THE PUBLISHING HOUSE
OF THE ROMANIAN ACADEMY

PROCEEDINGS OF THE ROMANIAN ACADEMY, Series A,
Volume 17, Number 1/2016, pp. 57–66

INNOVATIVE ROUND INSERT FACE-MILLING CUTTER – DESIGN AND VERIFICATION

Paul Dan BRÎNDAŞU, Gabriel Vasile ONIŢĂ, Livia Dana BEJU

"Lucian Blaga" University of Sibiu, 10, Victoriei Bd, 550024, Romania
Corresponding author: Livia Dana BEJU, E-mail: liviadana_beju@yahoo.com

Abstract. Machining operations represent a significant part of the entire mechanical processing that is done in industry. Current research in material processing techniques determines the necessity of new construction variants for the cutting tools, with more efficient, cheaper and intelligent exploitation. The present paper consists in an analysis of a new round insert face-milling cutter starting from the preliminary design phase, in which creative design methods are used, simulations by means of the finite element method, in order to obtain the optimum construction variant that can withstand milling conditions and finishing with physical cutting trials.

Key words: face-milling cutter, TRIZ, product lifecycle management, mechanical simulation.

1. INTRODUCTION

Machining operations currently represent a significant percentage of the entire mechanical processing that is performed worldwide. As stated by the CIRP Institute (International Institution of Production Research), machining represents more than 50% of all mechanical processing carried out at the industrial level, suggesting a high level of accuracy, productivity, efficiency and reliability [1]. Current trends in the material processing industry involve new solutions in the construction and use of cutting tools. The great variety of material processing and production processes determine the growing need for their optimization. The holistic nature of today's market, characterized by an economy of resources, a strong orientation towards the client and an unprecedented development of information technology, amid the increasing globalization, make necessary a more efficient, more affordable and even more intelligent products [2]. At this level of development, technological equipment namely cutting tools, cannot be excluded.

The evolution of cutting tools represents an important aspect that is closely related to other areas of technology, leading to the emergence of more efficient, cheaper and more intelligent cutting tools.

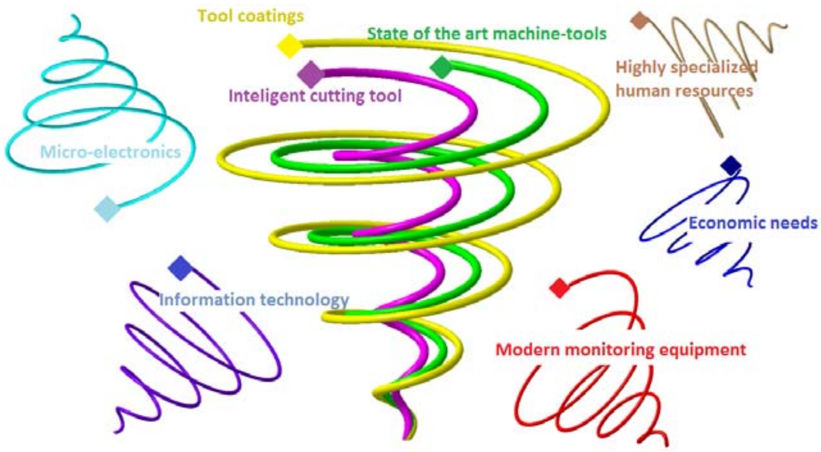

Fig. 1 – Evolution of technology.

2. RESEARCH OBJECTIVES

The present paper proposes a highly productive milling cutting tool, a central component in any intelligent milling process that can easily handle a custom production system, which is characterized by a quick change of the technological equipment, with a substantial reduction in working times and especially in auxiliary time. This type of construction allows changing the plan angle *Kr*, when using triangular or rectangular cutting inserts, by allowing the rotation of the insert around its axis; it also allows bringing a new cutting edge in the cutting area, when using round cutting inserts. Due to the large utilization of round insert milling cutters in face milling, profiled and cylindrical surface milling, a milling head with round inserts was chosen to be the starting point of the new design.

This requires a further step towards creating the intelligent cutting tool [3]. Many research papers on the cutting process have been published. Domains such as monitoring cutting forces are presented in [4–8], cutting vibrations [9, 10], tool wear and tool geometry [11–13] and research investigations needed for the integration of the monitoring sensors are underway [14–16].

In this respect, research is needed on new machining models that are appropriate for the new cutting tools and designing new types of tools that must meet a new series of intelligent functions in a manufacturing process. It is necessary to develop a design algorithm for the new tools and for model validation, and a numerical as well as an experimental analysis with the new milling cutter is needed. For this model, the main interest of this paper is in the mechanical part of the milling cutter, namely the tool's body, intermediate elements for locking/unlocking and rotating the inserts. They will be treated in detail in the following sections.

