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Surface Parameters, Tribological Tests and Cutting Performance of Coated HSS Taps

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Abstract

The paper deals with a study of 2D surface parameters, Coulomb´s coefficient of friction and cutting/forming performance of selected PVD coated HSS taps when machining of carbon steel C45 and forming of hardened steel 42CrMo4V. The main attention is focused on the analysis of physical parameters of loading (torque moment, total energy and specific energy) of the taps measured with the pieso-electrical dynamometer Kistler 9272. The relation between the quality PVD coatings and their effects on the quality of machined thread surfaces and tool life of the taps and the tribological and surface parameters has been found. The results showed a safe and stabilized cutting and forming with excellent quality of threads for HSSE with the TiN/DLC coating.

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Keywords: cutting tap; performance; torque moment; quality; roughness

1. Introduction

Internal threads are frequently used in a multitude of technical applications. There standard technology for production is cutting, but cold forming seems also to be a challenging technology due to chipless production, better tensile strength of the threads and superior corrosion and fatigue resistance of the contact surfaces [1-5].

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Nomenclature

a_p	mm	axial width of cut
E	J/mm^3	specific energy of cuttíng
n	1/min	number of rotations
v_c	m/min	cutting speed
f	mm	feed per rotation
A	J	deformation work
D_m	mm	middle diameter of thread
F_T	N	tangential force
F_N	N	normal force
M_c	Nm	cutting moment
M_t	Nm	torque moment
M_F	Nm	forming moment
T	s	time
Kr	°	principal cutting edge angle
μ	-	coefficient of friction

The fundamental material for the tools is high speed steel due to better machinability of complex shapes which must guarantee precise thread design and resist to the change in forward and reverse when cutting. The low heat resistance and relatively low hardness of the material compared to the cemented carbides can be enhanced with PVD coatings otherwise a short tool life can be expected [6-8]. As the special problems at tapping can be seen:

- a mismatch of machine feed and tap pitch,
- an inappropriate hole diameter that can cause the tap to break in tension or compression,
- a misalignment of tap and holes axes,
- a clogging with chips due to poor cutting performance or poor chip evacuation,
- a poor cooling or lubricating, low flow intensity and wrong orientation of the stream.

The problems can be solved effectively by:

- tapping attachments for pitch and feed compensations (tensile/thrust or universal),
- safe tap holding during threading, the run-in and run-out passes,
- new cooling fluids with high-pressure additives or lubricant applied with inner cooling through canals,
- wear-resistant hard protective coating [9].

The hard coatings for cutting tools are solely done with PVD processes that prevent the precise shapes of taps. The choice of the substrate or protective coating in the specific machining operation can have serious impact on machining productivity and economy. The coating protects the tool against abrasion, adhesion, diffusion, formation of comb cracks [11-13]. The widely used PVD hard coatings are TiN, Ti(C,N), (Ti,Al)N, (Al,Ti)N, (Ti,Al,Si)N, (Al,Cr)N and CrN on HSS tools. The reasons for the outstanding features of the (Ti, Al) - based coatings can be seen in [14]:

- very high hardness (25-38 GPa), with relatively low residual compression stresses 3-5 GPa),
- high hot hardness, resulting in low hardness loss up to temperatures of 800°C,
- high oxidation resistance (the same rate for Ti(C,N) at 800°C as for TiN at 400°C),
- low heat conductivity (the coatings are ceramics without any metallic bonds).

However, the reverse loading of a tap due to change of rotation in the stroke can course a sticking of the edge by the material and passive loading what can cause a breakage of the cutting edges. To resist such severe conditions the duplex or triplex coatings have been developed to improve the tribology of the contact surfaces. Especially, a very beneficial influence of DLC (diamond-like-coating, it means e.g. TiC-C, with sp^3 bonds) coatings is worthy for verifying because of the wide variety of stoichiometry and properties that can be achieved.

2. Theory of threading with taps

The time series of the torque moment for cutting or forming production of a thread are similar. The main loading of a tap is made by the cross section of material to be removed and specific cutting/forming force [6,7] – Fig. 1. However, the chip cross-section depends on the depth of the tap penetration into the material – Fig. 2.

