Modelling of teeth of a gear transmission for modern manufacturing technologies

Z Monica 1, W Banaś 2, G Ćwikła 3, and S Topolska 4
1,2,3 Silesian University of Technology, Faculty of Mechanical Engineering, Institute of Engineering Processes Automation and Integrated Manufacturing Systems
Konarskiego 18A, 44-100 Gliwice, Poland
4 Silesian University of Technology, Faculty of Mechanical Engineering, Institute of Engineering Materials and Biomaterials
Konarskiego 18A, 44-100 Gliwice, Poland

E-mail: zbigniew.monica@polsl.pl

Abstract. The technological process of manufacturing of gear wheels is influenced by many factors. It is designated depending on the type of material from which the gear is to be produced, its heat treatment parameters, the required accuracy, the geometrical form and the modifications of the tooth. Therefore the parameters selection process is not easy and moreover it is unambiguous. Another important stage of the technological process is the selection of appropriate tools to properly machine teeth in the operations of both roughing and finishing. In the presented work the focus is put first of all on modern production methods of gears using technologically advanced instruments in comparison with conventional tools. Conventional processing tools such as gear hobbing cutters or Fellows gear-shaper cutters are used from the beginning of the machines for the production of gear wheels. With the development of technology and the creation of CNC machines designated for machining of gears wheel it was also developed the manufacturing technology as well as the design knowledge concerning the technological tools. Leading manufacturers of cutting tools extended the range of tools designated for machining of gears on the so-called hobbing cutters with inserted cemented carbide tips. The same have been introduced to Fellows gear-shaper cutters. The results of tests show that it is advantageous to use hobbing cutters with inserted cemented carbide tips for milling gear wheels with a high number of teeth, where the time gains are very high, in relation to the use of conventional milling cutters.

1. Introduction
The subject of this study is included in the fourth part of business management, i.e. the analysis of finances. The work is designed to develop a system of assessments and indicators of a general nature that will allow us to estimate, at the planning stage, the possible costs of future implementation. This is particularly important for companies that procure production orders by tender. Thus, the accuracy of defining the tender determines the magnitude of the potential profit or loss.

In the case of cost management itself, you can also point to the existence of a similar dependency system [1-6]. Accurate determination is associated with the establishment of similarity parameters that will allow estimating the cost of new production orders based on previous experience. It must also refer to an existing machine park. For example, if medium-sized items have been implemented so far with new orders for large items, you need to have indicators to estimate the possible increase in costs.
associated with a change in size. Accurate estimation of this type is possible only on the basis of experimental indices and designation of an appropriate extrapolation method. This paper presents only a technological part of this process related to the determination of technological parameters as comparative for a narrow but very specialized technological group such as toothed wheels. A comparison of basic technological processes was included. The purpose of these preliminary, baseline studies was to obtain information on the estimation of gear machining costs, new types of tools and new machining centers, which in some cases can be treated as alternatives.

2. Analysis of machining tools
In the classic approach, in the case of toothed gears, screw mills are used, in case of mass production or Fellows, in the case of smaller scale production or in the case of atypical dentition. Technological advances in production technology have resulted in the creation of CNC machines that allow for repetitive execution of much more complex technological procedures and tools to increase the productivity of existing production systems. In addition to high-speed steel (introduced by Taylor), the modular tools have also been introduced to increase productivity with higher speeds and feed rates, while retaining the same level of quality. Thanks to interchangeable modules, the life of such tools is considerably longer, which results in lower costs. Examples of such tools include, but are not limited to, screw mills for interchangeable carbide inserts or Fellows chisel for carbide inserts. The following is a construction of a conventional milling cutter (figure 1).

![Figure 1. Conventional cutter [7].](image1)

Contemporary milling cutters, with modular construction, are segmented. They consist of a core with a hollow spiral and a number of segments attached to the core. They form milling rolls. These segments have tool plates (figure 2).

![Figure 2. Modular cutter [7].](image2)
3. Conducted experiments
In order to estimate the cost of milling operations using segmented tools compared to the costs of classical milling of the dentition, a comparative experiment should be performed. This will allow you to compare the envelope milling parameters using a conventional monolithic screw milling cutter made from high speed HSS steel with segmented worm cutter, which uses cemented carbide exchange plates. The experiment was carried out on a CNC-bound hedge milling machine. The experiment consisted of two short series of gear wheels (10 units) for two types (small diameter wheel with large diameter wheels). These wheels were made of the same material. They are constituent components of the planetary gear. The parameters of the milling process are given below (Table 1).

| Number of effective teeth | Parameters | Wheel 1 | Wheel 2 |
|---------------------------|------------|---------|---------|
| Conventional cutter       | feed Fz mm/rev | 0.6   | 0.6   |
|                           | cutting speed Vc m/min | 21 | 21 |
| Module cutter             | feed Fz mm/rev | 0.6   | 0.6   |
|                           | cutting speed Vc m/min | 21 | 21 |

