A NEW DESIGN OF ROUGHING MILLING CUTTER AND ITS MACHINING PERFORMANCE

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This paper deals with a new roughing milling cutter design made of high-speed steel by precision casting technology. Each edge of the innovated milling cutter has two special flutes that make so-called compensation edges which help to reduce tensile stress in the end of cutting teeth. Three kinds of PVD coatings ((Al,Ti)N, (Al,Ti,Cr)N and nanocomposite nACo) were used to preserve the tool life. The coatings were made with a cathodic-arc deposition process. Machining tests were carried out on the vertical milling machine FB 32V. Cutting conditions were constant and standard carbon steel C45 DIN EN ISO 4957 (W.Nr. 1.1191) was used as workpiece material. Monitored parameters were force loading and flank wear measured with Stemi 2000 Zeiss. Dynamometer Kistler 9575B/SW DynoWare were used for measuring of instantaneous force loading in long time series. The results confirm a good cutting performance of the new tool.

KEYWORDS
force loading, flank wear, high-speed steel, PVD coating, milling, stress analysis

1. INTRODUCTION

The most widely used materials for production milling cutters are cemented carbides [Humar 2008], but they cannot be used for all cutting applications. On contrary, cutting tools made of HSS prevail with a higher toughness and grindability and those can be used for many machining applications. The tools can be protected with wear resistant PVD coatings effectively [Cselle 2013, Jaros 2014]. Some new trends in the coating with Cr alloying and nanocomposite microstructures like (Al,Ti,Cr)N are still under development because of higher oxidation temperatures (up to 900°C) of cutting edges. However, a focus on a new design of the cutting tool with suppressed tensile loading of the cutting flutes can be also interesting, because for many machines or workpieces the higher values of cutting speeds needed for cemented carbides can´t be used or some machining conditions can be hazardous.

2. THE NEW DESIGN OF THE MILLING CUTTER

The milling cutters with straight teeth are prone to premature breakage when the tool enters cutting. For this reason the most cutting tools have helical teeth with a better rake geometry and gradual penetration into machined material. Unfortunately, these cutting tools have a tendency to be pulled into the cut and promote the tensile loading of the cutting edge. That effect can lead to undercutting the surface or a fracture of tool [Forejt 2006]. The new design for roughing operations suppresses the effects effectively. Each of the three left-hand edges is equipped with several special compensation edges which are used for reduction of tensile stresses in the end of the tooth to avoid pulling the tool towards the workpiece. The cutting tool has bigger recess for a chip removal, cooling and the geometry support pressure stresses. Moreover, it suppresses also the tendency of pulling the workpiece into cutting action and it is beneficial for machining of thin wall or unsupported parts either. The new tools were made by the investment casting technology, then ground, heat treated and covered with three kinds of hard PVD coatings. The cutting tool is called as "RMC" (Roughing Milling Cutter) in this paper – Fig. 1.

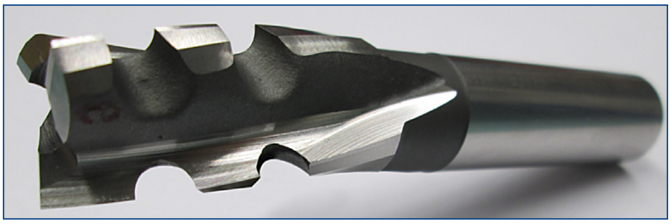

Figure 1. The new designed HSS milling cutter (called as "RMC")

3. EXPERIMENTAL WORKS

3.1 The aim of the experimental work

The main goals of these experiments were: to compare the cutting performance of the coated and uncoated HSS end milling cutters, characterized with a brand new design, and to identify the benefits of the compensation edges and PVD coatings on tool loading and wear. As monitored parameters the force loading when cutting and related flank wear in time were used.

3.2 Cutting tools

Four sorts of the new HSS end milling cutters (∅18.45x96mm) were used for the milling tests, each in series of three pieces.

