Analysis of cylindrical error deviation of surfaces when using reduced amount of coolants and lubricants in machining

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Abstract: - The paper pertains to experimental examination of cylindrical error deviations when machining of cylindrical workpieces by low volume of coolants and lubricants. The volume of coolants and lubricants was reduced to decrease the environmental pollution caused by cutting fluid. However, our aim was to get a function relation between cutting data (cutting speed, feed rate), parameters of coolants and lubricants (viscosity, consumed flow rate), and error deviation of machined cylindrical workpiece. The cylindrical surface is created when the workpiece is standing and the single point cutting tool having special fixture makes the principle (rotating) and auxiliary (linear) motions as well. Full factorial experiment design was used in the experimental study when executing this "outer boring" with a carbide insert in AISI 1045 steel. As the kinematics and rigidity of the machining examined here differs from the usual machining that is why it worth to examine it. The aim of the research is to determine empirical expressions between the technological parameters and the cylindrical error deviations. On the base of examinations, the appropriate parameter combination can be selected.

Key-Words: - Outer boring, reduced environmental load, cylindrical error deviation, Taguchi Experiment Design

1 Introduction

This paper presents the examination of machining of standing cylindrical surfaces by a single point cutting tool which executes the main and auxiliary motions as well on a milling machine. During experiments there were used different technological parameters, different type (having different kinematic viscosity) and volume coolants and lubricants. The experiments were done based on the Taguchi type full factorial experiment design [1].

After machining the different cylindricity error indicators were measured and evaluated. The aim of the experiments was to determine those parameter combinations which served the lowest cylindrical error deviation. Thus, a technological parameter combination, the type and volume of coolants and lubricants related to it could be determined within the examined range of the parameters. Evaluation of the measured values was accomplished by a program created in MathCAD environment. Showing the results in empirical formulas and 3D axonometric diagrams helps to determine and visualize the best parameter combination.

As our experiments involve the use of reduced amount of coolants and lubricants in the following a summary of the various modes of low-pressure machining is given.

2 Features of Cooling and Lubrication

In the Industry 4.0 all the equipment belonging to production engineering are interconnected for exchanging data and information with each other. Using this data exchange the Industry 4.0 makes extensive use of among others, e.g. artificial intelligence, precision machining, and environment protection [2]. Intelligent design and advanced metrology are key elements for precision manufacturing in modern manufacturing, [3-4]. They are used when design of environmentally friendly machining as well where machining can be done on completely dry or by using minimum quantity lubrication (MQL) [5]. There is increasing interest for environmentally friendly manufacturing in nowadays as well due to the development of pollution prevention legislation [6]. Biodegradable lubricants play an important role in environmentally conscious manufacturing. Although bio-based coolants and lubricants do not reach the cooling-lubricating properties of traditional or special coolants and lubricants in all aspects, but their environment pollution is less [7].

Originally, the coolants and lubricants were used to lubricate chip and tool as well as tool and workpiece interface, to remove heat from the workpiece and the cutting zone, furthermore to extract the chips from the cutting area [8]. Although

the definition of coolants and lubricants contains these four functions, according to certain literature, for example [9], the main function of the coolants and lubricants is cooling and lubrication. The use of coolants and lubricants is a traditionally applied method to reduce the temperature and friction of the cutting zone [10-11].

The type of coolants and lubricants used during machining plays an important role in increasing machining efficiency only when that is properly selected, applied and treated [12]. Extreme pressure-resistant additives are added to the coolants and lubricants for improving the effect of lubrication and cooling [13]. Pressurized, oil-based coolant-lubricating fluid flows may reduce the cutting force and improve surface roughness [14-15]. Therefore, coolants and lubricants increase the tool life, improve surface roughness [16], and facilitate the transportation of chips [17]. However, when using coolants and lubricants many issues arise, including health and safety of the workers, maintenance of the liquid system, liquid pre-treatment, handling, disposal, and environmental concerns [18]. Next to the cooling and lubrication the nanolayer thickness has great influence on performance of the cutting tool, so the performance on low environment load metal cutting [19]. According to Szabo [20] the environment conditions at ultraprecision turning is very important and he design of it.

To analyse the effect of environmental impact of machining processes Munoz and Sheng [6] worked out a model. In their model for developing the relationships between manufacturing parameters and environmental impact, four general aspects of the machining process are analysed:

the material removal mechanics,
tool life,
scrap production and
cutting-fluid flow (Fig. 1) [6].
The inputs to the process include
the type of operation (drilling, milling, turning, etc.),
the operating parameters,
the initial- and final-workpiece geometries,
the workpiece material,
the tool geometry and the tool material.
The outputs are
the process rate,
the process energy,
the machining forces and
the total volume of material removed.