For such parameters, a production experiment was conducted to determine the correctness of the process. As a result of the experiment it was found that from the wheel made with the conventional milling cutter from No. 5 show too high the value of the theoretical chip thickness parameter (last line in Table 2).

| Parameters | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|------------|---|---|---|---|---|---|---|---|---|----|
| Conventional cutter feed Fz mm/rev | 0.60 | 0.72 | 0.86 | 1.04 | 1.24 | 1.49 | 1.79 | 2.15 | 2.58 | 3.10 |
| cutting speed Vc m/min | 21 | 27.3 | 35.49 | 46.14 | 59.98 | 77.97 | 101.4 | 131.8 | 171.3 | 222.7 |
| theoretic chip thickness Hz mm | 0.2 | 0.22 | 0.24 | 0.265 | 0.29 | 0.318 | 0.35 | 0.383 | 0.421 | 0.462 |

| Parameters | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|------------|---|---|---|---|---|---|---|---|---|----|
| Module cutter feed Fz mm/rev | 0.60 | 0.72 | 0.86 | 1.04 | 1.24 | 1.49 | 1.79 | 2.15 | 2.58 | 3.10 |
| cutting speed Vc m/min | 21 | 27.3 | 35.49 | 46.14 | 59.98 | 77.97 | 101.4 | 131.8 | 171.3 | 222.7 |
| theoretic chip thickness Hz mm | 0.1 | 0.115 | 0.126 | 0.139 | 0.152 | 0.167 | 0.184 | 0.202 | 0.221 | 0.243 |

The chip thickness limit was determined by the Hoffmesiter formula. According to this relationship it is ~ 0.25 for conventional mills and ~ 0.25 for segment mills. It should be noted that the theoretical
value of chip thickness is a determinant of correct selection of technological parameters. Therefore, the milling process parameters for conventional milling were corrected, as shown in Table 3.

**Table 3. Correction of milling process parameters for conventional milling cutter**

| Parameters | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 |
|------------|----|----|----|----|----|----|----|----|----|----|
| feed \( F_z \) mm/rev | 0.60 | 0.72 | 0.86 | 1.04 | 0.86 | 0.86 | 0.86 | 0.86 | 0.86 |
| cutting speed \( V_c \) m/min | 21 | 27.3 | 35.49 | 46.14 | 35.49 | 35.49 | 35.49 | 35.49 | 35.49 |
| theoretic chip thickness mm | 0.2 | 0.2 | 0.22 | 0.24 | 0.265 | 0.24 | 0.24 | 0.24 | 0.24 |

A similar study was conducted for the type 2 wheel, that is, large diameter wheels and a much larger number of teeth. The tooth module for the two types of wheels is the same. This generally means the same size of the teeth themselves. Testing of a wheel of a different type but with the same tooth module allows determining the comparative parameters for the machining process with the same cutter. Results are presented in Tab. 4.

**Table 4. Parameters of the milling process during the experiment for a type 2 wheel**

| Parameters | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 |
|------------|----|----|----|----|----|----|----|----|----|----|
| feed \( F_z \) mm/rev | 0.60 | 0.72 | 0.86 | 1.04 | 1.24 | 1.49 | 1.79 | 2.15 | 2.58 | 3.10 |
| cutting speed \( V_c \) m/min | 21 | 27.3 | 35.49 | 46.14 | 59.98 | 77.97 | 101.4 | 131.8 | 171.3 | 222.7 |
| theoretic chip thickness mm | 0.278 | 0.305 | 0.334 | 0.368 | 0.402 | 0.442 | 0.485 | 0.533 | 0.585 | 0.643 |

As in the first case, it was necessary to adjust the machining parameters. The machined processing times have been measured for the machined processing parameters. The results are given in Tables 5 and 6. Cutting times depend primarily on the cutting parameters adopted in the experiment. It should be noted that regardless of their value, the ultimate goal was to obtain toothed wheels that meet quality standards and are suitable for use.
Table 5. Parameters of the milling process during the experiment for the type 1 wheel

| Parameters | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|------------|---|---|---|---|---|---|---|---|---|----|
| Conventional cutter | | | | | | | | | | |
| feed $F_z$ mm/rev | 0.60 | 0.72 | 0.86 | 1.04 | 0.86 | 0.86 | 0.86 | 0.86 | 0.86 | 0.86 |
| cutting speed $V_c$ m/min | 21 | 27.3 | 35.49 | 46.14 | 35.49 | 35.49 | 35.49 | 35.49 | 35.49 | 35.49 |
| milling time min | 226 | 145 | 93 | 59 | 93 | 93 | 93 | 93 | 93 | 93 |

| Parameters | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|------------|---|---|---|---|---|---|---|---|---|----|
| Module cutter | | | | | | | | | | |
| feed $F_z$ mm/rev | 0.60 | 0.72 | 0.86 | 1.04 | 1.24 | 1.49 | 1.79 | 2.15 | 2.58 | 3.10 |
| cutting speed $V_c$ m/min | 21 | 27.3 | 35.49 | 46.14 | 59.98 | 77.97 | 101.4 | 131.8 | 171.3 | 222.7 |
| milling time min | 359 | 230 | 148 | 94 | 61 | 39 | 25 | 16 | 10 | 7 |