Chemical composition of the cutting material is shown in Tab. 1. Three groups were deposited with PVD coatings (producer Liss Platit, a.s, Roznov pod Radhostem, Czech Republic). The coatings were synthesized with the cathodic-arc deposition using Al, Ti and Cr cathodes, so monolayers of (Al,Ti)N and (Al,Ti,Cr)N and the nanocomposite layer nACo® were made. The temperature of deposition all coatings was 450±5°C. Properties of the coatings are shown in Tab. 2. To compare the effect of side cutting edges a few samples of similar milling cutters (with the same geometry, apart of the side cutting edges, in the state of uncoated HSSE and HSSE/ (Al,Ti)N) were pre-tested also.

Table 1. Chemical composition of the milling cutters - HSSE PN 422993 [ZPS-FN 2015]

Chemical composition [weight %]	C	Cr	Mo	V	W	Fe
ZPS-FN PN 42 2993	1.15	4.10	3.10	3.10	6.50	balance

Table 2. Physical properties of the deposited PVD coatings [Liss 2015], [Rabinovich 2005], [Sreeharsha 2006], [Mattox 2010]

Coating	Color	Nanohardness [GPa]	Thickness [μm]	Coefficient of friction (against carbon steel) [-]	Maximal application temperature [°C]
(Al,Ti)N	black	33	2-4	0.70	850
(Al,Ti,Cr)N	gray-blue	34	2-4	0.55	900
nACo®	purple-black	45	2-4	0.45	1,200

3.3 Material of workpiece

In this experiment, the carbon steel C45 DIN EN ISO 4957 (W Nr. 1.1191) was used – Tab. 3, in material blocks 100x26-150mm (pre-machined after normalizing).

Table 3. Chemical composition of CSN EN 10083 (1.1191) [Bolzano 2015]

Chemical composition [%]	C	Si	Mn	P	S	Cr	Mo	Ni	Fe
CSN EN 10083 (1.1191)	0.40-0.52	0.43 max.	0.46-0.84	0.035 max.	0.035 max.	0.40 max.	0.10 max.	0.40 max.	balance

3.4 Cutting conditions

The experiment was carried out on the standard three-axis vertical milling machine FB 32V (producer TOS Kurim). Cooling emulsion Cimstar 597 (volume concentration of 5%) was used, with a flow rate of 15 l/min. Dynamometer Kistler 975B/ DynoWare equipped with eight-channel amplifier 5070A was used for measuring of force loading. Cutting conditions are shown in Tab. 4. A machine vice was used for clamping of the workpiece, and Weldon DIN 1835-B for fastening of the milling cutter – Fig. 2.

Table 4. Cutting conditions for the experimental climb milling

Cutting condition	variable	value
Cutting speed	v_c [m/min]	65
Feed speed	v_f [mm/min]	160
Feed per tooth	f_z [mm]	0.0476
Axial depth of cut	a_p [mm]	26
Radial depth of cut	a_e [mm]	2

