures, oxidation caused the formation of a thick chromium oxide surface layer. The CrWN coating shows a better thermal stability. No crack formation could be observed and the thickness of the surface layer was reduced. EDX measurements showed an enrichment of chromium and oxygen near the surface. CrTiN coatings showed a similar behavior. In the CrVN coatings the vanadium content starts to oxidize at temperatures above 550° C. The precipitated V_2O_5, which has a melting point of 690°C, is well known to reduce friction [Uch04]. On the other hand increasing vanadium content reduces the thermal stability and the maximum application temperature. In air a maximum application temperature up to 700°C seems to be possible with vanadium contents below 15 at%. At higher vanadium contents the maximum application temperature should be below 600°C. But this seems to be sufficient for fine blanking operations. On the other hand the amount of vanadium can influences the hardness and toughness of the CrVN coatings in a wide range. At vanadium contents below there is a drop in hardness down to 1800 HV for bias voltages of -150 V but an increase of the critical load Lc_2 from 41-48 N up to more than 65 N.

Due to the well-known friction properties and the possibility to vary the hardness and toughness in a wide range CrVN coatings were selected additionally to the CrTiAlSiN coatings for further coating experiments with the optimized tool materials from WP 2.

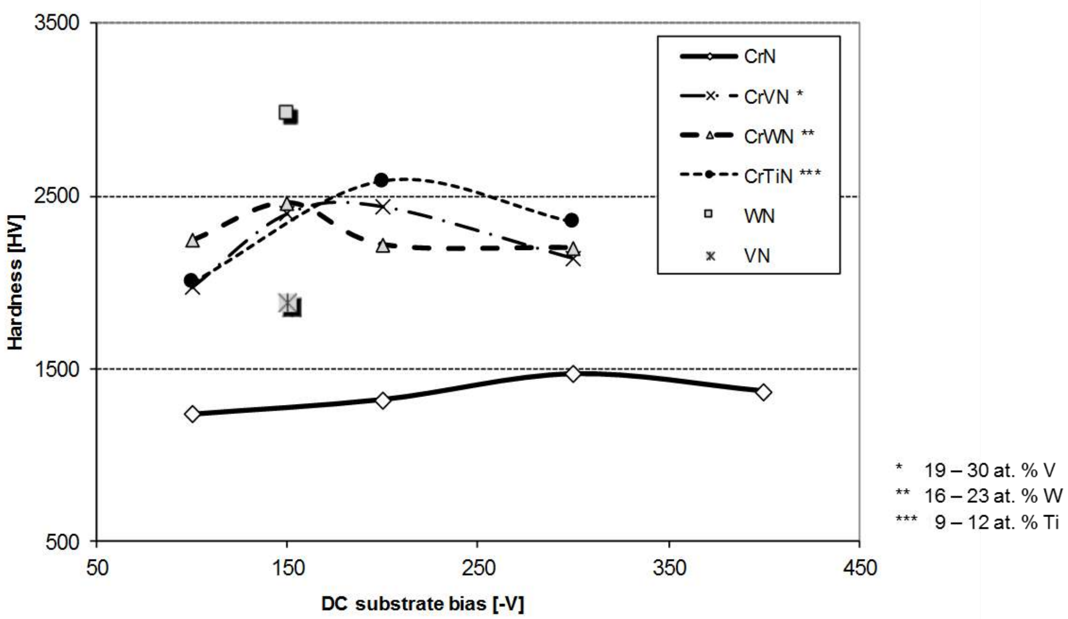


Figure 4-20: Coating hardness vs. the applied substrate bias of V, W and Ti-modified CrN coatings.

Selected coatings to apply on the optimized materials from WP 2:

Coating	**Hardness** [HV]	**Rockwell adhesion class** VDI 3198	**Abrasiv wear rate** [10^{-15} m³/Nm]
CrAlTiSiN	2500	1	4,3
CrVN	1800-2200	1	10,5

→ *higher wear and heat resistance*

→ *lower friction at elevated temperatures*

Table 4-2: Selected coatings for evaluation of their properties on the different treated tool materials from WP 2.

Characterization of the nitriding results:

The nitriding result was determined by measuring the hardness depth profile on cross sections of the samples. The crack resistance of the nitrided surfaces was determined by Rockwell-indentation-tests normally used for coating adhesion measurements. The target was the determination of the maximum possible nitriding treatment without visible cracks in the Rockwell-indentation-test. After optimization of the plasma nitriding treatment in this way the best samples were coated with CrTiAlSiN and CrVN to verify the effect on the coating adhesion by a second Rockwell-indentation-test. After that, cross sections of the samples with the best overall performance were investigated by SEM and EDX measurements. Examples of the characterization results of nitrided samples are shown in *Figure 3-9*. An overview of the nitride and examined samples is given in *Table 4-3*.

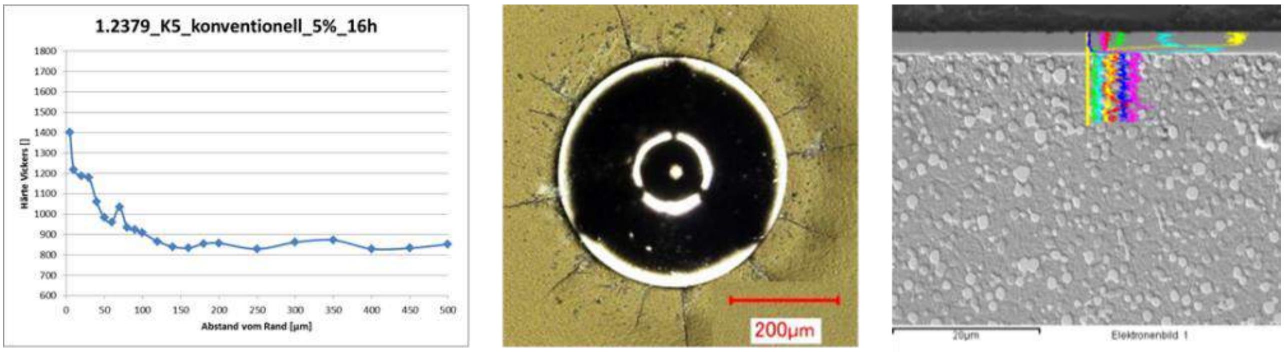


Figure 4-21: Examples of the characterization of nitrided samples; (left) hardness depth profile, (middle) Rockwell-indentation with insufficient crack resistance, (right) SEM image and EDX analysis of a CrVN coated sample.

Material	Heat-treatment	Plasmanitriding				
		without	4h, 5% N	4h, 10% N	16h, 5% N	16h, 10% N
1.2379	conventional	X	X	X	X	X
	DCT	X	X	X	X	X
Vanadis 4E	conventional	X	X	X	X	X
	DCT	X	X	X	X	X
Vanadis 23	conventional	X	X	X	X	X
	DCT	X	X	X	X	X
K890	conventional	X	X	X	X	X
	DCT	X	X	X	X	X
S390	conventional	X	X	X	X	X
	DCT	X	X	X	X	X

Table 4-3: Overview of the nitrided samples from WP 2.

Examination of the hardness depth profiles

The nitriding depth and the hardness gradient have a significant influence on the supporting function for the coating. That's the reason why a measurement of the hardness depth profile is necessary. Cross sections of all samples have to be prepared and polished. The local hardness was measured by micro-indentation with a Fischerscope HCU and an indentation force of 50 mN. The results for the conventional heat-treated materials are summarized in *Figure 4-22* and *Figure 4-23*.

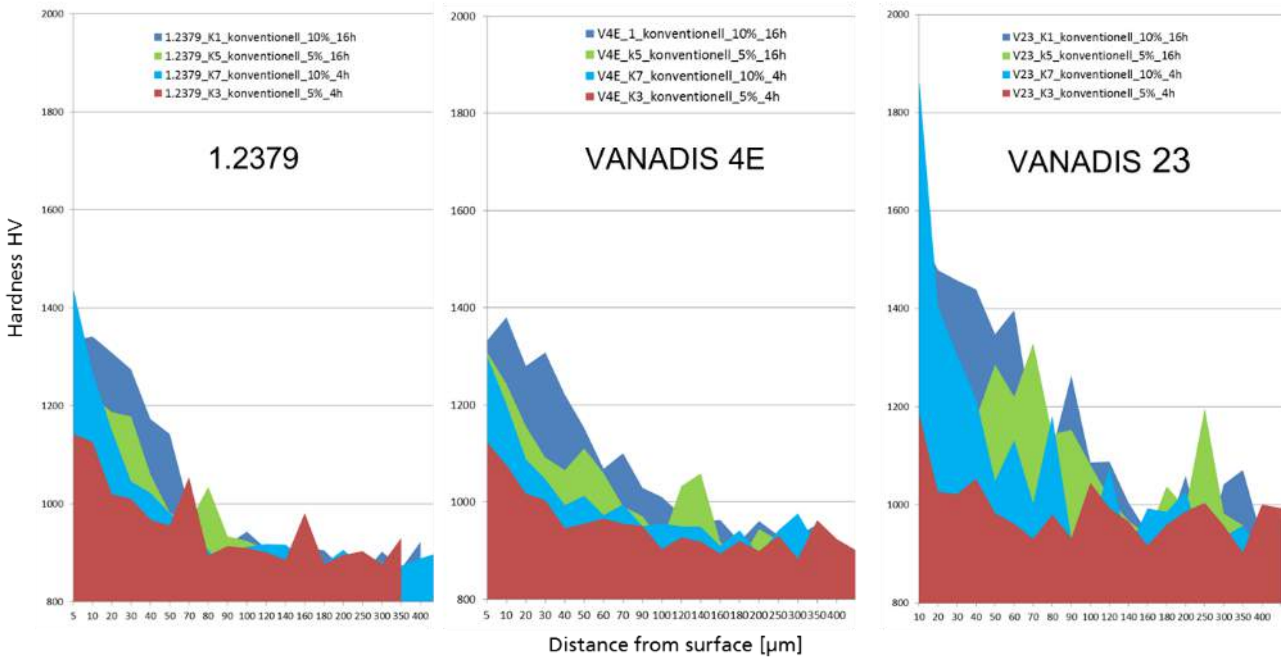


Figure 4-22: Hardness depth profiles in dependency on the nitriding parameters for conventional heat-treated 1.2379, Vanadis 4E and Vanadis 23

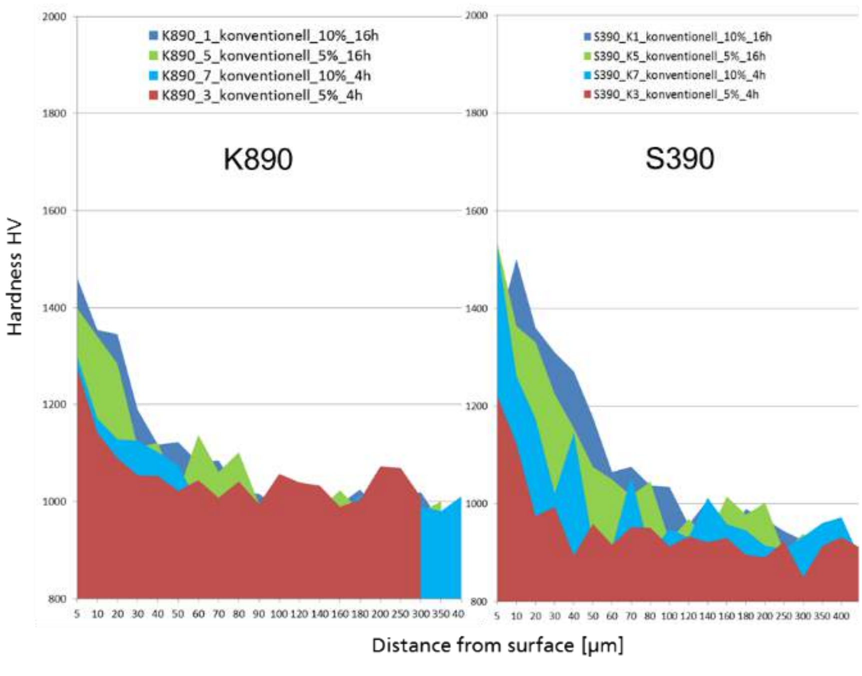


Figure 4-23: Hardness depth profiles in dependency on the nitriding parameters for conventional heat-treated K890 and S390

At low nitriding times (4 h) and nitrogen amounts in the process gas the hardness depth profiles are very similar for all materials and the maximum hardness at the surface was in the range of 1150 – 1250 HV. At higher nitriding times (16 h) and nitrogen amounts the influence of the alloying elements on the nitriding result is clearly visible. Especially the two materials with the highest amount of nitrid forming elements (Vanadis 23 and S390) show a higher nitriding depth and an increased hardness. Between the conventional and DCT treated materials are no significant differences concerning the hardness depth profiles (*Figure 4-24*). Only slight differences in the hardness of the base material are visible which are caused by the slightly different hardening and annealing temperatures.

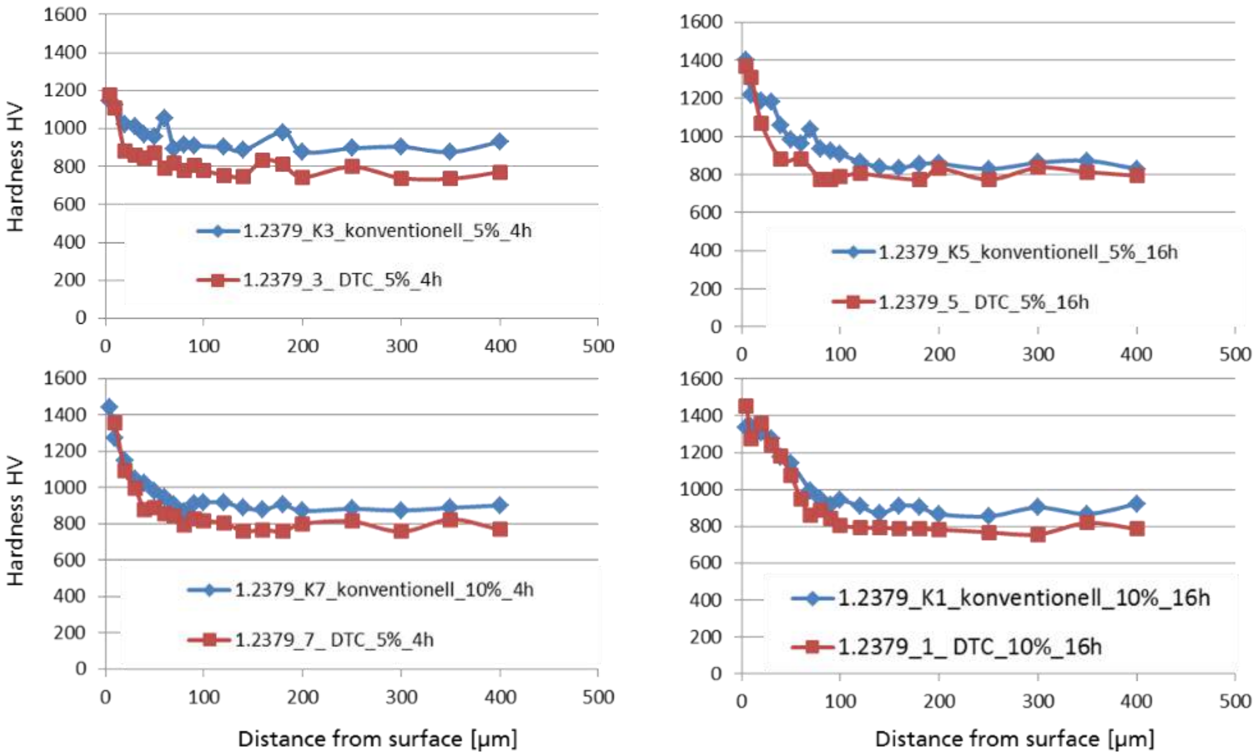


Figure 4-24: Hardness depth profiles in dependency on the nitriding parameters for conventional and DCT treated 1.2379

<u>Examination of the crack resistance by Rockwell-indentation-test</u>

Details of the examination of the crack resistance after nitriding by Rockwell-indentation-test are shown in *Figure 4-25*. Examples of the results for the materials 1.2379, Vanadis 23 and K890 with and without DCT treatment can be seen in *Figure 4-26* to *Figure 4-31*. The results of all materials are summarized in *Table 4-4*.

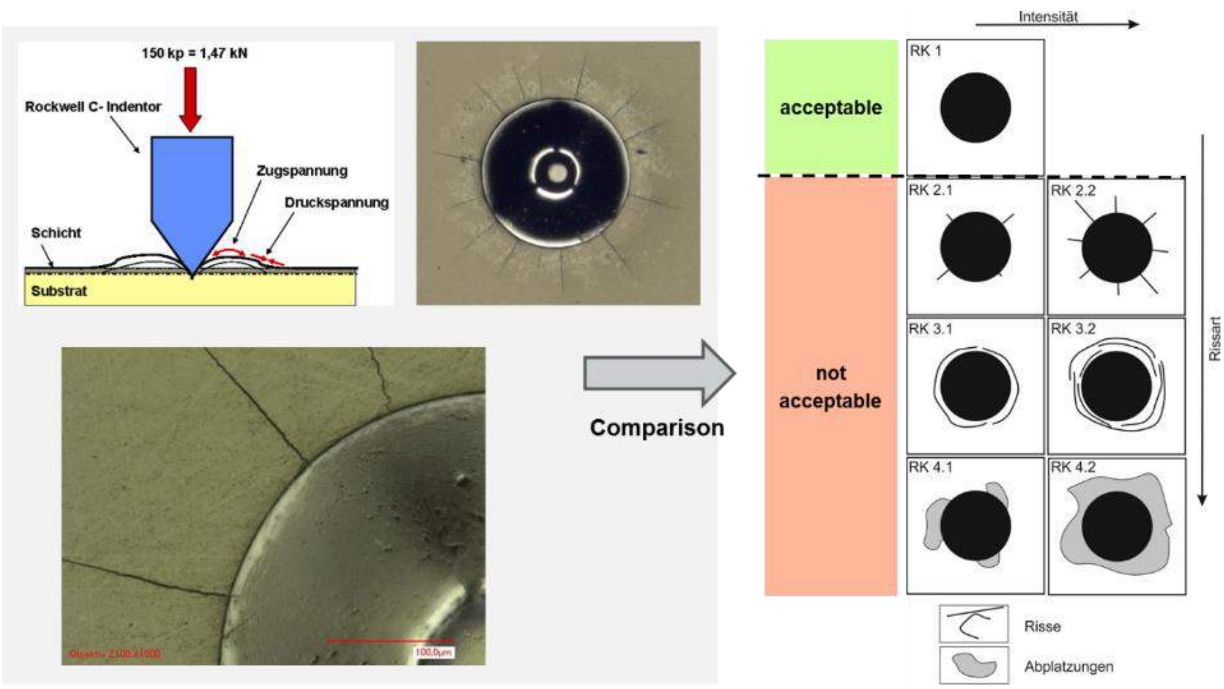


Figure 4-25: Examination of the nitriding result by Rockwell-indentation-test.

