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ORIGINAL ARTICLE

Application of selected surface engineering methods to improve the durability of tools used in precision forging

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Abstract The article presents a detailed analysis of the degradation phenomena and mechanisms of selected forging punches made of UNIMAX tool steel. Analyzed punches are used in the manufacture of a constant velocity joint boot forging (CVJB) applied in motorcars with front axle drive. The thorough analysis concerned the punches used in the fourth forging operation after a multi-operational process of forging at elevated temperatures, due to the lowest durability equaling only 4000 forgings. A comparison was made of 5 variants of surface thermo-chemical treatment including 2 types of nitriding (with a low and high potential) and 2 different coatings: CrN and AlCrTiN as well as a punch with and without additional thermo-chemical treatment. The performed complex analysis included a macroscopic analysis combined with scanning of the working surfaces, numerical modeling, microstructural tests, SEM microscopic tests, and microhardness measurements. The obtained results make it possible to select of the optimal variant of thermo-chemical surface treatment which improves the durability of these tools. In particular, the analysis included the manner and areas of wear of the punches as well as their resistance to the particular degradation mechanisms.

Keywords Semi-hot precision forging · Improvement of durability · Punch · Destructive mechanisms · Surface thermo-chemical treatment · Hybrid layers

1 Introduction

The development of forging makes advanced forging processes, such as precision forging, more and more frequently used. The main aim of precision forging is the production of forgings with the shape as close to the ready product as possible, the result of which is that the subtractive manufacturing of precision forgings is limited to the minimum or even completely eliminated [1]. Also, the forgings obtained in the precision forging process exhibit very good performance properties, and so this method is, at present, the most frequently used technology of producing responsible components, mainly for the automotive industry. Unfortunately, such an advanced technology has its faults, too. The most important of them is a very low durability of the shaping tools [2, 3].

The low tool durability in the precision forging process, on the one hand, results from the fact that these tools are more loaded than in the conventional die forging processes, which makes them much more exposed to the operation of

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degradation mechanisms. On the other hand, due to the use of minimal allowances for the finishing treatment and very narrow tolerance of shape and dimension for the produced forgings, even small values of wear cause the tools to be removed from the operation. All this makes the requirements of the quality and durability of the tools used in precision forging much higher than in the case of the tools applied in the conventional die forging processes, in which a certain level of tool wear is usually allowed. And so, the activities performed in order to improve tool durability are concentrated mainly on the area of surface layer, which is especially exposed to the operation of degradation factors and whose wear, in the case of tools used in precision forging, is unacceptable [2–7].

At present, the most popular method of improving the durability of forging tools in nitriding. Nitriding increases the abrasion wear of the tools, as well as their fatigue strength and corrosion resistance. The observations of many industrial forging processes in which nitriding of the tools was applied have shown that this procedure makes it possible to increase their durability even by a few times. The performed studies have demonstrated that, in order for a nitrided layer to effectively improve the durability of the tool, it must have a uniform and specific structure. In general, during the nitriding procedure, first, a diffusion zone of ferrite supersaturated with nitrogen with carbonitride and nitride γ' precipitates is formed and next, depending on the process parameters, on the surface, a continuous zone of nitrides and carbonitrides $\varepsilon + \gamma$' is created, with an increasing content of nitrides ε. It turns out that the nitrided layers with a surface zone of phase ε generally exhibit worse functional properties mainly because they characterize in low ductility, while exhibiting high abrasion resistance, and so they are useful for the operation under the conditions of lower dynamic loads. In turn, a layer constructed of carbonitrides and nitrides γ' increases the abrasion and frictional resistance as well as corrosion resistance. With regard to nitrided layers without a zone of compounds, they characterize in high fatigue strength and a lower tendency for thermal fatigue cracking, which makes them suitable for the operation under the conditions of high dynamic loads [8].

At present, the applied nitriding methods, owing to precise regulation of the chemical composition of the nitriding atmosphere and the nitrogen potential, make it possible to obtain nitrided layers of any kind of construction. An example of such a nitriding method is the ZeroFlow method elaborated by the Seco Warwick company, which is based on the use of one-component atmosphere, consisting only of ammonia, which dissociates inside the furnace retort (NH_3) and whose concentration determines the value of the nitriding potential [2].

The expectations connected with the durability of tools used in precision forging often require more advanced methods of durability improvement, which undoubtedly include hybrid technologies, consisting in the use of two or more surface engineering techniques, combining nitriding with PVD or CVD. At the same time, the presence of the two mentioned microstructure components, i.e., a nitrided layer and a selected PVD or CVD coating [9, 10], causes mutual, synergic cooperation, thus providing very good performance properties. The nitrided layer increases the surface hardness and the resistance of the substrate to plastic deformations, thus protecting the coating from losing its internal cohesion and adhesion to the substrate. In regard to the applied coating, it isolates the nitrided substrate, thus limiting the effect of the operation of external factors [9–18].

The CVD method is a process realized as a result of the chemical reaction of gases taking place on the substrate surface, on which a specific material is deposited. In the process of coating formation, also the substrate components participate. In the conventional CVD methods, the chemical reactions take place at 900–1000 °C, which significantly reduces their scope of application, especially in the case of forging tools which previously underwent thermal treatment. In the recent years, several types of CVD processes have also been elaborated, of which the methods of chemical deposition from the gaseous phase aided by PACVD/PECVD plasma seem to be the most prospective [19]. These methods are very attractive because of the low process temperature, the possibility to deposit non-equilibrium phases and a better control of the stoichiometry and purity of the coatings, owing to the possibility of cleaning by means of plasma. The low temperature of deposition in the CVD processes aided by plasma is obtained by way of using the latter to excite the particles of the gaseous mixture to the energy which is in accordance with thermal excitation. Then, the non-equilibrium reaction, as a result of which the desired product is deposited, can take place at a temperature below 600 °C, that is much lower than in the case of the conventional CVD techniques [17, 19–21].

The problem of temperature is not present in the case of the PVD methods, which consist in a physical deposition of coatings from the gaseous phase with the pressure lower than atmospheric and with the use of various physical processes to obtain deposited couples (e.g., nitrides, carbides, borides) [19, 22]. The couples of metals or compounds are deposited on a cold or heated (to 200–500 °C) substrate, owing to which it is possible to coat the tools after a previous thermal treatment without the risk of a drop of durability as a result of the operation of high temperature in the process of coating deposition. Joining the coating with the substrate is adhesive in character (less often, adhesive-diffusive) and it is weaker when the coated surface is less clean. At present, we know a few tens of types and modifications of the PVD methods, of which the PAPVD type is the most popular [21, 22]. The application of plasma in such a process additionally provides the possibility to clean the substrate, which ensures good adhesion of the coating to the substrate.

1.1 Application of hybrid layers on tools used in industry

In this field of applications, there are many studies concerning the selection of PVD coatings [21, 23], as well as optimization of the number of their components and the manner of their application [24, 25]. So far, studies have been performed on the use of nitrided tools coated with a single- or multi-layer PVD coating [26, 27], which have been tested in respect of thermal fatigue [28], especially for the application in steel casting molds for aluminum and bronze casting [28, 29]. The abrasive wear resistance of the PVD coatings was also tested [30–32] under normal conditions and at elevated temperatures, from which we can conclude that the coatings containing titanium nitrides (TiN) exhibit the highest resistance, whereas the coatings with chromium nitrides are the least resistant to abrasion, while exhibiting a higher resistance than the traditionally used tool steels [31]. Hybrid layers have been also successfully used on tools for metal injection (thixoforming) [33]. Among the numerous studies concerning the coating application technologies and coating properties, some refer to the possibility of applying coatings on forging tools in order to improve their durability [34, 35]. The authors point to the elevated resistance of a hybrid layer being a combination of a PVD coating and a nitrided layer to the simultaneously occurring degradation factors, that is thermal and mechanical fatigue as well as friction. In this field of research, it is the resistance to the combined operation of many factors that is important, rather than to individual ones. In Slovenia, attempts have been made to apply PACVD and PVD coatings for tools used in forging operations on hammers [36–38], whereas in North Korea, examinations have been performed of the durability of nitrided tools with multi-layer TiBN coatings of the PECVD type (chemically deposited from the gaseous phase) [39], assigned for hot die forging, whose resistance turned out to be over five times higher than the resistance of the tools used so far and three times higher than the nitrided ones. The research concerning the application of hybrid layers for forging tools has been conducted in several locations in the world. Under laboratory conditions, thermal fatigue tests have been made as well as test forging was performed on plasma nitrided dies with TiN/Ti(C,N)gradient, (Ti,Cr)N, (CrN/TiN) × 3, (Cr/CrN) × 3 and CrN coatings, which exhibited good results for the multi-layer (CrN/TiN) × 3 coating [40]. Studies on monolithic CrN coatings showed the optimal thickness of the CrN coating (equaling 4 ÷ 8 μm) [41]. Also, performance tests have been conducted under the industrial conditions, where hybrid layers with CrN and TiAlN coatings were applied for hot forging dies, with a nearly triple increase of the tool life [41]. Other performance tests conducted on the properties of PVD coatings obtained good thermal and corrosion resistance of the TiAlCrN and CrN coatings [42–45].

The aim of the study is an analysis of the durability of forging punches after different variants of thermo-chemical surface treatment, used in the fourth operation of the multi-operational process of forging a constant velocity joint body (CVJB).

2 Subject of study—punches in semi-hot forging process

The research concerned the forging punches used in the fourth semi-hot forging operation of a CVJB (constant velocity joint body) housing. The punches in this operation are characterized by a low durability average (only 4000 forgings). Figure 1 shows the CAD model of the analyzed punch made in Pro / Engineer. The analyzed punches are made of tool steel for hot operations under the trade name UNIMAX (1.2367, EN: X38CrMoV5-3), which has a good resistance at high temperatures, as well as resistance to tempering, high hardenability, and low tendency for plastic deformation. The punches after the heat treatment have the hardness of 540–580 HV (51-54HRC).

