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Simulation modeling and analysis on improved modular end mill cutter, for manufacturing of large gears

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Abstract— This article presents the results of conducted simulation research, imitating the real manufacturing conditions in which operates improved modular end mill cutter with hard-blade insert. Realized is a complex stress-strain test by finite element method, with reporting thermal and flow simulations. The tools are designed for finishing, medium and roughing machining operations of the evolvent profile of a large gears with a module m = 40mm.

Index Terms— Gear shaping by end mill cutters, stimulation modelling, improved modular end mill cutter (IMEMC), Finite element method (FEM)

1 Introduction

On the basis of the results of research on physical and mechanical parameters, thermodynamic characteristics and cutting conditions [2], [3] are conducted stimulation studies, imitating the real production conditions under which the operate improved modular end mill cutter with hard-blade insert by milling of a large gears with a module m = 40mm. They were implemented using the application "Simulation" of the CAD system Solid Works [16],[18],[22].

It's done individual fluid and thermal simulation as well as complex stress-strain testing by the finite element method with comprehensive of strength, thermal and fluid characteristics were performed on the stresses of von Mises σ[MPa] and the strain (the deflection) f [mm]. In this case, only the behavior of the machine-tool-detail system in the in milling of gear from steel 40X.

2. Exposition

The investigations were carried out on a parametrically designed improved modular end mill cutter, whose working part is shown in Fig. 1 [6],[7],[8]. The attachment part is universal (welded) made of the same tool steel 50 as the tool casing. Carbide inserts are made of a sintered metal ceramic solid alloy containing tungsten carbide (WC) and cobalt WC-Co.

In this case, the evolvent profile of a gear has been approximated with two segments of hyperbole. The angles which conclude forming straight lines with the hyperboloid axis, formed by the kinematic way of hyperbolas $\lambda_i = \beta$.

These corners, inclination of the cutting edges and are receiving the following values are obtained [9],[10],[11],[12]:

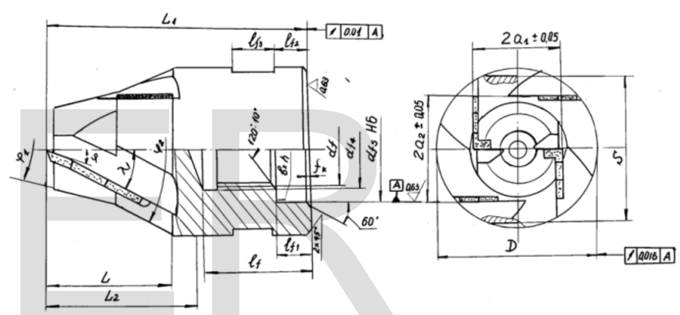

Fig.1 Parametric drawing of a workpiece from a improved modular end mill cutter with hard-blade insert

$$\lambda_1 = arctg\frac{a_1}{b_1} = arctg\frac{21{,}176}{36{,}639} = 30{,}03^o \quad (1)$$

$$\lambda_2 = arctg\frac{a_2}{b_2} = arctg\frac{29{,}763}{37{,}823} = 38{,}20^o \quad (2)$$

Characteristic of these tools is that they have sharp teeth and have cutting edges with a straight profile. The cutting edges are inclined at different angles to the axis of the milling cutter. In such cases, the method of teeth work differs from the method of copying.

The teeth profile in the normal section of gear is reproduced by a straight cutting edge and the rotary motion of the end mill cutter [10],[11].

The profiles of the transition areas of the teeth from gears are realized by the cutting edges of the milling cutter whose profile is a straight line and an arc of a circle with a radius R_b. The front surfaces of the cutting parts are planes [10],[11].

For the individual tooling materials are introduced them characteristic parameters. The input values of the variables necessary for the realization of simulation analyses are shown in tables 1-3 [4],[5].