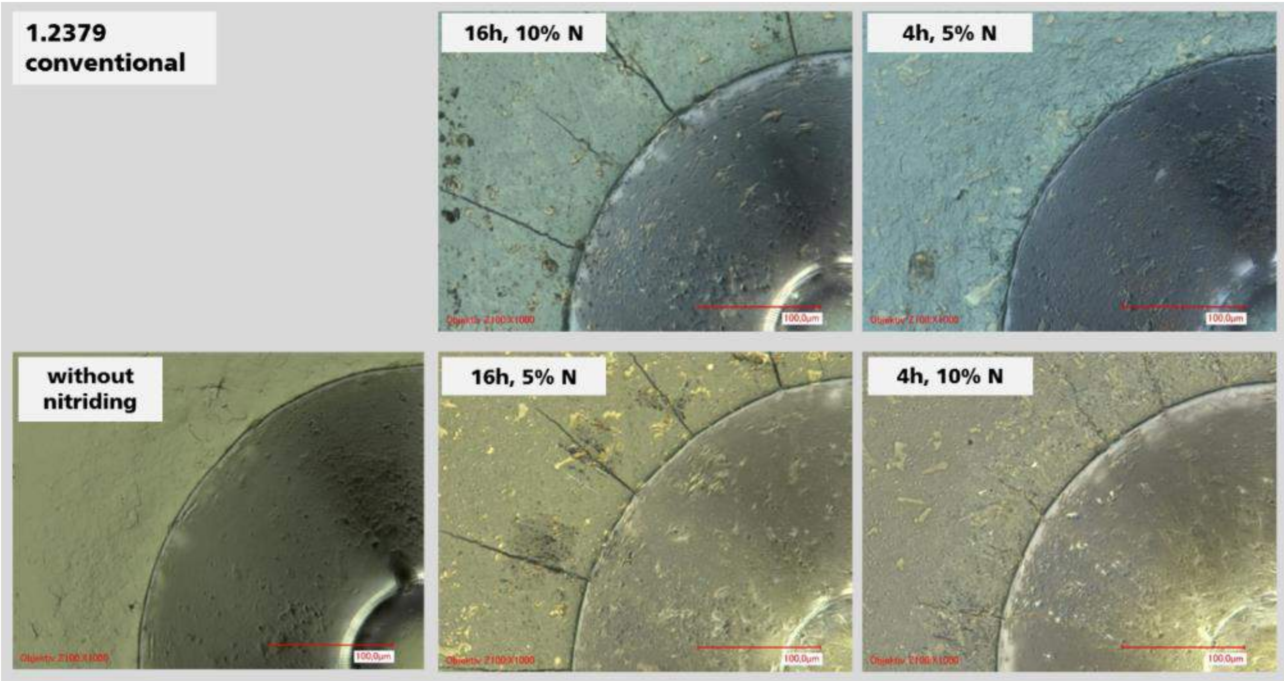


Figure 4-26: Crack resistance of 1.2379 with conventional heat treatment after plasmanitriding examined by Rockwell-indentation-test.

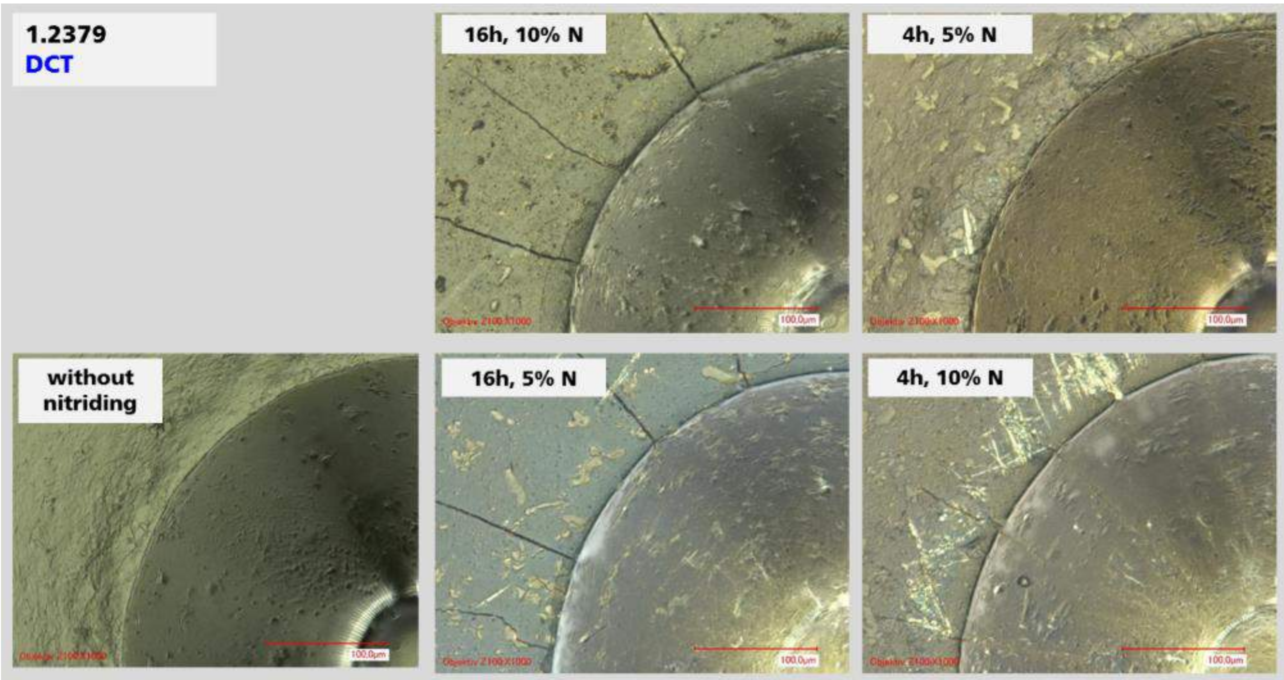


Figure 4-27: Crack resistance of 1.2379 with DCT after plasmanitriding examined by Rockwell-indentation-test.

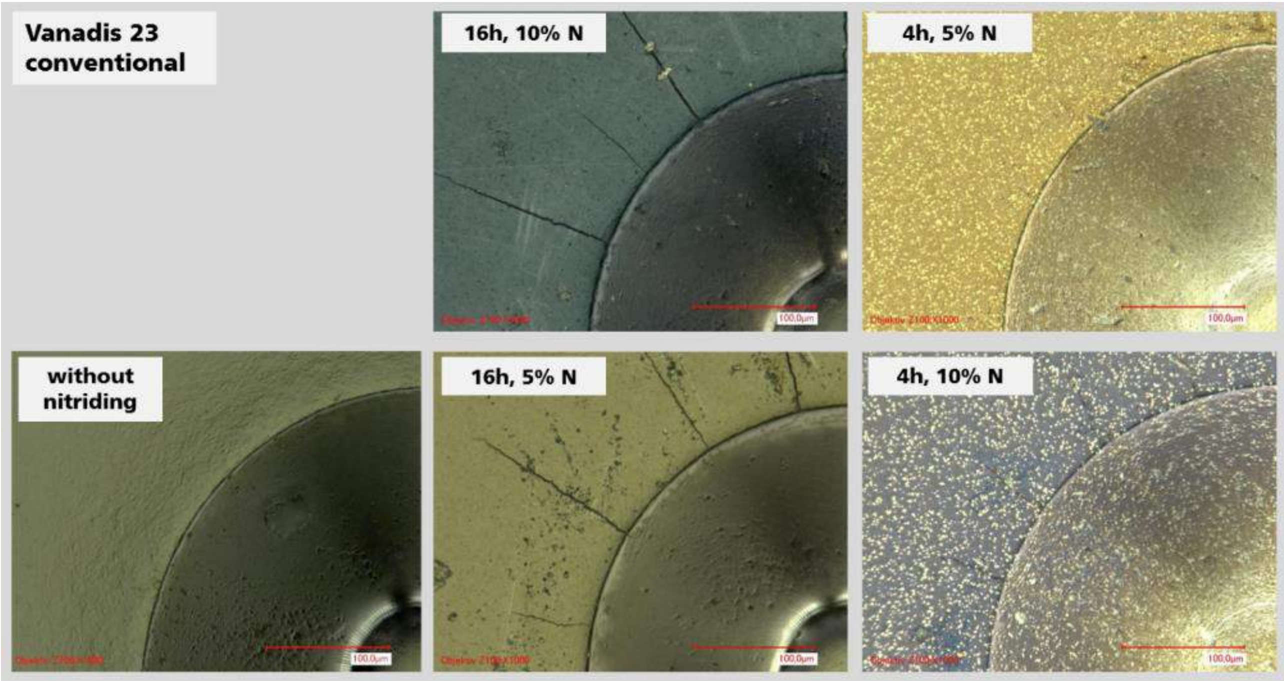


Figure 4-28: Crack resistance of Vanadis 23 with conventional heat treatment after plasmanitriding examined by Rockwell-indentation-test.

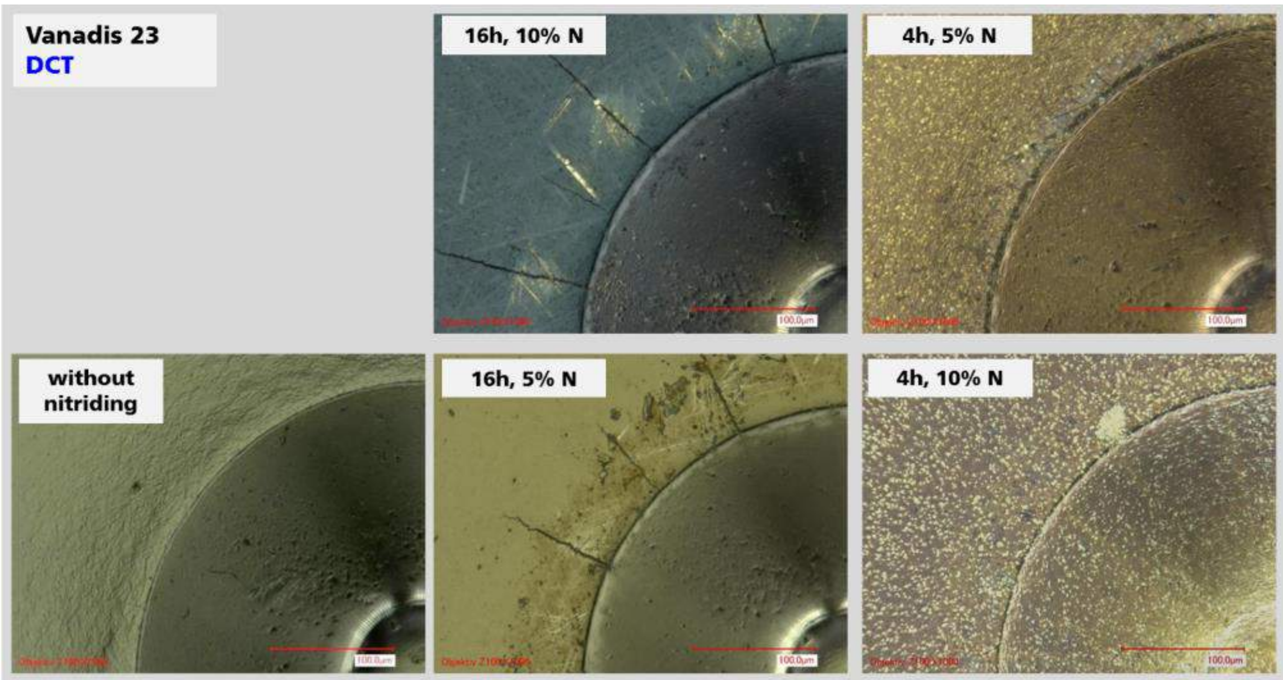


Figure 4-29: Crack resistance of Vanadis 23 with DCT after plasmanitriding examined by Rockwell-indentation-test.

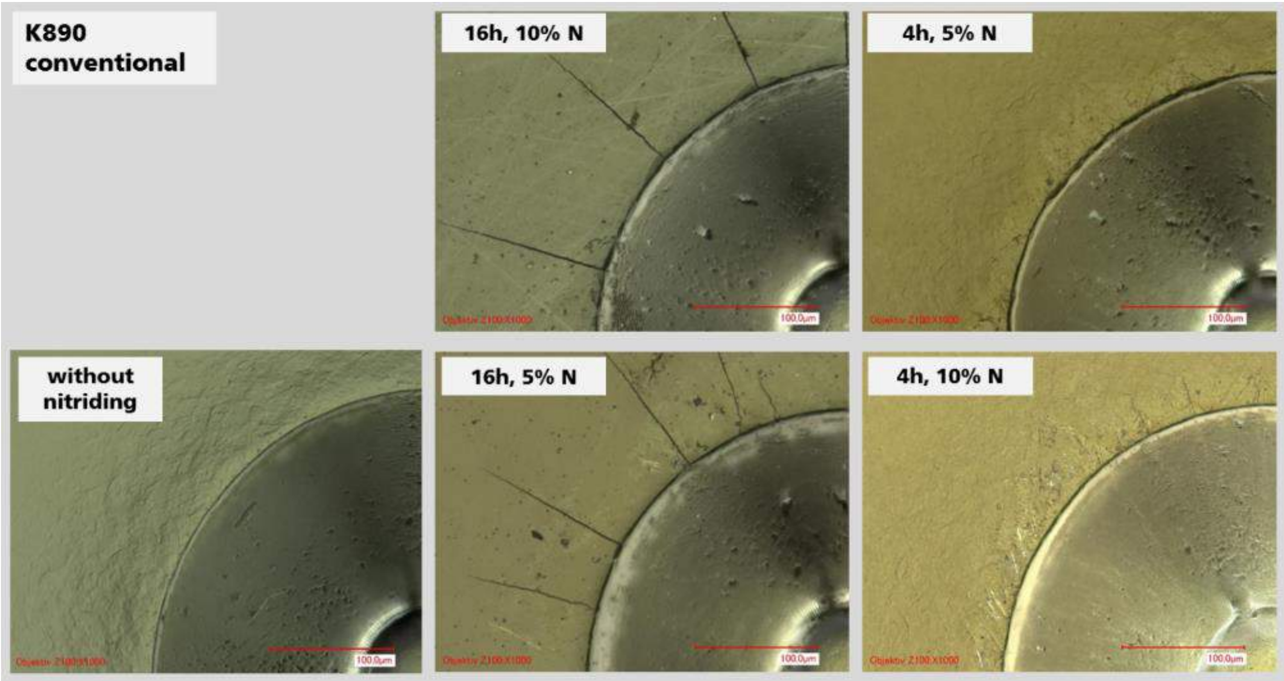


Figure 4-30: Crack resistance of K890 with conventional heat treatment after plasmanitriding examined by Rockwell-indentation-test.

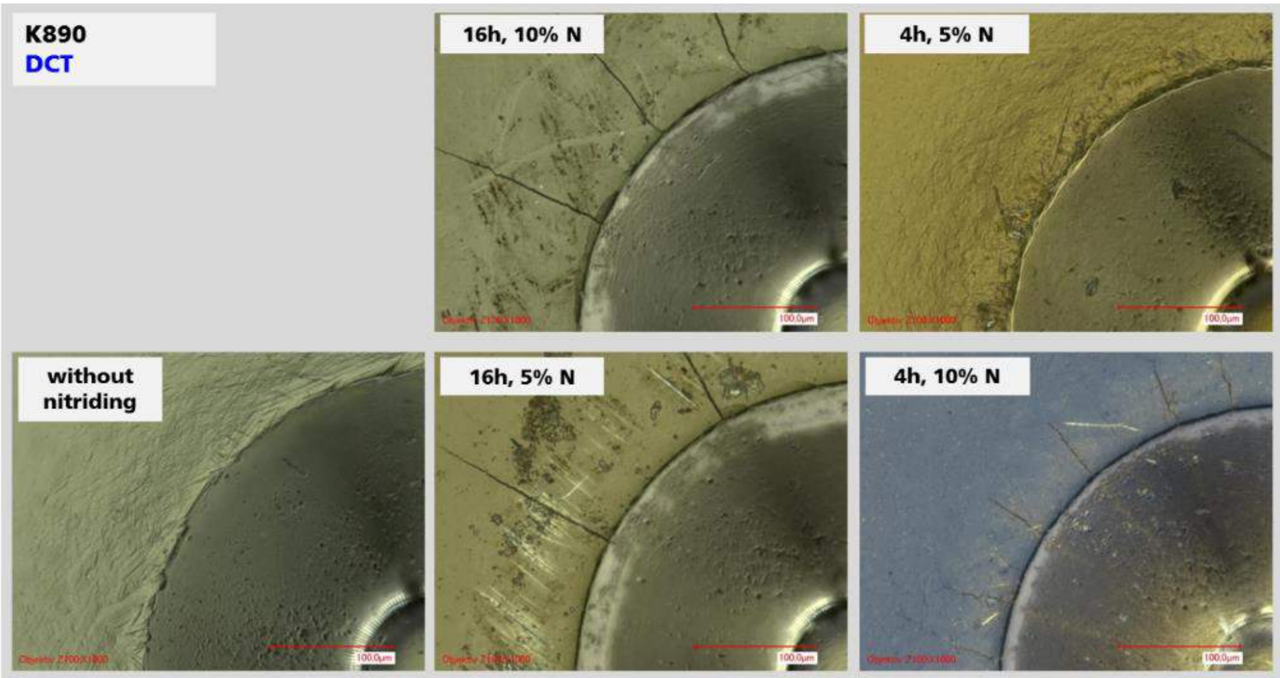


Figure 4-31: Crack resistance of K890 with DCT after plasmanitriding examined by Rockwell-indentation-test.