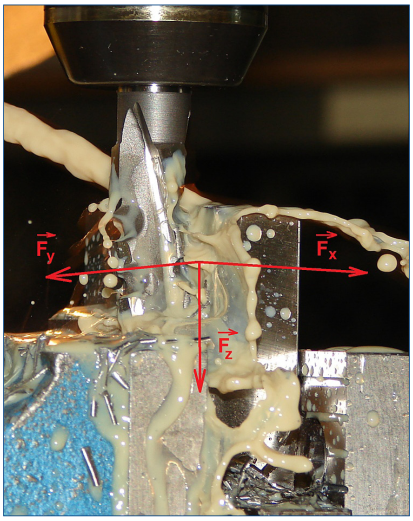

Figure 2. The experimental machining, orientation of the acting forces

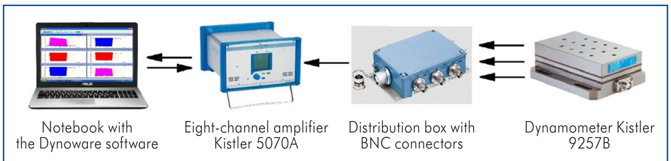

Figure 3. The Kistler force data acquisition and their processing

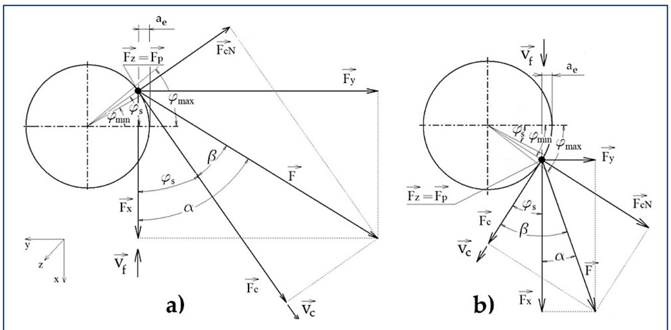

Figure 4. Distribution of force loading: **a)** conventional (up) milling, **b)** down (climb) milling

The experimental milling was carried out at two working arrangements:

- first, as cutting of a material block, clamped onto vice that was attached to the Kistler dynamometer,
- the second one, as cutting of a material block gripped in a vice fastened to the machine table (for the non-measured force loading). The sampling frequency was set up to 1,500Hz in each force channel, long time constant and SW DynoWare was used for the data acquisition.

The orthogonal forces (F_x, F_y, F_z) were transformed to the technologically coordinated system (F_c, F_{cN}, F_p) for the up and down milling – Fig. 3, 4, but this work concerns with down milling only (the results were found to be similar).

4. RESULTS

4.1 Force loading

First, the standard milling cutters (without the side cutting edges, uncoated and also coated) showed at the cutting conditions a tendency to chattering and production of machined surface with poor quality, especially for up-milling. They were able to cut with a lower axial depth of cut or lower feed per teeth only (with the reduction about 40%). The reason of tendency for chattering can be seen in production of long chips and higher passive loading of the tool – Fig. 5.

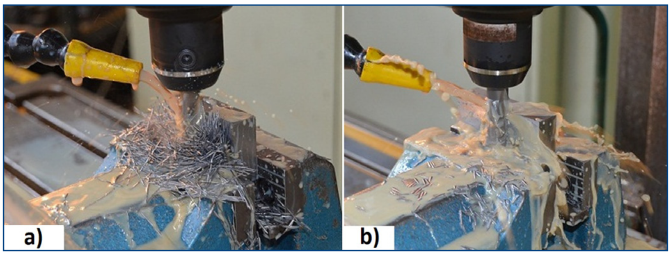

Figure 5. Chip production with the standard cutting tool (a) and RMC cutter (b) – short elementary chips are advantageous

Cuttings with the new uncoated and coated RMC cutters have run satisfactory. Fifty passes were performed with each tested cutting tool. Time series of force loading for the uncoated milling cutter is shown in Fig. 5, the force loading for RMC with PVD coating (Al,Ti)N is shown in Fig. 6. Each cutting tool was tested twice and the results were pooled. The time series showed a good consistency and regular time development in all components.