2.1 Description of the analyzed process

For the tests, the precision forging of a CVJB (constant velocity joint body) housing in closed dies was realized at the GKN Driveline Forge and it consisted of five operations: 4 hot forging operations, (last one—stamping) and one cold forging operation (Fig. 2). The initial billet was inductively heated to 920 °C. The forging's material was the XC45 steel. The semi-hot forging process was realized on the eccentric press SCHULER Forgemaster with the pressing force of 20MN (slide stroke: 630 mm, nbr of strokes/min: 18–40, work capacity: 500 kJ, bed ejector per station: 400kN).

The multi-operational forging on the press SCHULER Forgemaster can be performed by two methods: ASMO (Alternate Stroke Method Operation) or, as in the analyzed process, ESMO (EveryStrokeMethod Operation).

The normally used tools (punches) are not nitrided and not heated before the process; they are pre-covered with a special welding agent (Aerodag CERAMISHIELD) in order to reduce the risk of rupture in the thermal shock caused by the contact with the hot preform early in the process. In addition, the punches of the fourth operation are heated in a special device and 2 times immersed in a mixture of graphite and water (mounted on the press, unheated). The tools, after producing a few forgings, reach the operating temperature (250–300 °C). The lubricant is a mixture of water with graphite (LUBRODAL F 21). The high quality of the forging is ensured owing to the process stability and on-time control. Table 1 presents the chemical composition of the forging.

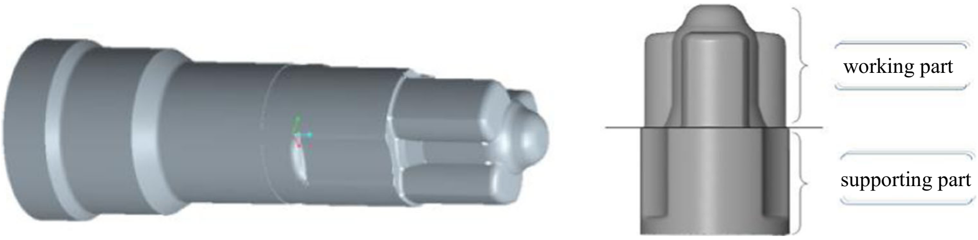


Fig. 1 CAD model of a punch used in the fourth precision forging operation of a CVJB housing. **a** View of the whole punch. **b** Division into the working part and the fixing part

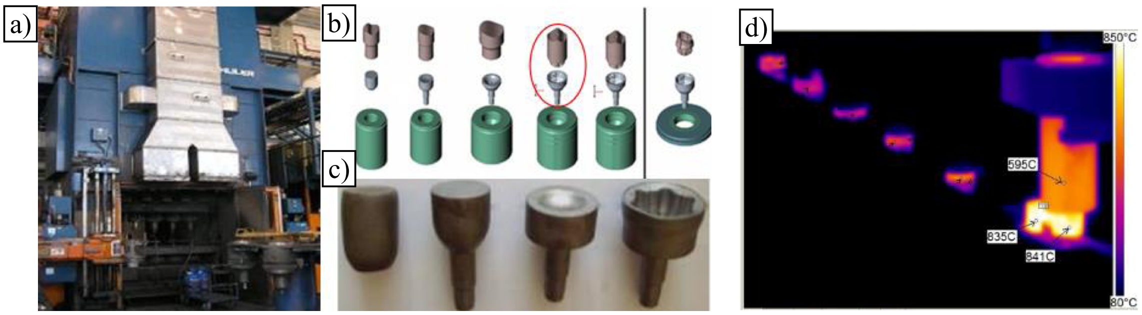


Fig. 2 The precision forging process. **a** Crank press. **b** Scheme of individual operations (V operation—marking). **c** Forgings after successive operations. **d** The thermovision research

The average durability of individual dies and punches varies; a greater durability is observed for the dies, which equals from 8000 forgings (dies in IV operation) to 47,000 forgings (dies in III operation). The lowest durability of all the tools was observed for the punch used in the fourth forging operation—in the backward extrusion process (Fig. 1).

2.2 Applied tool material and variants of thermo-chemical treatment

For the analysis, one punch made of Unimax steel was selected, which only underwent the standard thermal treatment, without surface treatment and which was the reference for the other treatment variants. It is a standard tool in the group of those used in the analyzed production process, which exhibit the average durability at the level of 4000 forgings. The *UNIMAX steel produced by* Uddeholm is a chromium-molybdenum-vanadium steel, characterizing in good wear resistance, as well as resistance to high operation temperatures and high thermal fatigue strength. Its chemical composition has been included in Table 2, whereas Table 3 shows its mechanical properties.

In order to improve the durability of the punches, 4 variants of thermo-chemical surface treatment were applied, including 2 types of gas nitriding by the ZeroFlow method (with a low and high potential) and 2 different hybrid variants, i.e., PN + Cr/CrN and PN + AlCrTiN. Sixteen tools were analyzed in the process, including punches without additional thermo-chemical treatment, from which one representative tool was selected for each type of treatment, as well as one reference punch, without any treatment.

The hybrid layers were designed and manufactured at the Surface Engineering Department of the Institute for Sustainable Technologies, at the National Research Institute in Radom. The process of a multi-step hybrid treatment of the analyzed tools was performed in three stages:

- stage I—vacuum thermal treatment of the steel substrate,
- stage II—creation of the nitrided layer by the ion nitriding method,
- stage III—processes of deposition of selected PVD coatings.

For the forging process, tools made of UNIMAX steel were designed, which then underwent thermo-chemical treatment by way of plasma nitriding, further denoted as PN. The nitriding conditions are presented in Table 4, whereas Table 5 presents the properties of the applied PVD coatings.

Table 1 Chemical compositions for workpiece material

Material	C	Mn	Si	P	S	Cr	Mo	V	Cu
XC45 (1.0503)	0.45–0.48	0.6–0.8	0.1–0.4	Max 0.025	0.015–0.03	–	–	–	Max 0.25

Table 2 Chemical compositions of tool steel

Material	C	Mn	Si	P	S	Cr	Mo	V	Cu
Unimax	0.5	0.5	0.2	Max 0.03	Max 0.03	5	2.3	0.5	–

The effect of the hybrid technology, with such a configuration as a hybrid layer consisting of a nitrided layer and a PVD, was described in details by the authors in the publication [26]. The various PVD coatings selected for the tests, characterized by different material properties, which are important for hot die forging processes are friction coefficient (CrN 0,32 < AlTiCrN 0,48), thermal resistance (CrN ≈ 700 °C < AlTiCrN ≈900 °C), etc.

Another type of thermo-chemical treatment used to improve tool durability is gas nitriding by the ZeroFlow method, offered by the SECO WARWICK Europe company [2]. The method enables a precise control of the nitriding process in order to obtain the appropriate layer of nitrides with a simultaneous economy in the use of the working gases (ammonia). Two types of treatment were proposed, which had similar courses of temperature changes in time and differed only in the value of the NH_3 potential in the furnace retort. The first variant assumed the obtaining of a diffusive nitride layer α, a zone of γ' precipitates and nitrides ε on the surface by way of nitriding with a higher potential. In the second variant, a much lower potential was used in order to avoid the formation of γ' type nitrides, which form nitride precipitates along the grain boundaries, thus increasing the brittleness of the diffusive layer. That is why the nitriding procedure was to create a layer of a slightly lower hardness and higher fatigue strength.

3 Applied scientific test methods

The tools prepared in this way underwent performance tests under the industrial conditions of the GKN Driveline Forge, where forgings were produced with the use of each punch. With the aim of a thorough analysis, the following stages of research were realized:

- Complex (macroscopic) tests of the tool surface including:

Table 3 Mechanical properties of Unimax steel after heat treatment

Hardness	54 HRC
Yield strength, Rp0,2	1720 MPa
Tensile strength, Rm	2050 MPa
Elongation, A5	9%
Reduction of area, Z	40%

Table 4 Parameters of ion nitriding and properties of the nitrided layer

Procedure	Temperature T[°C]	Pressure p[mbar]	Atmosphere	Time t[min]
Heating	≤520	2.5	25%Ar + 75%H_2	100
Nitriding:				
Stage I	520	4.3	8.1% N_2 + 91,9H_2	90
Stage II			7.6% N_2 + 92,4H_2	90
Stage III			6.7% N_2 + 93,3H_2	240
Cooling	<200	10^{-4}	-	60

i. Macroscopic surface analysis, enabling a visual evaluation of the degree of wear of the tool's working surface,
ii. dimensional analysis—3D scanning of the worn tools, after various numbers of produced forgings (maximum durability).

Next, a detailed complex analysis was performed of selected areas of the working surface of each tool by the following research techniques:

- numerical modeling (FEM);

xIn order to recognize the degradation mechanisms having an effect on the tool wear and the setting conditions (the, difficult to determine, temperature, pressures, e.g.).

- microhardness HV 0.1 measurements;

Vickers hardness profiles in the cross-section in the direction from the working surface into the tools were determined in accordance with the guidelines of the Standard PS-ES ISO 6507-1:2007—Hardness measured by the Vickers method: the testing method, at the loading force of 0.98 N.