Material	Heat treatment	Nitriding				
		without	4h 5% N	4h 10% N	16h 5% N	16h 10% N
1.2379	conventional	++	++	+/-	--	--
	DTC	++	++	+/-	--	--
Vanadis 4E	conventional	++	++	+/-	--	--
	DTC	++	++	-	--	--
Vanadis 23	conventional	++	++	+/-	--	--
	DTC	++	++	+	--	--
K890	conventional	++	++	+	--	--
	DTC	++	++	+/-	--	--
S390	conventional	++	++	+	--	--
	DTC	++	++	+/-	--	--

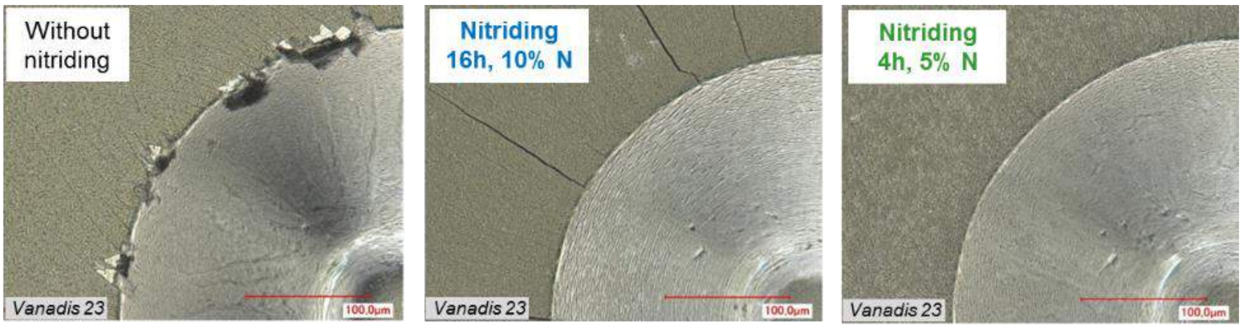
crack resistance	low	medium	high

Table 4-4: Summary of the crack resistance evaluated by Rockwell-indentation-test.

An acceptable crack resistance was only possible with low treatment times of 4 hours. With all materials no cracks occur with nitrogen amounts of 5 %. With some materials and heat treatments a slightly a higher nitrogen amount (up to 10 %) is possible without visible crack formation.

Influence of the nitriding treatment on the coating adhesion

To evaluate the influence of the nitriding treatment on the coating adhesion and load bearing capacity all samples were coated with CrTiAlSiN and CrVN. After the coating the Rockwell-indentation-test was repeated. Both coatings react very similar on the additional nitriding treatment. *Figure 4-32* shows the effect of two nitriding treatments on the CrVN coating for the material Vanadis 23 in comparison to an unnitrided sample. Without nitriding a local delamination and a crack formation in the coating are visible. A very good adhesion of the coating and no crack formation could be observed after nitriding with low intensity (4 h, 5% N). Longer nitriding times or higher nitrogen amounts promote crack formation in the substrate, independent from the DCT or conventional heat treatment.



Local delamination and crack formation in the coating | Good adhesion but crack formation in the substrate | Very good coating adhesion without crack formation

Figure 4-32: Influence of the nitriding treatment on the coating adhesion and load bearing capacity of CrVN on Vanadis 23.

SEM images of cross sections of the nitrided and coated samples (*Figure 4-33*) showed a uniform layer thickness and a good bonding of the coating on the substrate with only very few defects. In EDX line scans carbon enrichments due to carbide formation in the base material, the chromium adhesion layer and the CrVN top layer can be detected. After etching with Nital the diffusion zone of round about 20 µm from the plasma nitriding treatment is barely visible.

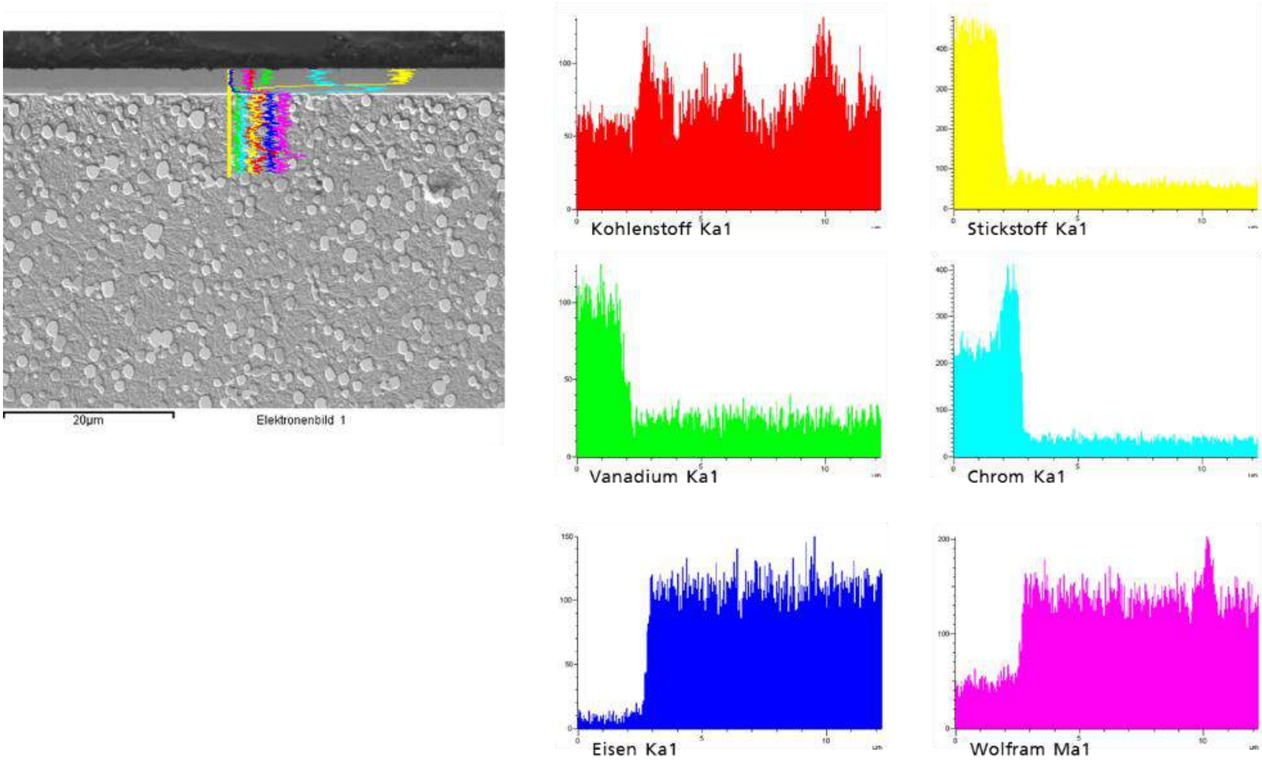


Figure 4-33: SEM image and EDX analysis of a cross section of nitrided and CrVN coated S390 with conventional heat treatment (Cross section etched with Nital).

Conclusions of WP3.2

All investigated materials can be nitrided by 4 hours with a nitrogen amount of 5% in the process gas independent from the previous heat treatment (conventional or DCT). A very good coating adhesion without crack formation in the substrate could be observed.

4.3.3 WP3.3 Coating of test and production tools

The best coatings should be applied on test tools (see *Figure 4-34 right*) for the cutting tests on laboratory scale in WP 4. After the wear analysis on the used tools in WP 3.4 the coatings should be optimized to achieve best results in the next loop of the cutting tests. Due to a change in the focus of the project only a limited quantity of test tools was available for tests with different coatings. Instead of that more tests were possible with different surface topographies (see WP 4.1 and WP 4.3). They showed a significant influence of the topography (blasted, polished or blasted + polished) on the wear mechanism and the cutting quality. Because of this matter only the CrVN coating could be applied with and without an additional plasmanitriding treatment on the test tools.

Before coating pictures were taken of all cutting edges with a digital microscope (*Figure 4-34 left*). After that the tools were cleaned with a special cleaning procedure for high alloyed steels in an industrial purification plant with a water-based cleaning agent. In the next step one half of the tools was nitrided for 4 hours with a nitrogen amount of 4%. After s second cleaning procedure the CrVN coating was applied with the same procedure as described in WP 3.1. Cross sections were prepared from reference samples with a similar geometry and examined by scanning electron microscopy. They showed a homogenous coating of approx. 5 µm on the three sides of the sample, on top the coating was slightly thinner (approx. 4 µm).

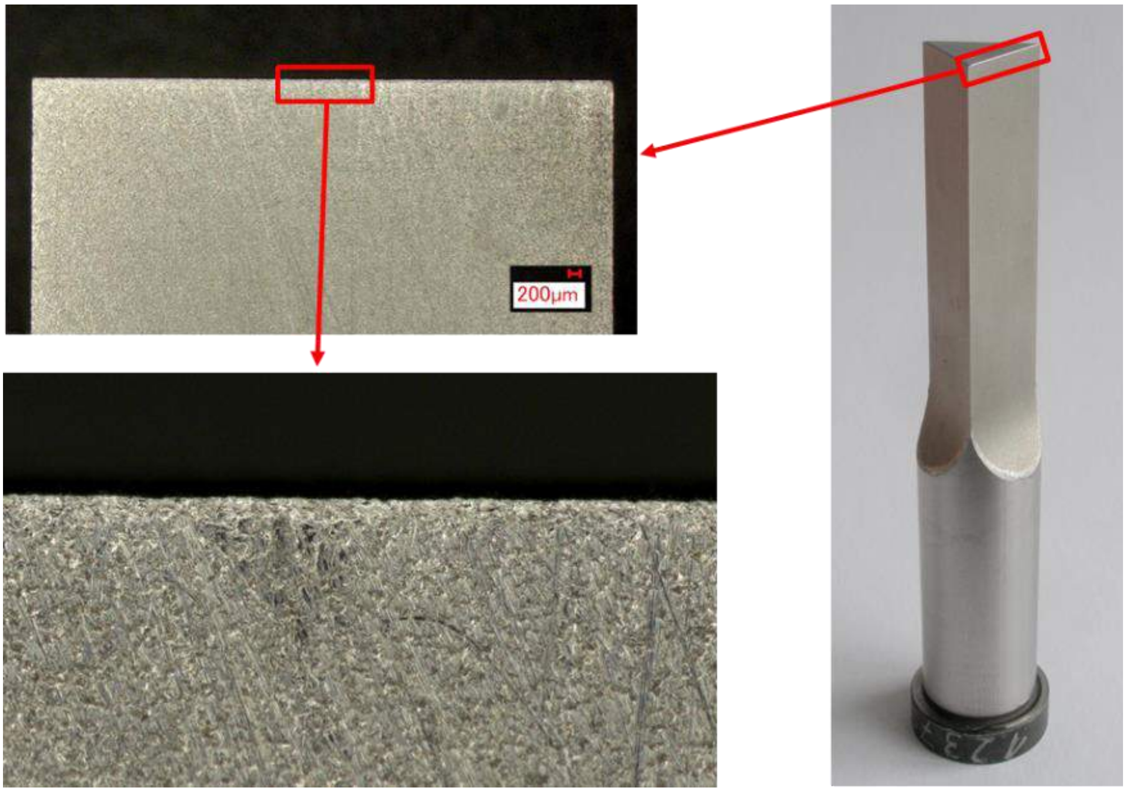


Figure 4-34: Tool for the cutting tests on laboratory scale in WP 4 before coating

4.3.4 WP3.4 Wear analysis after cutting tests

The wear analysis after the cutting tests in WP 4 delivers further information about the correlation between the selected tool materials, the heat and DCT treatment, the surface finish, the coating and the resulting wear mechanism. With different sets of tools three sheet materials were cut: stainless steel 1.4301 (1,5 / 0,4 mm) and DC04 (1,5 mm). The tested parameters in detail are described in WP4.3.

After testing the tools (*Figure 4-35*) were investigated by measuring of the cutting edges, optical microscopy and SEM analysis. *Figure 4-36* gives an example of the observed wear mechanism.

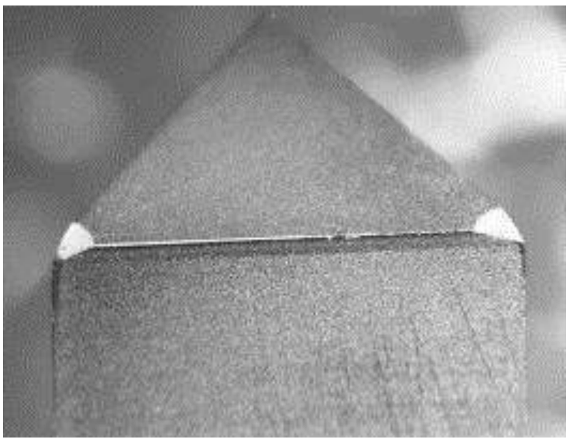


Figure 4-35: Tool after the cutting tests on laboratory scale before wear analysis

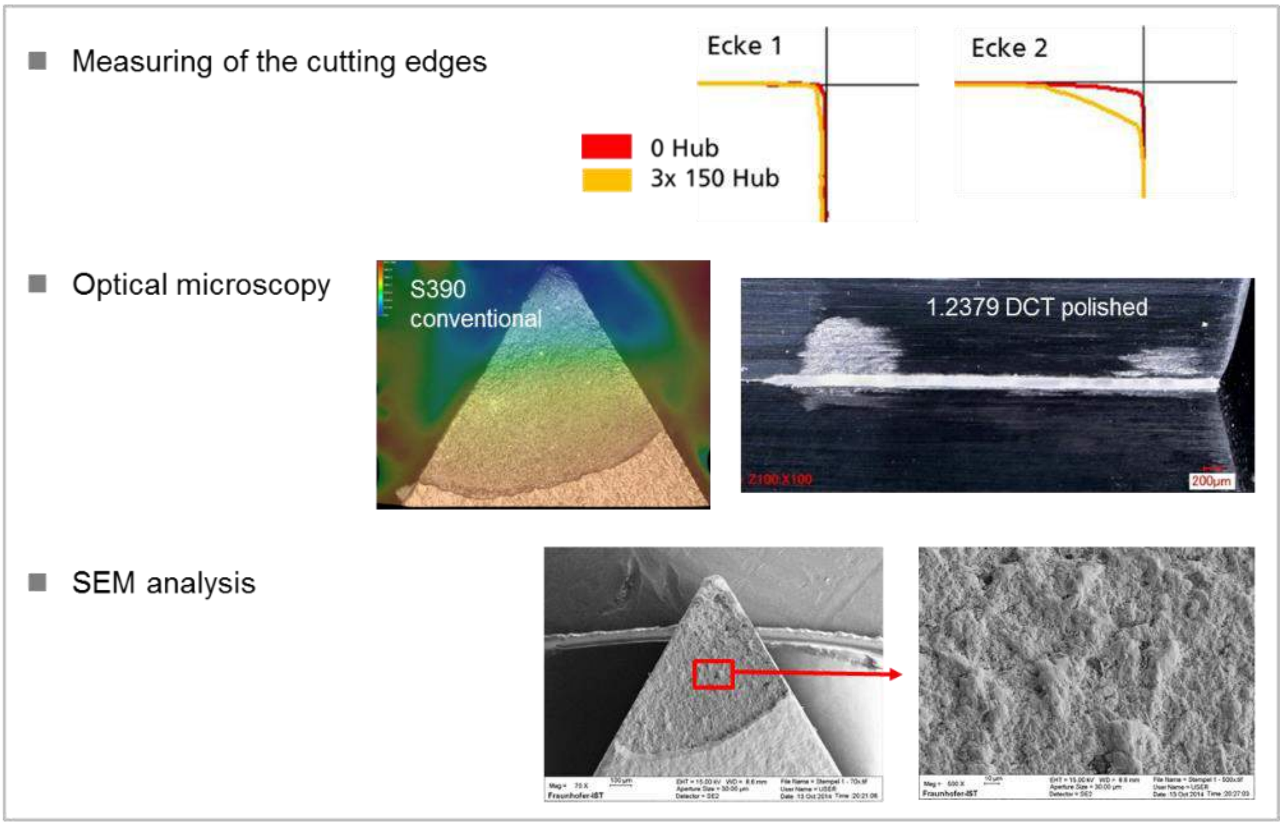


Figure 4-36: Used methods for wear analysis of the cutting tools after testing on laboratory scale.

<u>Wear after cutting stainless steel 1.4301 / 1,5 mm</u>

The conventional heat treated steels showed a different amount of wear after cutting stainless steel 1.4301 / 1,5 mm (*Figure 4-37*). Overall, both Vanadis steels showed less wear than the other materials. However, it has to be noted that the wear at the three cutting edges can be very different. In *Figure 4-38* is a comparison of all three cutting edges with and without DCT of Vanadis 4E and Vanadis 23. With DCT the wear was significantly reduced at both materials. A similar amount of wear reduction could be observed at the other material.

