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Original scientific paper

Machining of Spur Gears Using a Special Milling Cutter

Piotr BORAL, Antun STOIĆ, Milan KLJAJIN

Abstract: Spur gears have a wide application in the machine-building industry. Machining process primarily selected for these gears is hobbing method with modular hobs, or with Fellows cutters. Other methods which can be applied are profiling using the pull broaches, while the finishing can be done by gear shaving or grinding by the Maag, Niles or Reishauer methods. Moreover, in small (or unit) production, they may be formed using disc- or finger-type modular cutters. The article presents a method for cutting spur gears using a disc-type mill with a variable cutting plate profile. The influence of the number of blades of the presented milling cutter on the accuracy of the worked tooth profile was investigated.

Keywords: disc-type milling cutter; gear machining; surface roughness

1 INTRODUCTION

The involute profile in spur gears is commonly used and practically adopted by all standards worldwide. The durability and good operating conditions of the toothed gears are largely influenced by the manufacturing accuracy and the structure and roughness of the cooperating surfaces [1-3]. These gears are manufactured using many profiling and hobbing methods [4-7]. They are machined chiefly by the hobbing method with modular hobs or Fellows cutters, or by gear shaving by the MAAG or Sunderland method – Fig. 1. In unit production of gears with large modules, gear wheel teething may be shaped with disc- or finger-type modular mills. The axial profile of the action surface of a modular disc mill corresponds to the profile of the gear wheel inter-tooth cut. This is a curvilinear profile that is dependent on the parameters of the gear wheel being cut (the module, the number of teeth, the profile angle). In order that the blade profile will not change due to sharpening and to obtain the correct clearance angle during machining, these mills, just like all mills with a complex shape, are made with edges turned on the blade face (they are sharpened on the rake face). All mill blades are the same shape and their machining is technologically difficult. These are special, generally expensive tools. Machining is accomplished on special machine tools.

The use of modern multi-axis CNC machine tools and computer-aided design and manufacturing (CAD/CAM) programs provides the capability to make toothed gear wheels using universal tools by the step-by-step method – Fig. 2 [7-10]. The utilization of tools with interchangeable cutting inserts allows the use of high processing parameters, which increases the productivity of the whole manufacturing process [11]. The majority of numerically controlled machine tools are programmed using either universal computer-aided manufacturing (CAM) programs or the author's programs for assisting the preparation of the control code for the machine tool [8-10, 12, 13]. The progress in the machining and building of modern numerically controlled machines and engineering CAx software enables tool trajectories to be freely defined in order to carry out the machining accurately, thus contributing to the development of the toothed gear design and technology.

In numerous scientific research centres and manufacturing companies, gear analysis software is being built to assist the design of the geometry and technology of toothed gears [14-17].

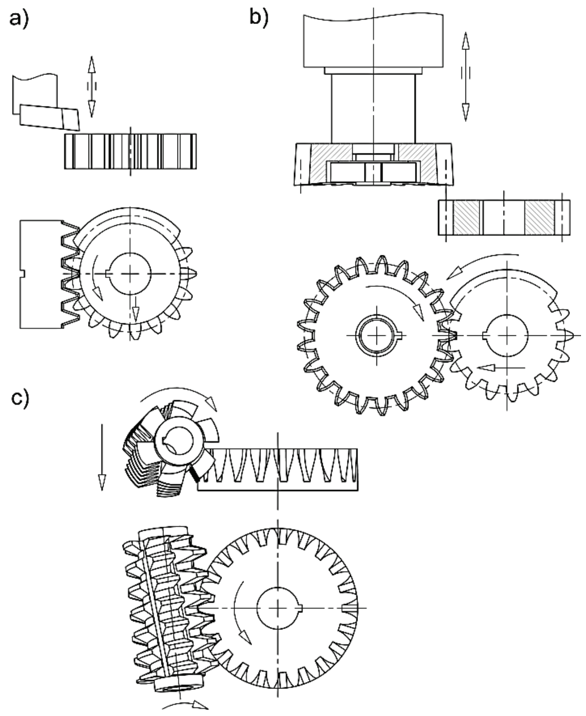

Figure 1 Envelope machining of gear wheel toothing by: a) the Fellows gear shaving method, b) the MAAGgear shaving method, c) hobbing