- optical microscopy;

Table 5 Main parameters of the used coatings

	CrN coating	AlTiCrN coating
Thickness	g ≈ 5.7 μm	g ≈ 3.8 μm
Hardness HV	2100 ± 140	3250 ± 315
Young's modulus	E = 215 ± 25 GPa	E = 360 ± 25 GPa
Coefficient of friction–steel	μ = 0.32	μ = 0.48
Roughness	Ra/Rz/Rt0.43/1.16/1.92	Ra/Rz/Rt 0.29/2.28/3.40
Adhesion	Fn_{C1} = 70 N, Fn_{C2} = 80 N, Fn_{C3} = 138 N	Fn_{C1} = 41 N, Fn_{C2} = 65 N, Fn_{C3} = 166 N

Table 6 Compilation of the analyzed tools

Denotation	Position	Type fo coating	Number of produced forgings
1	Punch used in fourth operation	Unimax	4372
2		Unimax / GN low potential	6249
3		Unimax / GN high potential	1412
4		Unimax / PN + AlCrTiN	1841
5		Unimax / PN + Cr/CrN	2000

Microscopic examinations—the structure of the samples cut out from the tools was examined with the use of the optical microscope OLYMPUS GX 51. The samples had been etched with a 3.5% alcoholic solution of nitric acid (Nital);

- scanning electron microscopy (SEM);

The structure of the samples and the working surfaces of the tools were examined by means of the scanning electron microscope TESCAN VEGA 3;

4 Tool surface tests

The performed experiments concerned the phenomena taking place in the surface layer of the tools, which produced different number of forgings and were then eliminated from further operation for the purpose of the tests. In the first part of the studies, a macroscopic analysis was performed as well as a measurement with a 3D scanner in reference to the nominal geometry.

From among 16 tools coated with 2 types of hybrid layers and 2 types of nitriding, which produced different numbers of forgings, 4 representative (and 1 standard without special treatment) punches were selected for the tests, characterizing in the maximum durability for each of the variants of thermo-chemical treatment. They are listed in Table 6.

4.1 Macroscopic analysis

In the analyzed process of precision forging, a visual control of the tool quality is performed. The operator stops the press, examines the surface of the tools in respect of visible damage, and makes a decision about their removal or return to further operation. And so, Figs. 3 and 4 show a macro-view of the particular tools with marked damaged areas, which caused their removal from production.

In Fig. 3, we can see damaged areas—deformation of the rubbing punch edge, which, according to the working condition analysis based on FEM analysis (Fig. 8), is exposed to especially high pressures, temperatures and the highest shear stresses. Probably, the tool undergoes plastic deformation and abrasion wear in the form of expansive, deep damaged areas.

Figure 4 shows 3 tools prematurely removed from production. On their surfaces, numerous cracks could be observed as well as spallings of whole fragments from the surface layer. These damaged areas are localized mainly on the side surface of the punch as well as at its base, in the contact area of the side surface with the horizontal surface, where disadvantageous stresses occur (Fig. 8).

4.2 The 3D dimensional analysis

The analysis of the tool wear was performed by way of scanning with the use of a measuring arm. The measuring arm ROMER Absolute ARM 7520si (Fig. 5) was used together with the Polyworks 2015 software and the Real Time Quality Meshing technology. The measuring arm is equipped with

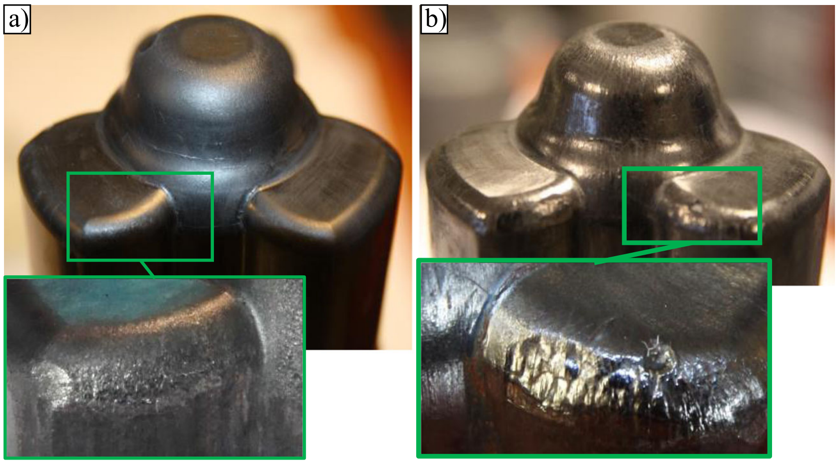


Fig. 3 Macro-view of the tools. **a** Made of Unimax steel after producing 4372 forgings. **b** A punch nitrided with a low potential after producing 6249 forgings

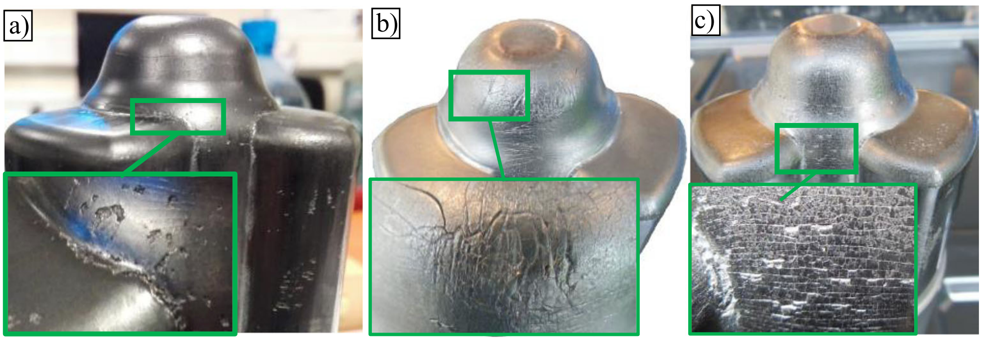


Fig. 4 Macro-view of the tools. **a** A punch nitrided with a high potential after producing 1412 forgings, **b** with a hybrid layer PN + AlCrTiN after producing 1850 forgings, **c** with a hybrid layer PN + CrN after producing 2000 forgings

seven spindles. Each spindle includes an absolute encoder, which measures the angle of rotation of the kinematic pair, which does not require initialization or heating. The arm enables classic measurements with the use of a contact measuring probe as well as non-contact measurements by means of a linear laser scanner RS3 integrated with the arm, which makes it possible to collect up to 460,000 points/s for 4600 points on the line, with the linear frequency of 100 Hz and the declared accuracy at the level of 2 sigma 30 μm.

Fig. 5 A forging selected for the analysis during scanning on the measuring station

After the measurement, a shape and dimensional analysis was performed. To align the measurement data, the best-fit algorithm method was used. The analysis results are presented in Fig. 6.

The performed dimensional analysis with the use of the 3D scanning technique enables a quantitative description of the wear and a confirmation of the degradation mechanisms described at the stage of the macroscopic analysis.

In the analysis of the results, one can notice that punch, which enabled the production of 4372 forgings (Fig. 6a), characterizes in the highest wear of all the analyzed punches, visible on the edge in the form of a long conoidal material loss with the maximal value of 0.5 mm. In the case of punches with low potential nitride layer (Fig. 6c), PN + AlCrTiN layer (Fig. 6d) and PN + CrN layer (Fig. 6e), which made it possible to produce 6249, 1851, and 2000 forgings, respectively, we can observe local wear, also located on the tool edges, at the level of 0.2 mm.

Additionally, the geometrical analysis shows that, on most of the punches (Fig. 6a–e), we can notice numerous grooves with the depths of up to 0.1 mm, which suggests the presence of abrasive wear in these areas. In the case of punch no. 2, with high potential nitriding, we can observe that the wear is practically scant, which is probably caused by the hardest and strongest surface layer.

5 Examinations of the surface layer cross-section

In the performed studies, next to macro the 3D measurements of the whole tool, a detailed analysis was also performed on the changes taking place in the tool's surface layer (5 selected areas) perpendicular to its working surface. A view of the analyzed cross-section with important dimensions is presented in Fig. 7.

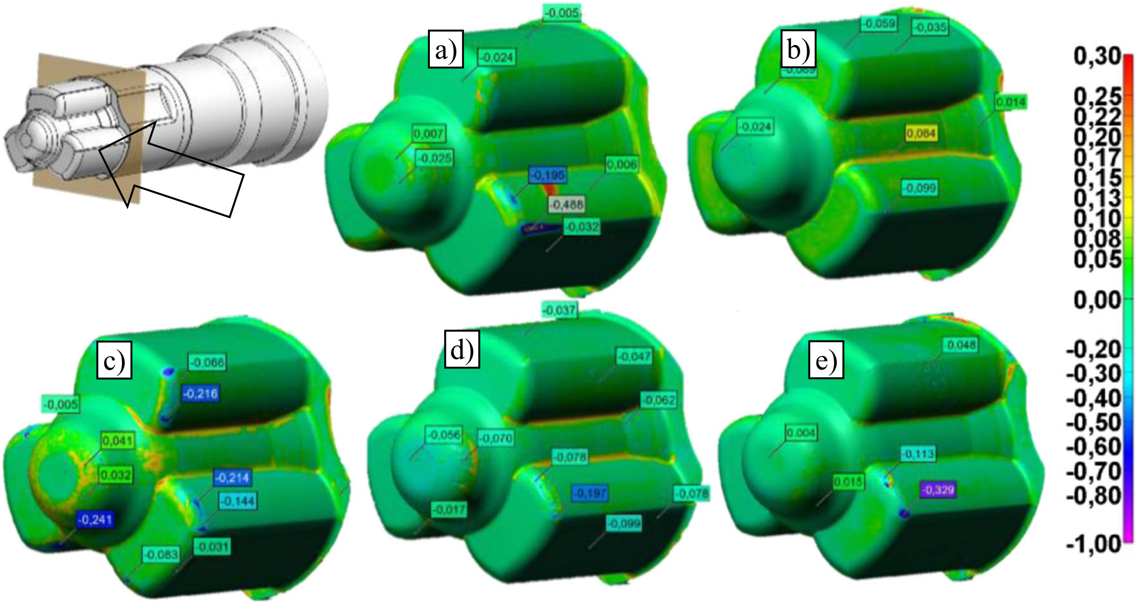


Fig. 6 Comparison of the geometry of punches with the CAD model of the tool. **a** Made of Unimax steel after producing 4372 forgings, **b** nitrided with a high potential after producing 1412 forgings, **c** nitrided with a low potential after producing 6249 forgings, **d** with a hybrid layer PN + AlCrTiN after producing 1850 forgings, **e** with a hybrid layer PN + CrN after producing 2000 forgings