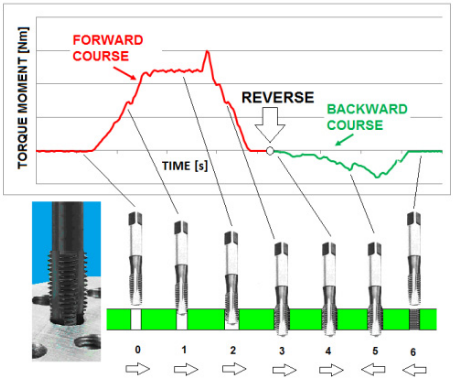


Fig. 1. The time series of the torque moment when tapping thread.

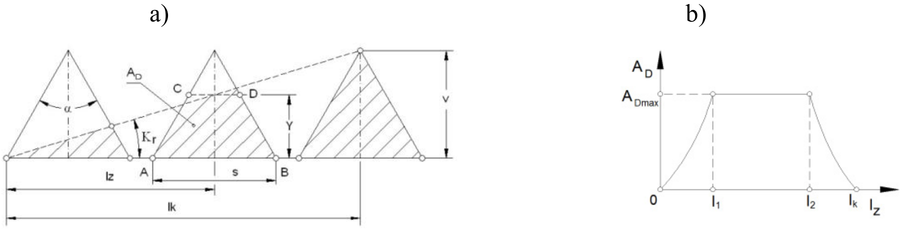


Fig. 2. a) chip cross section analysis, b) cross-section of the thread as a function of tool path.

For the individual time intervals a-b-c of non-deformed chip cross-section (depth of tap plunging) in the material of the L in total thickness the chip cross-section can be expressed according to the Fig. 2 as:

a) $l \in (0, lk)$

$$A_{D1} = A_{Dmax} \, . \, (2 \, . \, lz \, . \, tg\, K_r / v \; - \; lz^2 \, . \, tg^2 K_r / v^2) \tag{1}$$

b) $l \in (lk, L)$;

$$A_{D2} = A_{Dmax} = s.v / 2 \tag{2}$$

c) $l \in (L, L+lk)$

$$A_{D3} = A_{Dmax} \, . \, (1 - (2 \, . \, lz \, . \, tg\, K_r / v \; - \; lz^2 \, . \, tg^2 K_r / v^2)) \tag{3}$$

The most important period of cutting for the statistical evaluation is the period b, when the tap is totally cut-in and cutting tool is loaded in maximum. For a sharp tap that value is nearly stabilized, close to normal distribution and can be assessed by mean and standard deviation. For a worn tap the value is growing rapidly due to passive and active force loading. Cutting force Fc [N], cutting moment Mc [Nm] a cutting power Pc [kW] are defined by standards [15], where D_m is the middle diameter of a thread in [mm], number of rotations n [min^{-1}]) and k_c is the specific cutting force [MPa]:

$$F_c = k_c \,.\, A_D. \tag{4}$$

$$M_c = F_c \,.\, D_m, / 2000\,, \tag{5}$$

$$P_c = M_c \,.n / 9.55\,. \tag{6}$$

The calculations are more complicated when passive forces and wear are included in the calculations.

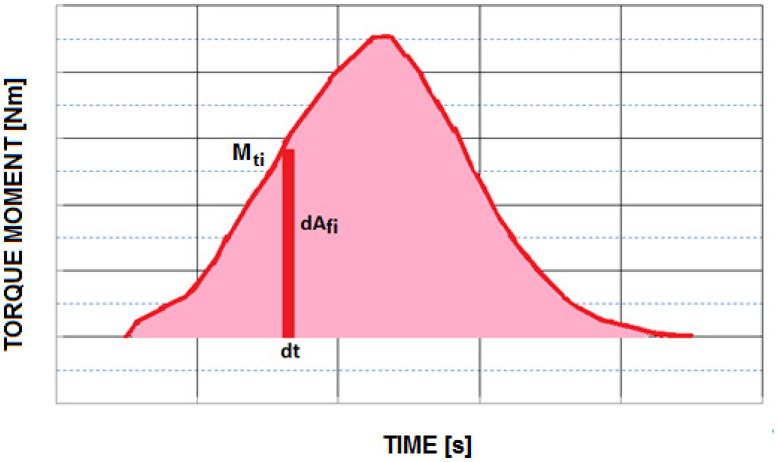


Fig. 3. Analysis of the elementary cutting/forming work.

