UDC 621.91.01 **doi: 10.20998/2078-7405.2022.96.12**

J. Kundrák, I. Deszpoth,
V. Molnár, Miskolc, Hungary

DECISION SUPPORT METHOD FOR THE APPLICABILITY OF HARD TURNING

Abstract. *In this study the applicability of hard turning is analyzed in the case of disc-shaped parts (gear wheels). The relevance of such parts has been increasing in the automotive industry; therefore, the efficiency of large series or mass production has high priority. The novelty of this paper is the collection of factors that has to be considered in preparation for applicability decisions of hard turning in order to ensure efficient machining. This can be the basis of the IT support, i.e. an automation solution for technologists. The introduced process is elaborated on the basis of theoretical considerations and production shop-floor experience.*
Keywords: *hard turning; automation; procedure selection.*

1. INTRODUCTION

The machinability of hardened surfaces has been an issue of high importance for decades in the automotive industry [1, 2]. With the appearance of new machine tools (e.g. hard machining centers) and procedure versions (e.g. hard turning and grinding in one clamping) applied for the efficient machining of hardened surfaces [3, 4], technological improvement has opened new research directions [5, 6]. Therefore, beyond the optimization of the applied technological parameters of a procedure [7, 8], a goal is now the selection of the potentially best procedures and procedure versions for a part [9, 10]. The type of the necessary machine tool on which a part can be machined depends, among other factors, on the specified accuracy and surface quality [11]. In addition to the specified accuracy [12-14] and roughness [15, 16] (e.g. Rz) parameters, functional requirement determining factors must also be considered. Decisions need to be made, for example, on whether periodic or random topography is allowed [17, 18]. The type of clamping and the hardness of the machined material [19] have to be considered, and whether the geometry of the tool and the tool holder allows machining [20]. Another important factor is that the rigidity of the machine tool and the tool have to ensure the specified accuracy [21]. In the topic of machining efficiency a number of issues were studied in our previous works: machinability of various types [22, 23] and geometry [24] of surfaces in the case of disc-shaped parts; ensuring accuracy [25] and surface quality [26] of hard turned and ground parts; optimization of technological data of hard machining [27, 28]; analysis of material removal efficiency [29, 30]; and the necessity of applying coolant and lubricant [31].

Based on the details above, it can be stated that some of thefactors influencing the applicability of hard turning differ from those for soft materials. A possible grouping of the factors influencing the machining (cutting) is the following.

1. Shape and dimensions of the part,
2. Size and continuity of the machinable surfaces,
3. Clamping possibilities on the machine tool,
4. The specified accuracy and roughness parameters,
5. The allowed position and form errors,
6. The hardness of the material and the allowances.

In this study applicability possibilities of hard turning are analyzed by the consideration of the listed factors. The study also aims to analyze how to reach a higher level of productivity and methods for deciding whether a single-point tool or abrasive tool can be used to fulfill the requirements specified in the part's drawing are. Based on the analysis of the listed influencing factors of machinability, a simple but comprehensive series of activities is suggested that can aid decisions on the applicability of the procedure. The novelty of the method is that it considers a number of factors in a complex manner and formally describes the steps of the decision process. The overview analysis is based on theoretical and empirical information and data (e.g. shape accuracy) specified for the part (plant specifications for a given transmission type) to guide the decision process. The method was elaborated for gear wheels often used in transmission systems.

2. FACTORS INFLUENCING THE APPLICABILITY OF HARD TURNING

2.1. Shape and dimensions of the part

The gear wheels built into transmission systems are disc-type parts. The machining technology of their bores is significantly influenced by the rate of the bore's length and diameter (l/d). When standard tools are applied, hard turning is only possible if the bore is short (short bore: $l/d \leq 0.5$; normal bore: $l/d = 0.5–3$). When longer bores are machined, vibration is experienced in the system due to the hard material, the high cutting speed, the chip formation characteristics and the lack of sufficient rigidity. Based on our experience, $l/d \leq 2$ can be recommended as boundary condition. In Table 1, based on the conclusions drawn from the machining of the analyzed gears, examples are demonstrated for the l/d rates of two gears (L_3/d_1 in the table). These falls on one hand to the short and on the other to the lower range of normal bores. This means, they can be turned in hardened state without any risks.