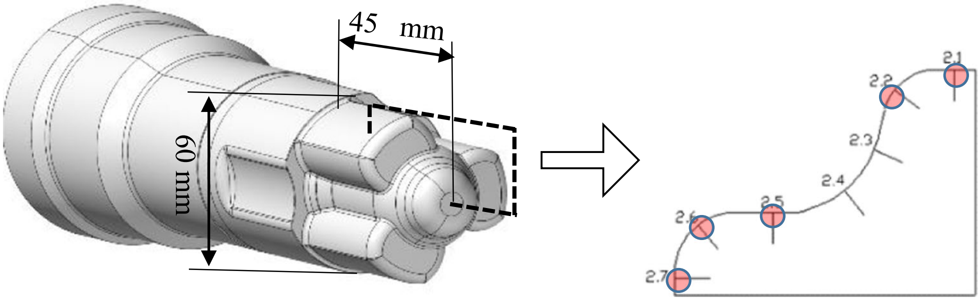
5.1 Tool working conditions based on FEM

In order to recognize the degradation mechanisms (in the selected 5 areas) having an effect on tool wear, numerical simulations were performed based on MES in the Marc Mentat program, dedicated to the modeling of plastic working processes. The forging operation was modeled in a planar symmetry deformation state for the most complex thermo-mechanical model. The geometry of the tools and the initial material, as well as the remaining technological parameters (type of press) of the process were entered into the program on the basis of the original CAD models. In FEM, for the initial billet, 8892 elements type TETRA 8 (with full integration) were adopted at the beginning and 23070 of the same elements at the end of the simulations (due to remeshing), with the constant number, 238356, of the same elements for the punch. The data of the material of the forging and the tools was taken from the Matilda materials base. The SHEAR bilinear friction model was applied, and the friction coefficients between the dies and the deformed material were accepted to be 0.35. The initial uniform billet temperatures are 920 °C and the initial temperature for the analyzed punch was 250 °C. The thermal exchange coefficient between the tools and the billet was fixed at 25000 W/(m^2 K), and between the environment and the two of them (tools and forging) was adopted to be htc 350 W/m2*K.

A FEM punch analysis was conducted in order to determine: the temperature distribution (Fig. 8a) on the punch and the contact normal stress (Fig. 8b), since it is known that they have a decisive influence on the tool life.

The simulation of the forces and temperature points to diversified intensity of the degradation mechanisms, which affect tool wear. The further away from the tool axis, the lower the forces and the temperature, which points to the fact that the hardest conditions are present in the central part of the front surface, and this is where the wear should start to occur. The temperature value (Fig. 8a) at the level of 650–700 °C corresponds to the

Fig. 7 Tool cross-section with the important dimensions and the marked area where the sample was cut out for the tests and the sub-areas denoted as surfaces



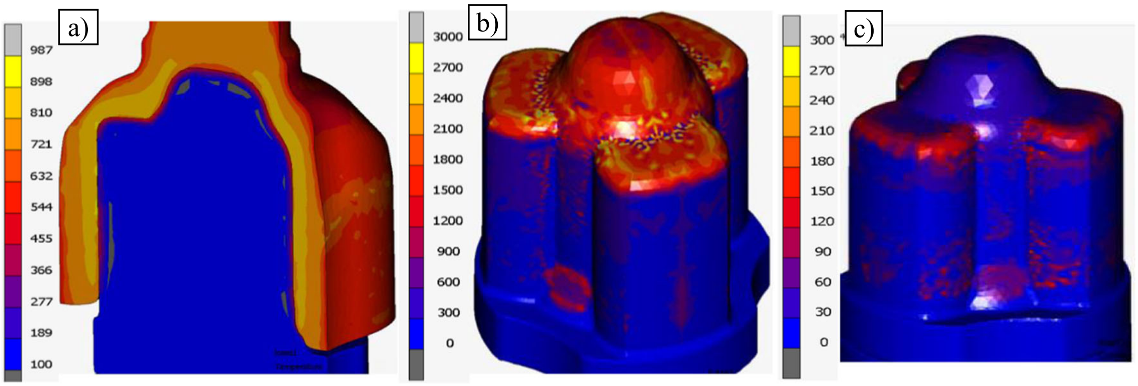


Fig. 8 Numerical results: **a** distribution of temperature on tool and forging (longitudinal section), **b** contact normal stress (MPa) on the contact surface, and **c** shear stress (MPa)

tempering temperature of the UNIMAX steel, from which the punches were made, which may cause local tempering in the case of a prolonged contact with the forging, whereas the periodical changes of temperature and the very high load (partially over 2400 MPa) may cause thermal and thermo-mechanical fatigue on the tool surface. In consequence, this can also lead to plastic deformation in these areas. The high value of shear stress (over 200 MPa) can cause detachment of the material particles, for example, the hybrid layer, or, at higher pressures, of the nitrided layer (Fig. 8c). Additionally, in order to verify the results of numerical modeling and to confirm the high mechanical load forces, the forces obtained from FEM in the 4th forging operation were compared with the courses of the forces obtained from the measurement system (developed by the authors) [46, 47].

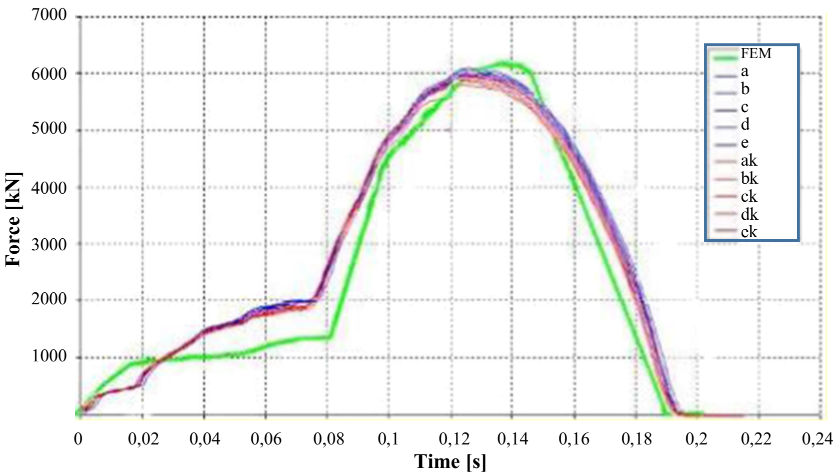
In the presented diagram of the forces (Fig. 9), one can see a great similarity in the character of the curves' shape, especially some typical points corresponding to the degrees of reduction of the forgings. Some differences may result from a mismatch between the numerical model resulting from a variety of tribological conditions (in the FEM model, constant coefficients of friction were assumed; in the industrial process, the friction forces change).

5.2 Microhardness tests

In order to determine the causes of wear of the particular punches, samples from their forming sections were collected (Fig. 7). Next, tests were performed in the surface layer in respect of the presence of cracks, traces of tribological wear and plastic deformations.

As the first test before the microscopic wear analysis, examinations of the mechanical properties were performed, by way of measurements of the microhardness in the function of the distance from the surface. The microhardness was tested by the Vickers method, with the load of 100 g, by means of the microhardness tester LECO LM-100AT, in several points distributed at the interval of 0–1 mm towards the inside of the material. The results are presented in diagrams, as a comparison of the examined tools in 5 representative areas marked in Fig. 7 as: 2.1, 2.2, 2.5, 2.6, and 2.7.

Fig. 9 Comparison of the forces obtained from the measurement system and the FEM for the fourth forging operation; *green curve*—from FEM simulation, *blue curves*—beginning of the process, *red curves*—after 8 h of the process



