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A STUDY OF CUTTING AND FORMING THREADS WITH COATED HSS TAPS

Tapping is a very common machining process for producing internal threads. A tap is a cylindrical or tapered thread cutting tool having threads of a desired form on the periphery. Combining rotary motion with axial motion, a tap cuts or forms the internal thread. Due to desired accuracy and versatility of thread profiles most taps are made of high speed steel. Physical surface coating taps (monolayer, duplex or triplex) increases tap life and improves thread finish. Regarding the CNC canned cycles the demands on safe tool performance of the threads are more and more urgent. This paper deals with a study of 2D surface parameters, Coulomb´s coefficient of friction, energy consumption and cutting/forming performance of selected PVD coated HSS taps when machining of carbon steel C45 and forming of hardened steel 42CrMo4V.

1. INTRODUCTION

Threaded parts are frequently used for an assembly or a union of two or several mechanical units in engineering and number of their applications in many variants can be seen in daily life [1],[2],[3]. Among of dozens of threads designs the mostly used ISO metric screws and their basic principles are defined in the international standard ISO 68-1 and the preferred combinations of diameter and pitch are listed in ISO 261 [9]. The smaller subset of diameter and pitch combinations commonly used in screws, nuts and bolts is given in ISO 262. The most commonly used pitch value for each diameter is the coarse pitch. For some diameters, one or two additional fine pitch variants are also specified for special applications such as threads in thin-walled pipes or other applications for a higher tightening or a better resistance to loosening in a dynamic loading.

There are two basic technologies for a standard production of the threads – machining and forming. Machining (cut tapping) prevails in a higher accuracy and a better shape precision, but the form tapping is able of strain hardening of the thread surfaces and enhancement of the material resistance to tensile loading, corrosion and fatigue [10],[11],[12]. However, the typical split crest of thread can course some problems when an automated insertion of bolts into holes is used and misalignment of matching counterparts can initiate serious problems of the unions.

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Apart of surface coating at inner threading operations and standard applications these technologies are final and no other post-treatment or fabrication of the threads follows.

2. THEORY OF THREADING AND WEAR OF THE TAP TOOLS

2.1. THEORY OF CUT TAPPING

The most decisive and sensitive parameter for cut tapping or tap forming is the torque moment – Fig. 1 – that varies in the time. From physical point of view, the torque moment for thread cutting can be expressed in the form

$$M_c = M_{c1} + M_{c2} \tag{1}$$

where M_{c1} means the part of torque needed for the plastic deformation of the machined material and M_{c2} is the contribution due to passive loading and friction of tap on the machined surface. According to the number of cutting teeth the empirical expression can take a form

$$M_{ci} = C_{ci} \cdot k_{ci} \cdot r_i^a \cdot s^b \cdot l_{zi}^c \cdot z_i \cdot tg(\varepsilon/2)^d, \tag{2}$$

where the constant C_{ci} reflects the cutting conditions, k_c corresponds to the specific cutting force of the machined material, r_i is the radius of the acting cutting force, s_i is the thread width, lz_i presents the depth of the thread, z_i is the number of the engaged cutting edge, ε is the thread angle and the exponents *a-d* vary according to the effect of variables.

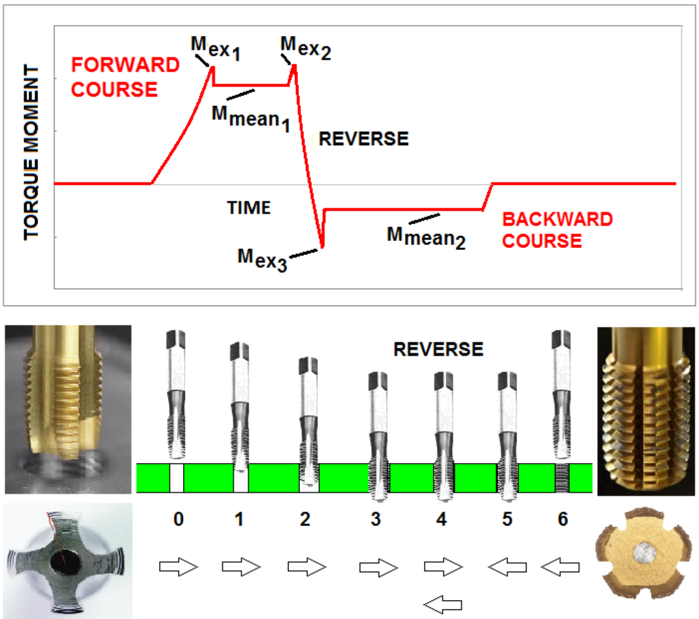

Fig. 1. A time series of the torque moment when cutting or forming a thread, marked mean torque moments and extremal values, peaks