In present outer boring examination, the inputs to the process include:
cutting speed,
volume of emulsion, and
feed rate,
while the output parameters are:
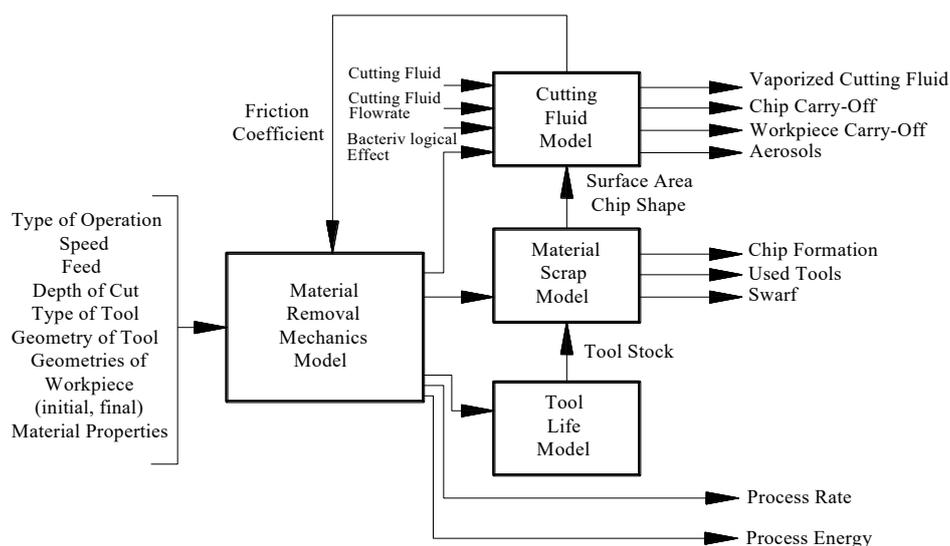the different features of cylindricity deviation.

Fig.1. Schematic of the machining model [6]

2.1 Roles of Coolants and Lubricants

The main task of using cooling lubricating fluids in cutting processes is to reduce the cutting temperature and friction wear by cooling, or lubrication, or heat dissipation with the combination of cooling and lubrication [21].

Aggarwal et al. [10] collected the limitations of the use of conventional coolants and lubricants. Some of these are:
- Possible health problems of the operator, such as skin and respiratory problems with a person who is in contact with the coolant and lubricant.
- Pollution of water and soil during the disposal of the coolant lubricant.
- Space required for the installation and operation of elements of the auxiliary system, for pumping, storage, recycling, cooling, etc.
- The costs of disposing of coolants and lubricants growing and growing as environmental regulations are strengthened.

The tasks of coolants and lubricants, according to Anton et al. [22], are as follows:
- cooling of machine tools, materials, equipment and tools,
- supporting chip breaking and chip transportation,
- reducing of friction
- reducing of creation of built up edge
- corrosion protection of the machine tool and workpiece.

According to O'Sullivan and Cotterell [23], the tool life of the cutting edge is greatly influenced by the cutting temperature, since a slight decrease in temperature can cause prolonged tool life.

2.2 Techniques of Cooling and Lubrication

According to Astakhov [24], a systematic method is needed to quantify and compare the performance of different coolants and lubricants. Although the coolants and lubricants are widely spread in the industry, a standard method for classifying them is not known yet. Due to the presence of hazardous ingredients, - e.g. the growth of chlorine and microbes in coolants and lubricants - constitute a dangerous substance for the health and environment of workers. In addition, extending environmental protection standards limits the use and increases the cost related with coolants and lubricants [25].

According to Klocke and Eisenblätter [26], the cost of coolants and lubricants is 7-17% of the total machining cost while the tool cost is only 2-4%. Therefore, when using MQL technology, typical machining costs can be reduced by reducing the amount of cooling-lubricating fluid used in cutting.

To do this, the air and lubricant must be mixed near the cutting zone. Two different mixing methods are known: an internal mixing nozzle and an external mixing one. Using the internal mixing nozzle, compressed air and lubricant are mixed within the nozzle. Lubrication is performed by the lubricant while the minimum cooling effect is achieved by

compressed air. The cooling effect of MQL is almost negligible.