Wear analysis by optical microscopy showed a different wear mechanism on the Vanadis steels in comparison to the other materials. The wear on 1.2379, K890 and S390 (*Figure 4-39* to *Figure 4-41*) was dominated by flaking of the cutting edges, when a conventional heat treatment was applied. After DCT treatment, the amount of flaking was significantly reduced. Please note the higher magnification of the cutting edges on the DCT treated materials. The cutting edges of both Vanadis steels were mainly worn out by abrasive wear (*Figure 4-42* and *Figure 4-43*). There again the amount of wear was reduced after DCT treatment.

A closer inspection by SEM confirmed the different wear mechanism on the Vanadis steels in comparison to the other steels (*Figure 4-44*). The type of wear mechanism and the influence of the DCT treatment on the wear behavior of the different tool steels are summarized in *Table 4-5*.

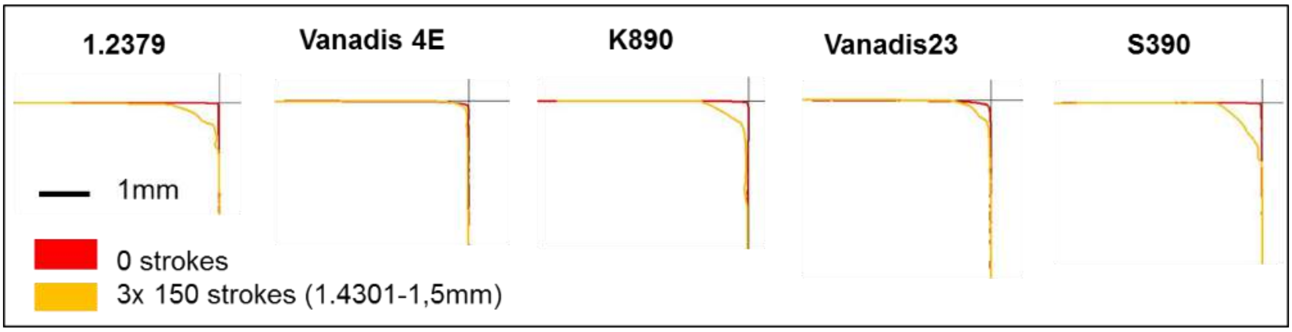


Figure 4-37: Wear measurement at the cutting edges of the conventional heat treated steels after cutting stainless steel 1.5 mm.

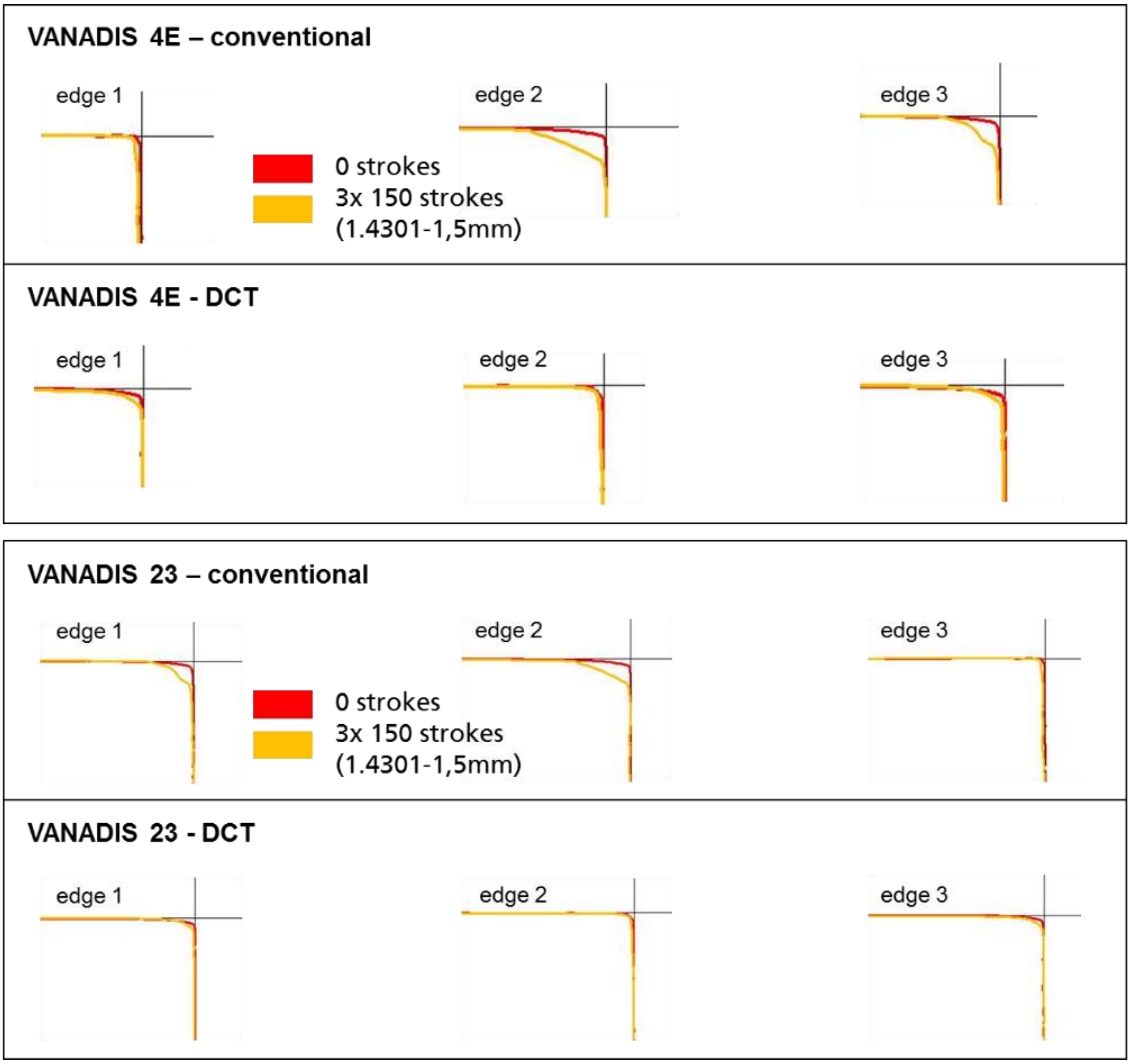


Figure 4-38: Wear measurement at the cutting edges of conventional and DCT treated Vanadis 4E and Vanadis 23 after cutting stainless steel 1.5 mm.

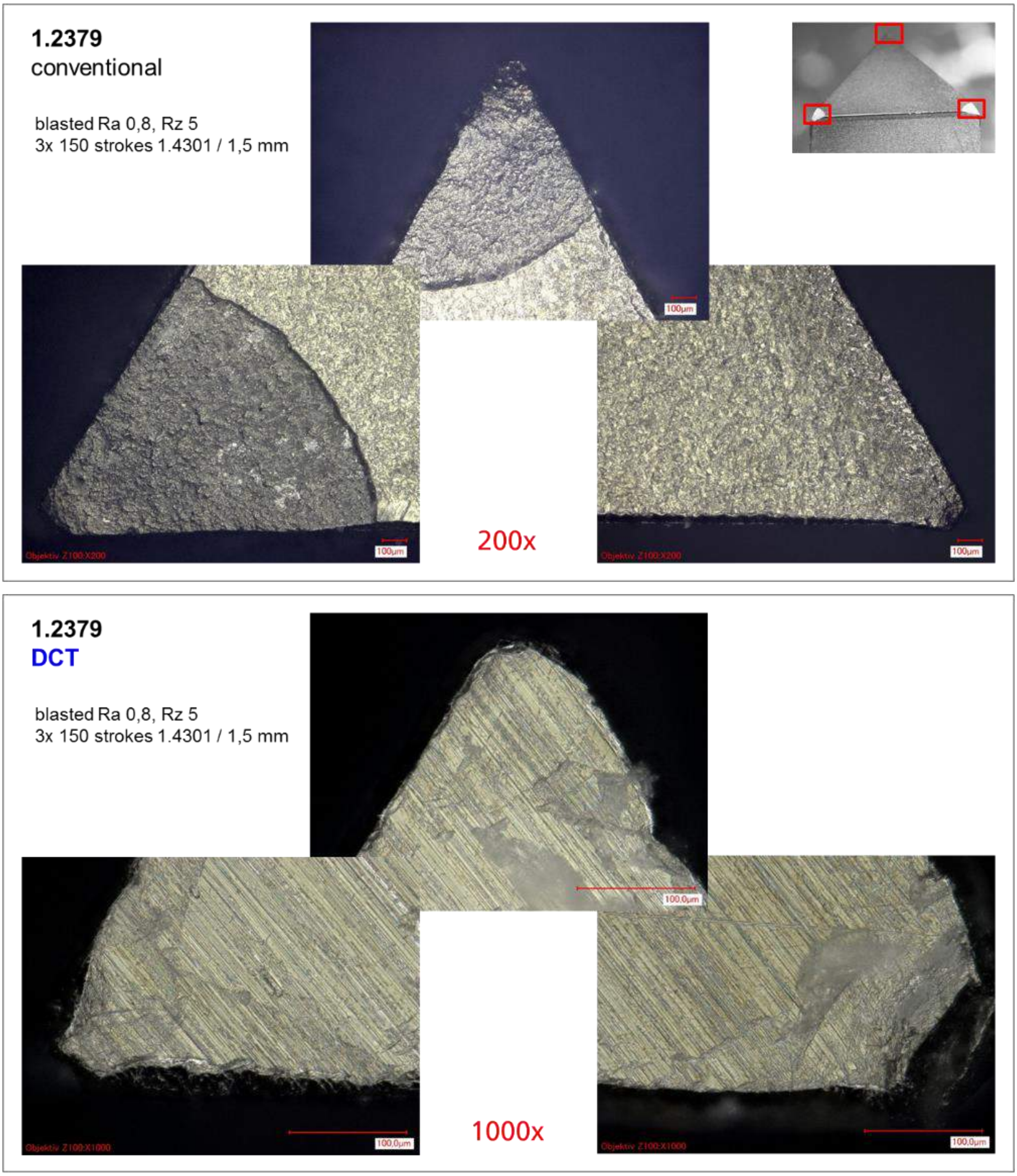


Figure 4-39: Comparison of the wear at the cutting edges of conventional and DCT treated 1.2379 examined by optical microscopy.

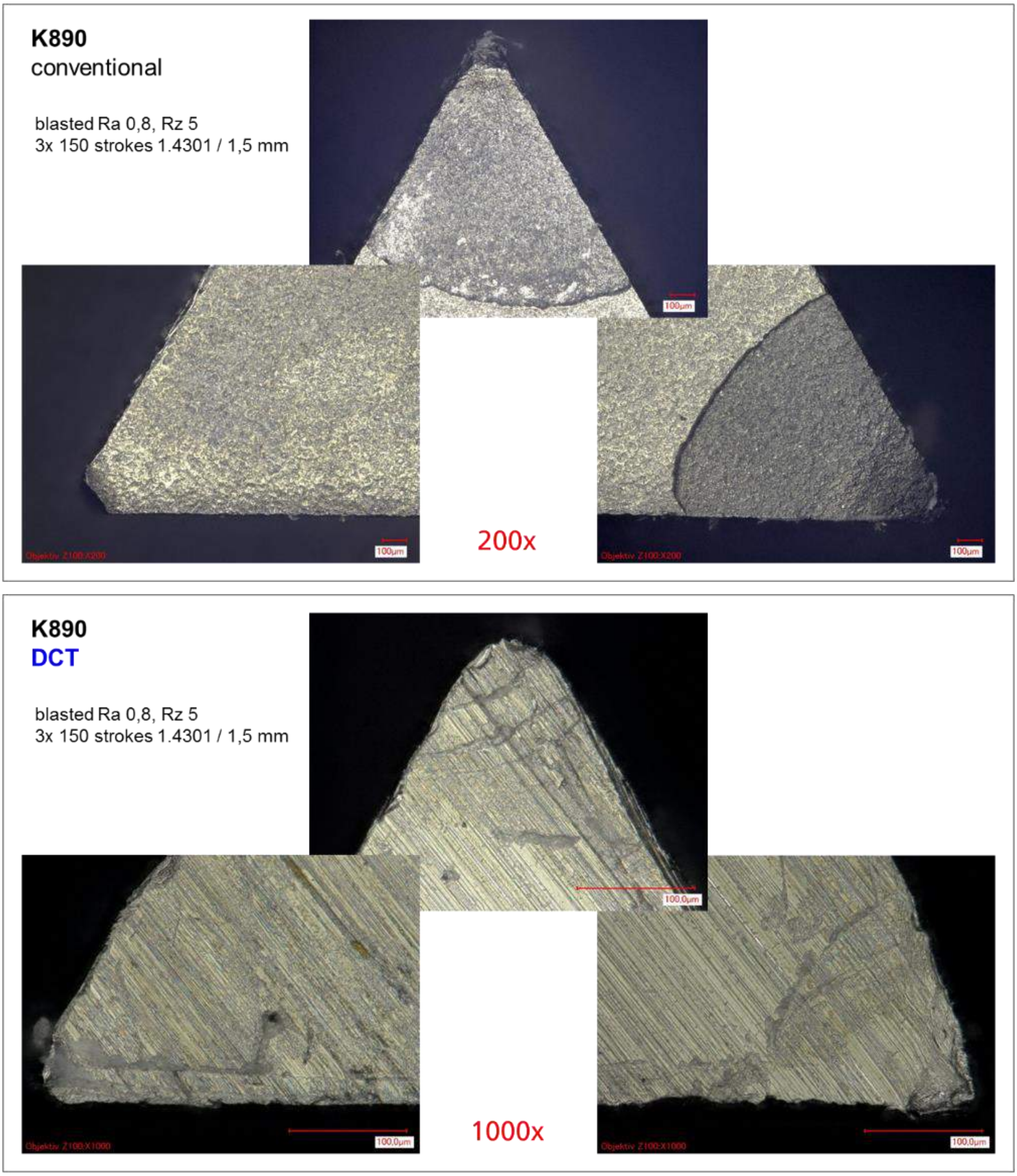
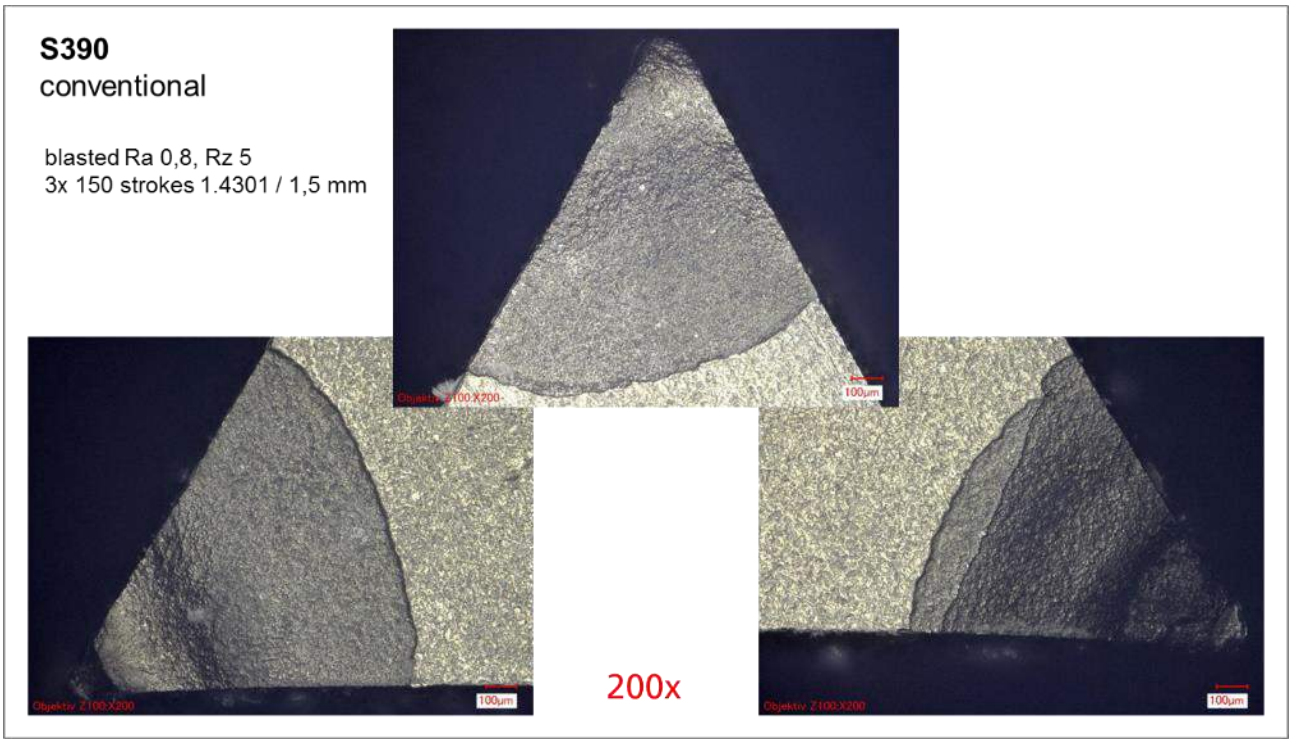


Figure 4-40: Comparison of the wear at the cutting edges of conventional and DCT treated K890 examined by optical microscopy.