3. APPLIED CONCEPT

By applying the PLM concept in the conception and production phase (Fig. 2), and applying creative design methods such as TRIZ [17], we identified the optimum construction variant for quick locking/ unlocking the inserts. Given the current worldwide achievements, we propose the designing of a new original construction variant for the milling cutter that consists in a quick change of the worn inserts.

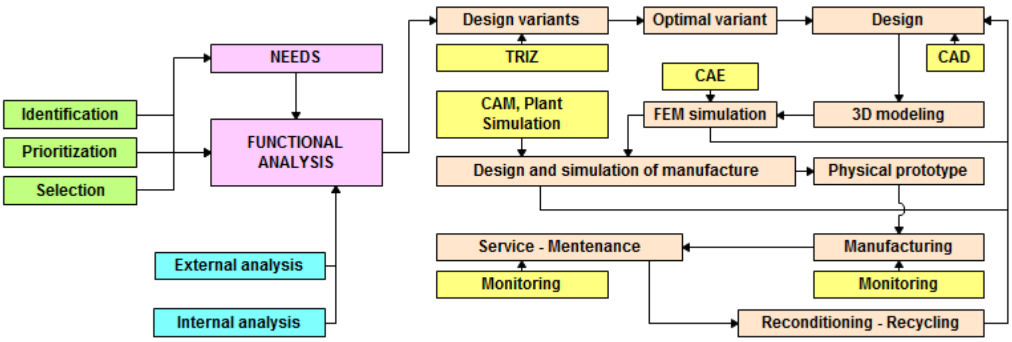

Fig. 2 – Product lifecycle management.

To obtain the new milling tool, in the preliminary conception phase, a design concept will be applied. The closest conception model in this respect is the holistic model (Fig. 3). It is based on four major areas, namely the customer domain, the functional domain, the physical domain and the process domain. To achieve the optimum milling head, it is first necessary to identify the clients requests (the customer domain), which must be prioritized, and then to select only those that are viable to be implemented in the future cutting tool (the functional domain). There is an iterative road between these four domains, which will ultimately lead to implementing the identified functions by appropriate technical solutions (the physical domain). Of course, we must opt for a technical solution that is cost-efficient and easy to implement (the process domain).

The main requirements (needs) that a milling tool must meet in any modern milling process are obtaining the shape and dimensions of the cutting area as specified, obtaining the machined surface quality according to specifications, high productivity, low operation/production costs, and reduced auxiliary time. These customer needs must be transformed into functional requirements following a detailed functional analysis that represents the second field (the functional domain) of the holistic conception model.

To this end, an external functional analysis is required, consisting of a Pieuvre diagram, necessary to determine the influences of the external environment on the functional requirements of the new milling tools. Through this, the service functions (consisting of main functions and constraint functions) are highlighted. The identified functions are the primary function: material cutting; constraint functions – high dynamic stability, quick setup, data regarding the state of milling tool, online decision-making ability, use for custom production parameters, adequate clamping system, usage safety, chip removal and maintaining a proper cutting geometry.

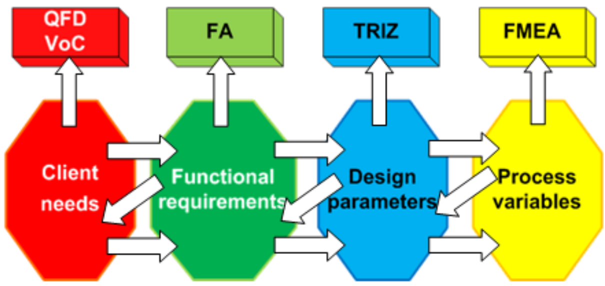

Fig. 3 – Holistic conception model.

In order to identify the multitude of possible variants, it is necessary to consider all functional requirements of the new milling cutters and formulate them in the form of existing contradictions in the operative area. To this end, the TriSolver Professional software was used, which allows the expression of contradictions as the 40 basic principles of the TRIZ method. For each pair of contradictions, the application automatically generates a set of principles to be applied, along with its occurrence frequency.

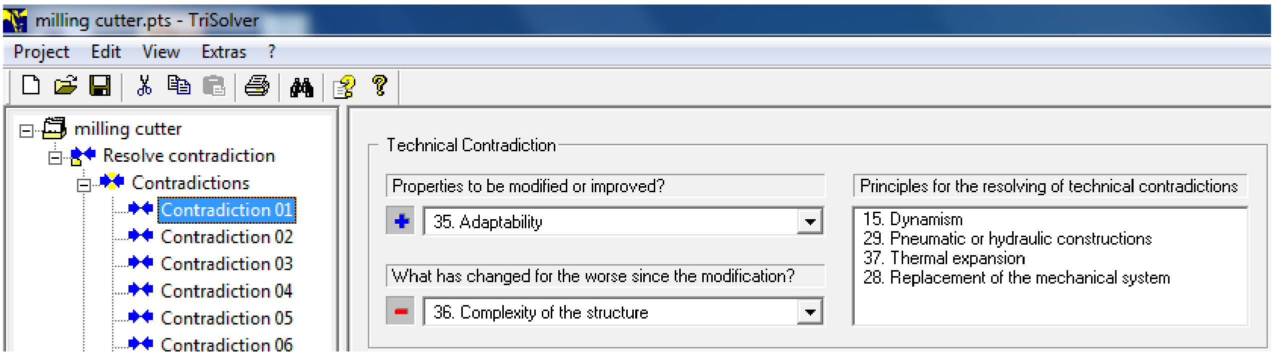

Fig. 4 – Generated TRIZ principles.