The elementary cutting or forming work – Fig. 3 – can be expressed as

$$A_f = \int_0^T dA_{fi} \cong \sum_{i=0}^{T} \Delta A_{fi} = \sum_{i=0}^{T} P_{fi} \,.\, t_i / 9.55 = \sum_{i=0}^{T} M_{fi} .n \,\Delta t_i / 9.55, \tag{7}$$

and the specific deformation energy as the ratio of deformation work and the volume of the material

$$e_c = A_f / V_m\,. \tag{8}$$

The tribological tests have been done on a special tribological stand (Fig. 4) and coefficient of friction was evaluated according to the Newtonian equation as the ratio of tangential and normal load:

$$\mu = F_T / F_N\,. \tag{9}$$

According to the previous tests the normal force and speed in the following test were very nigh to the real values of cutting/forming loading.

3. Experimental works and results

The material compositions and mechanical properties of the workpieces are listed in Table 1 and Table 2. The blank sheets 200x25-6000 mm (with dimensional and shape deviation tolerances according to EN 9445) were cut into 200 mm in length. The workpieces were mounted to the special wise which was fixed with screws on the top of the dynamometer. The dynamometer set was placed into the new CNC machining centre MCV 1210 (ZPS TAJMAC, Zlin) controlled with the Sinumerik 840D. Kistler dynamometer 9272, charge amplifiers 9011 and the Dynoware program for force and torque analyses of the sample loading were used. The sampling rate 3kHz, low-pass filter and the long-time constant were set for all data acquisition. A special CNC programme was written for automatic control of the taping operations with a use of the canned cycles. The following technological sequence of tools and conditions for production in whole sheet thickness was set:

a) for cutting taps

- solid carbide drills ø8,520mm, thermogrip Bilz – HSK A63 ø10 (vc=90 m/min, f=0.12 mm) – drilling the pilot holes,
- countersink 90°/ø30 mm, DIN 335, Guhring, Art. Nr. 327 tool holder - thermogrip Bilz – HSK A63 ø20, (vc=60 m/min, f=0.12 mm)
- the cutting taps M10-6HX Enorm1-Z, HSS-E, Emuge-Franken, un-coated and PVD coated with monolayer of TiN and multilayers of TiN+DLC coating, each sort in 6 samples (but three selected tested), the same thickness of coatings – bellow 2.0 μm in total). Cutting speed: 20m/min, feed per rotation: 1.5mm.

b) for forming taps

- solid carbide drills ø9.360 mm, thermogrip Bilz – HSK A63 (vc=70 m/min, f=0.10 mm)
- HSS-E cold forming taps M10-6HX InnoForm1, Emuge-Franken, un-coated and PVD coated with monolayer of TiN (thickness 2.0 μm) and TiN+DLC coating, each sort in 3 samples (the thickness of the top DLC coatings – 1,0 μm). Circumferential speed: 10m/min, feed per rotation: 1.5mm.

The cutting and forming taps (Fig. 5) - were gripped in the compensation adapteur Emuge Franken KSN Synchro IKZ for the push-pull loading. The Cimperial CIMSTAR 597 (volume concentration 10%, 60 bars in pressure, flood intensity 50 l/min) and outer system of cooling with an emulsion reservoir of 1,200 litres for the machining were used in all machining operations. The temperature of the cooling fluid was measured and observed in the range of 20-22°C during all machining.

The thread gauge M10-6H DIN ISO 13 Schmalkalden/UNIMETRA Ltd. was used for the first dimensional evaluations and Alicona IF-G4 for surface topography assessments. The hard coatings were applied with the PVD LARC® (LAteral Rotating ARC-Cathodes) and SCiL® technologies of the company Platit (Switzerland) - π411. The cathodes were built in very close to each other here and a highly ionized plasma, strong magnetic field and fast motion of the ARC-track were set.