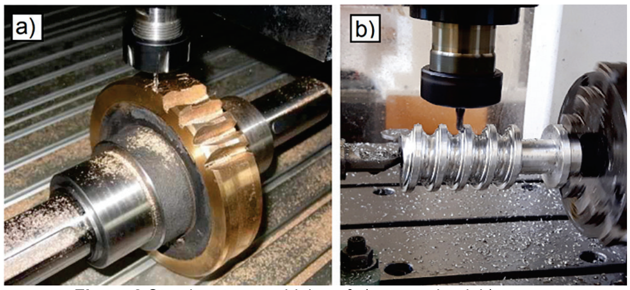

Figure 2 Step-by-step machining of a) worm wheel, b) a worm

The most efficient and accurate gear wheel machining method is machining using the modular hob. Hobs are made in various accuracy classes, while precision hobs (in class AAA) are made as very expensive. In the case of hobs, Fellows cutters, modular disc or finger mills, the cutting edge profiles of all tool blades are identical [4, 18, 19].

The article has taken into consideration a disc milling cutter having blades with a rectilinear cutting edge, but with different profile angles and varying blade widths. Thus the process of relative tool and machined gear wheel turning is contained within the tool's geometry. Gear machining with this mill is efficient and may be carried out on a conventional machine tool.

It was assumed that the machining was done on a toolmaker's milling machine and the tooth outline and surface roughness measurement was taken on a profilometer.

2 DETERMINATION OF THE MILL BLADE PROFILE

In the case of machining a spur gear using a modular hob having a limited number of blades with a rectilinear cutting edge, the tooth profile is the envelope of the family of hob blade profiles [20]. The gear tooth profile obtained as a result of hobbing with a multi-blade tool is a multi-angular profile, instead of representing a mathematically smooth envelope. Each hob blade shapes a tooth profile at the strictly defined point of tangency of the tool profile with the gear tooth profile involute.

The determined points of tangency of the profiles of hob blade cutting edges and the angles of their inclination in the plane perpendicular to the gear wheel axis are the basis for the design of the composite disc mill with replaceable plates. Whereas cutting a gear wheel with a hob must be carried out on a hobbing milling machine or a multi-axial CNC machine tool, in the case of a disc mill, the machining may be accomplished on a three-axis CNC milling machine with an index head, or on a conventional miller.

The involute profile of a gear wheel can be described with the system of equations – Fig. 3a

$$\boldsymbol{r}_\mathrm{e} = r_\mathrm{b}\left[\sin u - u \cdot \cos u, \quad \cos u + u \cdot \sin u\right] \tag{1}$$

where the following designations are adopted

$$r_\mathrm{b} = \frac{z \cdot m}{2} \cos \alpha_0 \tag{2}$$

where: r_b - the radius of the gear wheel base cylinder; u - involute profile parameter.

In the gear wheel positioning system, the tooth profile can be described with the following equation – Fig. 3b

$$\boldsymbol{r} = \begin{bmatrix} \cos\delta & \sin\delta & 0 \\ -\sin\delta & \cos\delta & 0 \\ 0 & 0 & 1 \end{bmatrix} \boldsymbol{r}_\mathrm{e} \tag{3}$$

where:

$$\delta = \frac{\pi}{2z} - \mathrm{inv}\alpha_0 \tag{4}$$

where: δ - the half-angle of the gear wheel cut profile on the base cylinder; m - module; d_2 - pitch diameter; α_0 - profile angle on the pitch diameter.