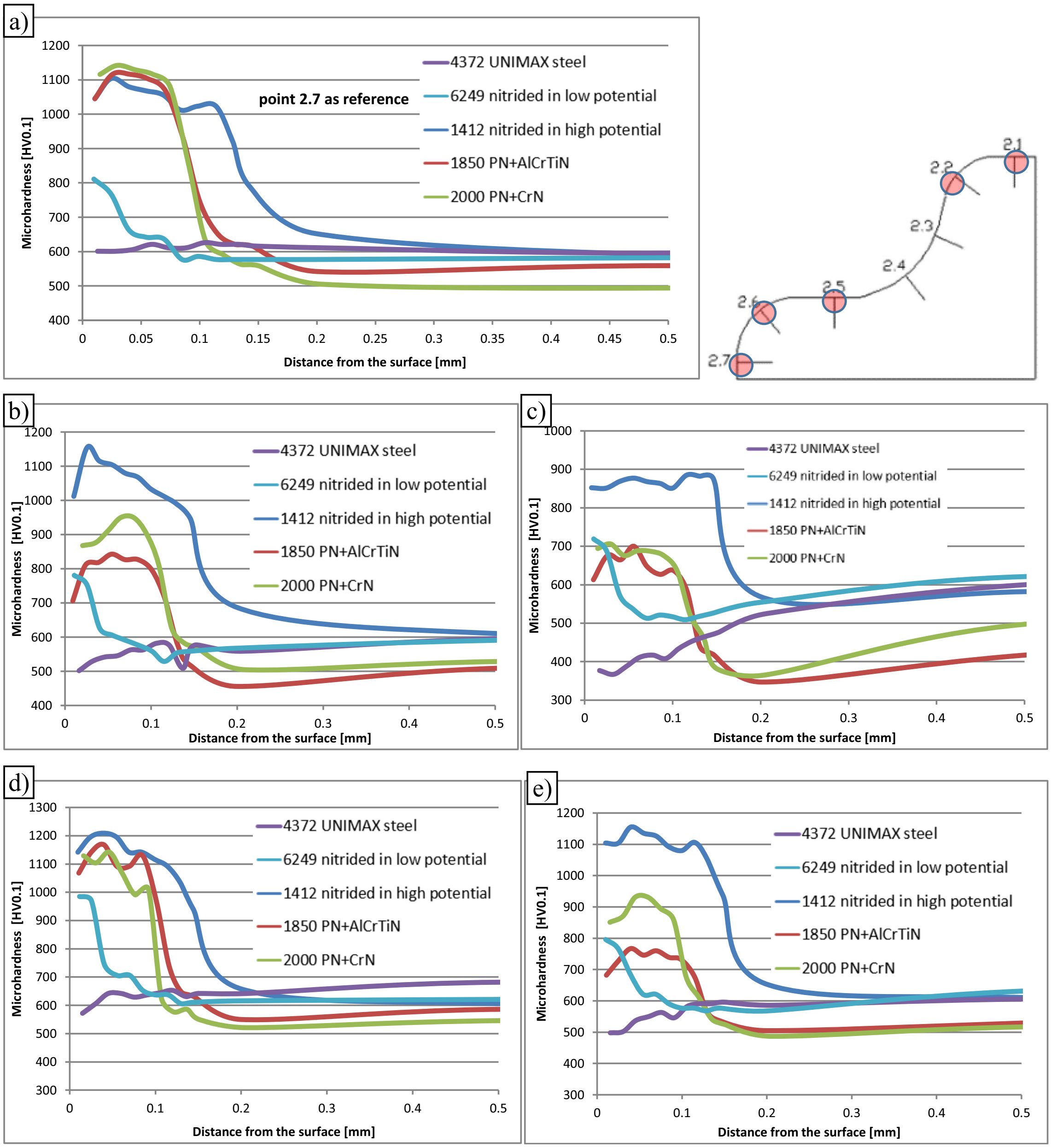


Fig. 10 Distribution of microhardness HV for selected areas in the cross-section of the examined tools in points: **a** 2.7, **b** 2.1, **c** 2.2, **d** 2.3, **e** 2.4

The results of the hardness measurement in Fig. 10a measured in reference surface layer which exhibit properties similar to initial conditions without any wear were used to define effective hardness of different nitride layers. The investigation showed the lack of a nitrided layer on the tool made of Unimax steel as well as the presence of a nitrided layer with the effective thickness of $g_{800} \approx 0.03$ mm for the tool which produced 6249 forgings, $g_{800} = 0.15–0.17$ mm for the tool removed from production after 1412 cycles and $g_{800} = 0.10–0.13$ mm for the tools with hybrid layers which performed 1850 and 2000 cycles, respectively (Fig. 10a). Also, it was demonstrated that, during the operation, a slight loss of mechanical properties is observed as a result of the contact with the hot material, mainly in the upper part of the punch, where the highest temperatures are present and the contact with the forged material is the longest. The tool nitrided with a high potential at an early stage of operation exhibited only a slight lowering of hardness in the most exposed area, i.e., point 2.2 (Fig. 10c). The case was similar for the tools with hybrid layers, which turned out to be slightly more prone to the effect of heat, while the tool covered with a thicker (about 8 μm) CrN coating was more resistant to the effect of temperature and the tool with a thinner ($g = 3$ μm) AlCrTiN coating exhibited a lower resistance.

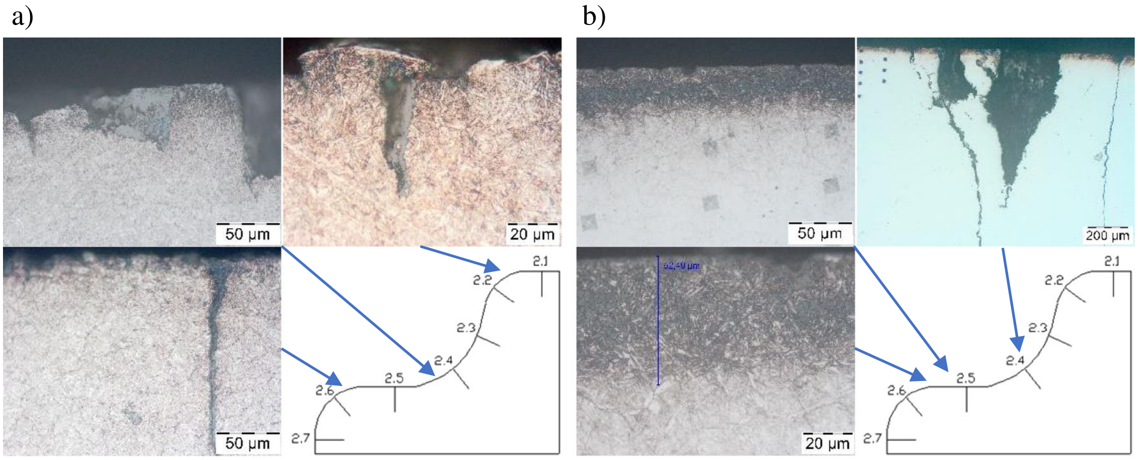


Fig. 11 Microstructural view of selected points marked on the cross-section of the tool: **a** made of Unimax steel after producing 4372 forgings, **b** a punch nitrided with a low potential after producing 6249 forgings

The presented results point to a nearly inverse proportion between the hardness of the surface layer and the obtained hardness of the tool in the analyzed process of precision forging. This results from the conditions of the shaping process, especially from the presence of elevated pressures and shear stresses on the tool surface (Fig. 8c). This is indirectly

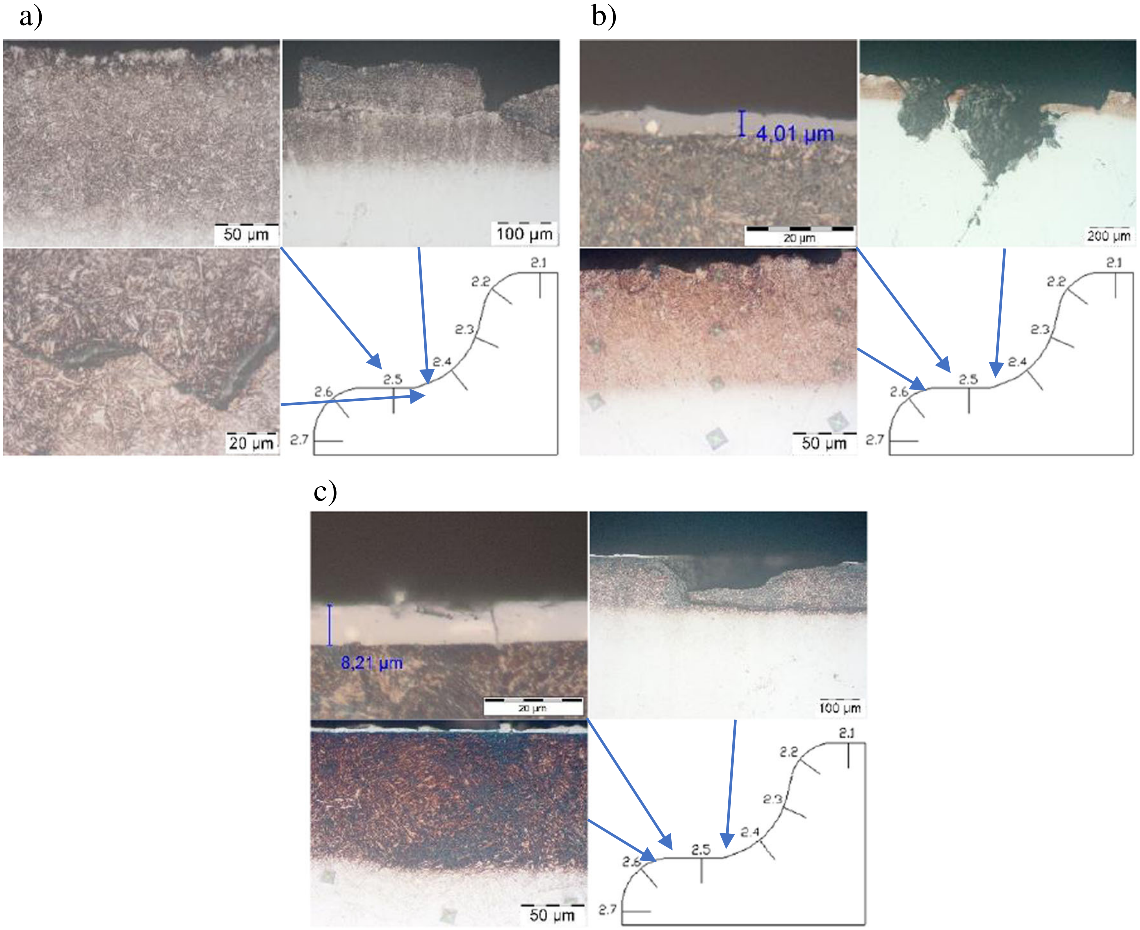


Fig. 12 Microstructural view of selected points marked in the tool's cross-section: **a** a punch nitrided with a high potential after producing 1412 forgings, **b** with a PN + AlCrTiN hybrid layer after producing 1850 forgings, **c** with a PN + CrN hybrid layer after producing 2000 forgings