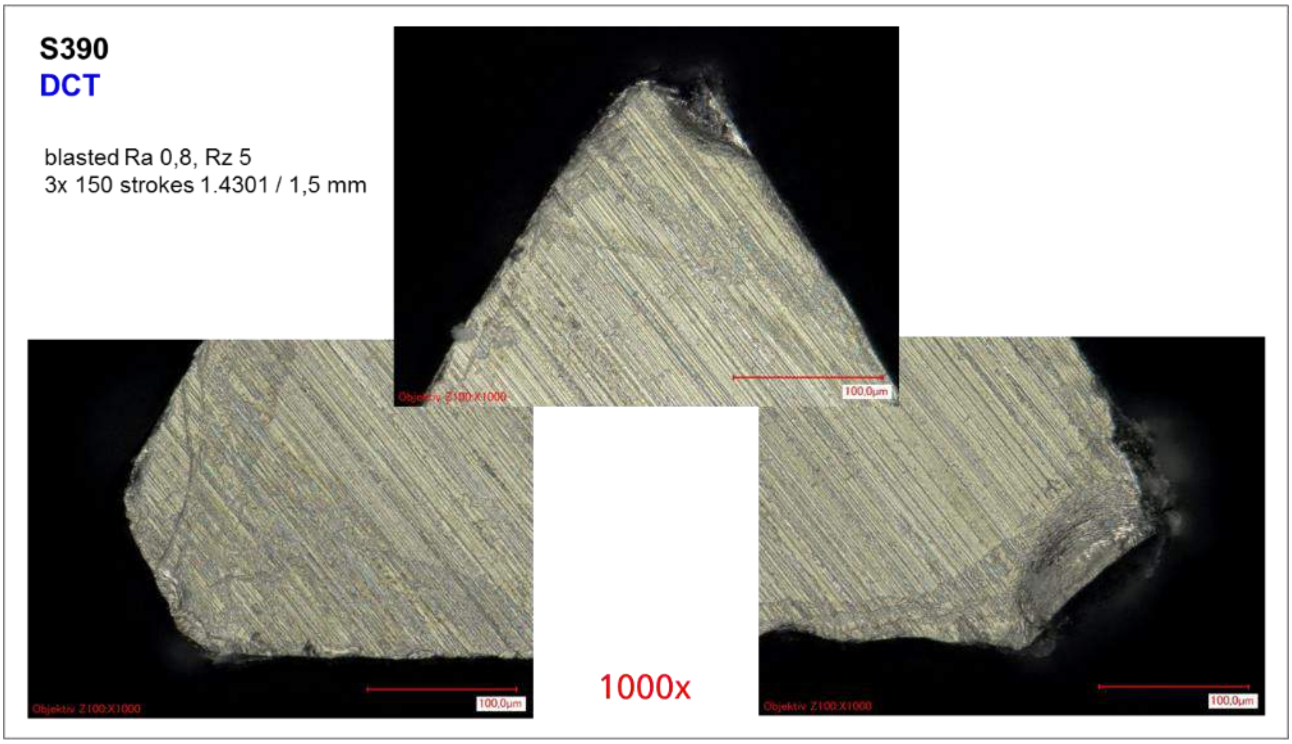


Figure 4-41: Comparison of the wear at the cutting edges of conventional and DCT treated S390 examined by optical microscopy.

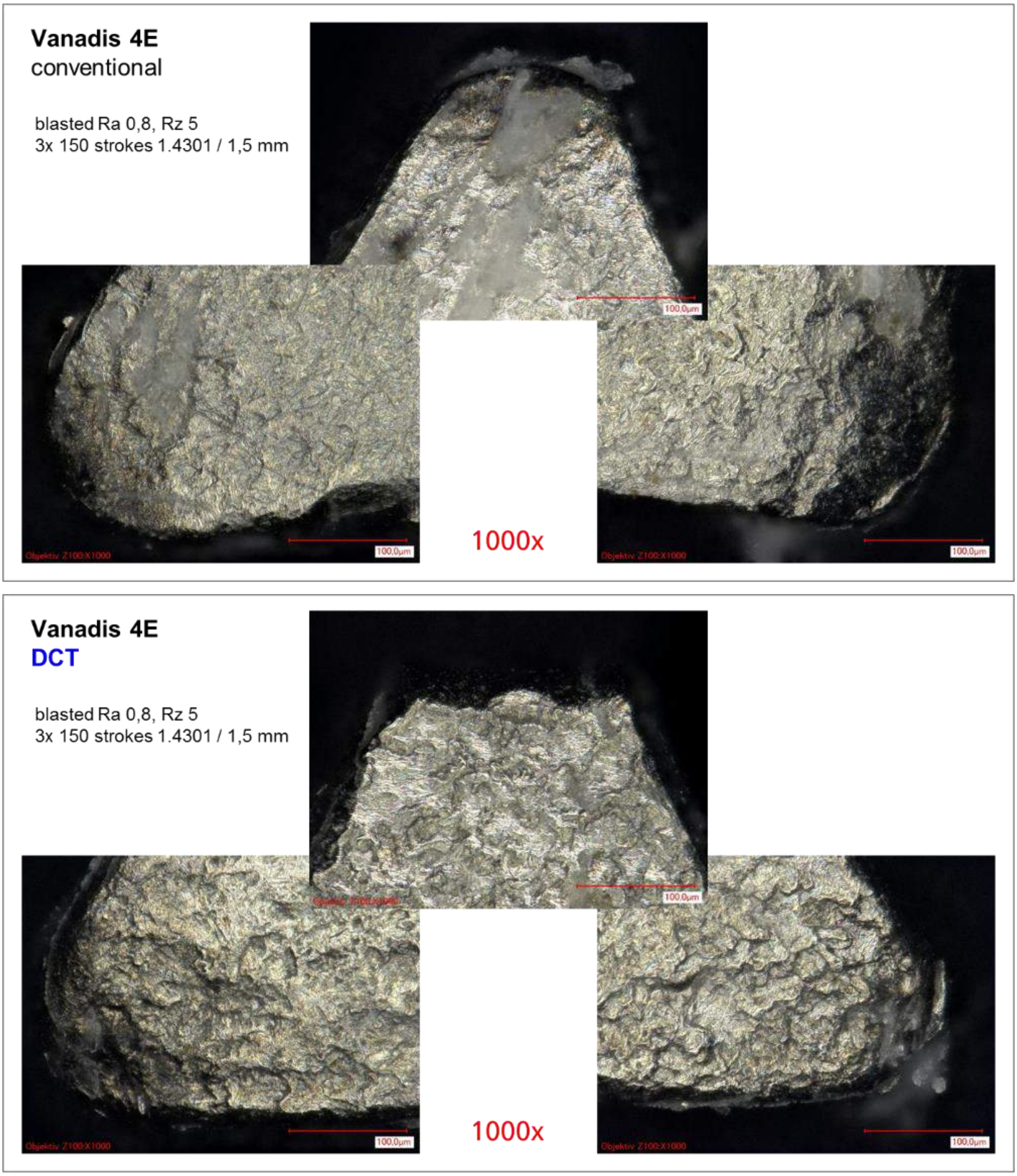


Figure 4-42: Comparison of the wear at the cutting edges of conventional and DCT treated Vanadis 4E examined by optical microscopy.

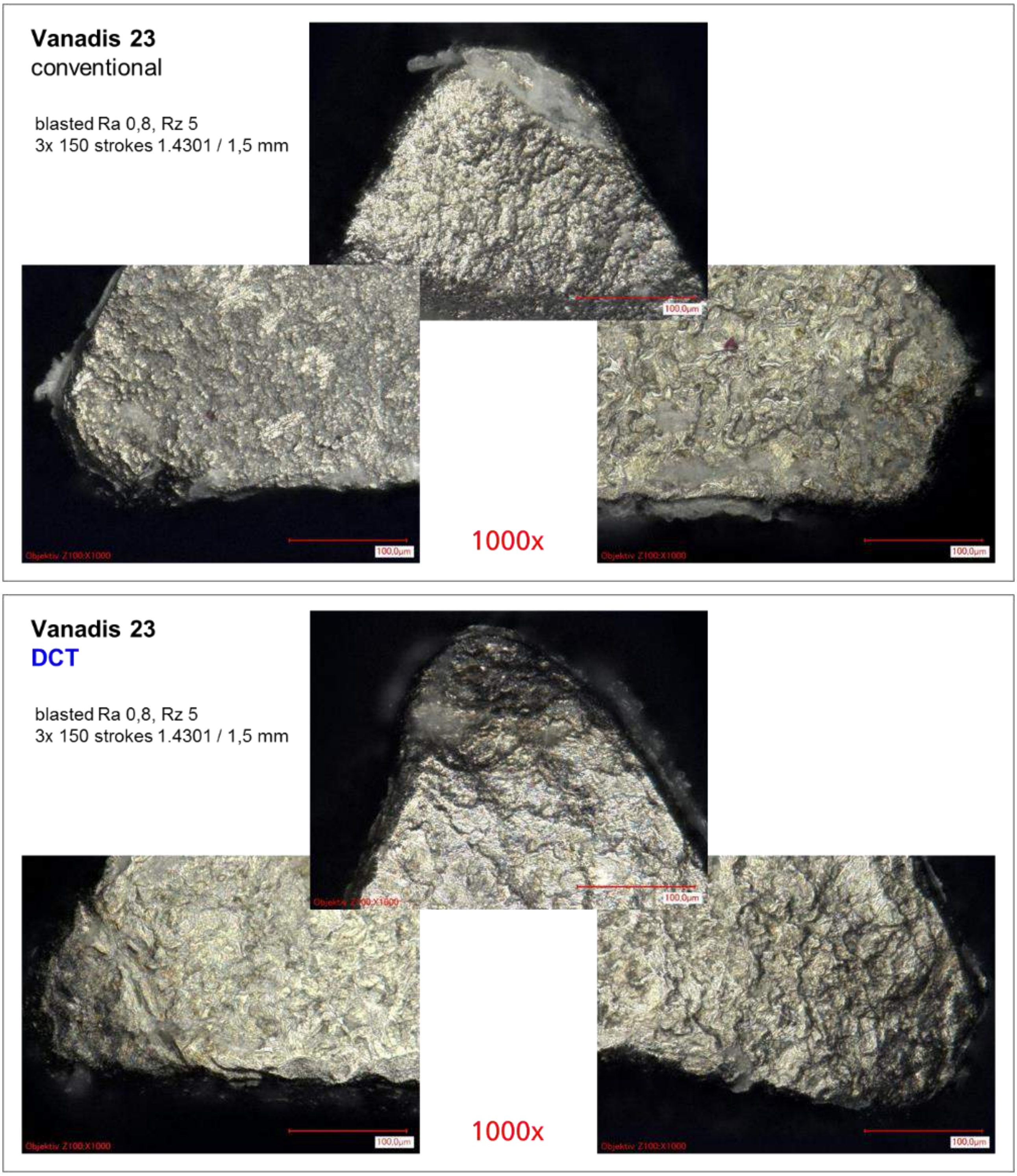


Figure 4-43: Comparison of the wear at the cutting edges of conventional and DCT treated Vanadis 23 examined by optical microscopy.

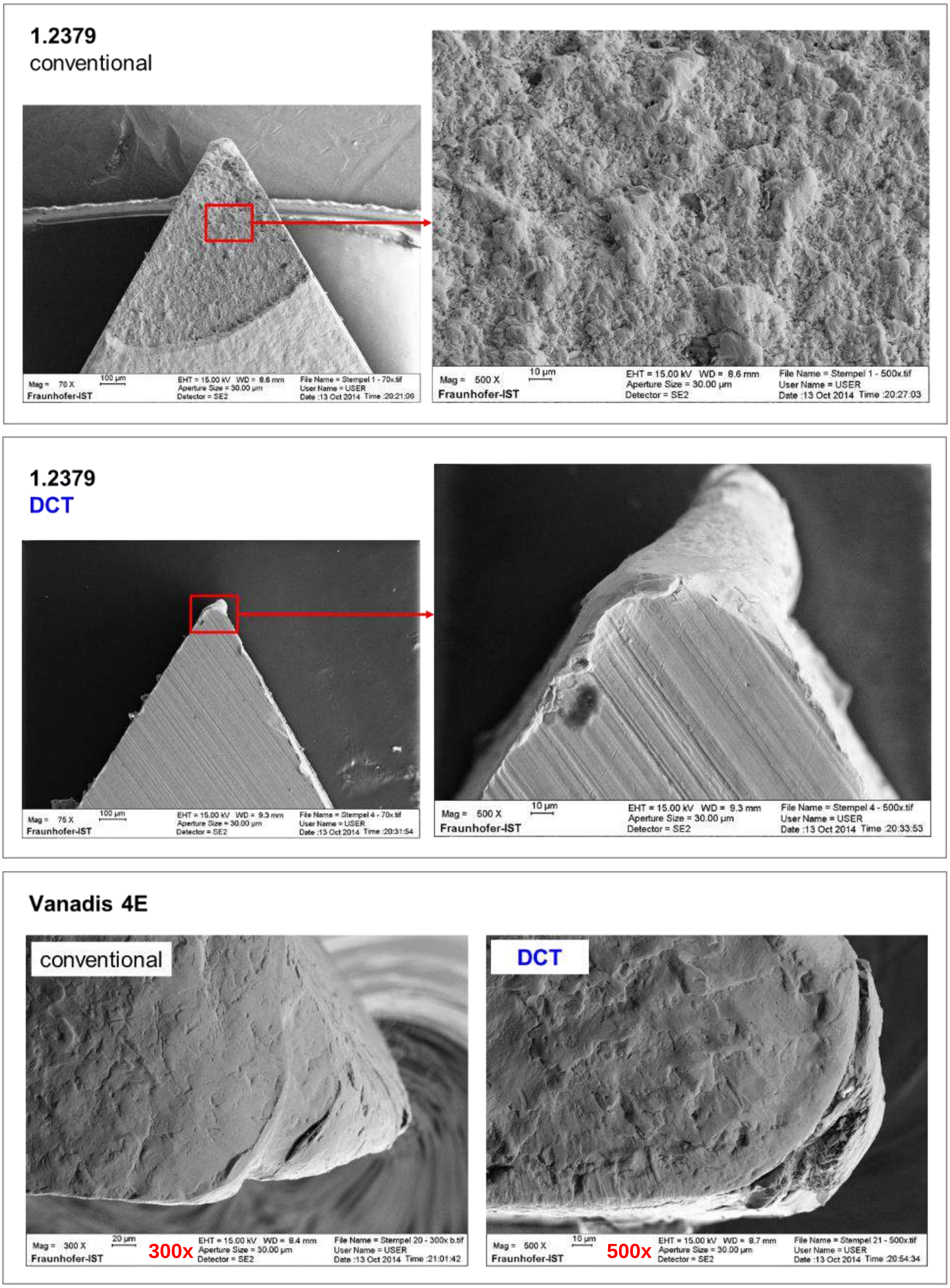


Figure 4-44: Comparison of the wear at the cutting edges of conventional and DCT treated 1.2379 and Vanadis 4E examined by SEM.

Material	Conventional	DCT
1.2379	Large flaking	Cracking, less flaking
K890	Large flaking	Cracking, less flaking
S390	Large flaking	Less flaking
Vanadis 4E	Abrasive wear no flaking	Less abrasive wear
Vanadis 23	Abrasive wear no flaking	Less abrasive wear

Table 4-5: Wear mechanism and influence of the DCT treatment on the wear behavior of the different tool steels after cutting stainless steel 1.4301 / 1,5 mm.

Wear after cutting stainless steel 1.4301 / 0,4 mm

After cutting stainless steel 1.4301 / 0,4 mm the tools showed a different wear behavior than after cutting the same material with a thickness of 1,5 mm. Abrasive wear is dominating and flaking of the cutting edges is significantly reduced (*Figure 4-45*). The amount of wear has a broad statistical spread on the three cutting edges of the tools. A clear difference between the wear resistances of the five tool steels with and without DCT treatment cannot be stated. Due to the lower mechanical loads at the cutting edges, when cutting the thinner sheet material, all tool materials could withstand the wear strain in a similar way.

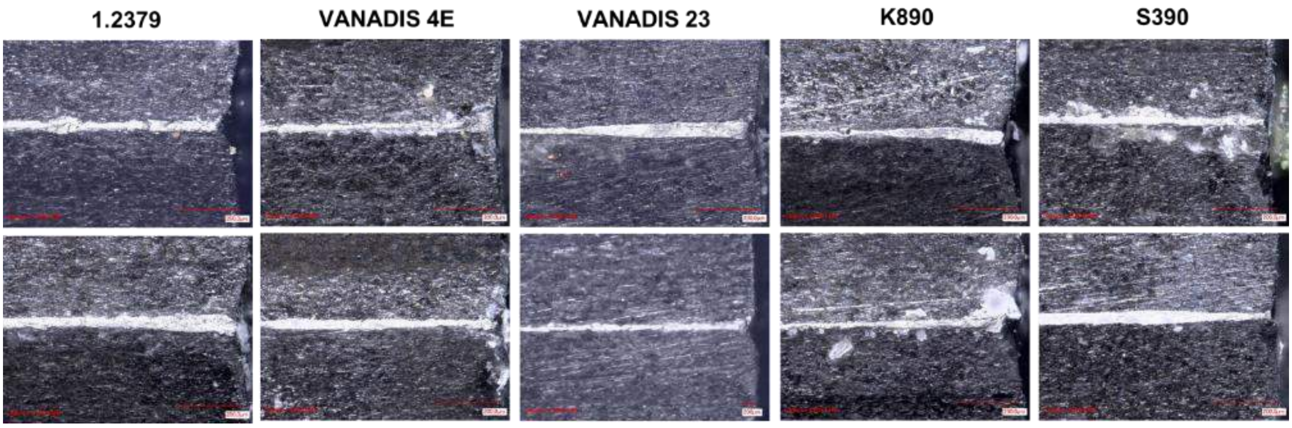


Figure 4-45: Wear at two edges of the tools with DCT treatment and blasted surface after cutting stainless steel 1.4301 / 0,4 mm..

Influence of the surface finish

The tools for cutting stainless steel 1.4301 / 0,4 mm were manufactured with three different surface finishings (*Figure 4-46*). After the cutting tests on the laboratory scale in WP 4 the tools were investigated by optical microscopy. *Figure 4-47* and *Figure 4-48* shows the different amount of adhesion on the blasted and the polished tools made from 1.2379, Vanadis 4E and Vanadis 23 with DCT treatment. Remarkable is the strong local adhesion of the workpiece material on the polished surfaces. On the blasted surface the adhesion was significantly reduced. The lowest amount of adhesion could be observed on the blasted and slightly polished surfaces. This is in accordance to the experience of a majority of companies in the user committee. It should be noted, that the tools were manufactured by electro-discharge machining. This causes a so called white layer on the surface. After blasting this layer is removed but not after solely polishing. The influence of the white layer on the adhesion behavior is unclear up to now.