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Table 1 Specific characteristics of tools materials [8], [9], [10]

Material	Elastic Modulus E [MPa]	Poisson's Ratio	Shear Modulus G [MPa]	Mass Density ρ [kg/m³]	Tensile Strength σ [MPa]
Steel 50	288	0.295	82	8160	998
WC-Co	321	0,25	172	6995	898

Material	Yield Strength [MPa]	Thermal Expansion Coefficient [1/°C]	Thermal Conductivity [W/m.K]	Specific Heat [J/kg.K]
Steel 50	845	11.2	297,15/54	146,85
WC-Co	738	5,98	35,8	39,254

The tool functions in cutting conditions derived through a classical optimization algorithm by parallel solving of two multifactor iterative one-parameter optimizations by facsimile scanning using a nonlinear mathematical programming method fully compliant with a reliable analysis methodology in the theory of cutting materials [13],[14],[15],[17]. The built-in models serve for cases of rough, medium and finishing machining operations of the evolvent profile of a large gears with a module m = 40mm.

The task is to calculate the extremum of a non-linear criterion function (target function) when satisfying a set of technical constraints (factors). They have the operational and technological character.

The temperature is determined according to the cutting speed values empirically (3) [4] and graphically fig.2. The results for cutting conditions and thermal characteristics of the materials are shown in Table 2.

$$\vartheta = 166{,}5.V_c^{\,0{,}23}.a_p^{\,0{,}04}.f^{\,0{,}14}.0{,}822 \qquad (3)$$

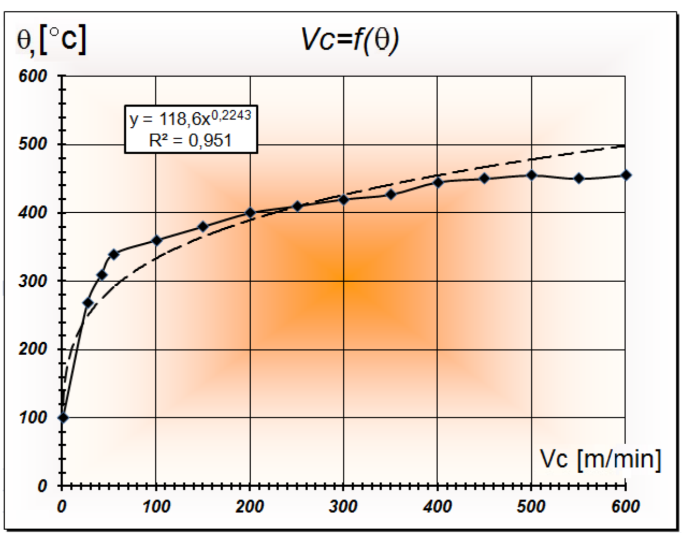

Fig.2 Diagram Vc – θ by gear shaping with improved modular end mill cutter of a large gears with a module m=40mm.

It's done a classical technology for introducing the Minimum Quantity Lubrication (MQL) in cutting zone.

Table 2 Cutting speed and thermal properties of materials [13],[14]

Material	Depth of cut a_p [mm]	Cutting speed Vc [m/min]	Feed f [mm/об]	Temperature of cut ϑ [°C]	Heat transfer coefficient [W/m².K]
Steel 50					
– finishing	6	27	0,32	268	47
– medium	4	42	0,5	310	
– roughing	2	55	0,75	340	
WC-Co					
– finishing	6	27	0,32	268	52
– medium	4	42	0,5	310	
– roughing	2	55	0,75	340	

Because of the low cutting speed at the cutting edge, they are not a prerequisite for structural destruction of the tool due to direct contact with the cooling medium.

The cooling agent is formed as an emulsion of the lubricating-cooling components and is introduced under high pressure into the cutting zone. The tool is cooled and lubricated evenly in terms of direct contact [2].

The simulation model is realized at a constant temperature of the cooling medium θ_{amb} = 20 ° C and represents the contact pattern of the coolant with the tool in the presence of a system of two pulsating nozzles [1],[23]. The system input pressure is P_1 = 5MPa, and output P_2 = 1MPa.