The returned principles will be combined in order to obtain a number of viable constructive variants to meet all the requirements of a modern cutting process, using the morphological matrix. In this respect it is important to establish the functional requirements weights, which will then help to underline the possible constructive variants. This was based on the following technical end economical evaluation criteria such as minimizing the auxiliary time, lower manufacturing costs, lower maintenance costs and easy recycling.

Cat.	*Classification criteria*	*Design parameters*	*Code*
A	Type of milling	End milling	A1
		Cylindrical milling	A2
		Cylindrical-end milling	A3
		Disk cutting	A4
B	Type of surface	Plane	B1
		Cylindrical	B2
		Complex	B3
...	...	...	...
F	Type of cutting inserts	Round inserts	F1
		Square inserts	F2
		Triangular inserts	F3
...	...	...	...
I	Type of clamping mechanism	Adjustable cassets	I1
		Tool's body elasticity	I2
		Intermadiate conical elements	I3
		...	I4
...	...	...	...

Fig. 5 – Possible constructive variants.

Among the highlighted functions we propose a further research in the direction of resolving one important market demand with minimum effort, namely a rapid reconditioning of the inserts by rotating them around their axis. This will allow to minimize the auxiliary time necessary with cutting tool change. The cutting process will not be stopped in order to change the cutting tool. We can thus outline the general model for the new milling tool, placed in an intelligent manufacturing system that contains elements belonging to different complex domains such as mechanics, programming, electronics and automation. Further, we will focus on the mechanical part of the cutting tool and mechanism for quick blocking and unblocking of the insert.

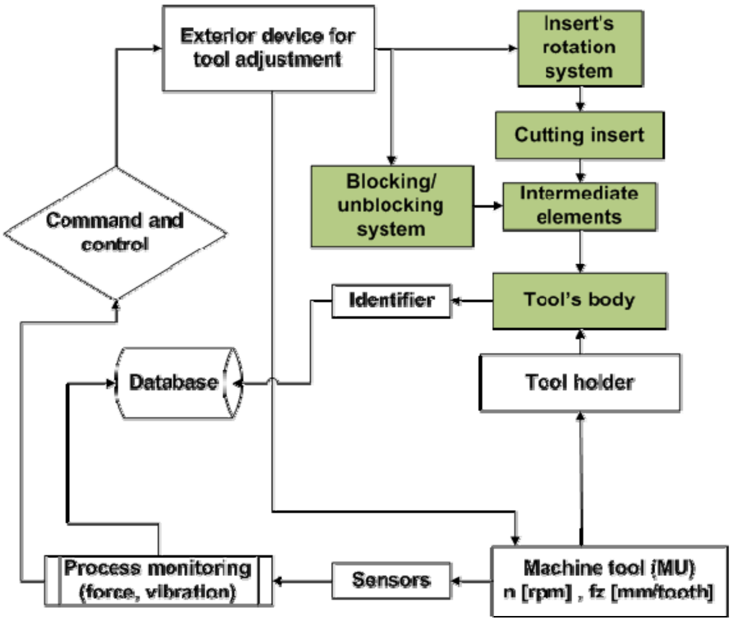

Fig. 6 – General model for an intelligent cutting tool.

4. CONSTRUCTION VARIANT

The design of the new milling cutter was performed using the Catia V5 R20 software. Because prototyping the model was necessary, the modelling started from two normed components, namely the insert and the tool's clamping system. The chosen cutting insert was of Sandvik origin having the RCHT 20 06 M0-PL code [18]. The geometry of the assembly is shown in Fig. 7.

