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MACHINING STRATEGIES FOR GEAR CUTTING WITH DISC-SHAPED MILLING TOOLS

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СТРАТЕГИИ ОБРАБОТКИ ЗУБЧАТЫХ КОЛЕС ДИСКОВЫМИ ФРЕЗАМИ

Purpose. Classification of different machining strategies underlying the known methods for gear cutting with disc-shaped milling tools as well as preliminary determination of their advantages and disadvantages before profound studies by simulations and experiments.
Design/methodology/approach. This paper is concerned with the analysis of the different methods for gear cutting with disc-shaped milling tools in order to determine their advantages or disadvantages in terms of flexibility, productivity and machining quality as well as to make a classification of the machining strategies underlying these methods.
Findings. By analyzing the gear cutting methods, it was found that they differ in strategies for material removal, tool movement and tool engagement. These strategies define advantages or disadvantages of the machining methods as well as their optimal application areas. Further, it was shown that some of the gear cutting methods are based on similar or even the same machining strategies.
Originality/value. The results of the analysis show that none of the known methods for gear cutting with disc-shaped milling tools is universally applicable. Some of them provide a higher productivity and flexibility, and the others – a better machining quality. It means that, in order to select a perfectly suitable machining method with the optimal process parameters for each individual manufacturing task and thereby to increase the efficiency of the gear manufacturing, the profound knowledge about achievable productivity, flexibility and quality parameters are required. The proposed classification of the machining strategies underlying the gear cutting methods creates a basis for further theoretical and experimental studies of the mentioned parameters.
Keywords: gear cutting; disc-shaped milling tool; machining strategy

Introduction

Gears are the most important and most common machine components used to transfer the mechanic power and motion, to change the kinematic and dynamic characteristics, to provide a certain position of the input and output shafts etc. **Ошибка! Источник ссылки не найден.**, 2, 3. Depending on the tasks to be fulfilled by them, gears can vary widely by geometric parameters (number of teeth, tooth alignment, flank line, profile shape), gear quality (tooth profile, flank line and pitch accuracy and surface roughness) and material properties (hardness, weight, corrosion resistance) 3, 4.

For an efficient single and small batch production of different gears, flexible manufacturing technologies which can be implemented by using conventional machines and cutting tools are required. Examples of these technologies are profile-independent cutting processes, such as the gear cutting with shank and disc milling tools (see Fig. 1), which are characterized by a loose connection between the tool and tooth profile 5, 6.

When comparing the gear machining with shaft and disc milling tools, the second one (see Fig. 1 b) seems to be less flexible due to the required run-out for cutting tools. On the other hand, this method is characterized by shorter

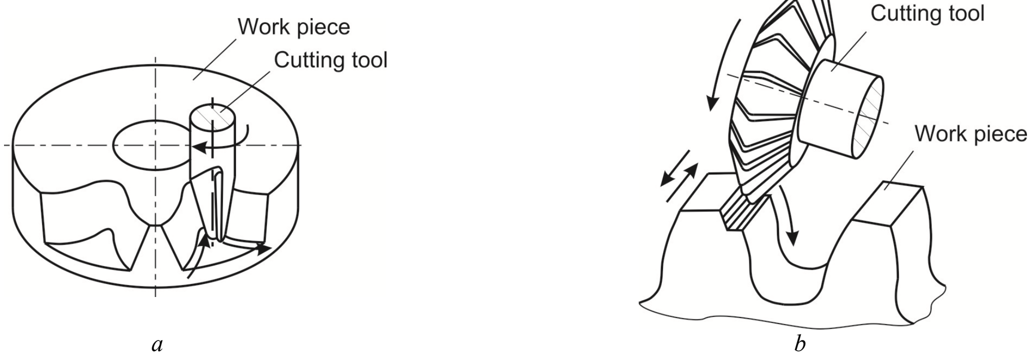

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Fig. 1. Gear machining with shank and disc milling cutters according to Roth 6

production times and a longer tool life, because the disc tools compared to the shaft tools have a higher stiffness and a greater number of cutting teeth.