Consequently, in thermal simulations, the cooling model is considered as a forced convection process with convective heat exchange coefficients different from the different types of instrument materials.

The goal of thermal analysis is the study of the distribution of the heat arising in the area of cutting. For each type of instrument material, the temperature field and the temperature gradient are plotted graphically - fig. 3 ÷ 5, b, c.

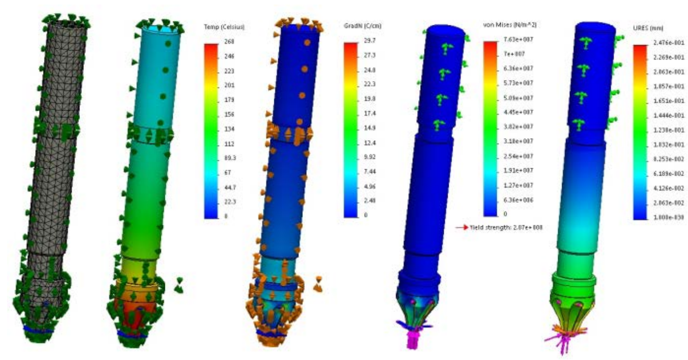

Fig.3 Simulation modeling and analysis of rough processing with improved modular end mill cutter:
a) meshing of the model, b) temperature field, (c) a temperature gradient, d) stress, e) deformation

The analysis was conducted in conditions of stationary, direct conductive heat exchange, limited to the instrument body and a heat exchange border phase in the form of a convective cooling environment (from the fluid simulation apparatus) - Table 1,2 [23],[24].

For each type of treatment in the area around the middle of the part, taking into account the tool temperature close to that of the cooling medium [2]. The highest is the temperature gradient in the tools for finishing processing, and lowest in the rough treatment.

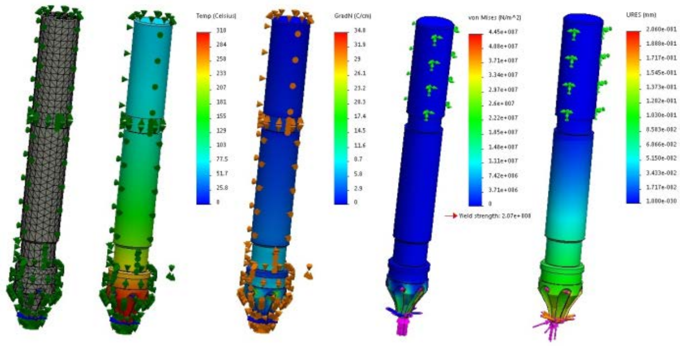

Fig.4 Simulation modeling and analysis of medium processing with improved modular end mill cutter:
a) meshing of the model, b) temperature field, (c) a temperature gradient, d) stress, e) deformation

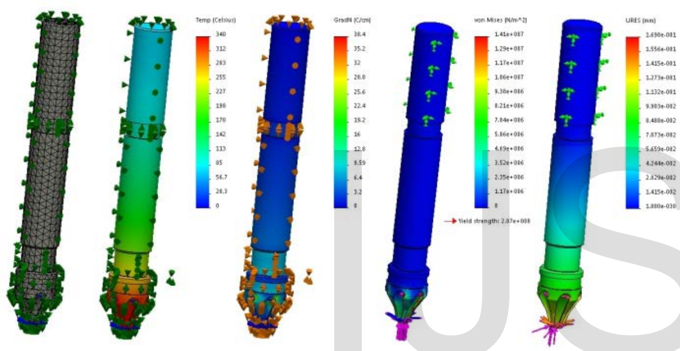

Fig.5 Simulation modeling and analysis of finishing processing with improved modular end mill cutter:
a) meshing of the model, b) temperature field, (c) a temperature gradient, d) stress, e) deformation

For each type of machining operations in the area around the middle of the part, taking into account the instrument temperature close to that of the cooling medium [2]. The highest is the temperature gradient in the tools for clean processing, and lowest in the rough treatment.