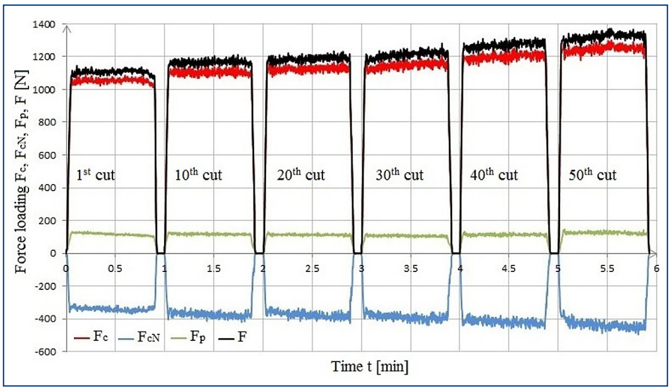

Figure 6. Time series of the force loading for uncoated HSS RMC

In general, the cutting force F_c proved to be the principal loading parameter, which confirmed that the cutting performance of the cutter was convenient and the most energy was turned into the chip production. The stabilized cutting and first superior results compared to HSS were achieved with RMC milling cutter and (Al, Ti)N coating. The PVD (Al,Ti,Cr)N coating showed similar mean values of F_c and their increase about 9%. The highest mean values (apart of uncoated HSS tool) were achieved by the milling cutter deposited with nanocomposite coating nACo® (23.7%). All reached values of cutting forces for all tested milling cutters are shown in Tab. 5. The gradual increase of cutting force F_c with increasing flank wear is shown in Fig. 7, 8.

Table 5. The mean value of cutting force F_c - at the time beginning and the end of testing

Cutting tool	mean Fc (1st pass) [N]	mean Fc (50th pass) [N]	increasement of mean Fc [N]	relative increasement of Fc [%]
RMC - HSS uncoated	1,052	1,247	195	18.5
RMC - HSS + (Al,Ti)N	**1,000**	**1,070**	**70**	**7.0**
RMC - HSS + (Al,Ti,Cr)N	975	1,062	87	8.9
RMC - HSS + nACo®	982	1,215	233	23.7