Table 1 – Accuracy, position- and form errors, diameter rates

Bore diameter	Surface	Allowed					L_3/d_1	d_{rc}/d_1
		Position error			Form error			
Ø35G6 Ø83G5	bore	//	0.006	Z1	○	0.012	0.37 1.05	1.45 3.13
	face	↗	0.03	Z1	▱	0.035		
	cone	↗	0.10	Z1	○	0.006		

In Fig. 1 the hard machined surfaces of gear wheels for transmission systems are demonstrated (bore: H, faces: I and II, cone: C). The machining of face and cone surfaces is not always carried out. In order to reach higher productivity and accuracy, machining takes place in one clamping; therefore, two tools are used, one of which is needed for turning the back face through the bore.

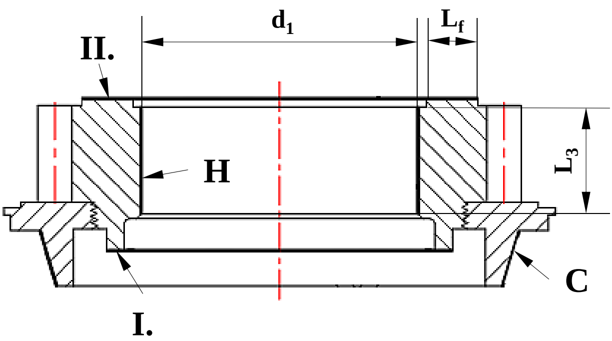

Figure 1 – Machined surfaces of transmission system gears

In the case of bores not only the l/d rate but the impact of the bore diameter has to be analyzed. The tool holder has to fit into the bore (Fig. 2) in such a way that its diameter allows the turning of the back face through the bore (Fig. 3).

For the first criterion the minimum bore diameter that allows the safe fit of the tool holder can be determined by Eq. (1) (the length c is the distance between the tool's center line and the tool tip; these data are provided by the tool manufacturer).

$$d_1 = \frac{d_{sz}}{2} + c + 1 \tag{1}$$

The second criterion can be defined based on Fig 2. The tool holder has to be fulfill the first criterion and the bore diameter has to allow the radial move of the tool for machining the L_f length. This criterion is determined by Eq. (2).

$$L_f \leq d_1 - d_{sz} \tag{2}$$

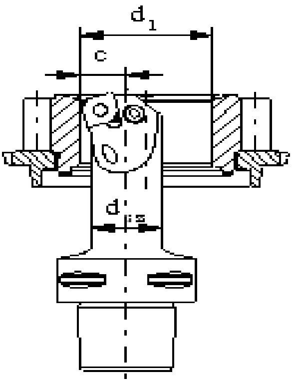

Figure 2 – Dimensions of the bore and the tool holder

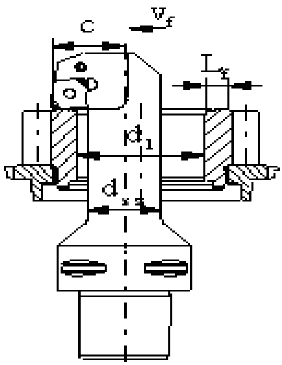

Figure 3 – Necessary bore diameter in face turning

For workpiece dimensions, the ratio of the external and internal diameter (D/d) must be analyzed. In Table 1 the notation of this rate is d_{rc}/d_1. If the ratio is low, i.e. the component is a thin-walled ring-feature part, then the clamping force can be limited, otherwise the deformation, i.e. the roundness caused by the chuck, could be too large.

It is recommended to check the calculated clamping force, although in the case of complex gears applying experiment-based force is suggested instead of calculations. Special chuck jaws are recommended if the diameter rate of the gear is lower than 1.4.

2.2. Size and continuity of machinable surfaces

The applicability of hard turning to disc-shaped gears is not influenced by the length of the machinable surface. Since the machinable surfaces are not very extensive, they do not cause large-scale tool wear on the feed path that would threaten the accuracy or surface roughness.

However, the continuity (interruptions) of the surfaces (e.g. for a lubricating groove) has to be considered. In the case of interrupted surfaces the correction of the cutting data (mainly the cutting speed) may be necessary. It is worth relying on the recommendations of tool manufacturers, because they recommend different tool materials for the same cutting speed. Based on the interruption, four types of surfaces can be defined: strongly, moderately, slightly interrupted and continuous surfaces. Based on the features and dimensions of the interruptions, the faces of the gears analyzed here are slightly interrupted. The recommendation for the cutting speed in this case is two-thirds of the cutting speed recommended for continuous surfaces, i.e. 200 m/min instead of 300 m/min.