Tribological test proved a very good consistency of the results (Fig. 4) with a prolonged period of the run-in period and lower friction for duplex coatings, but mainly for surfaces in the permanent contact. The abrasive character of surfaces prevails and the low-friction DLC is suppressed (Fig. 6). Anyway, a slight tendency to suppress sticking of the tool when the reverse of the tool occurs was observed what was beneficially for the tool life.

Cross-sections of the produced threads (Fig. 7) have been analysed in the ground and polished state with acid etching. The geometry of the cut profile is more filled-in compared to the formed profile that is also affected with the forming operation and typically split crest was produced.

An overview of the torque measurements according to exploiting time confirmed a parabolic time course of the torque moment for all forming taps (Fig. 8), and mostly linear for the cut threads (Fig. 9). Morphology of the worn edges confirmed the abrasive mechanism of the wear for both technologies (Fig. 10). As the criterion of wear the total torque moment for forming (30 Nm), and cutting (10 Nm) were calculated - Fig. 11. The specific variables after numerical integrations and statistical evaluations for new and worn tools are listed in Tables 3,4.

All produced threads were made in the ISO tolerance range. Furthermore, the surfaces of selected samples were analyzed by means of Alicona GF4 in the cross-sections – Fig. 7 and Fig. 12. A very good surface quality – see Table 5 – for production with all coated tools was found, especially for the first cuts. However, the best surface quality for the TiN+DLC coating have been measured.

Table 1. Composition and properties of the tested material – steel C45 DIN 17200-84 (1.1191).

Chemical composition (weight %)							
C	Mn	Si	Cr	Cu	P	S	Fe
0.50	0.69	0.25	0.15	0.12	0.023	0.017	rest
Mechanical properties							
Yield point $R_{p0.2}$ [MPa]			Tensile strength R_m [MPa]			Young modulus [GPa]	
342			580			211	

Table 2. Composition and properties of the tested material – steel 42CrMo4V CSN EN 10083-1: 1991+A1: 1996; DIN 17200 – hardened state.

Chemical composition (weight %)							
C	Cr	Mo	V	Si	P	S	Fe
0.38	0.15	0.15	0.15	0.22	0.013	0.017	rest
Mechanical properties							
Yield point R_e [MPa]			Tensile strength R_m [MPa]			Young modulus [GPa]	
920			1120			224	

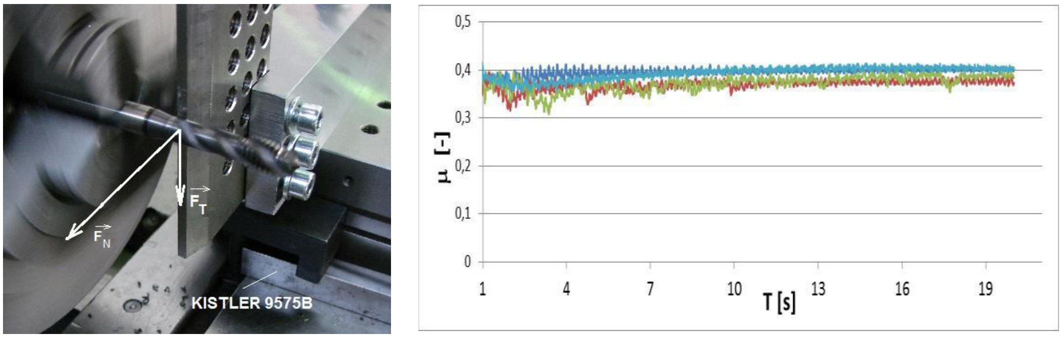
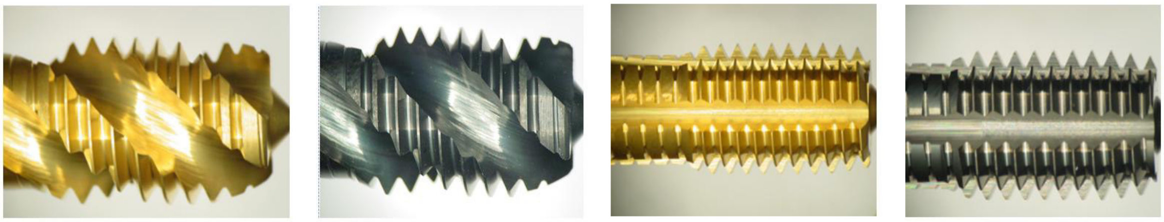
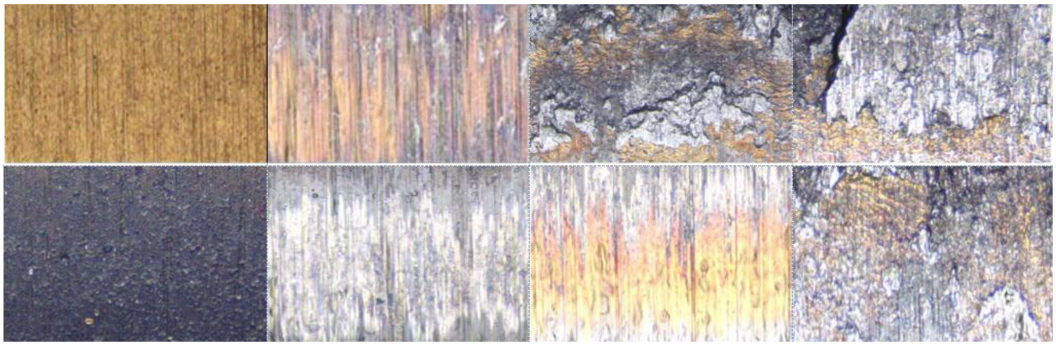