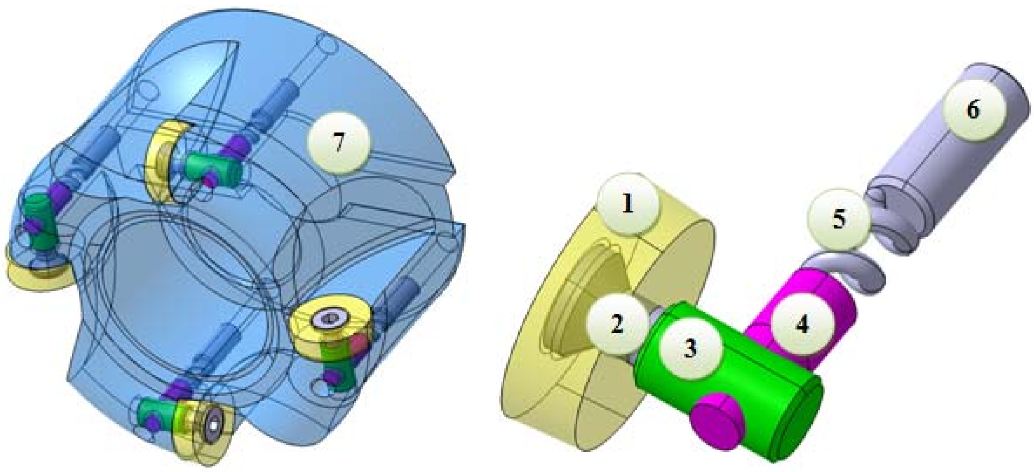

Fig. 7 – Geometry of the new cutting tool.

The system is composed of a tool's body (7) on which the insert (1) is mounted by tightening the central screw (2). This is screwed on the cylindrical pin (3) which is fixed by the conical pin (4) by tensioning the spring (5) with the dowel pin (6). In Fig. 8, *a* represents the milling cutter with the worn insert;

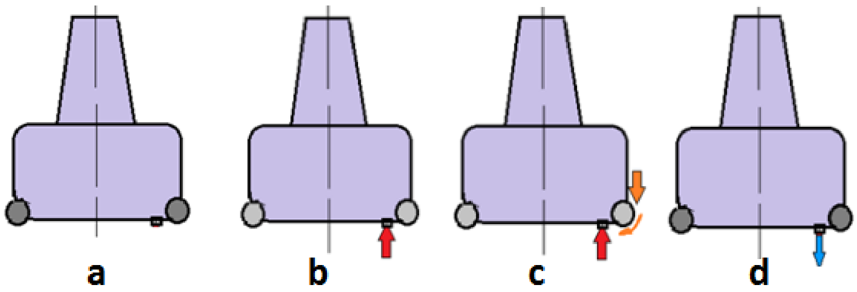

Fig. 8 – General functioning scheme.

b – the tapered pin (4) is pressed and a gap is created between the insert (1) and the tool's body (7); *c* – the insert is rotated with a certain degree, bringing in position the new cutting edge; *d* – the pressing is removed and the insert is again clamped in the new position. This operation can be performed individually for each cutting insert or simultaneously for all cutting inserts, either manually or automatically.

Depending on the number of cutting inserts available on the tool's body we have an auxiliary time necessary for insert reconditioning composed of:

$$T_{aux} = T_{rem} + n \cdot T_{ex/rec} + T_{mount}, \tag{1}$$

where: T_{aux} – auxiliary time for tool reconditioning; T_{rem} – time necessary for removing the tool from the spindle; n – number of cutting inserts; $T_{ex/rec}$ – time necessary for insert exchange/recondition; T_{mount} – time necessary for tool mounting.

By using this type of clamping in an automated manner, a substantial reduction in the auxiliary time is made. We propose an exterior automated device for simultaneous insert rotation, presented in Fig. 9.

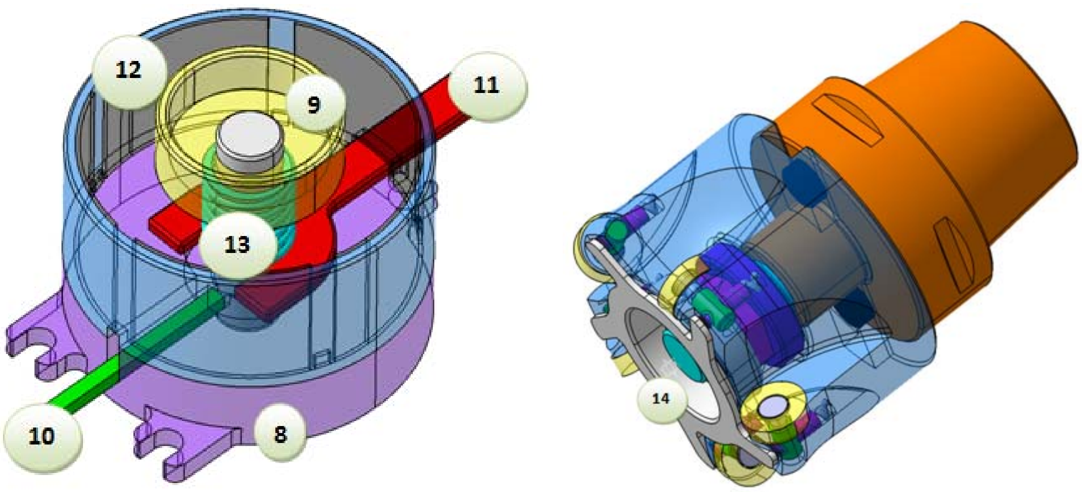

Fig. 9 – Exterior device for simultaneous insert rotation.