2.3. Clamping possibilities on the machine tool

This is a trivial criterion, but it must not be neglected. A decision about the clamping one is easily made based on the manual of the hard turning center. The existence of proper jigs or clamping jaws (sometimes of special design) is an issue. Jigs and clamping jaws corresponding to the geometrical dimensions, clamping force and the specified accuracy are required.

2.4. Specified accuracy and roughness parameters

The dimension accuracy realizable by hard turning depends mainly on the machine tool. Special precision or high precision lathes built for hard- turning operations are now available. Their static, dynamic and thermic rigidity and their spindle and sled structures can help achieve the accuracy of grinding and a level identical to the accuracy requirements of grinding machines.

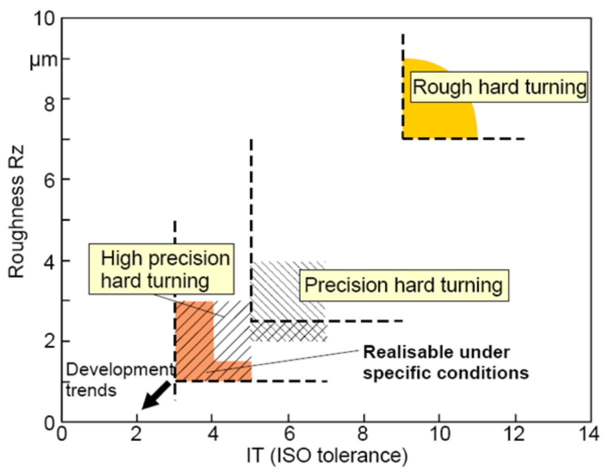

Figure 4 – Hard turning based on accuracy and surface roughness [32]

The machining accuracy of precision turning centers is between IT5 and IT7 (Fig. 4). If the accuracy specification is higher than IT5, an high precision machine tool is necessary. The surfaces that require higher accuracy (between IT 3 and IT5) and Rz<2 roughness, can be machined by precision grinding or honing.

In Table 2 surface roughness values of bores machined on a precision lathe are given as an example, compared to the measured values of the same part machined by grinding. The type of the applied lathe was PVSL Pittler. The lower limit of machining accuracy of this machine tool is IT5 and the Rz surface roughness can be realized between 2 and 6 μm. With this machine tool the required precision values were realizable.

Table 2 – Measured roughness data

Procedure	R_z [μm]	R_{max} [μm]	R_a [μm]
Grinding	2.27–2.31	2.64–2.84	0.27–0.28
Hard turning	1.61–2.67	1.76–2.91	0.27–0.43

Although not shown in the technical drawings, the relative bearing length can be important because of the functionality requirements of the parts. Some measured values are given in Table 3. Selecting the proper parameter values allows a significantly higher relative bearing length in hard turning compared to grinding. The 100% bearing length was obtained at a lower segment depth when the surface was hard turned than with grinding.

Table 3 – Measured relative bearing length

#	Bore diameter	Segment depth [μm]	Relative bearing length, t_p [%]	
			Ground	Hard turned
1	Ø35G7	0.2	0.34	1.65
		0.4	1.50	1.23
		0.6	6.12	24.28
2	Ø83G5	0.2	0.42	1.39
		0.4	2.20	6.49
		0.6	8.52	13.41

2.5. Specified position and shape errors

Based on the state-of-the-art and our measurement database, values can be designated below which the specified position and form error limit the use of hard turning. For position errors, the parallelism of bore slants and the axial run-out to the bore are specified; for form errors the allowed roundness and the face's flatness are specified. Data in the literature for the position and form errors:

- parallelism: 1–3 µm
- axial run-out: no data available
- roundness: 2–3 µm
- flatness: no data available

Our measurement results for the position and shape errors:

- parallelism: 2–3 µm
- axial run-out: 7–9 µm
- roundness: 2–8 µm
- flatness: 5–9 µm

Based on the literature and measurements, concerning position and form errors, hard turning can be applied if:

- parallelism > 0.003 µm
- axial run-out > 0.010 µm
- roundness > 0.003 µm
- flatness > 0.010 µm

Concerning the roundness it is noted that it can be realized if the clamping method and the clamping force correspond to the wall thickness of the gear. The position and form errors were compared for grinding and hard turning (Table 4). It was found that the values of hard turning can match those of grinding.