The results show, isolines of temperature fields with a significant density near the cutting area, where is the highest thermal load, and the temperature dropped sharply as it moves away from the main cutting edge. For each type of machining, in the area around the centre of the workpiece, is recorded a tool temperature near by this of MQL [2].

The highest is the temperature gradient for tolls for finishing operations, and the lowest for the roughing tool.

The strength - deformation check is carried out with imposed geometric constraints on the instrument, depriving it of all degrees of freedom, with applied force loads - axial F_p[N] and tangential F_c[N] [13],[19],[20],[21]. In addition, data from the realized fluid and thermal simulations is integrated in the analysis, which guarantees the reliability of the results, creating the conditions for maximum approximation of the simulation conditions to the real actual production - fig. 3 ÷ 5, d, e.

Table 3 Force characteristics of tools materials

Material	F_p[N]	F_c[N]	Mesh sizes
WC-Co			
— finishing	125	320	2.122mm/ 0.106mm
— medium		277	
— roughing		216	

The summarized results show that for each group of tools materials, with the same geometric characteristics of the tool, the von Mises - σ[MPa] and the strains URES f [mm] are lower than the maximum permissible. This is a prerequisite for sustainability of the process of cutting and allows for its realization with small value permanent errors. For each type of processing, the areas with emerging maximum stresses are located in the area of the cutting edges, which suffered the most serious force and thermal loads. Therefore, for the tools of this type is provided, use of interchangeable hard-alloy inserts.

On the other hand, the resultant graph of Fig. 6 clearly shows the tendency according to which, even though they suffer the most intense thermal impact, the tools for finishing machining operations, afford a relatively lower load at the lowest deformation.

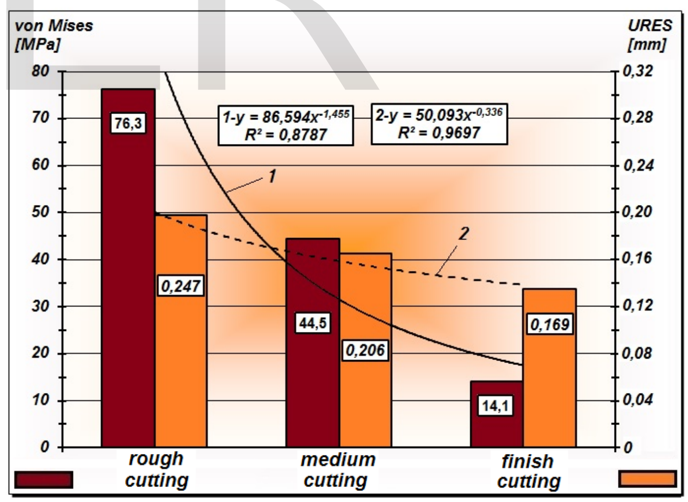

Fig.6 Strength and deformation analysis

3. Conclusions

1. On the basis of the results obtained, regarding to physico-mechanical parameters, thermodynamic characteristics and cutting conditions, have been successfully conducted simulation studies, imitating the real production conditions under which the function improved modular end mill cutter with hard-blade insert for finishing, medium and roughing machining operations of the evolvent profile of a large gears, with a module m = 40mm.

2. It is realized a complex strength and deformation verification by finite element method, analyzing the influence of the different types of tools materials and type of machining operations by introducing characteristic parameters. The results are obtained on the basis of combined power, thermal and fluid simulations.

3. The thermal simulation model is realized in conditions of stationary, direct conductive heat exchange with coefficients different for the different types of instrument materials, limited to the instrument body and a heat exchange border phase in the form of a convective cooling environment.

4. For each case of rough, medium and finishing machining operations, the von Mises bending stresses σ[MPa] and the URES f [mm] deformations are lower than the maximum permissible. This is a prerequisite for the resilience of the cutting process and allows for its realization with small value constant errors.

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