Fig. 4. The principle of the tribological test, a typical time series of the friction coefficient.



a) b) c) d)

Fig. 5. An overview of the coated tested tools - cutting taps (a,b), forming taps (c,d); coatings – TiN (a,c), TiN+DLC (b,d).



a) new surface b) wear in run-in period c) intensive abrasion d) end of the test

Fig. 6. Surface texture of the tool shank in the tribological test as a function of time and coating.
Upper series – TiN, bottom series – TiN+DLC (magnification 10x).

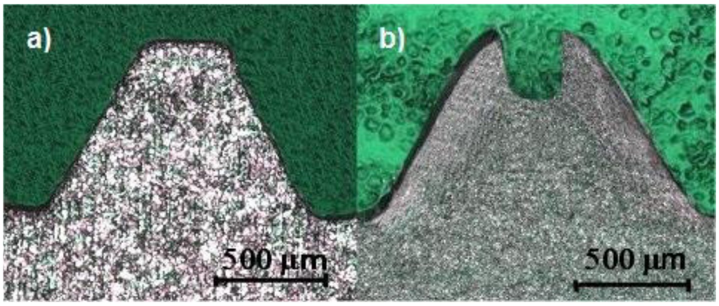


Fig. 7. Cross-sections of the produced threads (Nital 2%).
Left – cut thread in C45 steel, right – formed thread in 42CrMo4V steel (split crest).

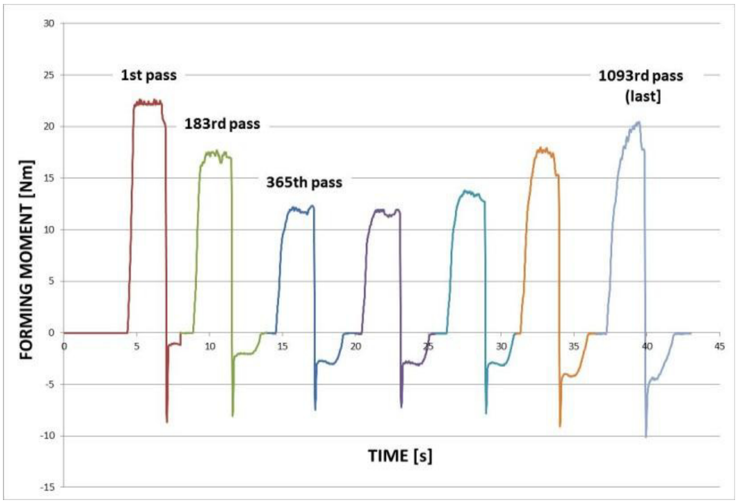


Fig. 8. Example of the time series of forming moments for threading with HSS+TiN+DLC coating.