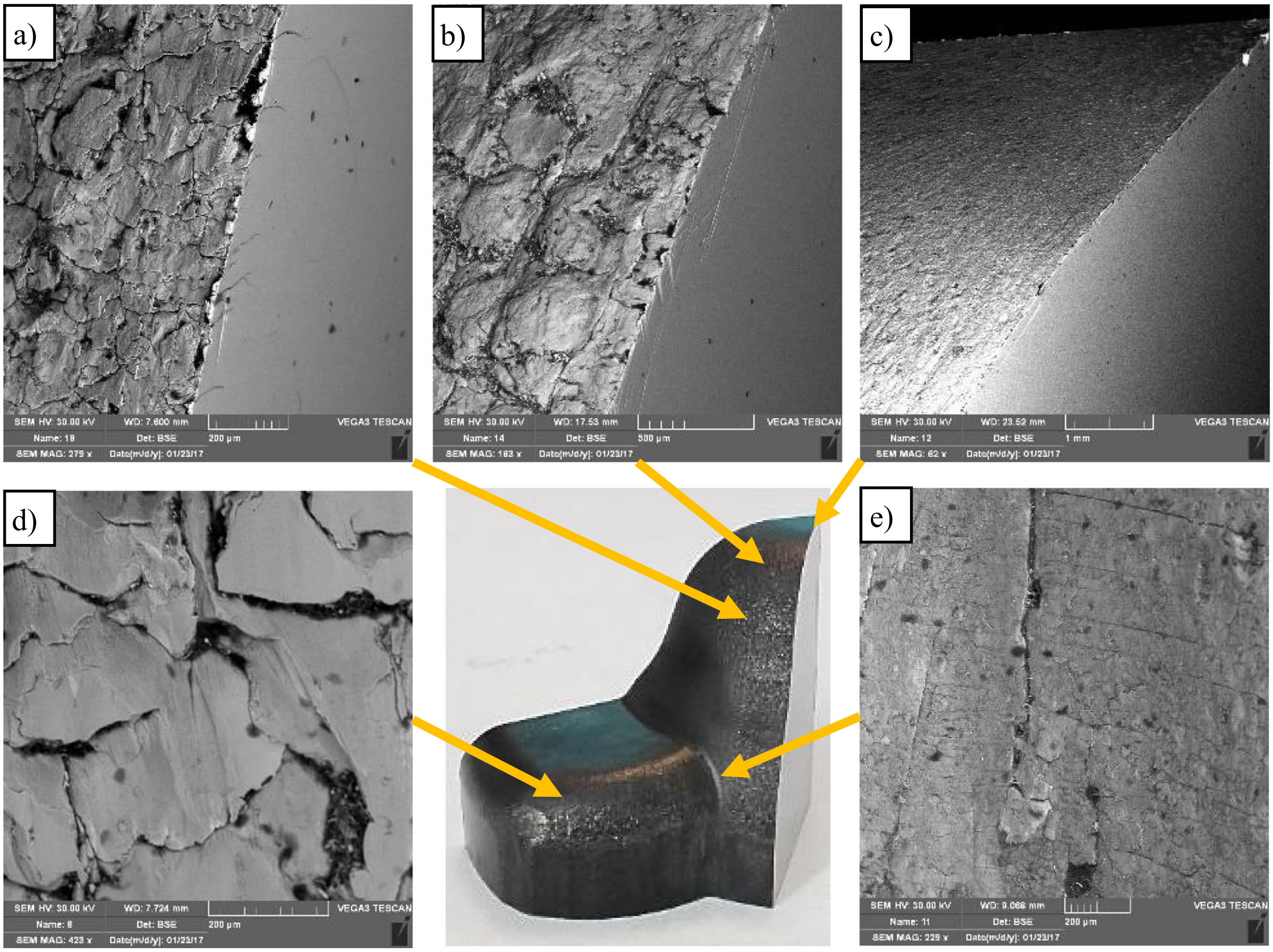


Fig. 13 SEM images of the surface of the analyzed tool made of Unimax steel after 4372 forgings with images of selected areas of the punch marked with *yellow arrows*

caused by the lower than usual (920 °C) temperature of the preform, which limits its plasticity and hinders the shaping, thus forcing the tool to work under a higher dynamic load. That is why it turns out disadvantageous to excessively increase the hardness in the surface layer, as it lowers its elasticity and fatigue strength.

5.3 Microscopic studies

The metallographic tests of the shaping punches concerned mainly their surface layer and the surface area in respect of the existing cracks and local damage, which could be a direct cause of their removal from production. The tests were performed on the light microscope Olympus GX51 with the magnification of up to ×1000. Figure 11 shows selected results of the microstructural analysis of the reference tool made of Unimax steel, without surface treatment and for the tool nitrided with a low potential. The performed microstructural analysis of the surface layer showed a relatively well-preserved surface of all the examined tools.

The reference tool made of Unimax steel (Fig. 11a) exhibited a uniform tempered martensitic structure with visible carbide precipitates on the grain boundaries of the former austenite, and the tool nitrided with a low potential (Fig. 11b) had a very thin layer of nitrides with the visible thickness reaching 50 μm. In each sample, the presence of fatigue cracks was observed in the form of a regular network, which were propagated almost perpendicularly towards the inside of the tool. The manner of the formation and propagation of cracks in the non-hardened or slightly nitrided surface tool layer was examined (Fig. 11). On the surface, typical fatigue cracks nucleate, which initially propagate at a small depth. One can suppose that the cause of their nucleation are the micro-laps formed on the uneven damaged surface of the tools. At the same time, the path of their development is influenced by plastic deformations present in the surface layer as well as the stresses occurring

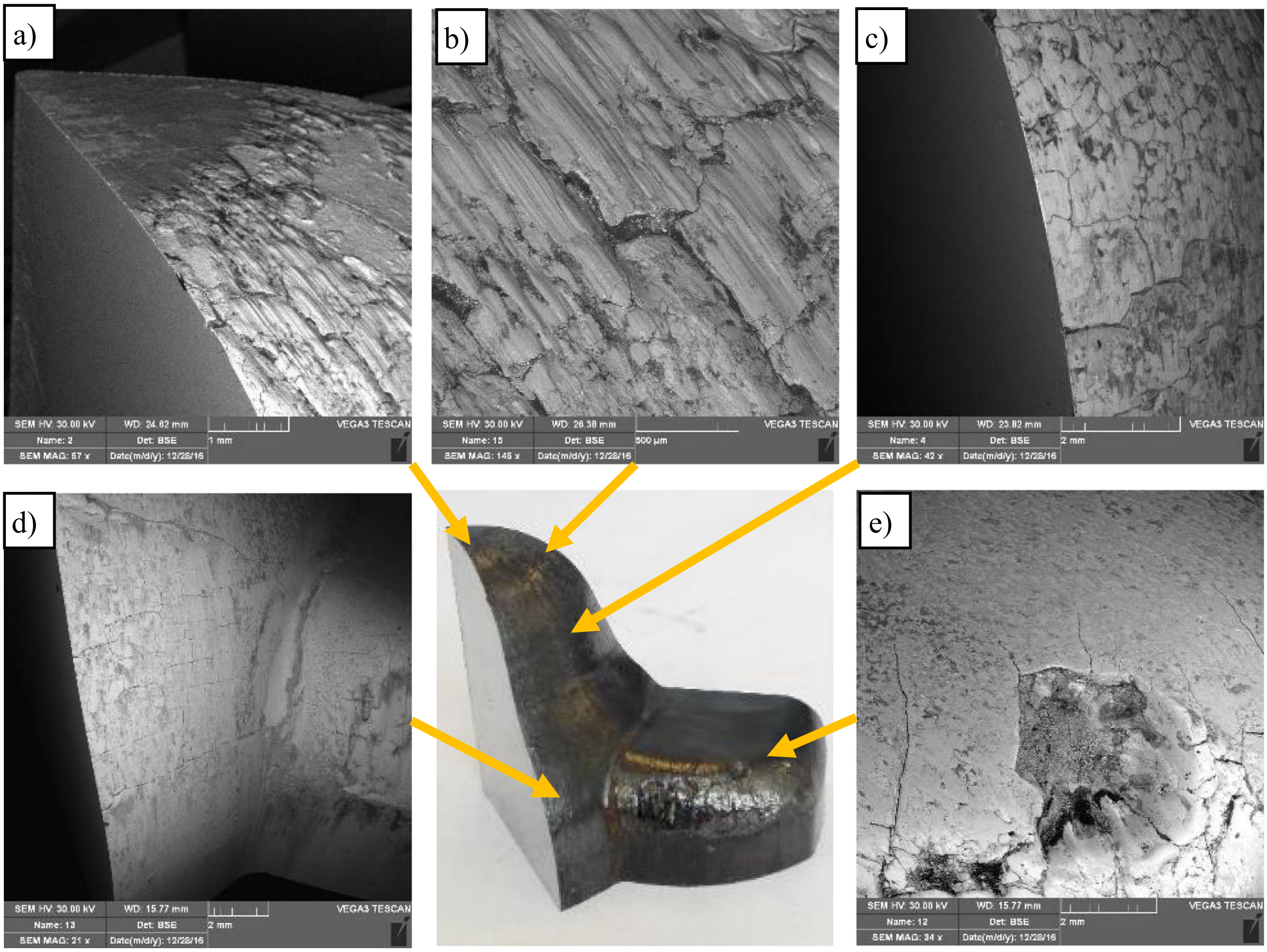


Fig. 14 SEM images of the surface of the analyzed tool nitrided with a low potential after 6249 forgings with images of selected areas of the punch marked with *yellow arrows*

in the areas of construction notches and the changes in the cross-section causing the propagation of cracks at a significant depth. These tools wear also tribologically, while the tool with a layer nitrided with a low potential exhibits an additional resistance to abrasive wear and plastic deformation, owing to which it obtained the highest hardness.

The analysis also included the tool nitrided with a high potential, in which a uniform diffusive layer was observed at the depth of about 150 μm. The tools with hybrid layers exhibited a similar layer of nitrides with the thickness of about 110 μm, additionally covered with AlCrTiN or CrN coatings with the thickness of 3 or 8 μm, respectively. Selected analysis results are presented in Fig. 12.