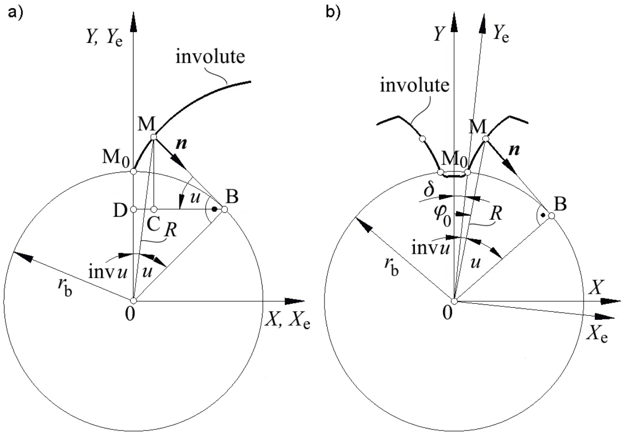

Figure 3 The profile of: a) the involute, b) the gear wheel tooth

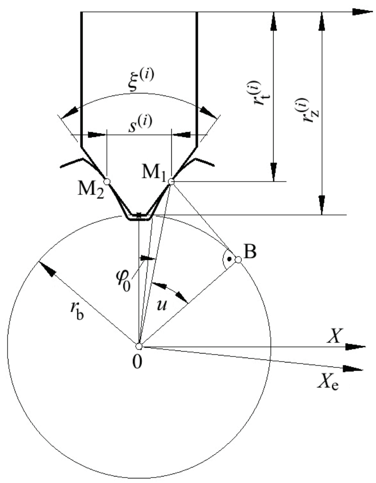

Figure 4 The profile of disc mill teeth

It is assumed that the number of disc mill blades will generally be twice the number of the blades of a conventional modular hob. The blade profiles (profile angles and blade width) can be determined from the condition of the constant profile angularity or assuming equal angles for determining the tooth profile points at the involute height – Fig. 4. For successive involute tooth profile points, the profile angle and the cut width are determined

$$u^{(i)} = (i-1)\frac{\arccos \dfrac{d_\mathrm{b}}{d_\mathrm{a}}}{n-1} \tag{5}$$

$$\xi^{(i)} = 2\left(\delta + \mathrm{inv}\, u^{(i)} + u^{(i)}\right) \tag{6}$$

$$s^{(i)} = \frac{d_\mathrm{b}}{\cos u^{(i)}} \sin\left(\delta + \mathrm{inv}\, u^{(i)}\right) \tag{7}$$

$$r^{(i)} = \frac{d_\mathrm{b}}{\cos u^{(i)}} \cos\left(\delta + \mathrm{inv}\, u^{(i)}\right) \tag{8}$$

where: n - the number of profile points; i - profile point number; ξ - gear wheel cut profile angle (the profile angle of the tool for forming the tooth profile at a preset point); s - cut width at a preset profile point (the width of the tool for forming the tooth profile at a preset point); (i) - gear wheel tooth profile point identification index; r - distance from the gear wheel axis to the chord connecting computational points on the tooth profile.

The following transmission gear with involute tooth-profile spurs gears was adopted: the module, $m = 4.5$ mm; the number of gear wheel teeth, $z = 15$; the profile angle, $\alpha_0 = 20°$.

The computation results: the pitch diameter, $d_2 = 67{,}5$ mm; the base circle diameter, $d_b = 63.429$ mm; the addendum diameter, $d_a = 76.5$ mm; inv $\alpha_0 = 0.0149044$; $\delta = 0.089815$; – Fig. 5.

m = 4.5 z = 15 α = 20

db = 63.4293 d2 = 67.5 da = 76.5

	u	u[deg]	invu	angle	s	t
1	0.000	0.000	0.000	10.292	5.689	31.587
2	0.066	3.777	0.000	17.856	5.708	31.655
3	0.132	7.553	0.001	25.487	5.788	31.861
4	0.198	11.330	0.003	33.252	5.971	32.207
5	0.264	15.106	0.006	41.225	6.304	32.698
6	0.330	18.883	0.012	49.488	6.845	33.343
7	0.395	22.660	0.022	58.132	7.669	34.153
8	0.461	26.436	0.036	67.266	8.874	35.139
9	0.527	30.213	0.055	77.020	10.592	36.316
10	0.593	33.989	0.081	87.554	13.005	37.693

Figure 5 The geometric parameters of disc mill blades

Based on the computed parameters, a disc mill intended for cutting a gear wheel with the parameters defined above has been designed, while assuming 10 blades with rectilinear cutting edges, satisfying the condition of the tangency of the tool profile with the gear wheel tooth profile involution – Fig. 6.

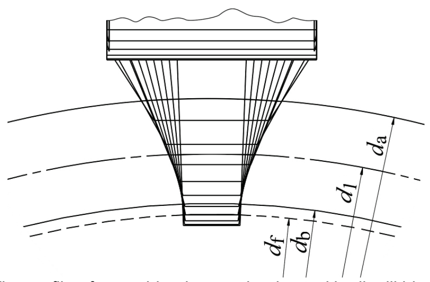

Figure 6 The profile of a machined gear wheel cut with all mill blades applied

Figure 7 The housing of a replaceable blade mill

The process of gear wheel tooth profile formation results from the proper distribution of varying-profile plates on the mill perimeter. As in the case of the modular disc mill, the cutting motion is composed of mill rotary motion and translational motion along the gear wheel inter-tooth cut.