Table 4 – Measured position and form errors after machining

#	Bore diameter	Surface	After hard turning					After grinding				
			Position error			Form error		Position error			Form error	
1	Ø35G6	bore	//	0.003	Z5	○	0.008	//	0.003	Z5	○	0.007
						⌭	0.013				⌭	0.019
		face	↗	0.007	Z5	▱	0.005	↗	0.023	Z5	▱	0.008
2	Ø83G5	bore	//	0.002	1ZR	○	0.003	//	0.003	1ZR	○	0.003
						⌭	0.008				⌭	0.003
		face	↗	0.007	1ZR	▱	0.006	↗	0.282	1ZR	▱	0.017

2.6. Hardness of the material and the allowances

The PCBN insert manufacturers define the operation range of the inserts in terms of hardness of the machined material between 50 and 65 HRC. This interval has to be considered as the application condition.

Concerning the allowance, the maximum and minimum values have to be determined. In the maximum value the recommendations of the tool manufacturers have to be considered. The gears of transmission systems are case hardened parts. Considering their dimensions and the fact that the finishing is carried out in one pass, an allowance 0.3 mm is recommended.

3. STEPS OF DECISION PROCESS FOR THE APPLICABILITY OF HARD TURNING

As a result of summarizing considerations discussed above, a method was elaborated for deciding whether hard turning or grinding is the more suitable technology to be applied. Based on the criteria system even a third technology can be used if there are too strict accuracy specifications.

Based on the particular situation of production the values of the criteria can be modified without influencing the steps of the process. The method facilitates IT support, meaning that the decision process can be automatized. The steps of the process:

1. Enter the data necessary for the decision.

2. Make a decision about the applicability of hard turning based on the hardness of the workpiece (a too soft or too hard surface is a reason for exclusion).

3. Decide about the applicability of hard turning based on the bore length and diameter rate.

4. Decide about the application of special clamping jaw or exclusion of hard turning based on the rate of root circle diameter and bore diameter.

5. Analyze whether the size of the hard turning center and the chuck jaw allows the workpiece to be clamped.

6. Decide about the applicability of hard turning of the bore (H) based on the accuracy, position and form error, and roughness specifications.

6.1. Select the tool holder, tools and inserts (the dimensions of the tool holder have to correspond to the bore diameter).

6.2. Analyze the allowance of the bore.

- Too small allowance is a reason for exclusion.
- Determination of the number of passes if the allowance is suitable (one or more roughing passes and one smoothing pass).

6.3. Determine the necessary clamping force.

7. Decide about the applicability of hard turning of the right face (I) based on the accuracy, position and form error, and roughness specifications.

7.1. Select the tool holder, tools and inserts

7.2. Analyze the allowance for the right face.

- Too small allowance is a reason for exclusion.
- Determination of the number of passes if the allowance is suitable (one or more passes).

8. Decide about the applicability of hard turning of the left face (II) based on the accuracy, position and form error, and roughness specifications.

8.1. Select the tool holder, tools and inserts.

8.2. Analyze the allowance of the left face.

- Too small allowance is a reason for exclusion.
- Determination of the number of passes if the allowance is suitable (one or more passes).

9. Decide about the applicability of hard turning of the cone surface (C) based on the accuracy, position and form error and roughness specifications.

9.1. Selectof the tool holder, tools and inserts.

9.2. Analyze the allowance of the cone surface

- Too small allowance is a reason for exclusion.
- Determination of the number of passes if the allowance is suitable (one or more passes).

10. If hard turning is not excluded at any of the previous steps, then determine the cutting data

SUMMARY AND CONCLUSIONS

The study is about the applicability of hard turning analyzed through specifications and values for hard turning and grinding and about the selection of technological data (both the factors that have to be considered and the order in which the data should be considered). Based on the introduced method (the series of analysis) and with the help of IT support, the determination of technological data can be realized for hard turning. The method was elaborated for disc-type parts.

The elaboration of the method (process) was based on theoretical and empirical considerations. The main findings are:

- A structured process (algorithm) can be prepared for supporting the decision of applicability of hard turning; therefore, the decision process can be automatized.
- The process can be generalized for hard turning and by applying basic technological calculations, the decision can be made for specific parts.

The method can be extended for other types of typical parts. In the current method the economic and financial factors of the output are not analyzed; the method can be extended by these factors in future research.