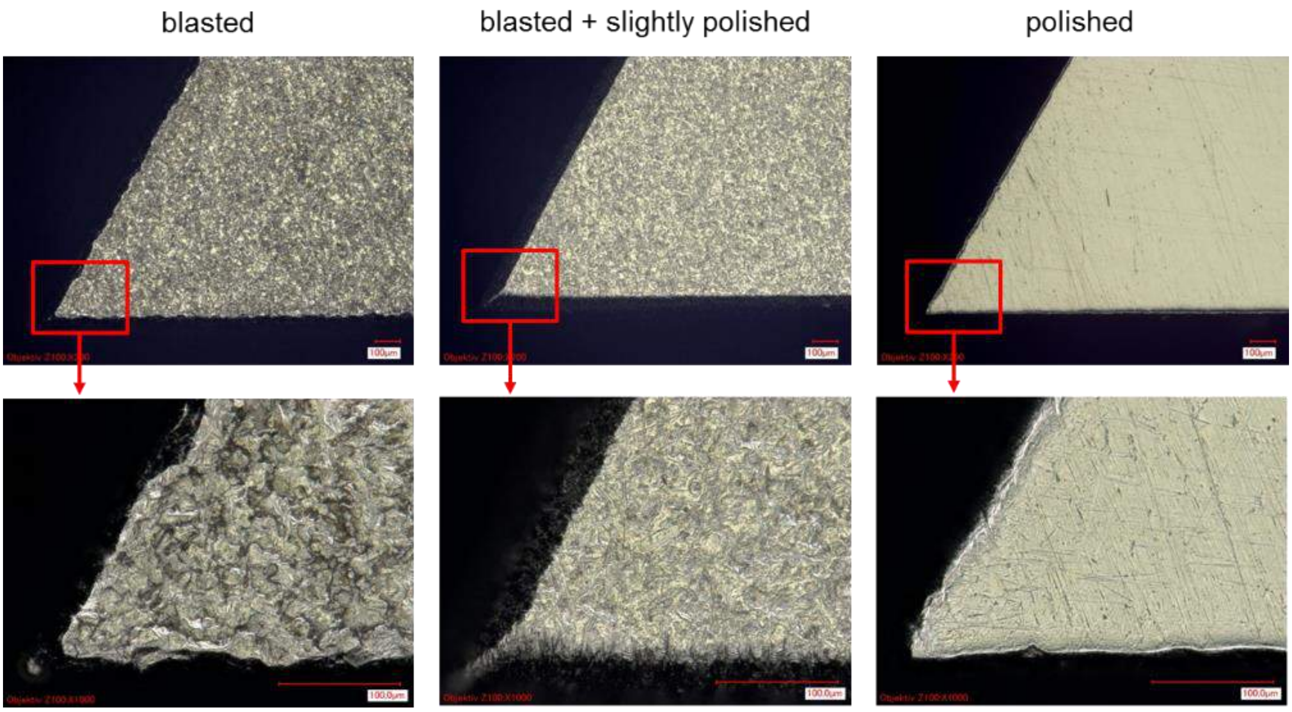


Figure 4-46: Surface finish at the cutting edges of 1.2379 before the cutting tests.

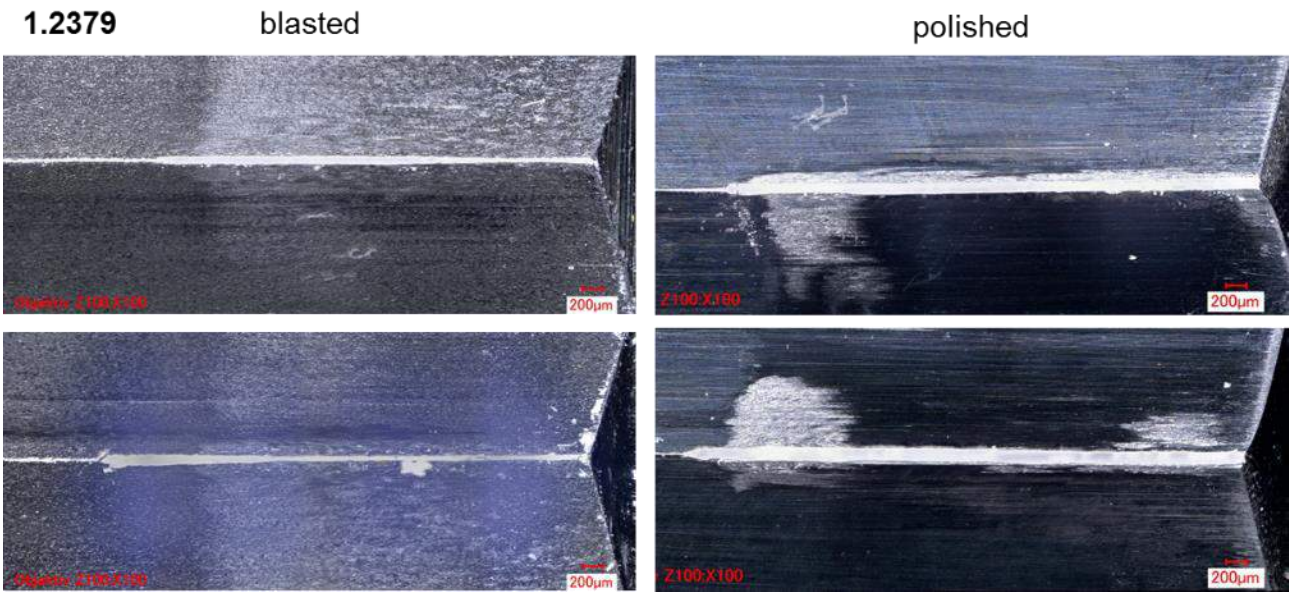


Figure 4-47: Adhesion on two edges of the tools made of 1.2379 with DCT treatment in dependency on the surface finishing after cutting stainless steel 1.4301 / 0,4 mm.

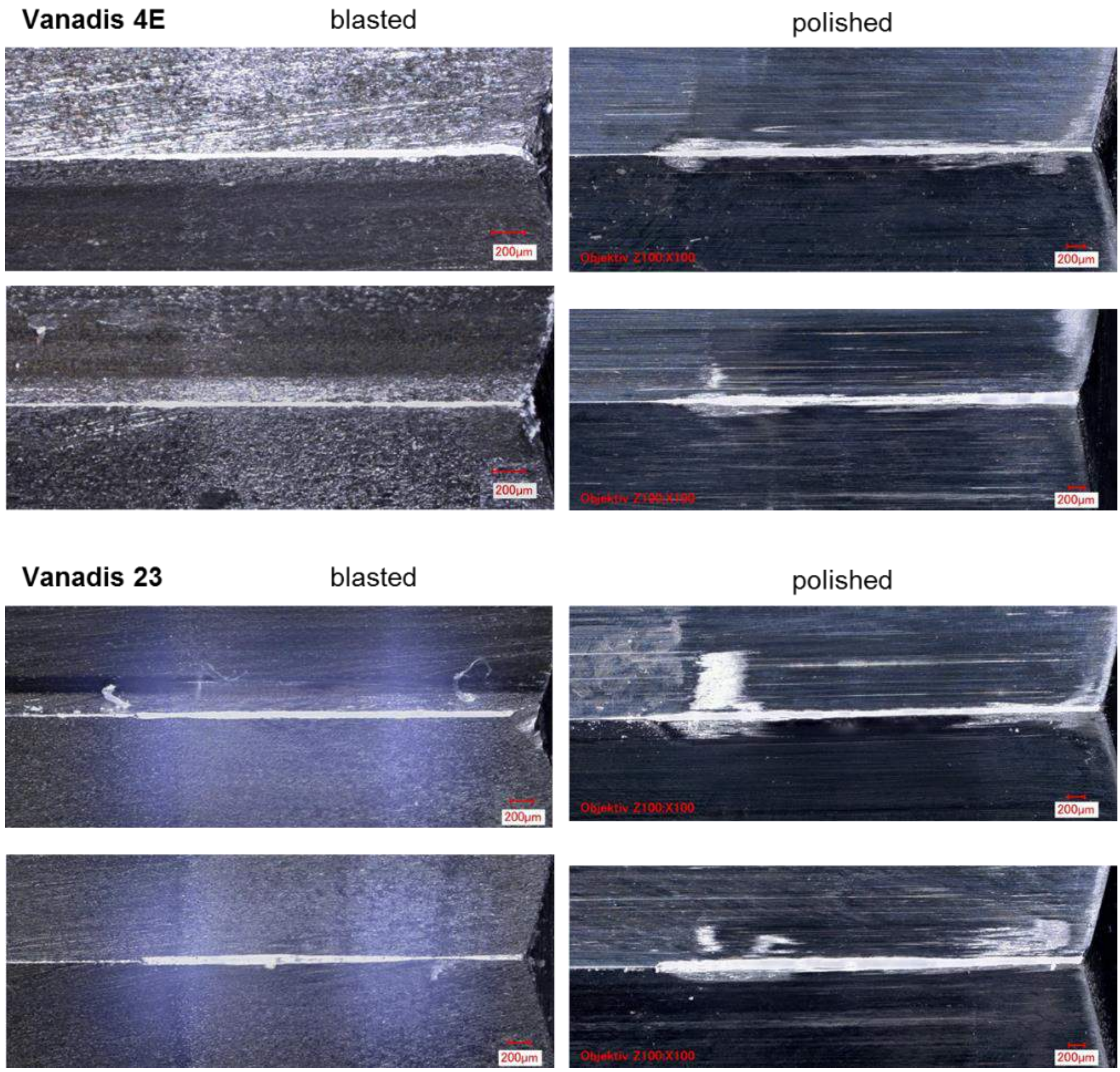


Figure 4-48: Adhesion on two edges of the tools made of Vanadis 4E and Vanadis 23 with DCT treatment in dependency on the surface finishing after cutting stainless steel 1.4301 / 0,4 mm.

Wear after cutting DC04 / 1,5 mm

The war after cutting DC04 / 1,5 mm was dominated by adhesion of the workpiece material and only slight abrasive wear could be observed at the cutting edges (*Figure 4-49*). The wear was more pronounced on the 1.2379 steel than on the K890 and S390. Their behavior was very similar. With DCT treatment the cutting edges appear slightly sharper after the cutting tests than with conventional heat treatment (*Figure 4-50*).

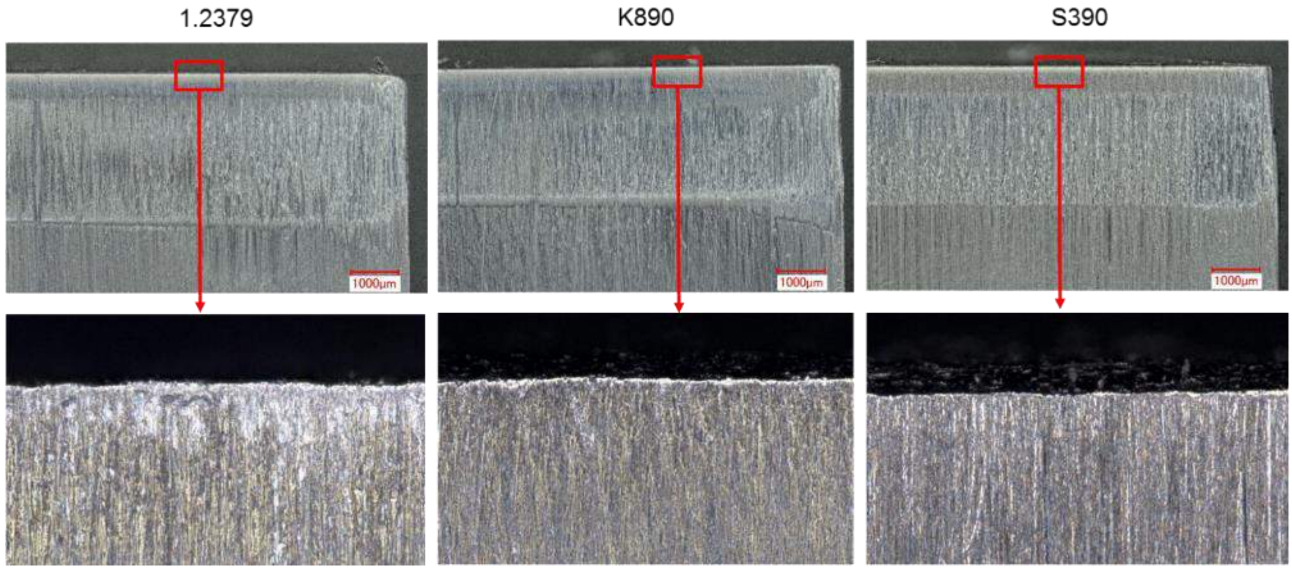


Figure 4-49: Wear at the cutting edges of the tools with DCT treatment and blasted and slightly polished surface after cutting DC04 / 1,5 mm.

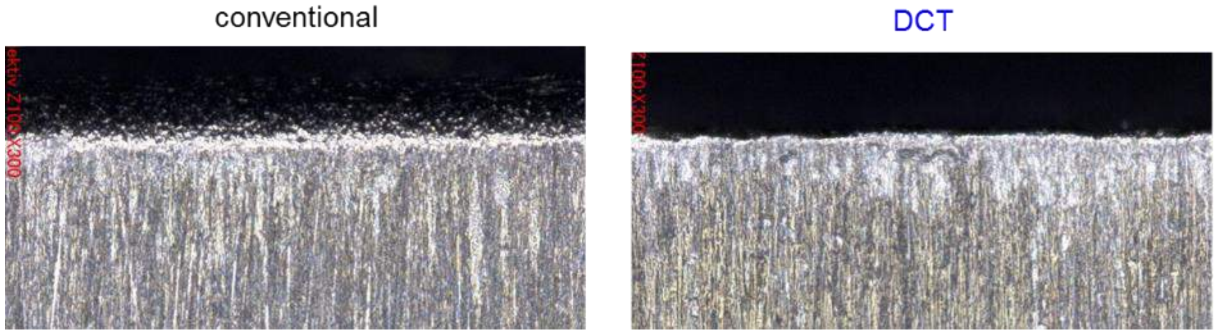


Figure 4-50: Wear at the cutting edges of 1.2379 (surface blasted and slightly polished) with conventional heat treatment and DCT treatment after cutting DC04 / 1,5 mm .

Influence of the coating

The influence of the CrVN coating wit and without additional plasmanitriding was investigated by cutting DC04 / 1,5 mm. The coating was able to reduce the amount of adhesion on the tool surface and the cutting edges remained sharper (*Figure 4-51*). No delamination or flaking of the coating could be observed with and without additional plasmanitriding. It should be noted that the load by cutting DC04 was very low, so that the advantages of the plasmanitriding could not appear. The marginal increased adhesion on the coated and plasmanitrided tool compared to the solely coated one can be explained by the slightly increased roughness due to the nitriding process. The small quantity of tested tools and the low load situation restrict the validity of the statements concerning the coating behavior. More tests should be done under more severe conditions.

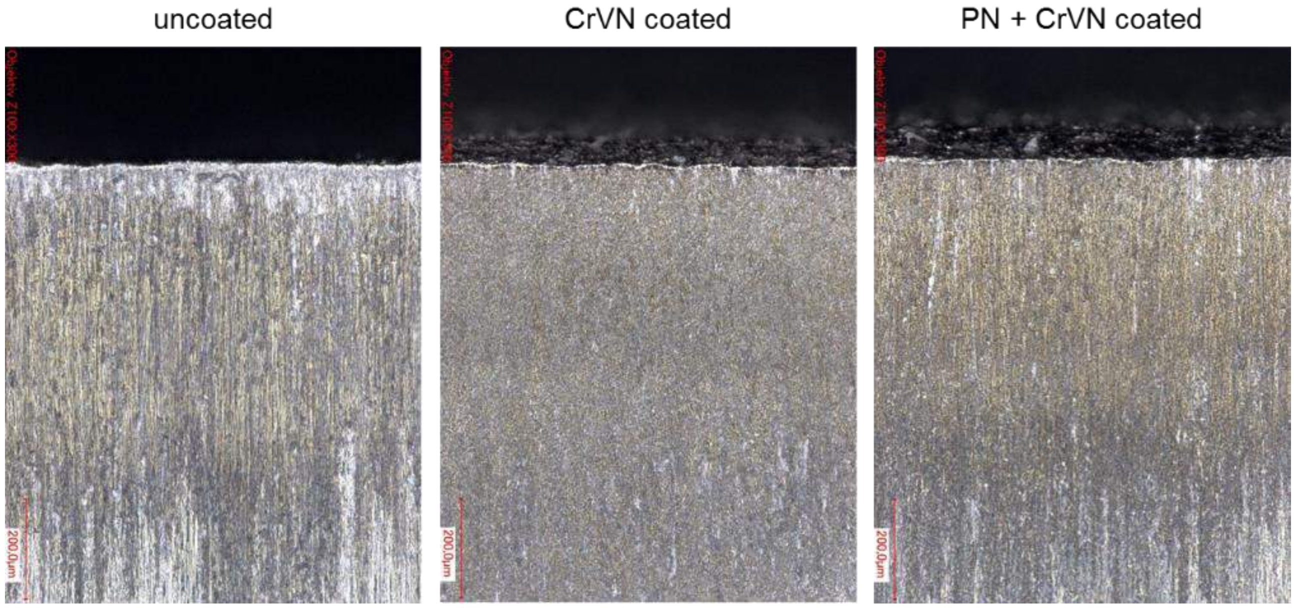
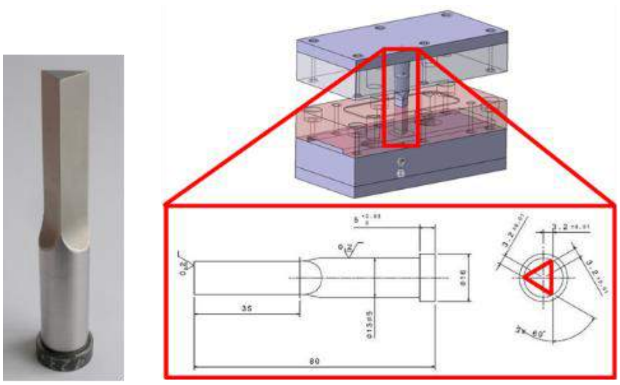


Figure 4-51: Adhesion on the cutting edges of DCT treated 1.2379 (blasted) with and without coatings after cutting DC04 / 1,5 mm.