However, the cutting moment is affected also with wear of the cutting tool, so in general

$$M_c = f(t). \tag{3}$$

Due to CNC grinding several designs of the cutting flutes can be made to split the thread profile into sections. For the individual time intervals of the non-deformed chip cross-section according to the depth of tap plunging, the chip cross-section per teeth can be expressed according to the Fig. 2 as:

$l_z \in (0, l_k)$

$$A_{D1} = A_{Dmax} \cdot (2 \cdot lz \cdot tg\ K_r / v\ -\ lz^2 \cdot tg^2\ K_r / v^2)\,, \tag{4}$$

$l_z \in (l_k, H)$

$$A_{D2} = A_{Dmax} = s \cdot v / 2 \tag{5}$$

where s is the width of the thread, α is the thread angle and K_r is the major tool cutting edge angle.

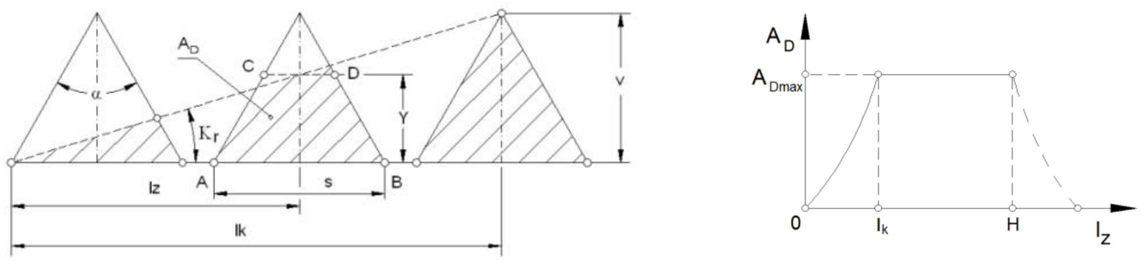

Fig. 2. Theoretical model of machined thread cross section – left, and its function of length of cutting part insertion – right (a standard grinding of a tap from the top)

2.2. THEORY OF FORM TAPPING

Analytical models of this forming process have been proposed in the works [4],[5],[6],[7]. In all the models the torque forming moment depends significantly on the material (that can be soft, ductile or even hardened today) and diameter of hole before tapping. Furthermore, the smaller is the diameter of the hole - the smaller will be the split crest at the top of the thread after the form tapping operation [9]. Similar equations like (1-3) can be derived, but as the work [10] confirms, they are still subject of the research. Nevertheless, in a simplified way the instantaneous torque forming moment can be defined as

$$M_{fi} = C_{fi} \cdot r_i \cdot k_{fi} \cdot A_{Di} \tag{6}$$

where the constant C_{fi} reflects the cutting conditions, r_i the radius of the acting forming force, k_{fi} corresponds to the specific forming force of the material and A_{Di} is the cross-section of the non-deformed material.

The most important period of cutting for the statistical evaluation is the period when the tap is totally cut-in and cutting tool is loaded in maximum. For sharp edges 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 power P_c [kW] is defined according to the standards [12] by equation (7) where M_c [Nm] is the cutting moment and n - number of tap rotations [min^{-1}]):

$$P_c = M_c \cdot n / 9.55 \tag{7}$$

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

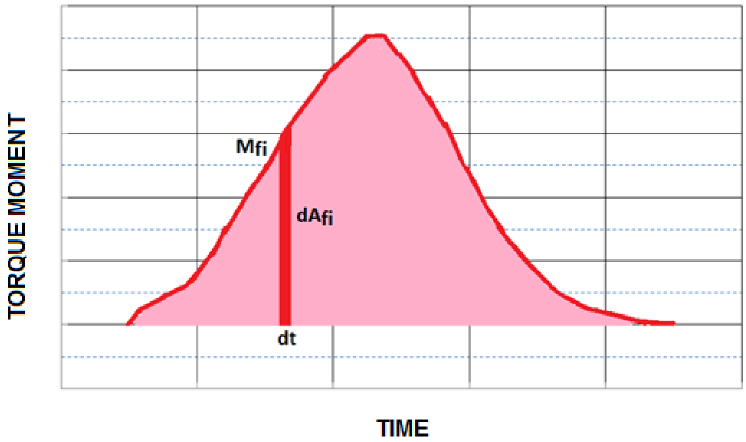

Fig. 3. Analysis of the elementary cutting/forming work (numerical integration using the Newton-Cotes trapezoidal rule)