This device can be placed on the machine tool's table, thus it is no longer necessary to remove the tool from the spindle. It functions as follows: when the cutting insert is worn out, the machine tool stops the cutting process and the spindle travels to the device located on the machine's table. The conical pin (4) (from Fig. 7) is pressed by the disc (9) and flange (14) with the helical spring (13). A gap is created between the cutting insert and the tool's body. In this position, the cutting inserts are rotated with the appropriate number of degrees by performing an axial movement of the spindle within the adherent surface (12). After the rotation is complete, the pin (10) is removed and the mechanism clamps again the cutting insert into the new position. The spindle then retreats and the cutting process continues. In this situation the T_{rem} and T_{mount} become 0 and the number of inserts is no longer relevant.

5. NUMERICAL VALIDATION OF THE MODEL

The analysis was conducted on a model having a diameter of 125 mm and five cutting inserts.

We have analyzed several models for the milling tool's geometry, followed by the finite element analysis to achieve geometry optimization. Finite element analyses were carried out with the help of the Abaqus 6.12 software. For simplification reasons, the static analyses were performed for one cutting insert.

Because no plasticity is allowed in the tool's body or in the intermediate elements, to define the material, an isotropic elastic steel was considered (E = 210 000 MPa, ν = 0.3). The meshed model is presented in Fig. 10.

The model contains a number of 111080 elements: 96915 C3D10M elements, 12884 C3D8 elements, and 1281 R3D4 elements. The number of nodes is 158 604.

The analysis was divided into four steps: pre-tensioning the central screw; replacement of the coil spring with its equivalent force; loading the forces developed during the cutting process and unloading.

The principal cutting force F_y has a value of 1 500 N and the vertical and axial forces (F_z and F_x) were considered as 25% of the principal cutting force having a value of 375 N. They were calculated using the relations 2, 3 and 4.

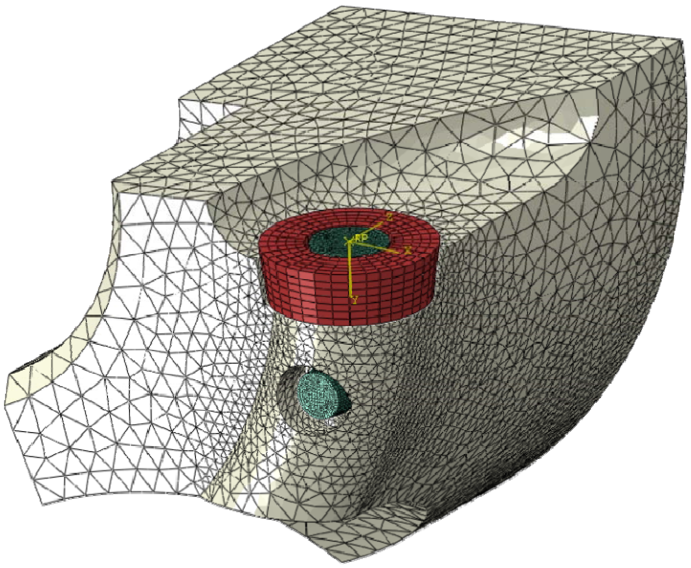

Fig. 10 – Meshed model.

$$h_m = \frac{360^o}{\pi \cdot \varphi_s} \cdot f_z \cdot \frac{B}{D} \cdot \sin \kappa_r, \tag{2}$$

$$K_c = \frac{(1\ \text{mm})^z}{h_m^z} \cdot k_{c1,1} \cdot K_\gamma \cdot K_v \cdot K_{ver} \cdot K_{st}, \tag{3}$$

$$F = b \cdot h_m \cdot K_c, \tag{4}$$

where: h_m [mm] – average chip thickness; φ_s^{o} – angle of approach; f_z [mm] – feed per cutting edge; B [mm] – workpiece width; D [mm] – diameter of the milling cutter; κ_r [$^{\text{o}}$] – plan angle; K_c [MPa] – specific cutting force; z – exponent (material constant); $k_{c1,1}$ [MPa] – specific cutting force related to 1 [mm^2] chip area; K – correction factors; F [N] – average major cutting force per milling cutter edge; b [mm] – width of cut.

As result of the static simulation, load-deflection curves corresponding to the insert's reference point are obtained, as it is shown in Figs. 11 and 12.

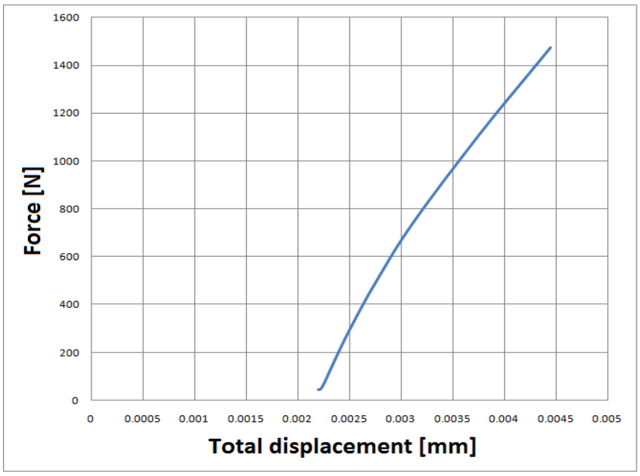

Fig. 11 – Force – total displacement.