4.4 WP4 Cutting tests on a laboratory scale

The cutting test on laboratory scale were done on a conventional blanking tool already available at Fraunhofer IWU with the test geometry from *Figure 4-52 left*, which allows the determination of tool wear and component quality under relatively short production cycles. The tests were be done in a conventional excentric press AMBOLD PEEV 25 at Fraunhofer IWU (*Figure 4-52 right*). An automatic feeder allowed continuous test series near to industrial applications with increasing temperature from stroke to strokeI. It was possible to cut with three punches per stroke in the testing tool. After the cutting tests the tool wear was analyzed in WP3.4. The results of the wear analysis and the component quality measurements were delivered to all project partners for a detailed evaluation of the best tool material, surface topography and coating combination for cutting tests under production conditions in WP5.



Tool geometry „Dreieckstempel“

Figure 4-52: Used tool geometry and press for the lab scale tests .

4.4.1 WP 4.1 Manufacturing of blanking tools for lab scale tests

The testing tools (active parts) were manufactured from the different tool materials after conventional or deep cryogenic treatment (DCT) by a toolmaker nearby IWU Chemnitz.

The used manufacturing chain is shown in *Figure 4-53*. After electro erosion (wire cutting) all tools were blasted. During the project it could be remarked that the influence of the surface quality of the tools on the cutting result is very evident especially for cutting high strength stainless steel. Therefore three different mechanical surface treatments were used after blasting: only blasted, blasted + slightly polished to remove the roughness peeks, blasted + fine polished.

The results and the live time of cutting punches are dependent from the process line regarding the mechanical treatment. A very important fact comes from the electro erosion process, the type of wire, the wire speed, the temperatures and chemical reactions on the material. The surface quality after electro erosion is defined by the “white zone”. This zone affects the adhesion of the workpiece material and the adhesion of coatings. The white zone has to be removed completely, for example by corundum blasting and additional blasting with glass bubbles to flatten the surface.

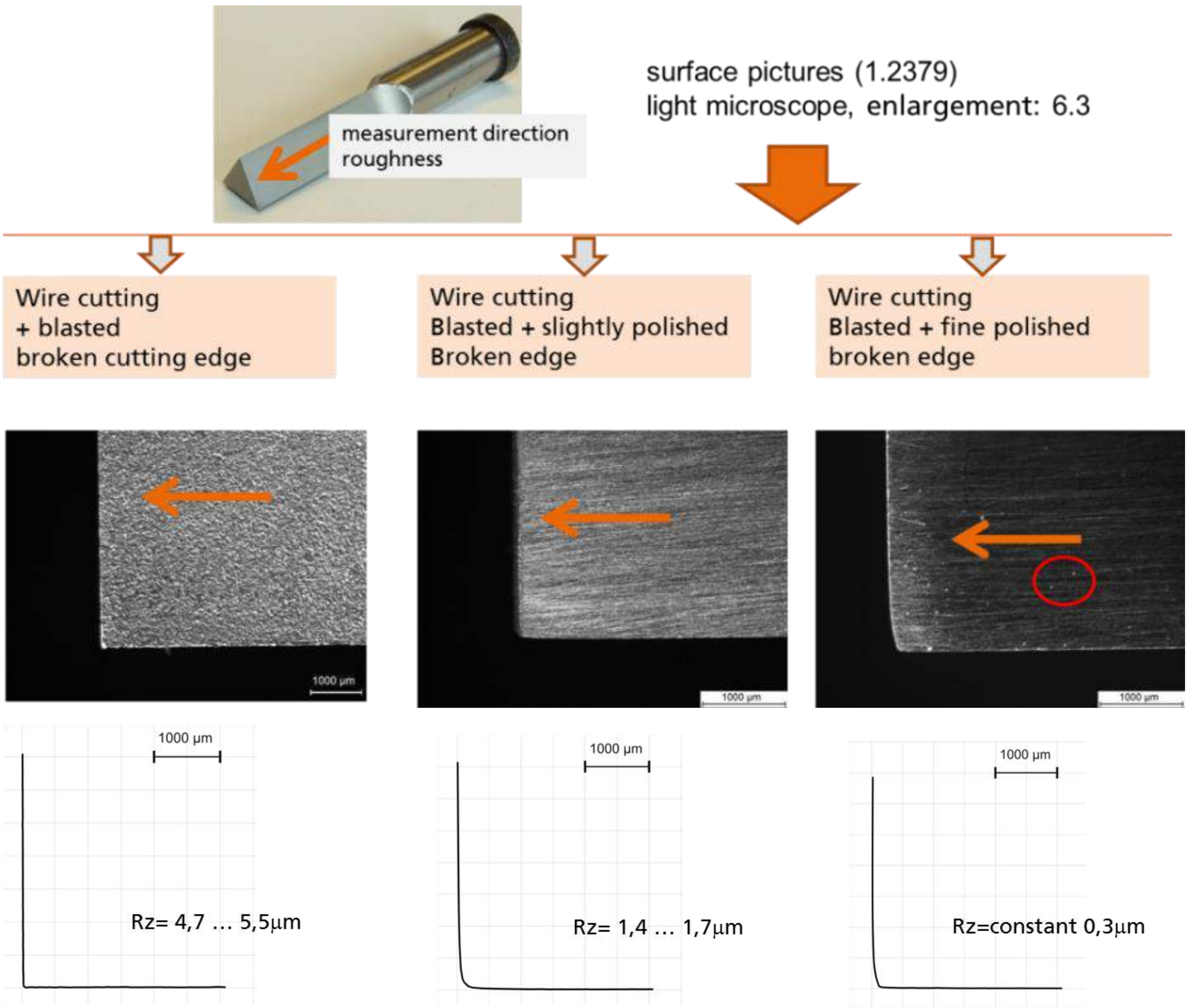


Figure 4-53: Manufacturing chain, surface topography, roughness and cutting edge of the tools for the lab scale tests

4.4.2 WP 4.2 Experimental tool life studies / state of the art tests
WP 4.3 Experiments on test geometries to improve tool life by DCT

The first step was to test the different tool materials selected in WP2.1, which were conventional heat treated, in order to achieve a basis for the tool time life and wear analysis to compare with. Within the test, the methods for cutting edge assessment and tool wear analysis were detailed. All tests were performed with constant process parameters. In the next step the materials were tested with additional deep cryogenic treatment and also with additional plasmanitriding and coating. The test parameters are summarized below:

<u>Test parameters:</u>

6 Tool materials:	- *1.2379* - *Vanadis 4E* - *Vanadis 23* - *K890* - *S390* - *Vancron 40*
2 Heat treatments:	- *conventional* - *DCT*
3 Surface topographies:	- *blasted* - *blasted+slightly polished* - *polished*
2 Nitriding treatments:	- *without* - *plasmanitriding 4 h, 5% N*
2 Coatings:	- *uncoated, CrVN*
3 Sheet materials:	- *Stainless steel 1.4301 / 1,5 mm* - *Stainless steel 1.4301 / 0,4 mm* - *DC04 / 1,5 mm*

After the cutting tests an assessment of the cutting edges in WP4.3 and a wear analysis in WP3.4 were carried out. The main results and conclusions are summarized below.

<u>Conclusions of the wear analysis after the cutting tests on laboratory scale</u>

Cutting stainless steel 1.4301 / 1,5 mm:

- The wear is dominated by fracture of the cutting edges.
- In all cases there was an improvement by DCT.

  → biggest improvement for 1.2379, K890, S390

  → best wear behavior: VANADIS 4E and VANADIS 23

Cutting stainless steel 1.4301 / 0,4 mm and DC04 / 1,5 mm:

- The wear is dominated by adhesion and abrasion (no fracture).
- There is only little influence of DCT on the wear behavior.
- There is a significant influence of the surface topography on the adhesion tendency.

  → best surface: blasted + slightly polished
- Abrasive wear and adhesion can be reduced by plasmanitriding + CrVN coating.

4.4.3 WP 4.3 Assement of the cutting edge / Evaluation of the cut part

The geometrical values of the cutting edge on punch and die side were be inspected by micrographs and laser scanning. Additional the roughness of the lateral areas of the punches were measured with a conventional Hommel-testing equipment to investigate the influence of the different mechanical pre-treatments. In addition to the investigations of the cutting edge of the punches, the cutting results (strip sections) were evaluated in terms of smooth cut proportion, ridge height and size of the catchment rounding.

The results are shown as a part of WP3.4 (*see Figure 4-37 and 4-38*) and WP4.1 (*see Figure 4-54*)

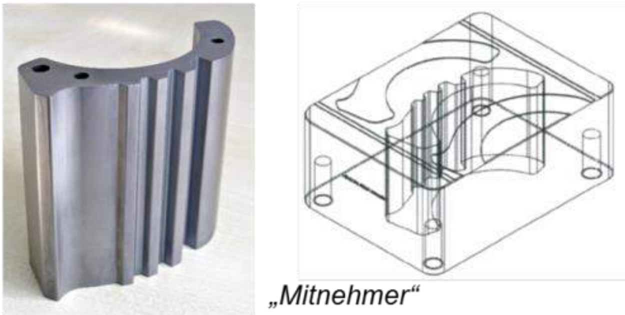
4.5 WP5 Cutting tests under production conditions

To verify the practical tests on laboratory scale, the best tool materials and treatments were used at supporting SME in Belgium and Germany for application trials under production conditions. Therefore the demonstrator tool were manufactured, heat treated and coated. After the tests the quality of components and tools was analyzed.

Regarding to the tools for industrial applications the necessary components for punch and die were manufactured/reworked and adapted to the specific demands of the supporting SME. The optimized heat treatments and the coatings were done in WP2 and WP3.

In the project was planned to transfer the results from the laboratory scale to both countries with industrial applications and different parameters for the cutting processes.

On the German side were selected two demonstrators and processes. A real fine blanking process was tested at the company „Meteor“ in Zella-Mehlis-Thuringia. In the following picture 4-54 you see the test parameters including the punch geometry.

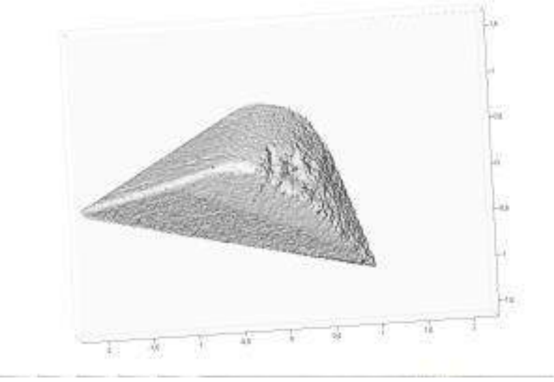


- Tool materials: Vanadis 4e, Unimax
  - → *cooling -80°C*
  - → *DCT*
- Sheet material:
  - → ***Sheet material: S700 MC***
  - → ***Thickness s = 4,5 mm***
- Cutting force: approx. *1300 kN*

Figure 4-54: Punch geometry and test parameters for the fine blanking process at company "Meteor"

In the tests was integrated an additional material from "Uddeholm" named "Unimax". This material was a conventional heat treated material with additional cryogenic treatment, but only at a temperature of –80°C. The advantage of this tool material is the very low price (≈ 8 €/kg). Three punches per test-variant were used to have a good statistic security.

After every test series the contour of the punch (2D/3D) was measured (*Figure 4-55*). The quality of the final workpieces was defined by the requirements of the customers of "Meteor".



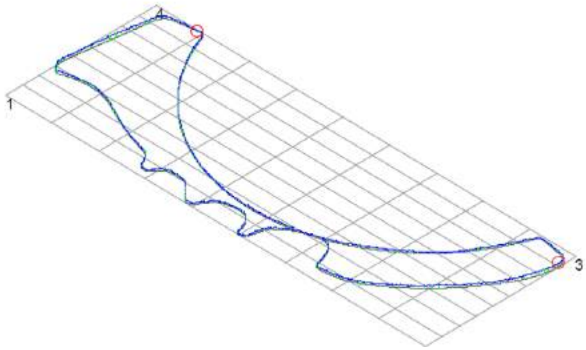


Figure 4-55: 3D-picture of the edge of the punch with abrasive wear (right) and a measurement of the tool contour (left)

The results of the industrial fine blanking process by the company „Meteor“ is shown in *Figure 4-56*. There is illustrated, that it is possible to increase tool life by nearly 100% with optimized cryogenic treated materials. It is also visible that the same live time can be achieved with a cheap tool material like „Unimax“ from Uddeholm in comparison to the more expensive “Vanadis 4e”.

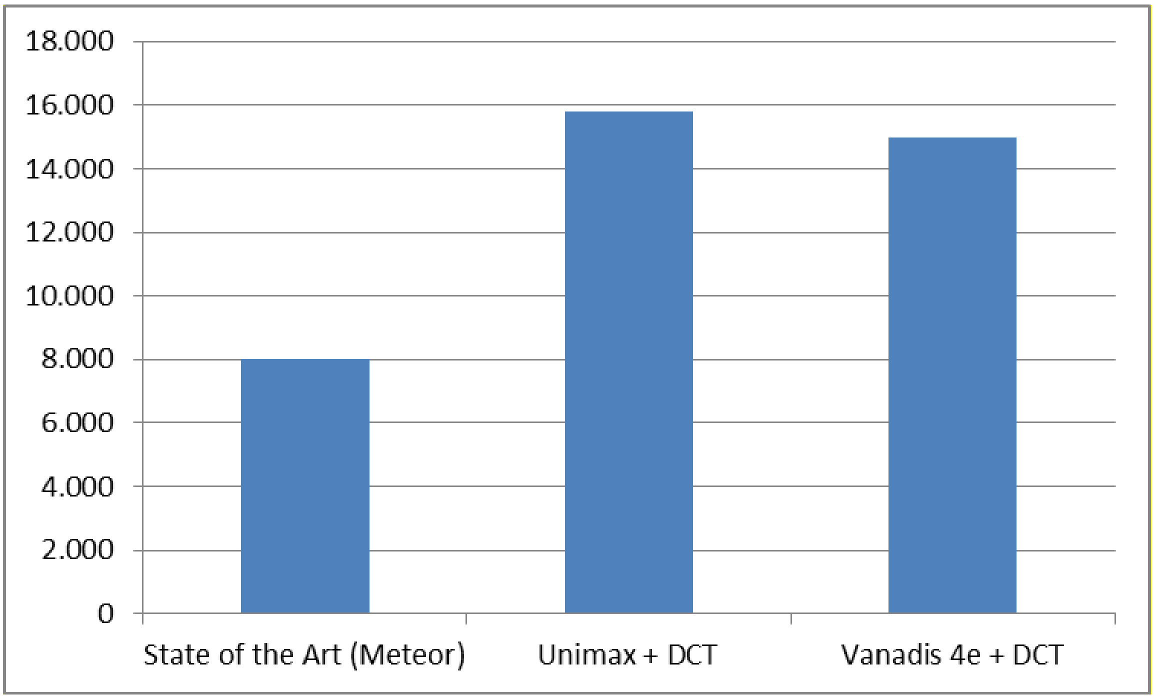


Figure 4-56: Overview of lifetime for industrial tests by company “Meteor”

Beside the fine blanking tests by “Meteor” another testing program was carried out by the company “Karl Naumann GmbH”. It was not a real fine blanking process, but the industrial tests were made with high strength stainless steel with strength of 1.200 N/mm^2 and a cutting gap of 3-5%. This is a very hard regime for tool materials.

In *Figure 4-57* an overview of the punch geometry, part geometry and test parameters is given. The company has to deliver approx. 100.000 workpieces per year from the selected geometry to his customer. The workpiece geometry had a very fine contour with demanding requirements concerning the tolerances and quality of the cutting area. Actually the company can cut with one punch round about 3.000 workpieces. The costs to manufacture one punch are nearly 800 €. The company has tested many new tool materials from different suppliers to increase the lifetime in the last years, but without success. The testing setup is summarized in Figure 4-58. All tests were performed with constant lubricant amount and same stroke-speed. From each tool material three punches were tested.