Therefore, the gear cutting with disc milling tools provides more possibilities for an increase in productivity and a reduction in costs 5, 6, 7. For these reasons, this machining process became more and more important nowadays.

In the last decades, various methods for the gear cutting with disc-shaped tools have been developed by scientists and engineers from all over the world, such as Koganov 5, Roth 6, Blagut 8, Jankevich 9, Nesterov 10, Wermeister 11, Zipse 12. After their development, some of these gear cutting methods were successfully implemented on the conventional machining centers (see Fig. 2) 7, 11, 12.

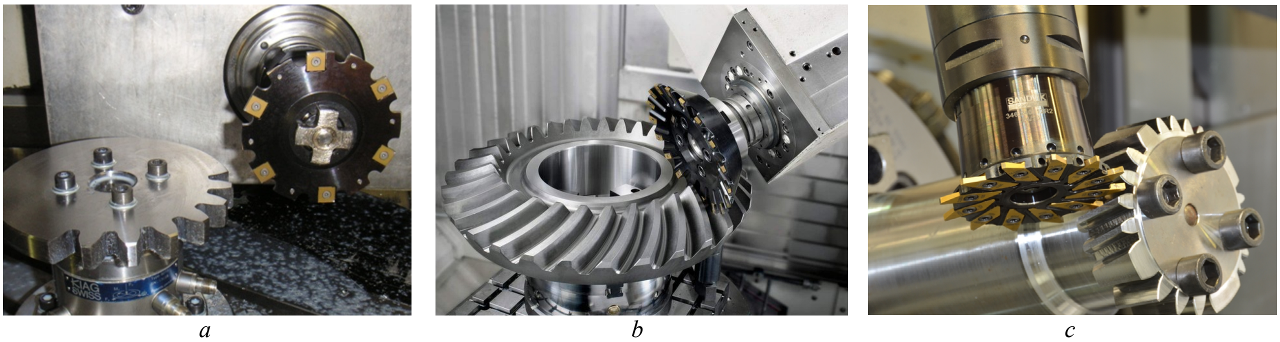
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Fig. 2: Implementation of gear cutting with disc-shaped milling tools: a) IfW, b) Heller; c) Sandvik 7, 11, 12

Since 2005, the focus of research at the Institute of Mechanical Engineering of the National Technical University of Ukraine “Kyiv Polytechnic Institute” and at the Institute for Machine Tools at the University of Stuttgart is on the gear cutting with disc milling tools. At the both research facilities, numerous theoretical and experimental investigations of the Koganov’s gear cutting process 5 have already been carried out within the framework of a cooperation agreement.

Firstly, a mathematical model of the form-shaping kinematics (movements of the tool relative to the work piece) was developed for the simulation of the manufacturing process 13. After that, trajectories, velocities and accelerations of the machine tool components as well as material removal rates when machining of spur gears were calculated by using this mathematical model 14, 15, 16.

Furthermore, experiments were conducted for gear cutting with disc milling tools on an available 4-axis machining center Hermle UFW 1202 (see Fig. 2) 7, 17. Here, tooth gaps of different profiles were machined with a carbide disc milling cutter according to the Koganov’s method 5. At the same time, dynamic process characteristics, namely components of the cutting force, were measured by means of a measuring chain built-up inside the machine tool. By analyzing the obtained data, new ways for process optimization were proposed 17.

Research objective

The results of the studies conducted at both research facilities show that the Koganov’s method has certain advantages and disadvantages which define its optimal application area (gear type, geometric parameters, batch size etc.). The same is valid for the other methods of gear cutting with disc-shaped tools. The exact knowledge of their advantages and disadvantages would allow to select a perfectly suitable machining method with the optimal process parameters for each manufacturing task (a batch of gears with pre-defined parameters) and thereby to increase the efficiency of the gear manufacturing as much as possible. To gain this knowledge, all known methods for gear cutting with disc tools have to be deeply studied with regard to the achievable machining quality, productivity and flexibility. For this purpose, firstly, they are to be analyzed and classified with respect to the underlying machining strategies. In this way, on the one hand, some advantages and disadvantages of each gear cutting method can be determined. On the other hand, the range of the subsequent investigations can be reduced, since some individual methods are based on similar or even the same machining strategies.