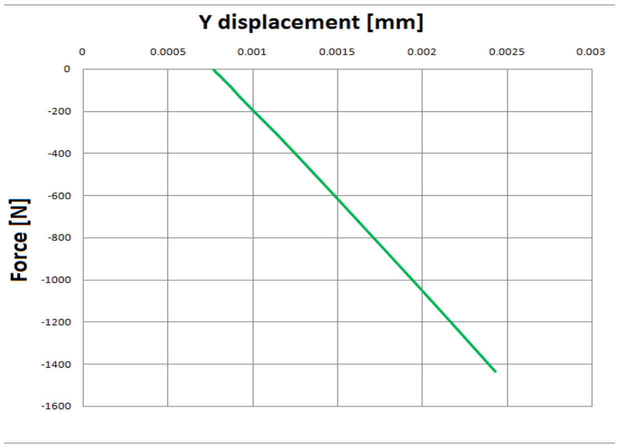

Fig. 12 – Force – *Y* displacement.

We can see that the total displacement of the reference point of the cutting insert has a maximum value of 0.0044 mm and corresponds to a total reaction force from the boundary of 1476 N. For the *X* and *Y* directions, the maximum displacement is 0.0026 mm and after the *Y* direction, it has a value of 0.0024 mm. The distribution of the von Mises stress is shown in Figs. 13 and 14.

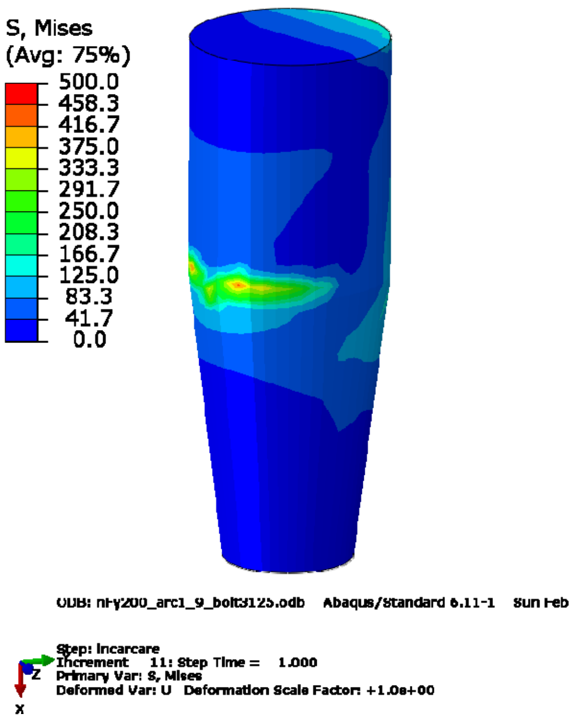

Fig. 13 – Von Mises stress – tapered pin.

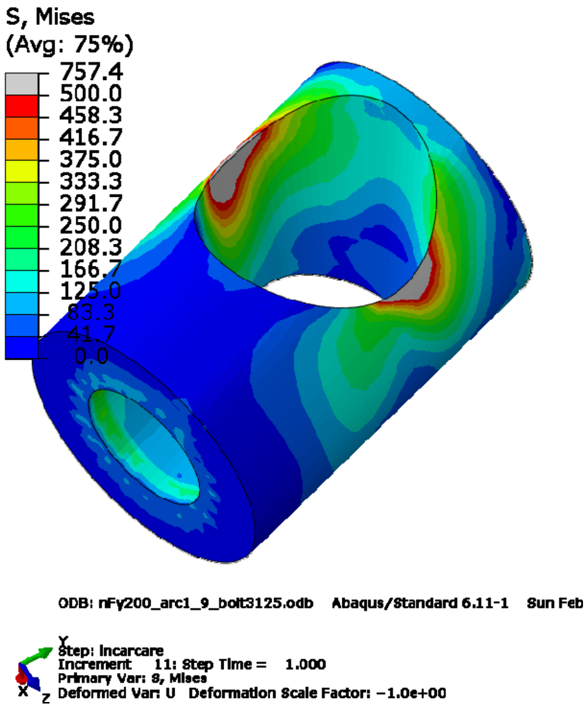

Fig. 14 – Von Mises stress – cylindrical pin.

In order to withstand the milling forces and to ensure that no plasticity appears in the intermediate elements, a material with the yield stress limit higher than 430 MPa should be used for the tapered pin and another one with the yield stress limit higher than 750 MPa for the cylindrical pin. For the tapered pin, the proposed material is steel S620Q, and for the cylindrical pin steel S890Q [19].