References: 1. *O. Koval'chuk, V. Nezhebovsky, O. Permyakov, O. Klochko, S. Ryabchenko*.: Processing of hardened cylindrical gear wheels of the cutting gearbox of the combine ukd 200-500, Cutting & Tools in Technological System, 95, 2021, pp.57–70. **2.** *Grabchenko, A., Fedorovich, V., Pyzhov, I., Ostroverkh, Y.*: Increase of efficiency of diamond grinding superhard of materials, Cutting & Tools in Technological System 93, 2020, pp.24–32. **3.** *Moriwaki, T.*: Multi-functional machine tool, CIRP Annals, 57, 2008, pp.736–749. **4.** *Kundrak, J., Mamalis, A.G., Markopoulos, A.*: Finishing of hardened boreholes: grinding or hard cutting?, Materials and Manufacturing Processes, 19, 2004, pp.979–993. **5.** *Klocke, F., Brinkmeier, E., Weinert, K.:* Capability profile of hard cutting and grinding process, *CIRP Annals, 54*, **2005**, pp.22–54. **6.** *Tönshoff, H.K., Arendt, C., Ben Amor, R.* Cutting of hardened steel, *CIRP Annals, 49,* **2000**, pp. 547–566. **7.** *Hernandez, A.E.B., Beno, T., Repo, J., Wretland, A.*: Integrated optimization model for cutting data selection based on maximal MRR and tool utilization in continuous machining operations, CIRP Journal of Manufacturing Science and Technology, 13., 2016., pp.46–50. **8.** *Qiu, J., Ge, R.*: A theoretical model and experimental investigation to predict and evaluate cutting capability of turning center based on material removal rate, 104, 2019, pp. 3287–3302. **9.** *Konig, W., Berktold, A., Koch, K.F.*: Turning versus grinding—A comparison of surface integrity aspects and attainable accuracies, *CIRP Annals, 42,* **1993**, pp. 39–43. **10.** *Bana, V.*: Manufacturing of high precision bores, PhD dissertation, 2006. **11.** *Liao, Y., Liao, B.*: Dynamics modeling and modal analysis of machine tool considering joints parameters, Manufacturing Technology 19(2), 2019, pp. 267–272. **12.** *Linins, O., Krizbergs, J., Boiko, I.*: Surface texture metrology gives a better understanding of the surface in its functional state, Key Engineering Materials, 527, 2013, pp. 167–172. **13.** *Yakimov, O., Bovnegra, L., Tonkonogyi, V., Vaysman, V., Strelbitskyi, V., Sinko, I.*: Influence of the geometric characteristics of the discontinuous profile working surfaces of abrasive wheels for precision and temperature when grinding, Cutting & Tools in Technological System 94, 2021, pp. 115–125. **14.** *Prisco, U., Squillace, A., Scherillo, F.,Coticelli, F., Astarita, A.*: Form and dimensional accuracy of surfaces generated by longitudinal turning, Manufacturing Technology, 16(3), 2016, pp. 595–600. **15.** *Neslušan M., Rosipal M., Kolařík K., Ochodek V.*: Application of barkhausen noise for analysis of surface integrity after hard turning, Manufacturing Technology, 12(1), 2012, pp. 60–65. **16.** *Popov, A., Khramenkov, M.***:** Effect of hydraulic oil entering the cutting fluid on the tool life and roughness in turning of stainless steel, Manufacturing Technology, 19(4), 2019, pp. 664–667. **17.** *Kundrak, J., Nagy, A., Markopoulos, A.P., Karkalos, N.E.*: Investigation of surface roughness on face milled parts with round insert in planes parallel to the feed at various cutting speeds, Cutting & Tools in Technological System, 2019, pp. 87–96. **18.** *Zawada-Tomkiewicz, A.*: Analysis of surface roughness parameters achieved by hard turning with the use of PCBN tools, Estonian Journal of Engineering, 17, 2011, pp. 88–99. **19.** *Kundrak, J., Mamalis, A. G., Gyani, K., Bana, V.*: Surface layer microhardness changes with high-speed turning of hardened steels, International Journal of Advanced Manufacturing Technology, 53, 2011, pp. 105–112. **20.** *Zhang, S.J., To, S., Zhang, G.Q., Zhu, Z.W.*: A review of machine-tool vibration and its influence upon surface generation in ultra-precision machining, International Journal of Machine Tools and Manufacture, 91, 2015, pp. 34–42. **21.** *Mamalis, A.G., Kundrak, J., Horvath, M.*: On a novel tool life relation for precision cutting tools, Journal of Manufacturing Science and Engineering, 127, 2005, pp. 328–332. **22.** *Kundrak, J., Molnar, V., Deszpoth, I.*: Comparative analysis of machining procedures, Machines 6, 2018, pp. 1–10. **23.** *Kundrak, J., Molnar, V., Markopoulos, A.P.*: Joint machining: hard turning and grinding, Cutting & Tools in Technological System, 90, 2019, pp. 36–43. **24.** *Kundrak, J., Deszpoth, I., Molnar, V.*: Effects of the bore-hole geometry on the productivity of hard machining, Proceedings of the Thirteenth International Conference on Tools: ICT 2012, Miskolc, 2012, pp. 157–164. **25.** *Kundrak, J., Sztankovics, I., Molnar, V.*: Accuracy and topography analysis of hard machined surfaces, Manufacturing Technology, 21, 2021, pp. 512–519. **26.** *Molnar, V.*: Tribology and topography of hard machined surfaces, Cutting & Tools in Technological System, 94, 2021, pp. 49–59. **27.** *Molnar, V., Deszpoth, I., Kundrak, J., Markopoulos, A.P.*: Efficiency of material removal and machining in cutting, Cutting & Tools in Technological System, 92, 2021, pp. 35–47. **28.** *Kundrak, J., Nagy, A., Markopoulos, A.P., Karkalos, N.E., Skondras-Giousios, D.*: Experimental study on surface roughness of face milled parts with round insert at various feed rates, Cutting & Tools in Technological System, 92, 2020, pp. 96–106. **29.** *Molnar, V., Kundrak, J., Deszpoth, I.*: Some economic issues of hard machining, Proceedings of the 3rd International Scientific and Expert Conference with simultaneously organised 17th International Scientific Conference CO-MAT-TECH 2011, Trnava, 2011, pp. 251–254. **30.** *Kundrak, J., Deszpoth, I., Molnar, V.*: Comparative study of material removal in hard machining of bore holes, Tehnicki Vjesnik-Technical Gazette, 21, 2014, pp. 183–189. **31.** *Kundrak, J., Molnar, V.*: Comparison of hard machining procedures on material removal rate, Hungarian Journal of Industry and Chemistry, 39, 2011, pp. 219–224. **32.** *Byrne, G., Dornfeld, D., Denkena, B.*: Advancing cutting technology, CIRP ANNALS, 52(2), 2003.