Shokrani et. al. [27] illustrates various environmentally conscious machining techniques that have successfully reduced or eliminated the disadvantages of using conventional refrigerant lubricants in metal cutting operations (Fig.1). They found that none of the techniques being in Fig. 1 can be pretend as a general method for the case of all tool-workpiece pairings. MQL is a technique that can reduce the problems of flood cooling lubrication caused by the high volume of coolant and lubricant (CL) liquids, such as high cutting costs, environmental pollution, and the health damage of the workers [28]. It is therefore important to know all the advantages and limitations of this technique. Attanasio et al. [28] investigated the benefits of using a minimum quantity lubrication technique for turning of normalized steel 100Cr6. In their study, the results of the experimental examinations are reported. They stated that lubricating the rake surface of the insert with a minimum quantity lubrication technique does not provide significant wear reduction. However, lubricating its flank surface minimizes the tool wear and increases tool life. According to their study, minimum quantity lubrication (MQL) gives some advantage when turning, but there are limitations on whether the lubricant achieves surface to be lubricated. Fig. 2 contains cryogenic machining as well. Kaynak et al [29] analyzed the tool-wear when cryogenic machining of NiTi shape memory alloys and compared it with dry and MQL machining.
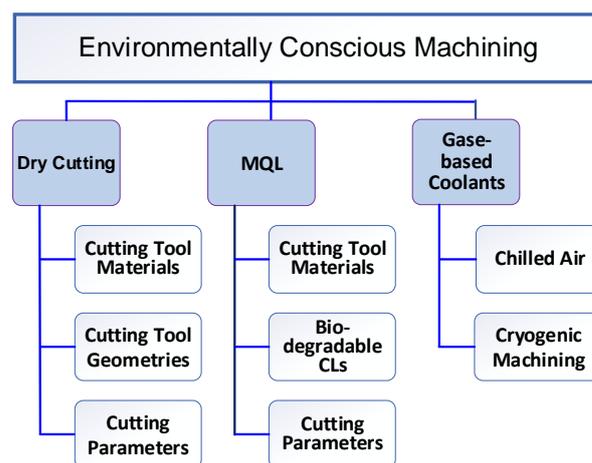

Fig.2. Classification of different environmentally conscious machining techniques [27]

The minimum amount of cooling-lubrication is introduced into the cutting zone to lubricate them, thus reducing the heat generation at the desired location [30]. The minimum amount of lubrication

[31] is the technique used for metal cutting to achieve their environmental and economic benefits. Further advantages of the use of MQL can be found in the paper [32].

Among others the advantage of MQL (depending on the amount of lubricant) is as follows [20]:

• the chips, workpiece and tool holder do not hinder lubrication: their cleaning is easy and economical;
• the cutting area is not flooded during machining, so that the cutting operation can be observed well.

The disadvantage of the MQL method is that it cannot cool the cutting surface. This means that MQL is not advantageous if it is intended for a cutting operation where the cooling effect is strongly desired, such as grinding [33-35]. It is very important to define correctly the conditions the application of MQL technique in order to their expected benefits could be realized. MQL can be used in drilling [11], deep hole drilling [36] and milling [5], [38] as well. Due to the direct connection among the excessive heat production, the cutting speed and cutting temperature in the cutting zone, the cutting speed of dry cutting is limited by the material of the cutting tool and workpiece [27]. MQL can be used for machining of different workpiece materials, such as aluminium too [38]. Furthermore, the main environmental problem with the minimal quantity lubrication is the fact that it is still uses of coolants and lubricants.

The use of air as a coolant has been studied for several years. However, it is known that air has poor thermal conductivity and cooling ability. Thus, some researchers used chilled air to cool the cutting zone, though the effect of chilled air on machinability is inconsistent and largely dependent on the technological parameters and the matching of the tool-workpiece material [39]. The best approach of reducing the usage and cost of coolants and lubricants is that when they are not used at all [40]. However, dry cutting, in certain cases, does not provide the desired tool life of the cutting tool and surface roughness of the workpiece. When using dry machining the tool life of cutting tool and surface quality of the machined surface worse related to ones using coolants and lubricants [41]. Krolczyk et al. [42] predicted the tool life in dry machining of duplex stainless steel. During their examinations they used the Factorial experiment design. The equation established by them shows clearly that the main influencing factor of the tool life was the cutting speed. their model is time and cost saving as well.