6. EXPERIMENTAL VALIDATION OF THE MODEL

The purpose of conducting these tests was to determine the maximum forces developed in the 3 directions during milling with the new round inserts milling cutter and to compare the values obtained by experimental means to the ones determined through analytical calculation. The experiment consists in a factorial 3^2 experiment, which was based on two parameters of the cutting regime (cutting depth a_p and chip thickness h_{ex}) each with three levels of variation. Their values were adopted based on the recommendations from the tool catalogs. In the experiments, the cutting speed was considered constant $v_c = 260$ m/min, which, for the processed metal material (steel S355 DIN EN 10025-2) [19] and a milling head diameter of 125 mm, has a corresponding spindle speed of 600[rpm]. In the experiment, we used the feed/tooth parameter (f_z) which was determined [18] with respect to the relation (5)

$$f_z = \frac{h_{ex} \cdot iC}{2 \cdot \sqrt{a_p \cdot iC - a_p^2}}. \tag{5}$$

The cutting trials were made on a CNC milling machine with 3 axes, DMC 635V. The dynamometer used is a Kistler stationary 9257B dynamometer (–5 ... 10 kN, size 100 × 170 mm) connected to a charge amplifier 5070A × 11xx and a computer with the LabView 8.5 software preinstalled. Cutting trials were done with a total engagement of the cutting tool. The machining parameters that were used during cutting trials are presented in Table 1.

Table 1

Machining parameters

Trial	a_p [mm]	h_{ex} [mm]	f_z [mm/tooth]
2	0.5	0.05	0.16
9	0.5	0.08	0.26
1	0.5	0.11	0.35
3	0.75	0.05	0.13
8	0.75	0.08	0.21
4	0.75	0.11	0.29
6	1	0.05	0.11
7	1	0.08	0.18
5	1	0.11	0.25

The signal acquisition and analysis were performed using the LabView 8.5 software together with a virtual instrument, through which we determined the maximum and minimum values for each component of the signal.

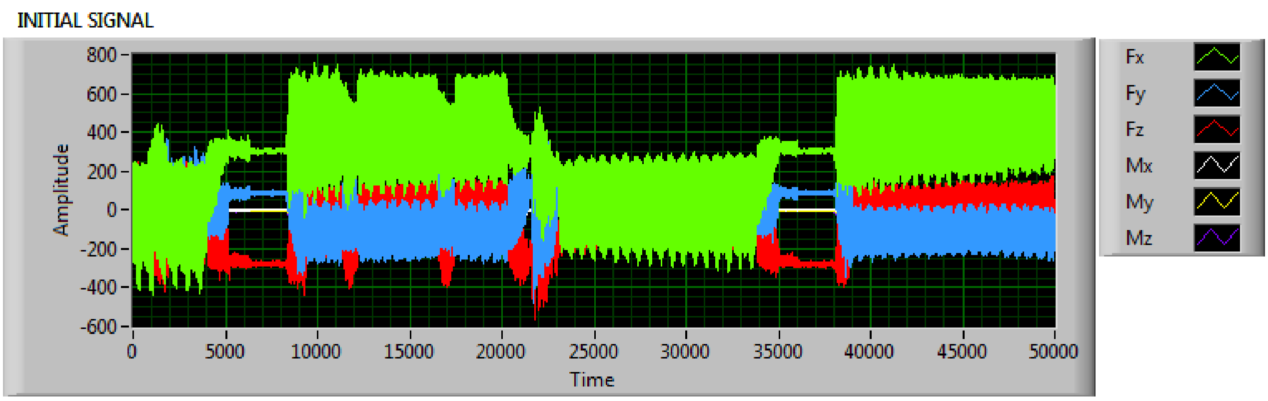

Fig. 15 – Initial signal monitored for no. 1 cutting trial.

The values obtained for the nine cutting trials are presented in Fig. 16.

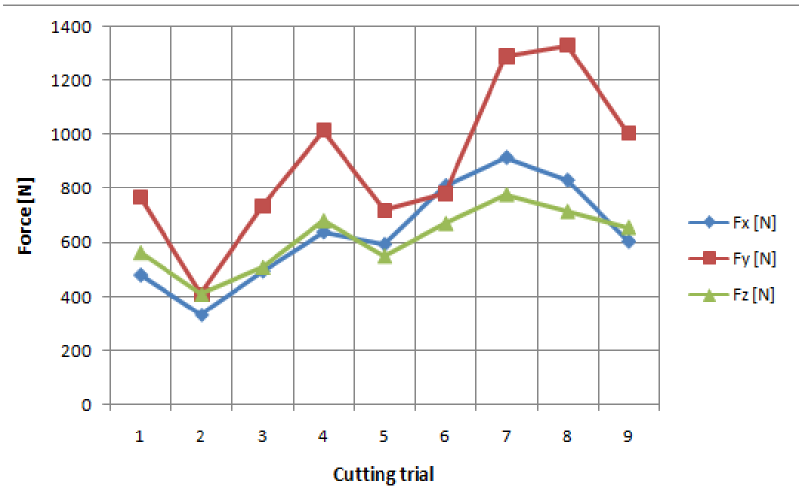

Fig. 16 – Forces obtained after the *X*, *Y*, and *Z* directions.