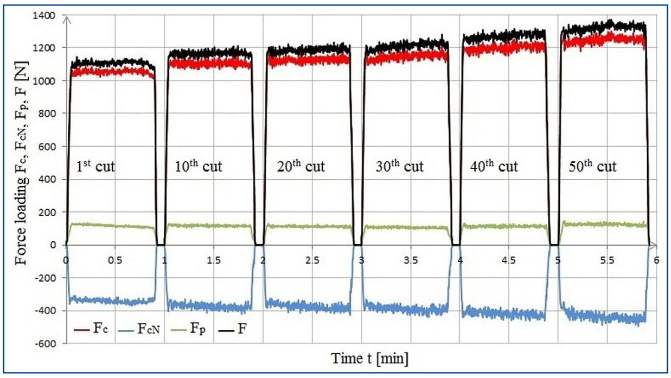

Figure 7. Time series of the force loading for HSS RMC with (Al,Ti)N coating

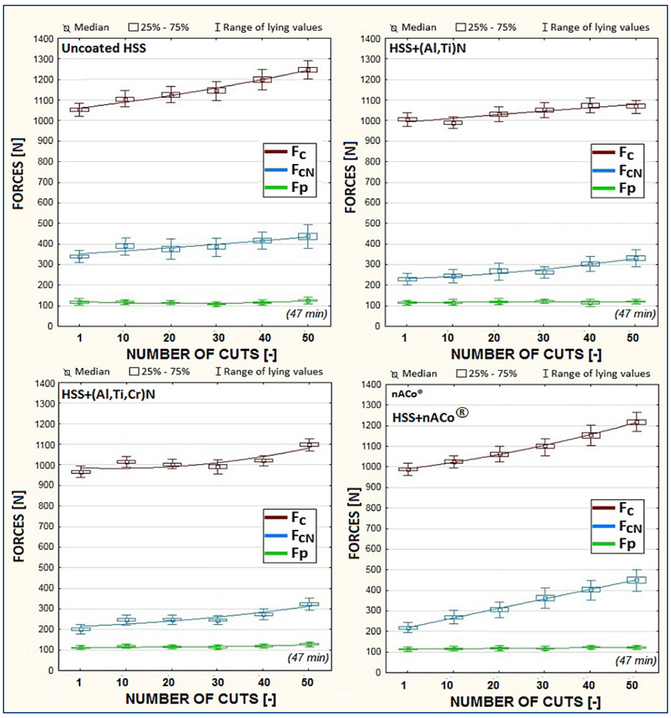

Figure 8. Time series of cutting forces for all tested milling HSS RMC cutters

4.2 Flank wear of cutters

The value of flank wear was measured with the tool microscope Alicona IF G4. Flank wear was measured on the three edges and was observed as mostly uniform. As expected, the maximal flank wear limit was VB=0.2 mm for the uncoated cutting RMC HSS tool, what corresponded 50 passes of cutting and cutting time 47 minutes. For the same material removal e.g. the cutting tool deposited with (Al,Ti,Cr)N the lowest value of wear was achieved (VB=0.10 mm) – Fig. 9.

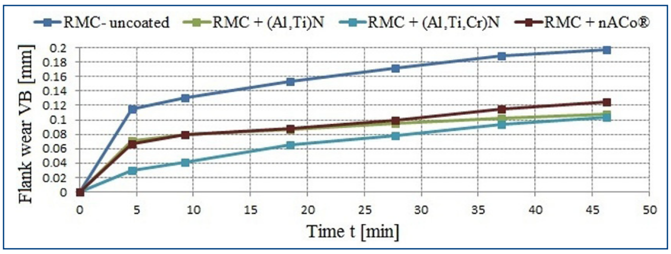

Figure 9. Comparison of flank wear of the HSS RMC milling cutters (with the coatings)

The wear mechanism was analysed with light and the electron microscopy – Fig. 10-13. Mostly abrasive wear was observed for all tools, but with different intensity and participation of other wear mechanisms. Uncoated HSS tools may not be recommended for such application anyway because of high contact pressures causing a higher intensity of wear.

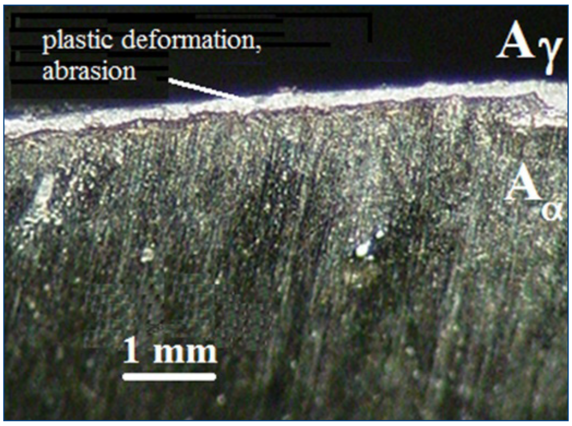

Figure 10. Flank wear of uncoated milling cutters RMC after machining (light microscopy)

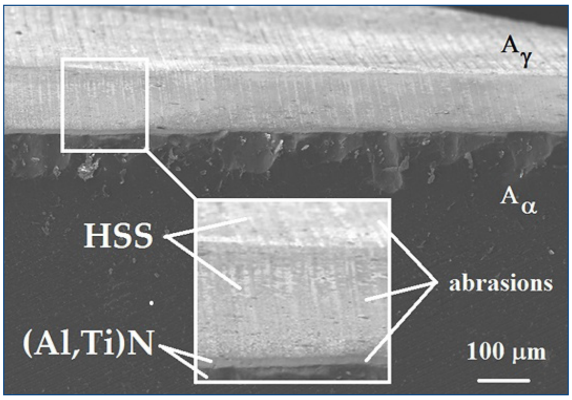

Figure 11. Flank and face wear of coated milling cutters RMC after machining (BSE)