To verify the proposed solution, a mill casing with interchangeable blades was designed – Fig. 7.

Then, cuts were made in a gear wheel with the same geometrical parameters, but with different numbers of blades – Fig. 8. The machining tests were carried out with 8 blades, 10 blades and 12 blades, respectively.

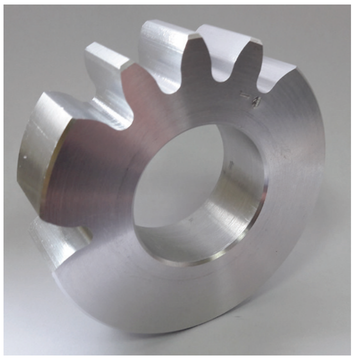

Figure 8 Spur gear machined during the test, the module m=4.5mm, the number of gear wheel teeth z=15

3 SURFACE ROUGHNESS AND TOOTH OUTLINE EXAMINATION

The measurement of the tooth profile, roughness and topography of the machined gear wheel surfaces was taken using a Taylor Hobson New Form Talysurf 120 – 2D/3D profilometer, while for the presentation of the data in the form of the diagrams below – Figs. 9 ÷ 11, the TalyMap Platinum software was employed.

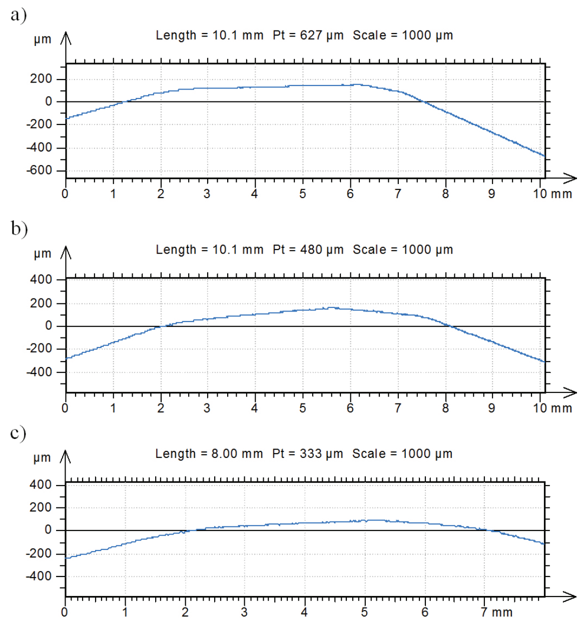

Figure 9 The angularity of the tooth profile of a gear wheel machined with a mill having:a) 8 blades, b) 10 blades, c) 12 blades.

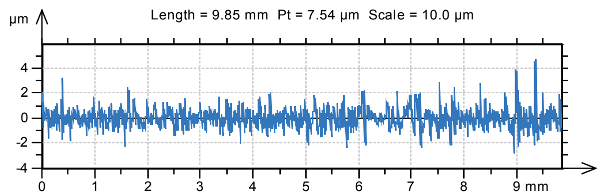

Figure 10 Surface roughness on the gear wheel length

The smoothness of the surface in the gear wheel tooth line direction depends on the feed – Fig. 10. The feed along the tooth line influences the machining performance. The tooth surface topography is similar to that obtained from hobbing with a modular hob and favours a good lubrication of the mating gear wheel tooth surfaces – Fig. 11.

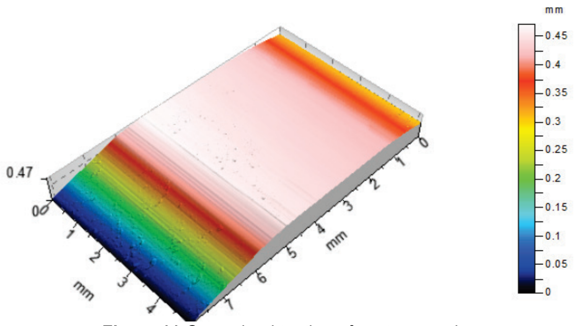

Figure 11 Gear wheel tooth surface topography

The angularity (smoothness) of the gear wheel profile depends on the number of mill blades – Fig. 9. In case 10 mill blades are used, the maximum deviation of the machined profile relative to the involute is 30μm.

4 CONCLUSION

Modular disk cutters are used for machining of spur gears with a form-shaped method. The axial profile of the acting surface of the rotary modular milling cutter is a curvilinear with blades of the same shape. During the work of such tools there is a high load because each of the blades cuts the entire length of the cutting edge. This causes vibrations, worsening the smoothness of the surface being machined.