Table 6. Parameters of the milling process during the experiment for a type 2 wheel

| Parameters | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|------------|---|---|---|---|---|---|---|---|---|----|
| Conventional cutter | | | | | | | | | | |
| feed $F_z$ mm/rev | 0.60 | 0.60 | 0.60 | 0.60 | 0.60 | 0.60 | 0.60 | 0.60 | 0.60 | 0.60 |
| cutting speed $V_c$ m/min | 21 | 27.3 | 35.49 | 35.5 | 35.5 | 35.5 | 35.5 | 35.5 | 35.5 | 35.5 |
| milling time min | 123 | 95 | 73 | 73 | 73 | 73 | 73 | 73 | 73 | 73 |

| Parameters | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|------------|---|---|---|---|---|---|---|---|---|----|
| Module cutter | | | | | | | | | | |
| feed $F_z$ mm/rev | 0.60 | 0.72 | 0.86 | 1.04 | 1.24 | 1.49 | 1.79 | 2.15 | 2.58 | 3.10 |
| cutting speed $V_c$ m/min | 21 | 27.3 | 35.49 | 46.14 | 59.98 | 77.97 | 101.4 | 131.8 | 171.3 | 222.7 |
| milling time min | 196 | 125 | 81 | 51 | 33 | 21 | 14 | 9 | X | X |

By analyzing the results, it can be concluded that milling with low-end cutters is not advantageous in terms of total machining time. Shortening of the machining time can be seen only with the machining parameters of the sample 5. The increase of the machining time gives a lower standard of
time. It should be noted that the high time for the first samples also results from the process of adjusting the processing time to the normative time.

A similar arrangement of machining times is observed for the wheel 2. The machining time reduction, in this case, is observed for the gear milling parameters (sample) 4. The results are shown in Figure 7. The results for samples 9 and 10 are the result repeat for the sample 8, because this sample has reached the process temperature limit values. The coolant cooling system was not able to cool the milled element with more visibility.

4. Conclusions
In the case of machining a gear wheel of a small number of gear teeth and relatively wide tooth space it seems reasonable to use the interlocking cutter. The comparison of hobbing cutters with inserted cemented carbide tips with conventional, monolithic cutters shows that the higher the number of gear teeth of a machine gear wheel the more profitable is to use the hobbing cutter with inserted tips. For this reason, the parameter that should be taken into account when choosing between cutters with or without tips is the size of production series of gears and the size of the gear wheel itself. Additionally analyzing the application of supporting CAM programs one should state that is uneconomical to use them for universal milling stations due to the use of large amounts of tools, while obtaining times corresponding to the processing times on specialized gear-milling stations. However, one advantage of this approach is the ability to manufacture various gears, various modules, various pressure angles etc.

The subject of this paper was to present the idea of experimental analysis of gears working time as an element of estimating productivity of production system and as a basis for estimating production costs. The purpose of this approach is to build more reliable business models for strategic approaches, especially with regard to estimating the cost of potential production. Hence, this study included a general analysis of business model issues, including cost issues. In contrast, the basic level of work presents characteristics of two experiments aimed at estimating production times. At this stage, the assumption about proportionality between the time of production and costs is assumed. Such an assumption can be considered sufficient for a traditional accounting formula based on averaged cost values. An additional element limiting the scope of the subject matter is to include in this presentation only issues related to external machining of the milling method. However, it should be emphasized that this type of manufacturing technology and this type of dentition are the most common.

5. References
[1] Ociepka P and Herbuś K 2016 Application of the CBR method for adding the process of cutting tools and parameters selection IOP Conf Ser: Mater Sci Eng 145 022029
[2] Monica Z 2015 Virtual modelling of components of a production system as the tool of lean engineering IOP Conf Series: Mater Sci Eng 95 012109
[3] Banaś W, Sękala A, Foit K, Gwiazda A, Hryniewicz P, Kost G  2015 The modular design of robotic workcells in a flexible production line IOP Conf Series: Mater Sci Eng 95 012099
[4] Golda G and Kampa A 2014 Modelling of cutting force and robot load during machining Adv. Mater. Res. 1036 715
[5] Kalinowski K, Zemczak M  2015 Preparatory Stages of the Production Scheduling of Complex and Multivariant Products Structures Advances in Intelligent Systems and Computing 368 475
[6] Ćwikła G and Foit K 2017 Problems of integration of a manufacturing system with the business area of a company on the example of the Integrated Manufacturing Systems Laboratory MATEC Web of Conferences 94, UNSP 06004
[7] LMT FETTE 2016 Gear cutting tools and knowledge Schwarzenbek