The present paper is dedicated to the analysis and classification of the known methods for gear cutting with disc milling tools as well as the discussion of their advantages and disadvantages.

Strategies for gear machining with disc-shaped milling tools

As mentioned before, there are many methods for gear cutting with disc milling tools. They fundamentally differ by underlying machining strategies or relative movements of the tool and work piece during machining.

When gear cutting according to Roth (see Fig. 1) [6] and Zipse (also known as the uP-gear method of Heller Maschinenfabrik – see Fig. 2 b) [12], the tooth gap is generated by a combination of reciprocating movements of the tool along the flank line and its periodic adjustment movement along the tooth gap profile. A simplified representation of the corresponding strategy for material removal is shown in Fig. 3 a. The adjustment movement of the tool along the tooth gap profile can be carried out in two different directions: either from the tooth tip to the tooth root (see Fig. 4 a) or vice versa (see Fig. 4 b). In the first case, the tool runs into the tooth gap and cuts the work piece material primarily with the main cutting edge. In the second case – vice versa – it runs out from the tooth gap and cuts primarily with the secondary cutting edge. To shorten the tool adjustment paths, one tooth flank is usually machined by the running-in of the tool and the opposite flank by its running-out.

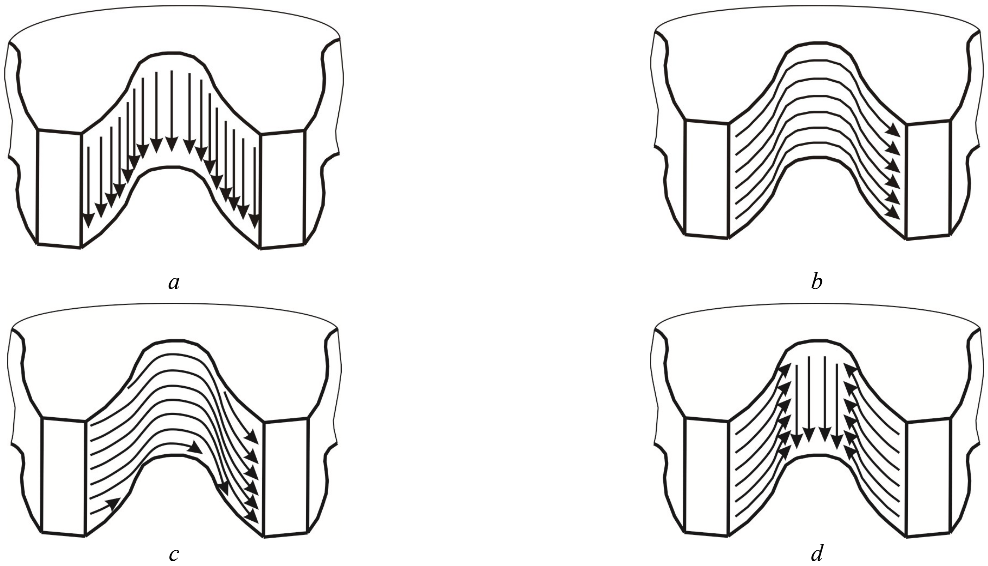
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Fig. 3. Strategies for material removal when machining the tooth gap