7. CONCLUSION

The original construction of the milling head enables an easy reconditioning of the cutting insert by simply lifting the clamping element and rotating the insert axially. Experimental tests were conducted after a theoretical and numerical verification of the loads that appear during the cutting process, confirming the force values and the correct behavior of the structural elements.

Following the experiment, we conclude that the maximum force obtained using the recommended cutting parameters for the specified dimensions of the cutting tool and the processed material is 1 330 N, within the limits that were calculated using the analytical method and used in the finite element analysis, *i.e.* 1 500 N.

REFERENCES

1. TETI R., JEMIELNIAK K., O'DONNELL G., *Advanced monitoring of machining operations*, CIRP Annals, **59**, pp. 717–739, 2010.
2. ZÜHLKE D., *SmartFactory – from Vision to Reality in Factory Technologies,* Proceedings of the 17th IFAC World Congress, Seoul, 2008.
3. KLOCKE F., KULJANIC E., WIRTZ G., *Development of an Intelligent Cutter for Face Milling*, Int. Conf. AMST'08, Udine, 2008.
4. MARINESCU I., AXINTE D., *A Time-frequency Acoustic Emission-based Monitoring Technique to Identify Workpiece Surface Malfunctions in Milling with Multiple Teeth Cutting Simultaneously*, International Journal of Machine Tools and Manufacture, **49**, *1*, pp. 53–65, 2009.
5. SANTOCHI M., DINI G., TANTUSSI G., BEGHINI M., *A Sensor Integrated Tool for Cutting Force Monitoring*, CIRP Annals, **46**, *1*, pp. 49–52, 1997.
6. KIM JH., CHANG HK., HAN DC., *Cutting Force Estimation by Measuring Spindle Displacement in Milling Process,* CIRP Annals, **54**, *1*, pp. 67–70, 2005.
7. ALTINTAS Y., PARK S., *Dynamic Compensation of Spindle Integrated Force Sensors*, CIRP Annals, **53**, *1*, pp. 305–308, 2004.
8. RIADH C., MOEZ A., *Mathematical methodology for optimization of the clamping forces accounting for workpiece vibratory behaviour*, International Journal for Simulation and Multisciplinary Design Optimization, Volume 5, 2014.
9. SONG D., OTANI N., AOKI T., KAMAKOSHI Y., *A New Approach to Cutting State Monitoring in End-mill Machining*, International Journal of Machine Tools and Manufacture, **45**, pp. 909–921, 2005.
10. AXINTE D., GINDY N., FOX K., UNANUE I., *Process Monitoring to Assist the Workpiece Surface Quality in Machining*, International Journal of Machine Tools and Manufacture, **44**, pp. 1091–1098, 2004.
11. KULJANIC E., SORTINO M., TOTIS G., *Application of Wavelet Transform of AE Signal for Tool Condition Monitoring in Face Milling,* 39th CIRP Int. Sem. on Manuf. Systems, 2006, pp. 39–44.
12. KAMARTHI S., SANKAR G., COHEN P., KUMARA S., *On-line Tool Wear Monitoring Using a Kohonen's Feature Map*, Int. Conf. on ANNIE'91, St. Louis, 1991, pp. 639–644.

13. WANG W., HONG G., WONG Y., ZHU K., *Sensor Fusion for On-line Tool Condition Monitoring in Milling*, International Journal of Production Research, **45**, *21*, pp. 5095–5116, 2007.
14. SEGRETO T., TETI R., *Sensor Fusion of Acoustic Emission and Cutting Force for Tool Wear Monitoring during Composite Materials Machining*, 6th CIRP Int. Conf. on ICME, 2008, pp. 221–226.
15. SEGRETO T., NEUGEBAUER R., *Sensor Fusion of Sensor Signals during Machining of Difficult to machine Metal Alloys*, AITeM 2009.
16. * * *, EC FP7 NoE on IPROMS, http://www.iproms.org.
17. MICHAEL A. ORLOFF, *Inventive Thinking through TRIZ – A Practical Guide*, Second Edition, Springer-Verlag, Berlin, Heidelberg, 2006.
18. * * *, *Sandvik Rotating Tools Catalogue*, http://www.sandvik.coromant.com/.
19. ULRICH F., HEINZLER M., *Mechanical and Metal Trades Handbook*, 3rd edition, Verlag Europa Lehrmittel, 2011.

Received October 10, 2014