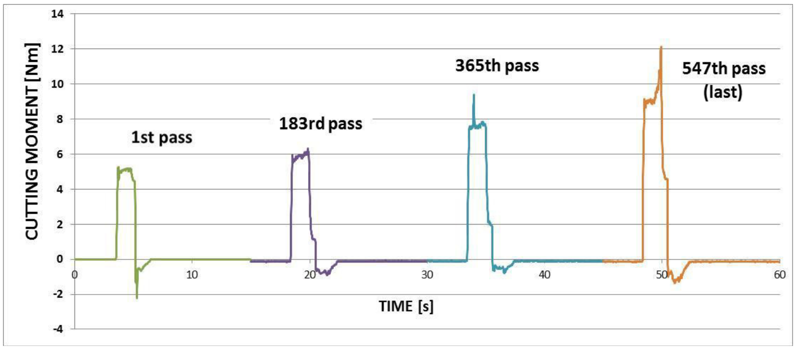
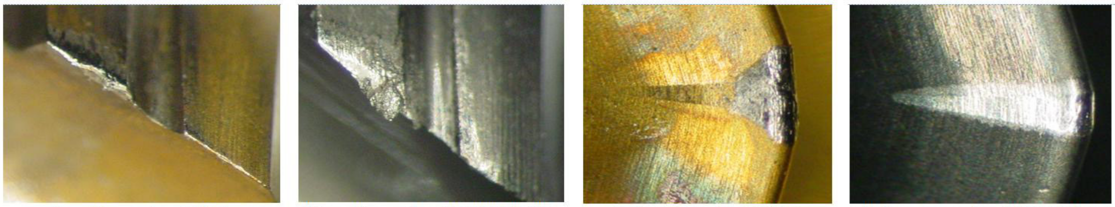


Fig. 9. Example of the time series of cutting moments for threading with HSS+TiN+DLC coating.



a) cutting edge (TiN) b) cutting edge (TiN+DLC) c) forming edge (TiN) d) forming edge (TiN+DLC)

Fig. 10. A typical wear morphology of the tested tools.

Table 3. Specific forming energy for the threading and coatings, a statistical evaluation.

THE SORT OF COATING	Specific forming energy [J/mm^3] first cut	Specific forming energy [J/mm^3] last cut
HSSE	32.622±3.82	-
HSSE+TiN	22.242±0.562	24.924±0.562
HSSE+TiN+ DLC	20.684±0.414	21.266±0.420