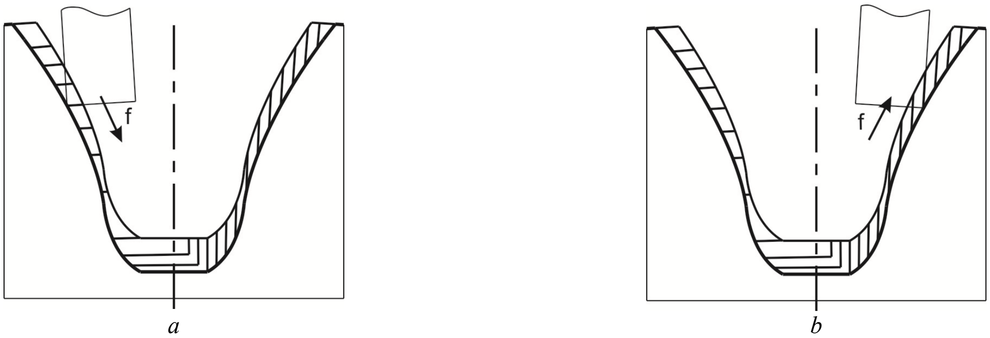

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Fig. 4. Strategies for tool movement when machining the tooth flanks

When machining according to Koganov [5], the tooth gap is generated – on the contrary to the previous method – by a composition of a continuous feed movement of the tool along the tooth gap profile and its periodic adjustment movement along the flank line (see Fig. 3 b). One tooth flank is machined by the running-in of the tool (see Fig. 4 a) and the opposite one by its running-out (see Fig. 4 b).

When gear cutting according to Blagut and Jankevich, the work piece material is simultaneously removed along the flank line and the tooth gap profile 8, 9. The tooth gap is generated by a continuous feed movement of the tool in both directions (see Fig. 3 c). As in the previous cases, one tooth flank is machined by the running-in of the tool (see Fig. 4 a) and the opposite one by its running-out (see Fig. 4 b).

When machining according to Nesterov 10 and Wermeister (also known as the Invomilling process of Sandvik Coromant – see Fig. 2 b) 11, each tooth gap is generated in several successive steps (see Fig. 5). The material removal is separately carried out along the flank line and the tooth gap profile (see Fig. 3 d). First, the tooth gap bottom is pre-machined in one or three steps (see Figures 1, 2 and 3 in Figure 5) along the flank line similar to the Roth's method. After that, the tooth flanks are sequentially generated along their profiles similar to the Koganov's method.

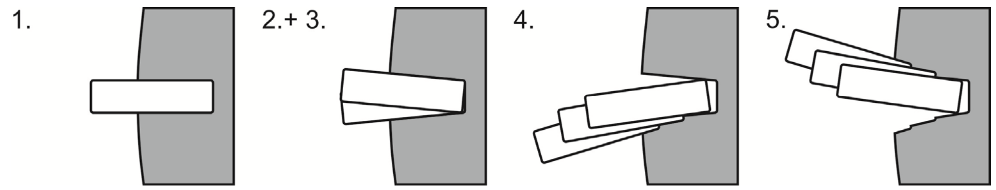

Fig. 5. Gear machining with disc milling cutters according to Wermeister 11

In addition to the strategies for material removal (see Fig. 3) and for tool movement (see Fig. 4), the known methods for gear cutting with disc milling tools also differ in strategies for tool engagement. As for example, the symmetry axis of the disc tool can run either through the center of the work piece (see Fig. 6 a) or under a certain constant angle to the tooth flank profile (see Fig. 6 b). In the second case, it usually runs tangential to the tooth flank.