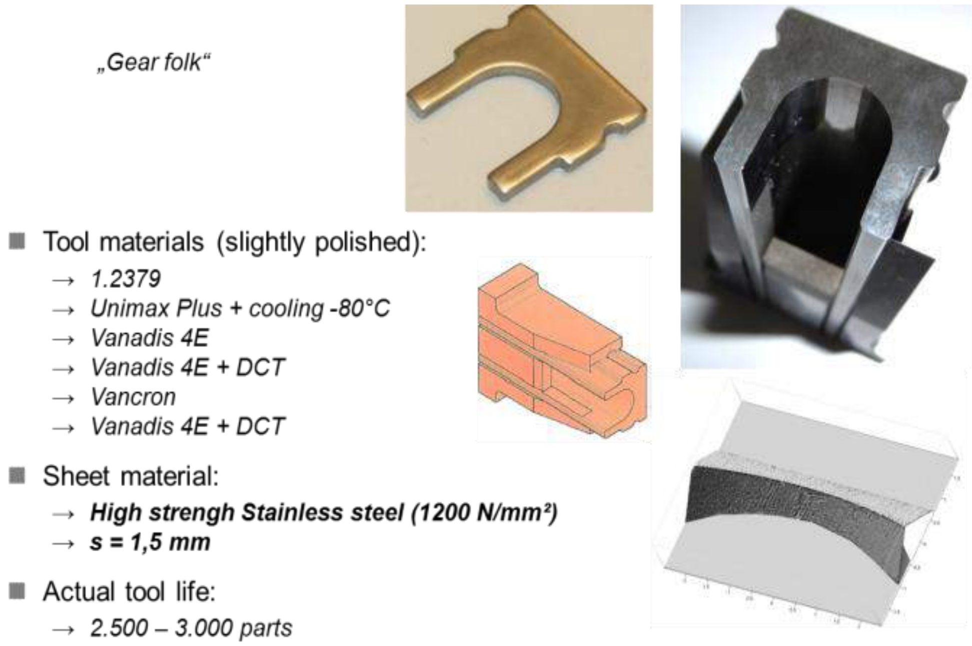


Figure 4-57: Punch geometry, part geometry and test parameters of the blanking process at company "Karl Naumann GmbH"

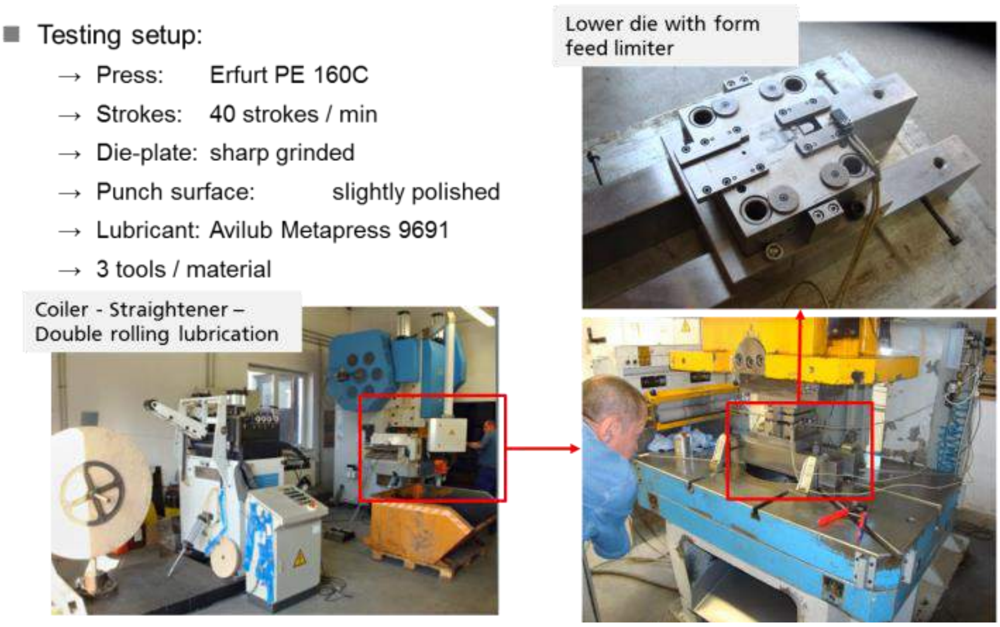


Figure 4-58: Overview test equipment by "Karl Naumann GmbH"

After cutting every workpiece was examined comparable to the real production process (*Figure 4-59*). The part deformation and the size of the burr were evaluated manually. The 3D-contour was determined by a mess machine equipped with special software in critical areas like marked in *Figure 4-59* bottom right. The lifetime of the tools was determined by the defined workpiece quality (*Figure 4-61*).

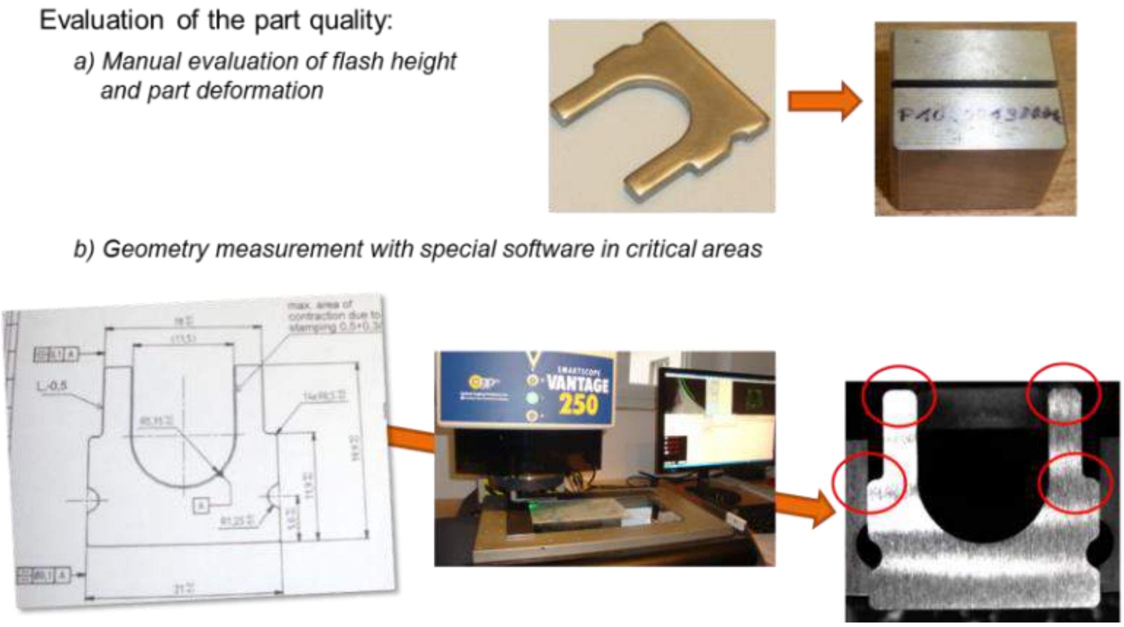


Figure 4-59: Examination of the work piece quality by "Karl Naumann GmbH"

The cutting tests by "Karl Naumann GmbH" confirmed the results from the fine blanking tests by "Meteor". With the DCT treated Vanadis 4e a lifetime increase of 200 % compared to the 1.2379 reference material and of more than 100% compared to the untreated Vanadis 4e could be realized (*Figure 4-60*). In the same way the very good results with the tool material „Unimax + cooling -80°C" could verified.

Additional to the conventional materials a „Vancron 40" - a new material from Uddeholm with a kind of "self-lubrication" property - was investigated. But the cutting edges of the punch were rounded quickly, which caused a very pronounced burr and the quality of the parts fell out of the acceptable tolerances (*Figure 4-61*). After DCT treatment the lifetime of the tool made from "Vancron 40" dropped down further.

In a second test series the tool life was evaluated after regrinding the punches. The differences between the materials became smaller and the effect of the cooling treatments (-80°C or DCT) was significantly reduced. This can be explained by the formation of micro cracks in deeper material zones, which reduce the strength of the material. Maybe a more profound regrinding can help to increase the lifetime again (*Figure 4-60*).

- Tool life:
  - → *Best results with Vanadis 4E + DCT*
  - → *Good results with Unimax plus + cooling -80°C*
  - → *No improvement with Vancron 40 + DCT*
- After regrinding significant reduced tool life
  - → *maybe due to micro cracks in deeper zones of the material caused by the previous tests*

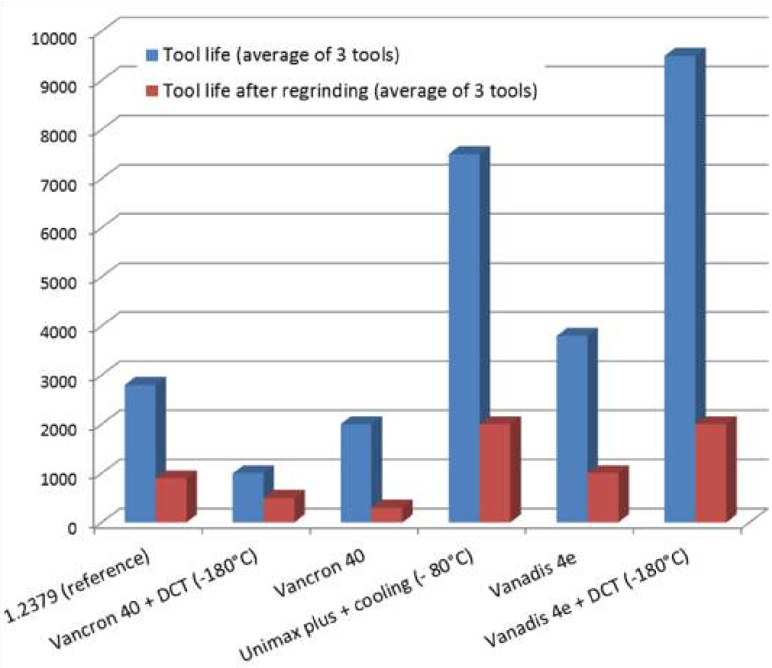


Figure 4-60: Tool life for different punch materials before and after first regrinding

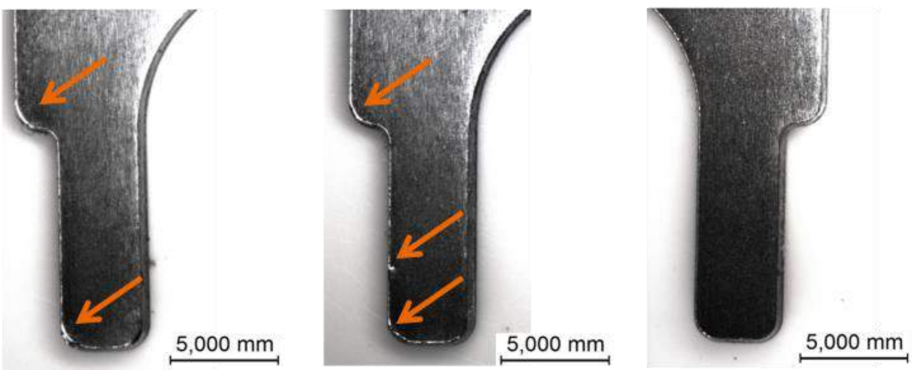


Figure 4-61: Critical burr formation at workpiece "gear folk" for different tool materials

Additional industrial tests were carried out in Belgium. A set of rectangular punches was prepared by the Belgian company Tools&Dies (toolmaker) and heat treated by Ventec and Nitrotechnics for the company ETAP (Malle, Belgium). In daily practice Sleipner is used as tool steel for the punches and cutting oil LIONOIL VAPOIL 2 EP. For the present tests Vanadis 23 was chosen as tool steel and no lubricant. The sequence of the manufacturing was as follows:

- Premachining
- Hardening
- Electro-discharge-machining (EDM)
- Grinding

This sequence resembles the preparation sequence followed by Fraunhofer IWU except for the blasting and polishing. Two types of heat treatment were executed: a conventional treatment (HT) and a special heat treatment with DCT (HT+DCT). The aimed hardness of 60 HRC was confirmed by measuring both treated punches. The punches were mounted in automatic press machine to cut rectangular holes in Zincor steel plate (DC01+ZE25/25) with thickness s=1,5 mm.

The two punches were tested until galling occurred. There was no addition of a cutting lubricant since the presence of a zinc layer acts as a solid lubricant.

The result of the test can be seen in Figure 4-62 after 8400 strokes with the HT punch and 10000 strokes of the HT+DCT punch.

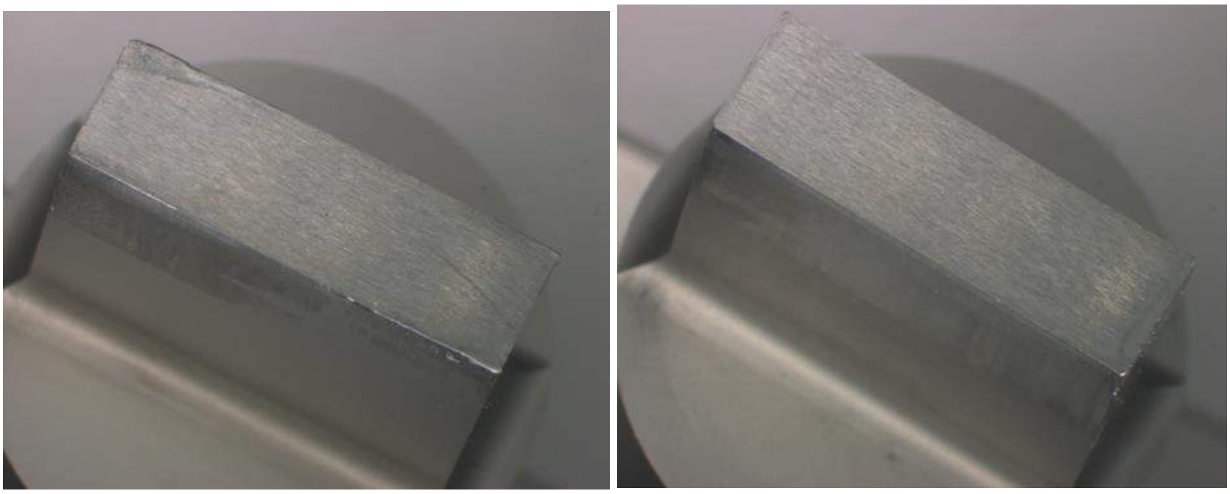


Figure 4-62: Detail of the punch HT (left) after 8500 strokes and the punch HT+DCT (right) after 10000 strokes

4.6 WP6 Evaluation and systematization of the experimental results, final report

The results of the above mentioned cutting tests in WP4 and WP 5 were compared and evaluated in order to determine the performance of the examined combination of substrate and coating for blanking and fine blanking.

From the above results it can be concluded that all the selected steel substrates performed well during blanking operations. The best results were found with the Vanadis 4e and 23 steel in uncoated condition. A special coating can improve the adhesive wear of the reference steel 1.2379 in case of the PM steels the use of a coating is optional. Furthermore DCT treatment could improve the flaking and wear behaviour in both the lab scale and industrial tests. The surface preparation after EDM is found to have an important positive influence on the wear especially when the surface is blast and polished. The industrial blanking tests confirmed the positive contribution of DCT on several sheet materials.

5 Necessity and adequacy of advanced work

The funds were completely utilized for the executed studies and work packages in the project within report period. The execution of each work package was carried out by the project leader respectively, with one research assistant and partially undergraduate assistants as planned in the proposal. The staff funds were used as planned. The executed activities proved to be required and in the executed frame as adequate. The gained results are in accordance to the planned activities in the proposal.

6 Result transfer to the industry

6.1 Dissemination plan into the industry during the project period:

Dissemination	Responsible	2013	2014	2015	2016
User committee meeting					
User committee Germany User committee Belgium	IST, IWU SIRRIS	 10.09.2013	15.04.2014 / 02.10.2014	20.10.2015 & 05.02.2015 / 03.09.2015	27.01.2016 / 27.01.2016
Exhibitions / Trade Fairs					
Euroblech	IWU		10/ 2014		
Intec Leipzig	IWU			03/2015	
Conferences and seminars					
33. Industrie-Arbeitskreis Werkzeugbeschichtungen und Schneidstoffe (IAK)	IST			05.11.2015	
EU-COST Meeting	IWU			19.10.2015	
5. ICAFT & SFU Chemnitz	IWU			11/2015	
Demonstrations					
Manufacturing with optimized tools	SIRRIS-ETAP			10-11/2015 "Meteor"	01/2016 "Karl Naumann GmbH"

6.2 Dissemination plan into the industry after the project period:

Dissemination	Responsible	2016	2017	2018
Internet				
Publication of the final report on the website of VOM and EFB		June 2016		
Poster				
Final poster		10/2016		
Annual Report Fraunhofer IWU Chemnitz and IST Braunschweig	IWU, IST		03/2017	03/2018
Conferences and seminars				
3rd Int. Conference Heat Treament and Surface Engineering in Automotive Applications	SIRRIS	10.05.2016		
3rd MCHT&SE Slovenia	IWU	26.-28.09.2016		
Sächs. Fachtagung für Umformtechnik (SFU 2016, SFU 2017, SFU 2018)	IWU	12/2016	11/2017	11/2018
Consulting				
Werkzeugbau Winkelmühle	IWU, IST	Complete 2016	Complete 2017	
Böhler & Uddeholm	IWU	Complete 2016	Complete 2017	
Publications in journals and periodicals				
UMFORMtechnik	IWU, IST	June 2016		
Techniline	SIRRIS	April 2016		
VOM Info	SIRRIS	May 2016		
Exhibitions / Trade Fairs				
Hannover Messe	IST, IWU	April, 2016		
Euroblech	IST, IWU	October 2016		10/2018
Intec Leipzig	IWU	03/2016	02/2017	02/2018

Demonstrations					
Werkzeugbau Hartmann	IWU	08-10/2016			
Koki Stanztechnik	IWU, IST		03/2017		
Bilateral projects:					
Stanova Stanztechnik	IWU, IST	10/2016-09/2018 (ZIM)			
Werkzeugbau Ullmann	IWU, IST	07-12/2016			

7 Utilization of the funding in Germany

Forschungsinstitut	**Wissenschaftlich-technisches Personal** (Einzelansatz A.1 des Finanzierungsplans)	**Gehälter für übriges Fachpersonal** (Einzelansatz A.2 des Finanzierungsplans)	**Geräte** (Einzelansatz B des Finanzierungsplans)
IWU	21,12 Personalmonate	8,73 Personalmonate	17.000€
IST	22,73 Personalmonate	10,27 Personalmonate	keine

To accelerate the lab scale tests and to get industry-oriented conditions a strip feet unit with a 3-time punch tool (geometry “Dreieckstempel”) was constructed and integrated in the excentric press AMBOLD PEEV 25 at Fraunhofer IWU. This was the basis for testing many different material combinations to find the best materials for the industrial application tests later on.

Förderhinweis

Das IGF-Vorhaben 102 EBG der „VOM – Vereinigung voor Oppervlaktebehandeling van Materialen“ (Belgien) wurde über die AiF im Rahmen des Programms zur Förderung der Industriellen Gemeinschaftsforschung und -entwicklung (IGF) vom Bundesministerium für Wirtschaft und Technologie aufgrund eines Beschlusses des Deutschen Bundestages gefördert.

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