In the case of the tool nitrided with a high potential, the cracks reach the depth of the nitride layer (layer of elevated hardness) and propagate mainly on the grain boundaries. In the following stage, on the grain boundaries, cracks parallel to the surface propagate as a result of the occurring shear stresses (Fig. 12a, Fig. 8c). Then, one can observe a detachment of a whole fragment with the thickness up to about 100 μm as a single mesh of the fatigue crack network. These damaged areas present locally mainly at the base of the punch and at the side surface were the cause of its removal from further operation.

The cracking of the tool with the PN + AlCrTiN layer (Fig. 12b) took place in two stages, i.e., the cracking of the PVD coating and the propagation of cracks towards the inside of the tool. Also in this case, local spalling could be observed, smaller in their surface area but much deeper, reaching as much as 500 μm (Fig. 12b), which constitutes an unacceptable damage of the tool during a precision forging operation. A similar crack mechanism was observed on the tool with the PN + CrN layer, while the CrN coating cracked more easily, forming numerous minor cracks, which do not cause its removal from the tool surface but shift the changeable shear stresses and limit the propagation of cracks towards the inside of the tool. Unfortunately, despite the small depth of the cracks (up to 100 μm), we can observe propagation of cracks within the horizontal level (Fig. 12c) and spalling of its whole fragments.

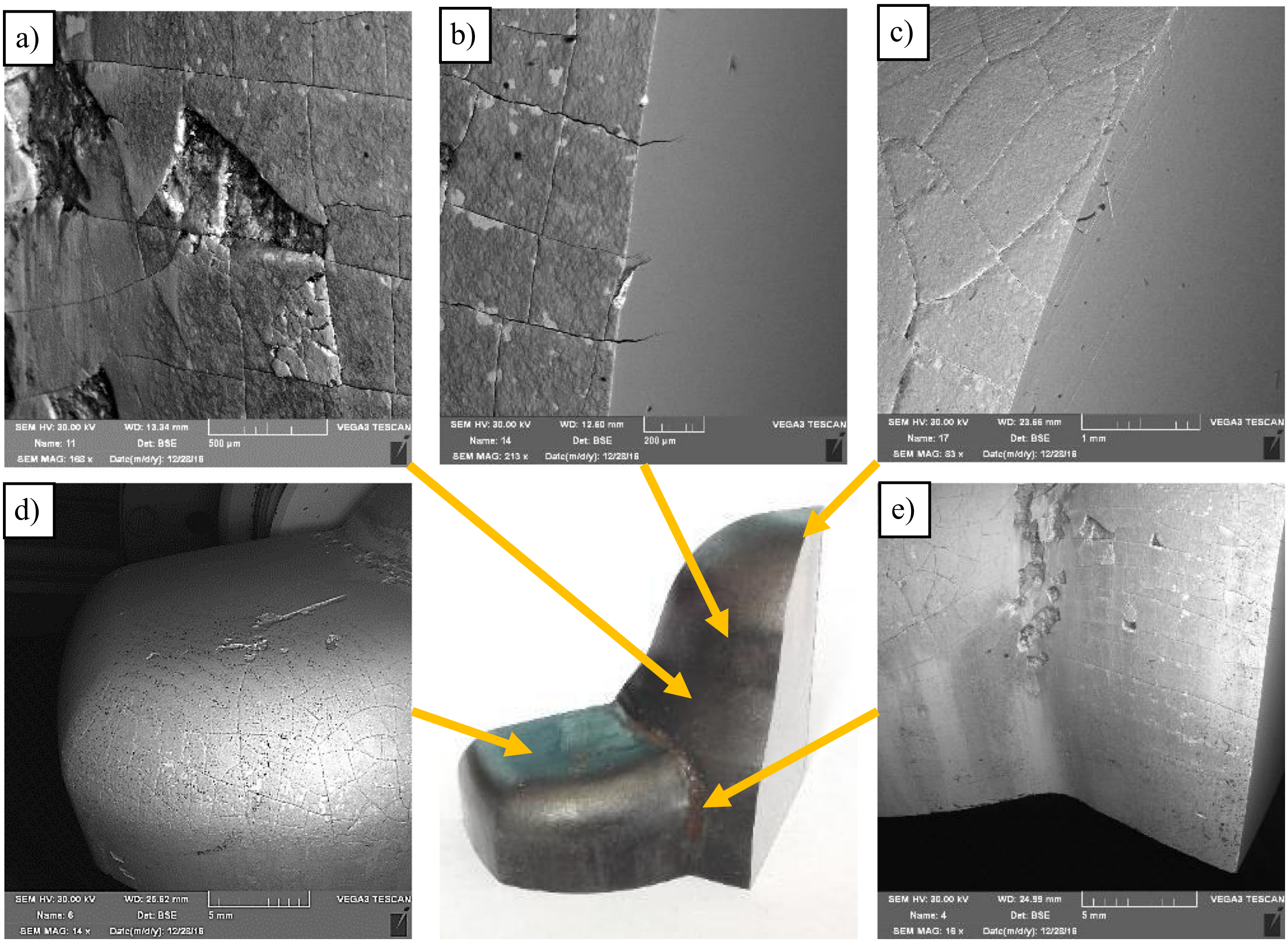


Fig. 15 SEM images of the surface of the analyzed tool nitrided with a high potential after 1412 forgings with images from selected areas of the punch marked with *yellow arrows*

The performed microstructural analysis of the five selected tools showed that the lack of thermo-chemical surface treatment leads to micro-laps and surface damage but limits cracking, whereas excessive hardening of the surface layer causes a disadvantageous development of cracks and the formation of premature damage on their surface. The optimal treatment variant turned out to be nitriding with a low potential, which only slightly hardness the surface layer, thus prolonging the durability of the examined tools.

5.4 SEM analysis

On the surface of the analyzed tools, a network of thermo-mechanical cracks occurred. The microscopic SEM analysis was performed on the surfaces showed in Fig. 7. These images, taken by means of the TESCAN VEGA 3 SEM microscope, are showed in Figs. 13, 14, 15, 16, 17. On the surface of the punch made of UNIMAX steel, without additional methods of surface layer modification, after 4372 forgings have been produced, a thermo-mechanical crack network is formed (Fig. 13). Additionally, within the radius in the punch front area, the surface layer deforms plastically, which is proved by the curved cracks visible in the cross-section (Fig. 13a, b). As the numerical analysis showed, the pressures in the area reach the value of 2500 MPa at the temperature reaching 650 °C, which exceeds the value of yield point of UNIMAX steel at such temperature. The plastic deformations are present also within a smaller radius (Fig. 13d); the deformed crack network visible in this area resembles "scales." Also, in the corner of the punch (Fig. 13e), one can see a longitudinal crack, formed as a result of a stress concentration in this area.

At the front of the punch which produced 6249 forgings, one can see traces of sticking of the material (Fig. 14a), which was also demonstrated by the measurements with the use of a scanner (Fig. 6c). Also, on the surface of this punch, one can see a fine irregular crack network (Fig. 14b–d). The use of nitriding with a low potential made it possible to obtain a diffusive zone with carbonitride precipitates, which effectively increased the resistance of the surface layer to abrasion wear and plastic deformation.

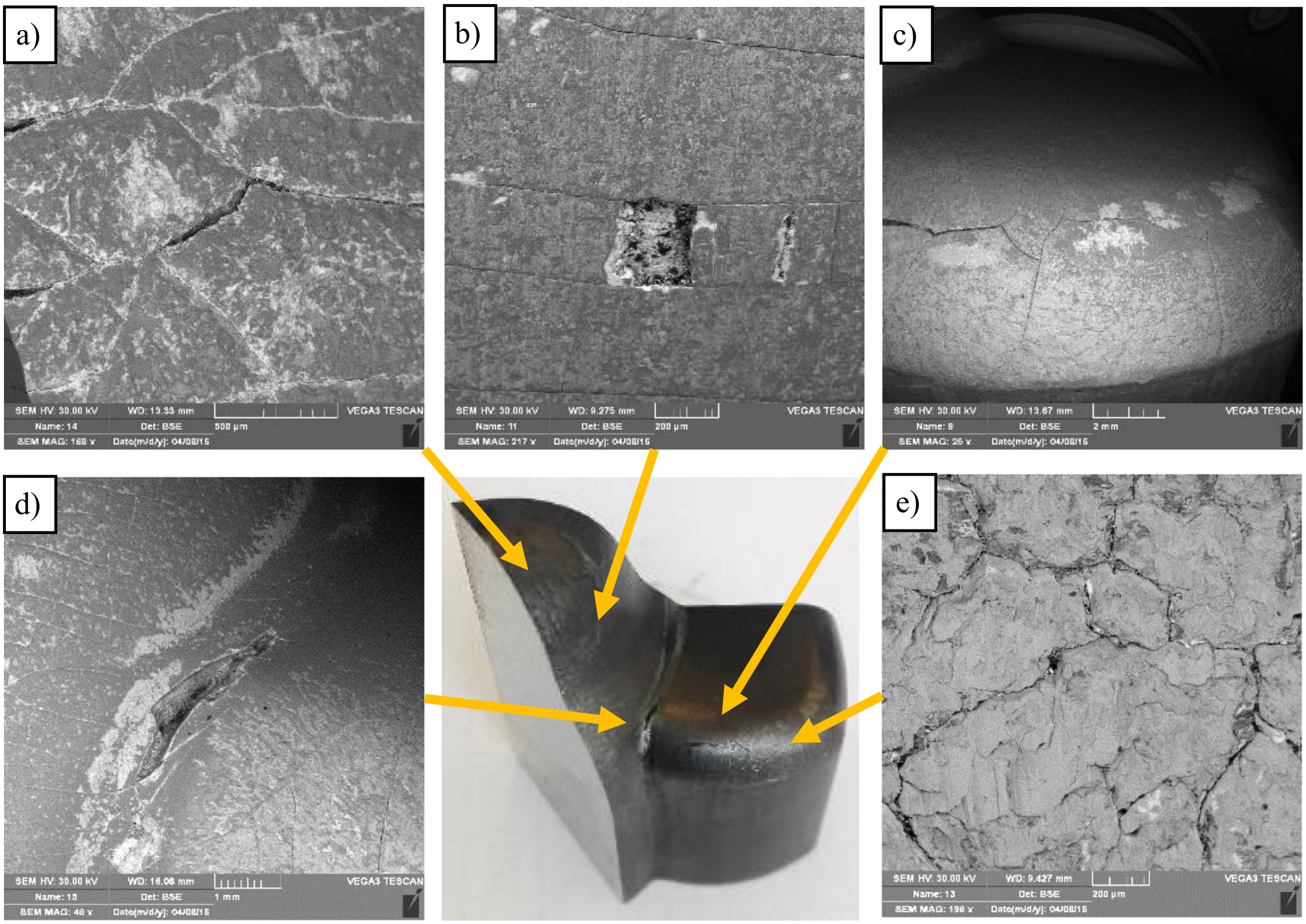


Fig. 16 SEM images of the surface of the analyzed tool with a PN + AlCrTiN hybrid layer after 1850 forgings with images of selected areas of the punch marked with *yellow arrows*