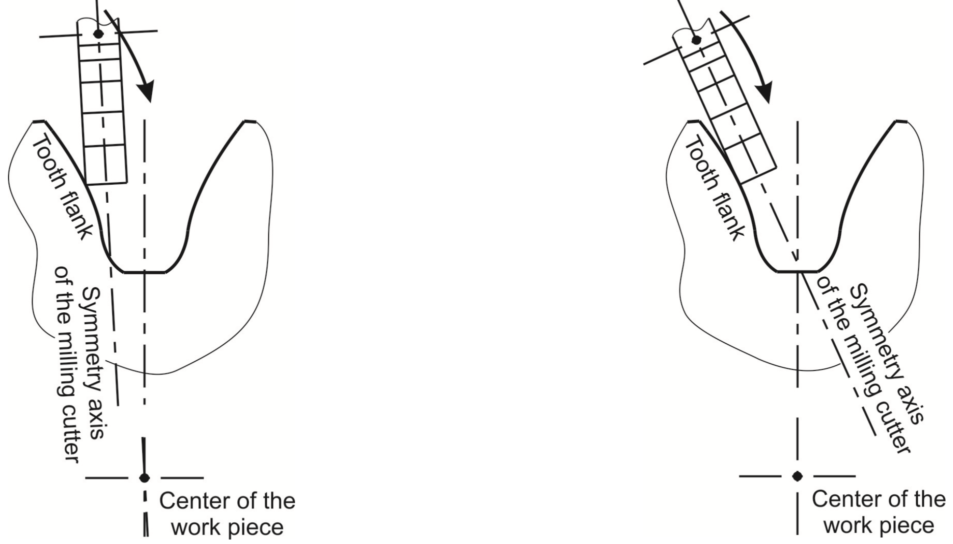

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Fig. 6. Strategies for tool engagement when machining the tooth flanks

Discussion of the different gear machining strategies

As can be seen from the results of the analysis carried out, every one of the known methods for gear cutting with disc-shaped milling tools represents a combination of the different strategies for material removal, tool movement and tool engagement. These strategies largely determine the flexibility, productivity and quality of the machining process.

By using every method considered in this paper, gears with any possible geometric parameters can be machined as long as the cutting tool fits into the tooth gap. This indicates that they possess an approximately same flexibility. However, when their productivity is considered, certain differences can be noted. As for example, for accurate machining of the single tooth gap when removing material along the flank line (see Fig. 3 a), an essentially higher number of the reciprocating movements of the tool is necessary comparing with the alternative material removal strategy (see Fig. 3 b). This leads to longer part manufacturing times and to a lower machining productivity. The reason for this is that the periodic adjustment feed along the tooth profile when removing material along the flank line have to correspond to the continuous tooth feed of the tool in the same direction when removing material along the tooth profile in order to achieve the similar surface roughness in both cases (see Fig. 7 a).

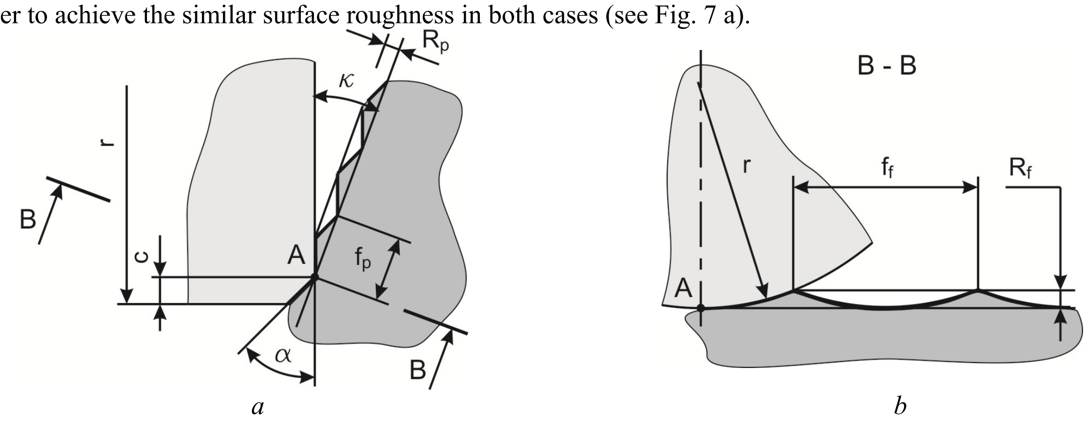

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Fig. 7. Schemes for calculating the surface roughness along a) the tooth profile and b) the tooth flank line

Even if the work piece material is simultaneously or stepwise removed in the both directions (see Fig. 3 c and d), the productivity of machining is lower than in the case of material removal along the tooth gap profile (see Fig. 3 b) due to the longer cutting paths and/or tool adjustment paths.