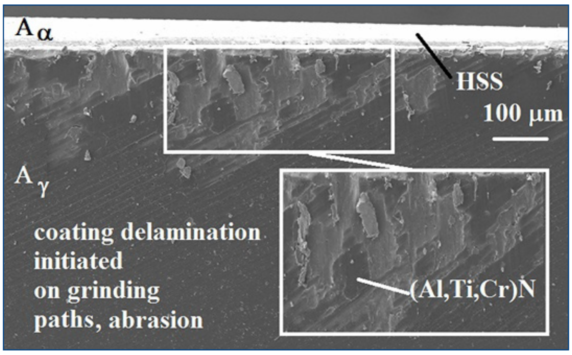

Figure 12. Flank and face wear of coated milling cutters RMC after machining (BSE)

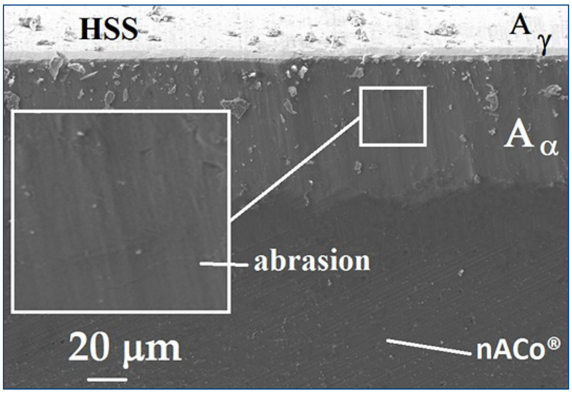

Figure 13. Flank and face wear of coated milling cutters RMC after machining (BSE)

4.3 Stress analyses

The measured force data from cutting tests were used for the stress analyses. The analyses were performed with Autodesk Inventor 2015 software. It was necessary to split loaded area to eight surface segments (see Fig. 14), because the edges of milling cutter RMC comprise the compensation edges. The finite element mesh was made from equilateral triangles 0.2mm in size that were re-meshed to 0.1mm in the expected areas of high stress concentration. The expected force loading and finite element mesh of calculation model are shown in Fig. 14.

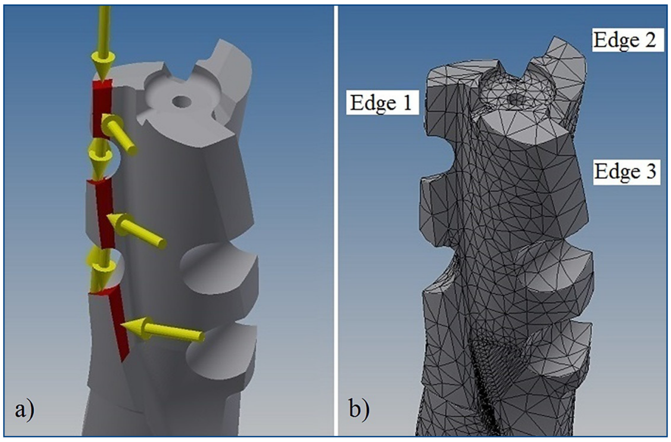

Figure 14. Orientation of the force loading (a) and the finite element mesh of the tool (b)

As predicted parameters the reduced stresses according HMH theory - von Mises (σ_V) were used - and the axis displacements at the start and the end of milling. In those calculations the stresses reached maximal values of 299.3MPa at the beginning of machining and 359.2MPa at the end of machining for uncoated tool, which represents 20% relative increase of the stress, and also 20% relative increase of the displacements (see Fig. 15). The best results were achieved by the milling cutter with PVD coating (Al,Ti)N, with only approximately 7% rise in the von Mises stress and displacement (see Tab. 6).