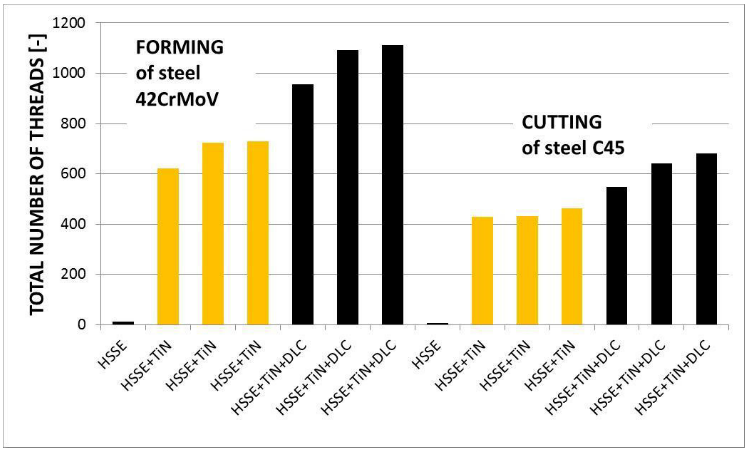
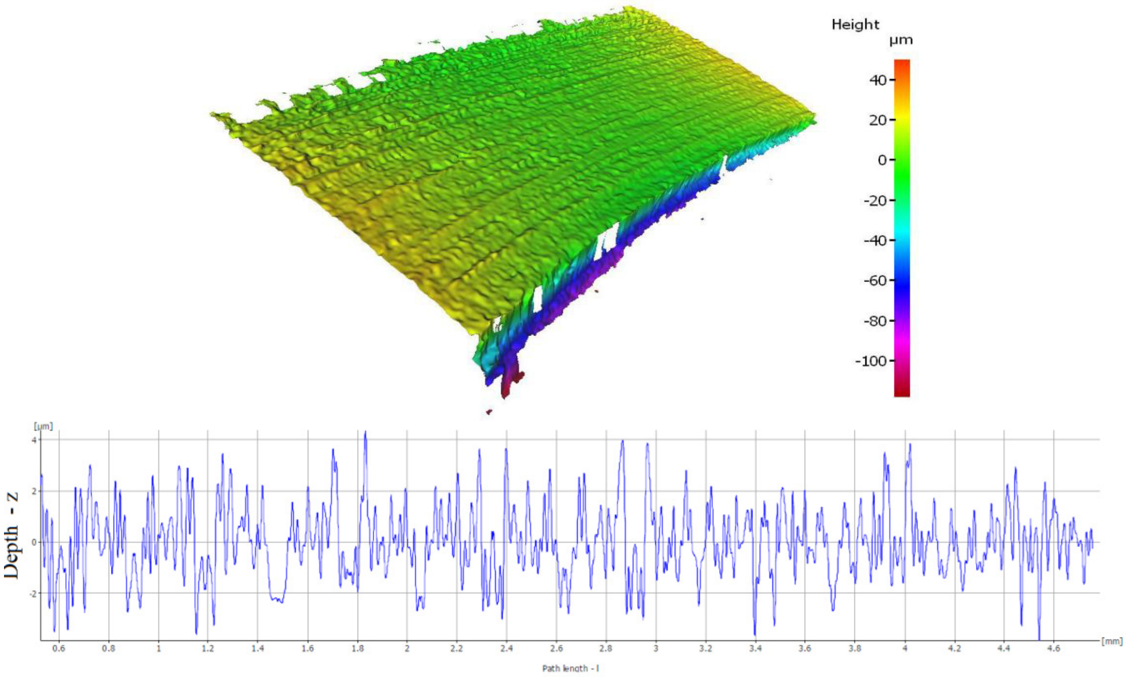


Fig. 11. Tool life of the cold forming and cutting taps expressed in number of threads.

Table 4. Specific cutting energy for the threading and coatings, a statistical evaluation.

THE SORT OF COATING	Specific threading energy [J/mm^3] first cut	Specific threading energy [J/mm^3] last cut
HSSE	6.842±0.862	-
HSSE+TiN	5.824±0.148	5.914±0.136
HSSE+TiN+ DLC	5.186±0.124	5.244±0.104



Ra: 1.0617 µm Rq: 1.3656 µm Rz: 7.0862 µm

Fig. 12. An example of machined surface quality evaluation – thread made with the HSSE+TiN+DLC cutting tap.

Table 5. The arithmetic average of the roughness profiles of the threads, statistical evaluation.

	FORMING		CUTTING	
THE SORT OF COATING	Roughness Ra[µm] first cut	Roughness Ra[µm] last cut	Roughness Ra[µm] first cut	Roughness Ra[µm] last cut
HSSE (uncoated)	1.242±0.226	-	1.424±0.220	-
HSSE+TiN	0.886±0.248	1.116±0.211	1.212±0.368	2.466±0.562
HSSE+TiN+ DLC	0.668±0.142	0.916±0.236	0.912±0.240	2.262±0.422

Conclusions

The combination of PVD TiN+DLC surface coatings can be recommended for a very effective and safe tapping in the steels, even in the hardened state. A very good accuracy in the range of IT 9-10 for the threads made by both technologies, roughness Ra<1.6 µm, tool life for production of 1,000 threads (for forming operation) and 600 threads (when cutting) can be expected. Without the coating the technology does not works and a premature fracture of the taps and poor quality of the thread surfaces can be observed. The research will continue with triplex (Ti,Al)N coatings, use of inner cooling and application on nano-structured (Ti,Al,Si)N materials and 3D surface texture analyses. The next works also include the tensile strength, fatigue and corrosion resistance of the produced threads.

Acknowledgements

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