The total cutting or forming work – Fig. 3 – can be expressed with a certain error as

$$A_f = \int_0^T dA_{fi} \cong \sum_{i=0}^{T} \Delta A_{fi} \cong \sum_{i=0}^{T} P_{fi} \cdot \Delta t_i / 9.55 \cong \sum_{i=0}^{T} ((1/2) \cdot (M_{fi} + M_{fi-1})) \cdot \Delta t_i \cdot n / 9.55 \tag{8}$$

and the specific deformation energy as the ratio of the total deformation work and the deformed volume of the material Vm:

$$e_c = A_f / Vm \tag{9}$$

The time incremental of wear of a single cutting edge can be described in the form

$$dM_{c1} = \frac{\partial M_{c1}}{\partial t} \cdot dt = \frac{\partial M_{c1}}{\partial \gamma_o} \cdot d\gamma_o + \frac{\partial M_{c1}}{\partial r_n} \cdot dr_n + \mu \cdot dF_{p1} \tag{10}$$

or for a single forming edge in a similar relation

$$dM_{f1} = \frac{\partial M_{f1}}{\partial t} \cdot dt = \frac{\partial M_{f1}}{\partial \gamma_o} \cdot d\gamma_o + \frac{\partial M_{f1}}{\partial r_n} \cdot dr_n + \mu \cdot dF_{p1}, \qquad (11)$$

where $\underline{\gamma_o}$ is the orthogonal rake angle, $\underline{r_n}$ is the edge radius and $\underline{F_p}$ passive force acting perpendicularly to the cutting force (axial force is not taken into a consideration). The typical and unique problem for tapping operations is the total reverse of the force and speed vectors, that can result in extremal peaks of friction coefficient that doesn´t follow the Coulomb´s formula (also due to the deceleration of speed) and a micro-fracture of the cutting (forming) edge or a fracture of the built-up-edge that leads to the discontinuous wear. The built-up edge is a very common phenomenon because the tools try to fulfil the worn-out cutting material with the machined material.

3. EXPERIMENTAL WORKS

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 3 kHz, 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 ø8.52 mm, thermogrip Bilz – HSK A63 ÷Φ10 (cutting speed v_c=90 m/min, feed per rotation f=0.12 mm) – drilling the pilot holes,
- countersink 90°/ Φ 30 mm, DIN 335, Guhring, Art. Nr. 327 tool holder - thermogrip Bilz – HSK A63 Φ 20, (vc=60 m/min, f=0.12 mm),
- the cutting taps M10-6HX Enorm1-Z, HSS-E, un-coated and PVD coated with monolayer of TiN, thickness of coatings – 2.0±0.1 μm, Ra=0.8-1.0 μm, 3 samples; (v_c=20 m/min, f=1.5 mm).

Fig. 4. The type of the tested cutting tap

b) for forming taps

- solid carbide drills Φ 9.360 mm, thermogrip Bilz – HSK A63 (vc = 70 m/min, f = 0.10 mm)
- HSS-E cold forming taps M10-6HX InnoForm1, PVD coated with monolayer of TiN, thickness of coatings – 3.8±0.18 μm, Ra=0.8-0.9 μm, 3 samples, v_c=10 m/min, f=1.5 mm.

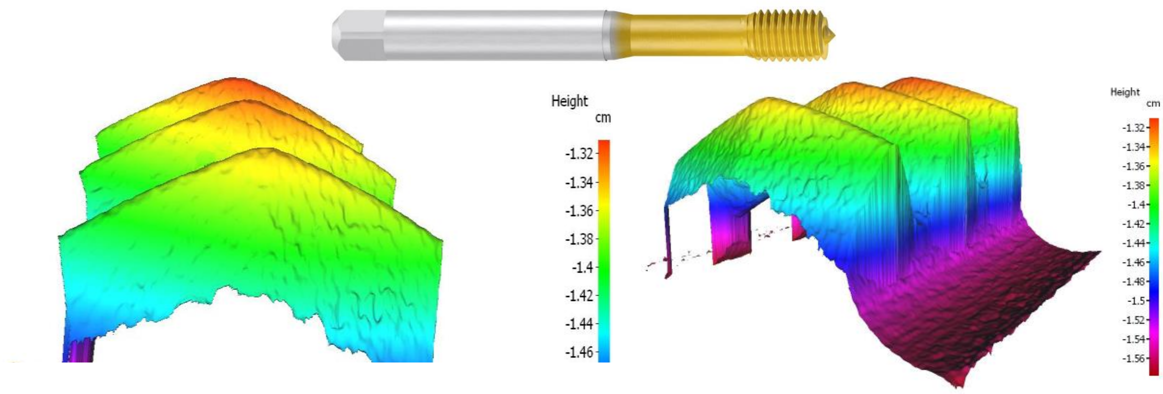

Fig. 5. The type of the tested forming tap, 3D analysis of the front forming lobes

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.