Another analyzed punch (Fig. 15) also underwent the nitriding procedure. On the whole punch surface, one can see an intensive regular crack network. In some areas, fragments of the network undergo spalling (Fig. 15a–e), while other fragments, directly adjoining the spalled ones, remain intact. In the corners of the punch (Fig. 15e), this phenomenon can be explained by the elastic deformations as a result of high mechanical loads, in effect of which spalling of fragments of the hard layer occurs.

In turn, on the remaining surfaces, the spallings are caused by high shear stresses as a result of friction of the shaped material onto these surfaces (Fig. 8c). This phenomenon did not take place in the previously analyzed punch (after nitriding with a low potential), as the obtained nitrided layers differed in their construction, which, as it turns out, significantly affected the manner of wear of this punch. Also, as in the previous case, the applied nitrided layer effectively increased the resistance of the punch's surface layer to plastic deformation. The appearance of the punch surface with the applied PN + AlCrTiN hybrid layer after producing 1850 forgings (Fig. 16) is very similar to the appearance of the punch after nitriding shown in Fig. 15. The differences in the manner of cracking are small and mainly concern the shape of the crack network, which is irregular, as well as the depth of the cracks, which locally expand, forming very deep grooves (Fig. 16a, d). Due to these cracks and the local spallings (Fig. 16b), the tool was also prematurely removed.

In the case of the punch with the PN + CrN hybrid layer, after producing 2000 forgings, on the surface, one can see an intensive network of thermo-mechanical cracks (Fig. 17), while the cracks on the sample cross-section (Fig. 17a) did not exhibit the presence of plastic deformations of the surface layer.

Regardless of the above, similarly to the previous cases, one can see numerous spallings of the crack network. The form of these spallings as well as the deformations of whole meshes of the crack network (Fig. 17c, d) clearly point to the operation of excessive shear stresses. Due to this fact, despite the low value of the general wear observed in the scan images (Fig. 6e), such a form of wear is very disadvantageous, as even the smallest damage on the tool surface significantly lowers the quality of the produced forgings, which is unacceptable in the case of precision forging.

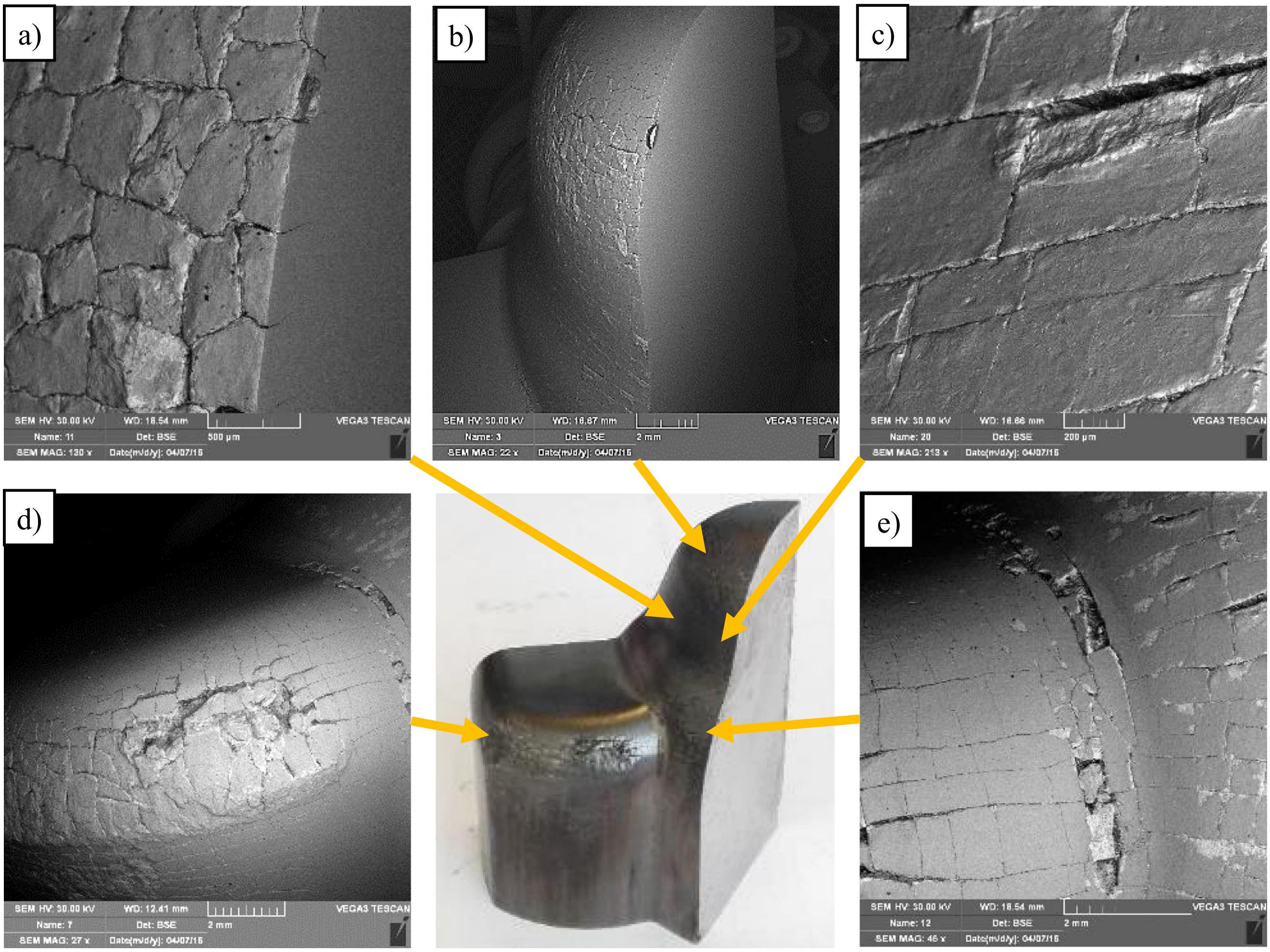


Fig. 17 SEM images of the surface of the analyzed tool with a PN + CrN hybrid layer after 2000 forgings with images of selected areas of the punch marked with *yellow arrows*

6 Conclusions

The performed complex analysis of the durability of the selected punches made of UNIMAX tool steel (after 5 different variants of thermo-chemical treatment, used for the production of a CVJB) forging), made it possible to identify a range of mechanisms degrading the forging tools and determine the faults present on their surface. For the all analyzed tools, the most intensive damage takes place in the area of the longest contact (within the radii of the roundings of the punch's working surface) with the deformed material. The most hazardous phenomena, especially for punches of elevated hardness of the surface layer, are mechanical cracking and thermo-mechanical fatigue. The microhardness measurements in various areas of all the tools revealed lowered hardness in the areas where the material flow was slower and so the contact time was longer, which caused tempering of the punch material. The temperature distributions on the contact surface between the tool and the forging, determined form FEM, reach locally even above 700 °C. The results obtained from electron microscope confirmed the previously observed numerous cracks of the surface layer. Also, a microcrack network was revealed, which pointed to the main degradation mechanism of the punch, that is thermo-mechanical fatigue, which is caused, beside the high temperature gradients, also by the high normal pressures reaching over 2500 MPa (Fig. 8). The detailed comparative tests showed that the best results for the whole working surface of the tool were obtained for the punch nitrided with a low potential, while the worst results were obtained for the tool nitrided with a high potential.

Additionally, the research conducted by the authors concerning the use of surface engineering techniques to increase tool life in other die forging processes has shown that for each forging process and even every operation of it, should be chosen of surface engineering technics individually. This is due to the specificity of particular process, mainly tribological conditions, such as temperature, load, type of lubricant, and the shape of the tool and preform [26, 43, 48, 49]. There are many other ways and methods to improve the durability of forging tools. For example, use of a different tool material or a change in the design or shape of the tool, as well the use of pad welding techniques and subzero treatment, etc. Most of these methods, with which the authors have their own experience, were presented in the work [8].

With regard to the research directly on the protective coatings used on the forging tools conducted by the other scientists which tested of hybrid layers and coatings containing Al, Ti, and Cr [34, 40, 50], they are similar especially in their resistance to thermo-mechanical fatigue [51]. Are carried out also studies with using of alternative multi-layered coatings PACVD, on the basis of B and Ti, as well only nitrided tool surface [36, 40, 52–55] for which operational results are similar to obtained in this work.

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