With regard to the strategies for tool movement when machining the tooth flanks, the cutting with the main cutting edge when the tool runs into the tooth gap (see Fig. 4 a) appears to be more advantageous compared to the cutting with the secondary cutting edge when it runs out from the tooth gap (see Fig. 4 b). One reason for this is that the clearance angle of the main cutting edge normally is greater than the corresponding angle of the secondary cutting edge. This leads to better heat removal from the cutting area, to lower friction between the clearance face of the tool and the surface of the work piece, to lower cutting forces etc. The other reasons are lower axial loads and deformations of the disc-shaped tool when machining by the running-in of the tool. This results in a better processing quality. Thus, it makes sense to machine the both flanks of a tooth gap by the running-in of the tool. However, this requires additional adjustment movements which reduce the overall productivity of the manufacturing process.

The strategies for tool engagement when machining of the tooth flanks also have certain advantages and disadvantages. The first strategy (the axis of symmetry of the tool runs through the center of the workpiece – see Fig. 6 a) is characterized by shorter tool paths and part manufacturing times compared to the second strategy (the axis of symmetry of the tool runs under a small, constant angle to the edge profile – see Fig. 6 a). This has a positive impact on the productivity of the machining process. A major advantage of the second strategy is a smaller angle between the working plain and secondary cutting edge (see Fig. 7 a) comparing with first strategy. It allows achieving a higher surface quality without reducing the feed rate. However, only convex surfaces can be machined by using the second strategy. Moreover, the machining process can be possible only when the cutting tool runs into the tooth gap (see Fig. 4 a). When machining concave surfaces and/or when the cutting tool runs out from the tooth gap, the use of the alternative machining strategies or the adjustment of the tool engagement angle is essential. In this way, the flexibility of the manufacturing process decreases.

Conclusion and prospects

By analyzing the known methods for gear cutting with disc-shaped milling tools, it was found that these differ in strategies for material removal, tool movement and tool engagement as well as can be classified according to these strategies. Moreover, the knowledge gained through this analysis shows that the gear cutting methods of Roth and Zipse as well as the methods of Nesterov and Wermeister are based on the same machining strategies. Therefore, it is possible to dispense with their separate investigations.

Furthermore, through the analysis, it was discovered that none of the gear cutting methods discussed in the paper is perfect and universally applicable. Some of them (such as the Koganov's method) provide a higher manufacturing productivity and flexibility, and the others (such as the Nesterov's method) – a better machining quality. In order to select an optimal cutting process for a specific manufacturing task, the knowledge about kinematic, dynamic and economic characteristics of the known methods for gear cutting with disc-shaped milling tools (such as tool paths, feed speeds, material removal rates, cutting forces, surface quality, tool life etc.) as well as about their application areas (such. as the manufacturing of gears with a small diameter to width ratio) is necessary. These data should be further obtained by appropriate theoretical and experimental studies.

Анотація. *Стаття присвячена аналізу різних методів нарізання зубчастих коліс дисковими фрезами з метою визначення їх переваг та недоліків щодо гнучкості, продуктивності та якості обробки. Крім того, в статті наведена класифікація стратегій обробки, які лежать в основі вищезгаданих методів зубообробки і були ідентифіковані шляхом їх аналізу.*

Ключові слова: обробка зубчастих коліс; дискова фреза; стратегія обробки

Аннотация. *Статья посвящена анализу различных методов нарезания зубчатых колёс дисковыми фрезами с целью определения их преимуществ и недостатков относительно гибкости, производительности и качества обработки. Кроме того, в статье приведена классификации стратегий обработки, которые лежат в основе вышеупомянутых методов и были идентифицированы в ходе их анализа.*

Ключевые слова: обработка зубчатих колёс; дисковая фреза; стратегия обработки

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