Table 1. Composition and properties of the tested 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 tested steel 42CrMo4V CSN EN 10083-1: 1991+A1: 1996; DIN 17200 (heat treated)

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	

The standard thread gauge M10-6H DIN ISO 13 Schmalkalden/UNIMETRA Ltd. was used for the first dimensional evaluations and Alicona IF-G4 for surface topography of produced surfaces.

Cross-sections of the produced threads 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.

4. RESULTS

The experimental works were running according to expectations and references – Fig. 6,7,8,9. The tool life of the uncoated taps was short due to chip clogging and deteriorated quality of thread surfaces. The analysed torque moments and calculated energy confirmed several times higher specific loading of the formed surfaces undergoing the intensive strain hardening – Table 3,4. Nevertheless, the dimensions and quality of the produced surfaces was good – Table 5, in spite of some imperfections in the formed tap crests – Fig. 10. The tool life of coated tools was satisfactory as well, with a good consistency of the results – Fig. 11,12. Two basic mechanisms of wear have been observed – abrasion and adhesion (in the form of the built-up-edges) – Fig. 13,14.

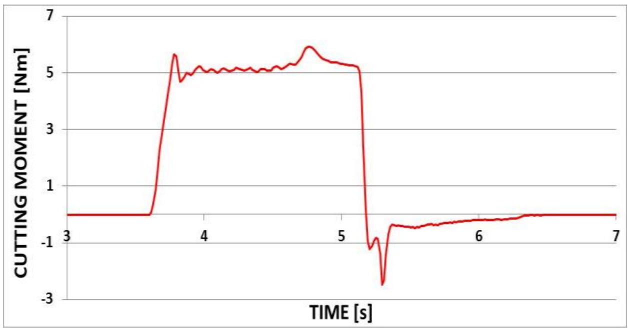

Fig. 6. A time series of the cutting moment

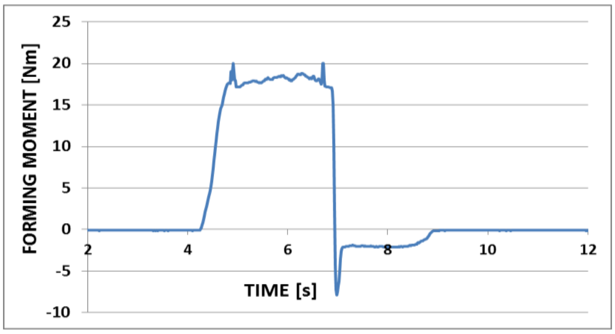

Fig. 7. A time series of the forming moment

Table 3. 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

Table 4. 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

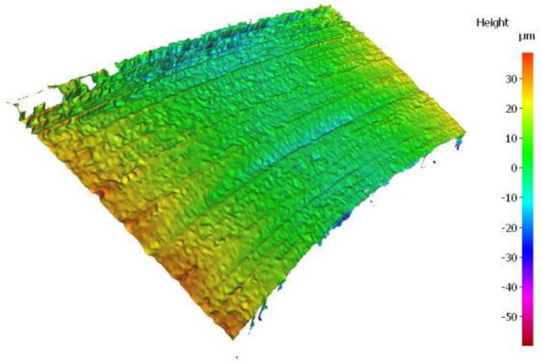

Fig. 8. The texture of cut thread surface

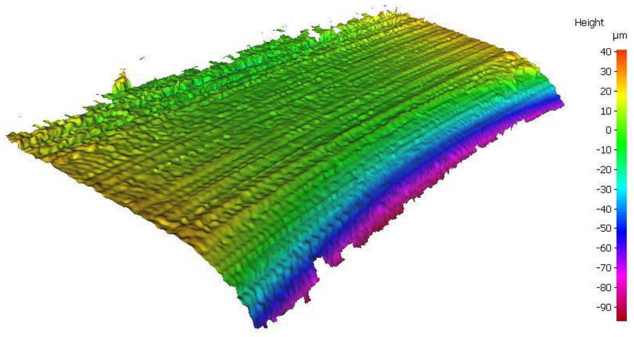

Fig. 9. The texture of formed thread surface

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

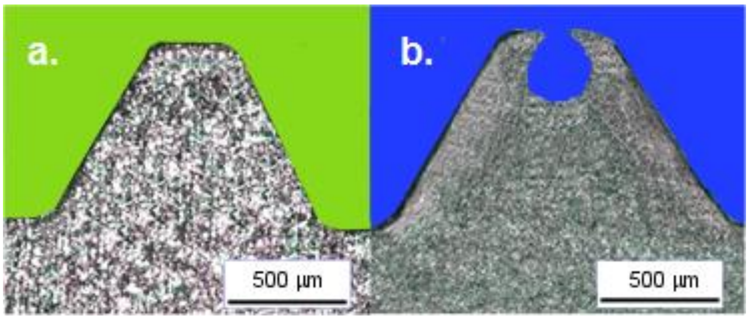