Янош Кундрак, Іштван Дезпот,
Віктор Мольнар, Мішкольц, Угорщина

МЕТОД ПІДТРИМКИ ПРИЙНЯТТЯ РІШЕННЯ ПРО ЗАСТОСУВАННЯ ЖОРСТКОГО ТОЧІННЯ

Анотація. *У цьому дослідженні проаналізовано застосування жорсткого точіння для дискових деталей (зубчастих коліс). Актуальність таких деталей у автомобільній промисловості зростає; тому ефективність великосерійного чи масового виробництва має першорядне значення. Новизною цієї статті є сукупність факторів, які необхідно враховувати при підготовці рішень щодо застосування жорсткого точіння для забезпечення ефективної обробки. Це, можливо, буде основою IT-підтримки, тобто рішенням щодо автоматизації для технологів. Представлений процес розроблено на основі теоретичних міркувань та виробничого досвіду. Оброблюваність загартованих поверхонь протягом десятиліть є проблемою, що має велике значення в автомобільній промисловості. З появою нових верстатів і інструментів (наприклад, твердосплавних різців, оброблювальних центрів) та варіантів процедур (наприклад, жорстке точіння та шліфування з однієї установки), що застосовуються для ефективної обробки загартованих поверхонь, відкрило нові напрямки досліджень. Дане дослідження також спрямоване на аналіз того, як досягти більш високого рівня продуктивності, та методів прийняття рішення про те, чи можна використовувати одноточковий або абразивний інструмент для виконання вимог, зазначених на кресленні деталі. На основі аналізу факторів, що впливають на оброблюваність, пропонується простий, але всеосяжний ряд дій, які можуть допомогти прийняти рішення щодо застосування процедури. Новизна методу у тому, що він комплексно розглядає низку чинників і формально визначає етапи процесу прийняття рішення. Оглядовий аналіз заснований на теоретичній та емпіричній інформації та даних (наприклад, точності форми), зазначених для деталі (технічні характеристики установки для даного типу трансмісії), щоб спрямовувати процес прийняття рішення. Метод був розроблений для зубчастих коліс, що часто використовуються в трансмісійних системах. Метод може бути поширений інші типи типових деталей. У чинній методиці не аналізуються економічні та фінансові фактори виробництва; Метод може бути розширений цими факторами у майбутніх дослідженнях.*

Ключові слова: *токарна обробка; автоматизація; вибір процедури.*