The presented cutter of the new construction allows for easy modification of the wheel outline and increases the accuracy of the profile. The cutter is characterized by the fact that the cutting blades (cutting inserts) are rectilinear, have the shape of an isosceles trapezoid with different side sizes and different contour angles. The angle of the lateral cutting edges of each subsequent blade is greater than the angle of the lateral cutting edges of the previous blade. The distance from the axis of rotation of the milling cutter for the next cutting blades and their dimensions are selected in the sequence allowing for obtaining the full assumed outline of the machined toothed wheel. Thanks to the fact that each blade has a different width and angle profile, the appropriate cutting layer takes place. The tool's operation is more stable and uniform (there are less vibrations).

Thanks to the use of replaceable carbide inserts, much higher cutting speeds can be used compared to classic monolithic high speed steel cutters, by which the performance and durability of such tools is much greater.

In the case of machining of curvilinear outline surface with a straight-cut tool with straight cutting edges, the obtained surface profile is not smooth.

The resulting outline consists of a specified number of straight sections equal to the number of blades involved in machining.

Based on the above-described tests of machining of gears with the same geometrical parameters, made with tools with different number of blades, deviations of the gear tooth profile from involute outline were respectively: for spur gear made with a cutter with 8 blades - maximum deviation 40 μm, 10 blades – 30 μm, 12 blades – 22 μm, 14 blades – 17 μm.

The obtained surface roughness of the tooth lateral surface, expressed in the R_z parameter, was 4,0÷5,75 μm. During the measurement, the measuring tip moved radially along the axial cross-section of the tooth.

The roughness of the machined surface was also checked by moving the measuring tip along the tooth line. The value of the obtained roughness, expressed in the R_z parameter, was 1,93 ÷ 2,58 μm.

Theoretical calculations show that the deviations of the maximum tooth profile from the involute outline for the number of blades used are respectively: for spur gear made with a cutter with 8 blades - maximum deviation 33,444 μm, 10 blades - 20,807 μm, 12 blades - 14,449 μm, 14 blades - 10.439 μm. 16 blades – deviation 7,959 μm.

The presented measurements show compliance with the increase in the conformity of the shape of the axial profile of the gear tooth with theoretical calculations along with the increase in the number of cutter blades. The deviations resulting from the machining are greater than the deviations obtained analytically.

These discrepancies result from the difficult working conditions of the tool (high cutting resistance, intermittent operation) and the accuracy of setting individual blades in relation to each other.

In the presented research, the machining of the gear tooth was made using a single-edged tool with replaceable blades - Fig. 7, operating in a specific order, allowing to obtain the assumed outline. The use of a stiffer tool body, in which all the blades are placed working simultaneously, will increase the accuracy.

With an increased number of disc mill blades, the accuracy of the machined gear tooth surface increases.

Nevertheless, it can be seen that in the considered case of machining a wheel with the parameters set above, adding higher number of blades does not cause a significant increase in accuracy.

The developed disc milling cutter is convenient for use, because it can be used either on a conventional milling machine or on a three-axis CNC milling machine with an indexable head.

Unlike, for example, the method of hobbing with a modular hob, in the case under consideration no gear tooth undercutting occurs with a small number of teeth. It is, therefore, very easy to modify the gear tooth profile by only changing, for instance, the plate profile angle.

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Contact information:

Piotr BORAL, PhD Eng.
Czestochowa Univertsity of Technology
Ul. Dąbrowskiego 69, 42-201 Częstochowa, Poland
E-mail: piotrek@itm.pcz.pl

Antun STOIĆ, Full Prof. PhD
Mechanical Engineering Faculty,
J. J. Strossmayer Univertsity of Osijek,
Trg Ivane Brlić Mažuranić 2, HR-35000 Slavonski Brod, Croatia
E-mail: 2.antun.stoic@gmail.com

Milan KLJAJIN, Full Prof. PhD
Mechanical Engineering Faculty,
J. J. Strossmayer Univertsity of Osijek,
Trg Ivane Brlić Mažuranić 2, HR-35000 Slavonski Brod, Croatia
E-mail: mkljajin@sfsb.hr

University North,
University Center Varaždin
Jurja Križanića 31b
42000 Varaždin, Croatia
E-mail: mkljajin@unin.hr