Fig. 10 A comparison of the thread cross-sections (Nital 1%):
a) cut, b) formed

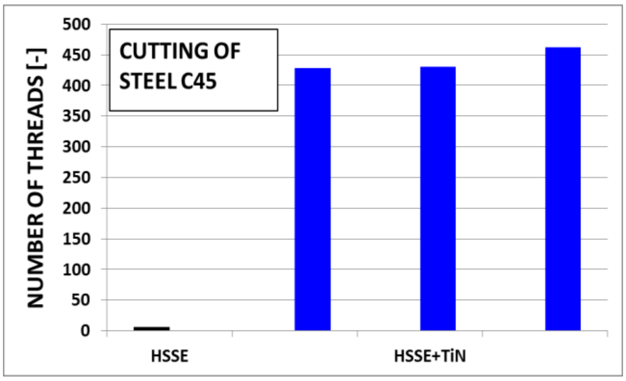

Fig. 11. Tool life as number of correctly produced threads

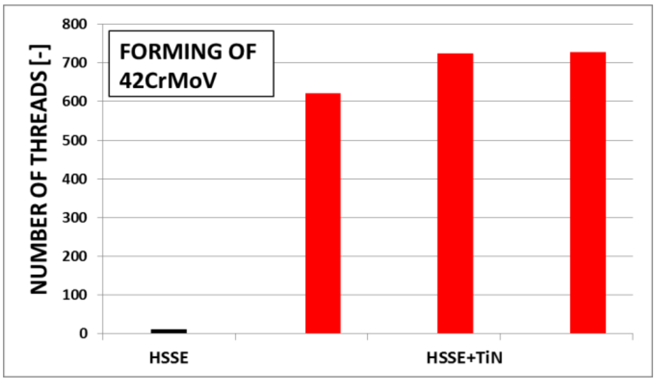

Fig. 12. Tool life as number of correctly produced threads

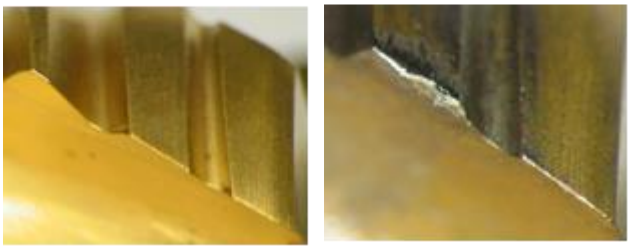

Fig. 13. The new and worn cutting edge

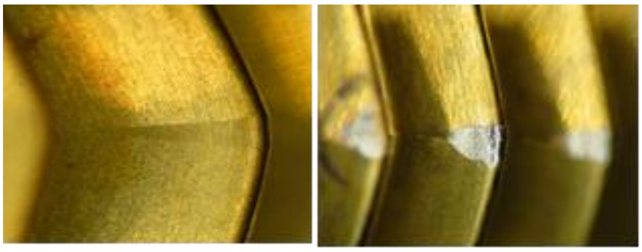

Fig. 14. The new and worn forming lobes

5. DISCUSSION

Both technological operations are industrially applicable. No breakage or a massive fracture of the taps has been observed. The high cutting conditions for series production of the threads can be used, but as a very important operation affecting the results the drilling can be regarded. The precise position of the hole, diameter, cylindricity and accurate dimensions and even roughness are the necessary presumptions for a high quality production of the threads. If the prerequisites are not satisfactory met, the tapping operation can lead to production of misfit parts and scraps.

6. CONCLUSIONS

The combination of PVD with TiN surface coatings can be recommended for a good and safe tapping in the steels, even in the hardened state, with satisfying reproducebility of measured values. A very good accuracy in the range of IT 9-10 for the threads made by both technologies, roughness at the middle diameter of threads Ra<1.6 μm, tool life for production of 624-728 threads (for forming operation) and 428-462 threads (for cutting) can be expected under the defined technological parameters. Without the coating the technology does not work and a premature fracture of the taps and poor quality of the thread surfaces can be observed. The research will continue with duplex and 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.

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