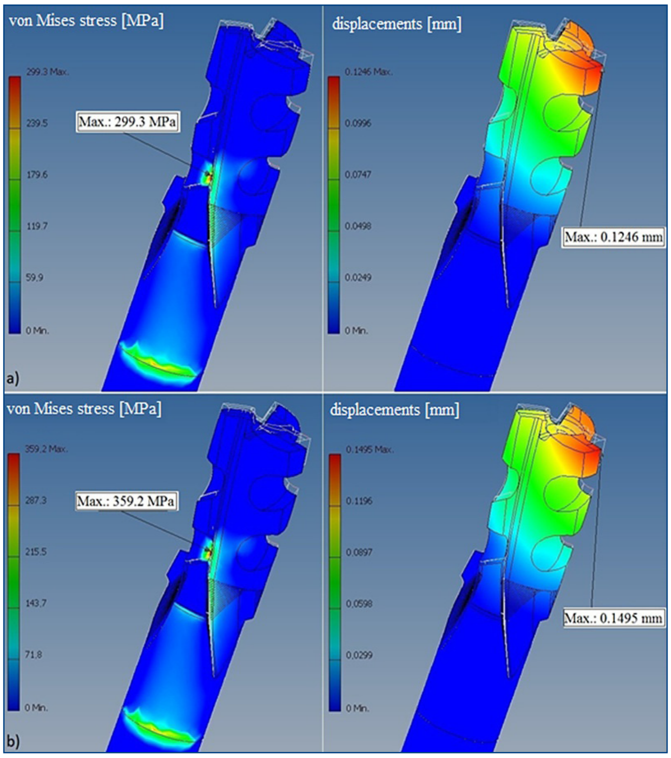

Figure 15. Static analysis of reduced stresses and displacements for uncoated HSS RMC: **a)** in the beginning of machining; **b)** in the end of the tool life (47 minutes of cutting)

The maximal value of the reduced stress (at all tested cutting tools) was concentrated at the special compensation edges which were designed precisely for these applications. An increased reduced stress can be observed in place of tool clamping also. Maximal displacement was 0.1246mm (at the 1st pass) and 0.1495mm (at the 50th pass) for the uncoated tool. The values of the reduced stresses and displacements for coated milling cutters are shown in Tab. 6.

5. CONCLUSION

Based on the force loading, flank wear and stress analysis of the experimental climb milling of constructional steel C45 the following conclusions for the new milling cutter design and wear resistant coating materials can be made:

- the novel design of the milling cutter showed a very good cutting performance characterized with a short chip production,
- all tested milling cutters RMC reached 50 passes what represents the machining time 47 minutes for the cutting conditions,
- the best wear resistance in terms of lowest increase of cutting force and flank wear during testing was achieved with RMC milling cutter deposited with (Al,Ti,Cr)N PVD coating; but the differences with other coatings were not significant,
- the nanocomposite coating nACo® deposited on milling cutter RMC also confirmed an increased cutting performance, especially compared to the uncoated HSS cutting tool,

Table 6. The calculated values of the maximal reduced stresses and displacements

Cutting tool	The reduced von Misses stress (the 1st pass) [MPa]	The reduced von Misses stress (the 50th pass) [MPa]	Relative stress increace [%]	Value of displacement (1st pass) [mm]	Value of displacement (50th pass) [mm]	Relative increase of displacement [%]
RMC – HSS (uncoated)	299.3	359.2	20.01	0.125	0.149	19.98
RMC + (Al,Ti)N	286.2	306.7	7.16	0.119	0.128	7.05
RMC + (Al,Ti,Cr)N	273.1	315.5	15.53	0.114	0.131	15.49
RMC + nACo®	281.8	341.7	21.25	0.117	0.142	21.33

- the uncoated HSS cutting tool reached the limit flank wear VB=0.2mm for 50 passes; the other coated HSS RMC milling cutters reached approximately half value of the limit flank wear (for the same machining time),
- the lowest increase of the von Misses stress (HMH) was achieved with HSS RMC milling cutter protected with (Al,Ti)N, and the highest increase with cutting tool deposited with nanocomposite coating nACo®,
- milling tools coated with (Al,Ti)N and (Al,Ti,Cr)N proved also to work at higher cutting and feed speeds what is a subject of the next research,
- the new design of the cutter is a subject of a patent pending.

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