Varadarajan, et al [43] investigated the dry finish cutting of hardened steels using cubic boron nitride (CBN) and polycrystalline diamond (PCD) tools. The application of dry machining is an effective method for reducing the environmental pollution problems, because obviously all negative effects caused by coolants and lubricants can be eliminated [44]. Cast-iron materials are particularly suitable for dry machining as their cutting temperatures are significantly lower than steel. However, the ductile cast iron type FCD700 is difficult to machine due to its special microstructure and high tensile strength [45]. Minimum quantity lubrication (MQL) applying a minimum amount of coolant lubricating fluid, offers an alternative solution for reducing unfavorable environmental impacts [46]. In the case of MQL fluid applications, the flow rate of lubricating fluid is about 500-600 ml/h. Its advantage is that the resulting atomized fog arrives directly to the interface of cutting tool-workpiece [47]. The MQL fluid reduces occupational hazards.

To obtain better efficiency through increased wear resistance, many techniques are applied. Among them are surface engineering technologies, including relatively new ion implantation methods, which appeared to be very promising as reported by Narojczyk et al. [48]. Authors demonstrated also reduction of cutting forces that causes direct energy savings. The machining of hardened bore holes can be performed by using environmentally friendly hard turning instead of grinding [49]. The use of MQL influences the wear of the cutting tool as well [45]; however, this paper does not deal with the examination is cutting tool wear. Now, we intend to determine whether are there any effect of the different volume of and the different kinematic viscosity coolants and lubricants applied on the cylindricity deviation of the machined cylindrical surface.

3 Features of Machining of Cylindrical Surfaces

Type of the applied machine tool is PERFECT-JET MCV-M8 (Fig. 3) on which the cylindrical workpiece to be machined is standing and the cutting tool performs the rotating movement (main cutting movement) and the feed (auxiliary cutting movement) (Fig. 4). The system for cooling and lubrication was developed at the Institute of Manufacturing Science in The University of Miskolc because the CNC machine tool cooling system was suitable for flood cooling only (Fig. 5). The 5% emulsion was delivered to the working area by two tubes, where it was sprayed onto the workpiece and cutting tool.

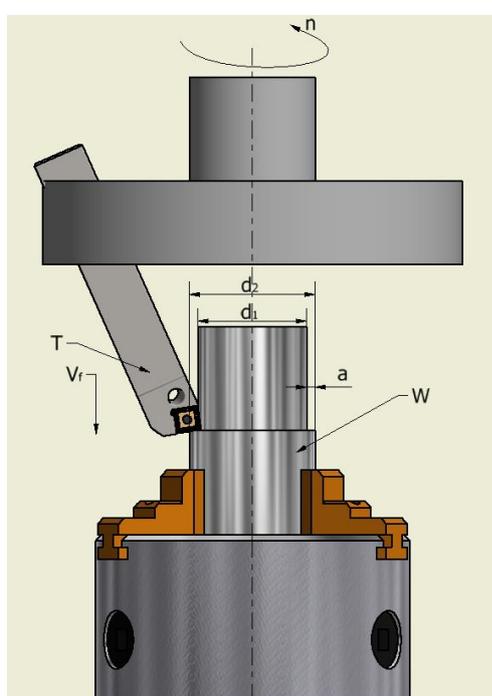Fig.3. Machine tool applied for outer boring (PERFECT-JET MCV-M8)

Fig.4. Outer boring with single point cutting tool having defined edge geometry

Fig.5. The position of the spraying heads relative to the workpiece in the machining area before cutting

The method of lubrication is shown in Fig. 6. The rigidity of the Workpiece - Fixture - Machine tool -

Cutting tool system of the examined machining differs from the conventional one, which influences cylindricity deviation, circularity error, and surface roughness of the machined surface. During our examination, it is determined how the technological parameters (cutting speed, feed rate), the volume of the applied coolant and lubricant, and the different kinematic viscosity affect the cylindricity deviation of the machined workpiece. Positioning of the cutting tool was done according to the diameter to be machined. In contrast to machining with cutting tool having multi edges (milling cutter), here only feed of the tool into Z-axis is required, so this process can be considered very productive.

Fig.6. Outer boring during machining

4 Experimental Conditions

During the experiments, a CNC milling center type Perfeckt Jet, MCV-M8 CNC was used. The material of the specimen was steel type AISI 1045; its chemical composition can be seen in Table 1 and its mechanical properties in Table 2 [50].

Table 1, Chemical composition of AISI 1045 [%] [50].

	C	Fe	Mn	P	S
Min.	0.42	98.51	0,56		
Max.	0.50	98.98	0.8	0.040	0.045

Table 2, Mechanical properties of AISI 1045 [50]

Density [kg/dm^3]	Tensile Strength, Yield [N/mm^2]	Tensile Strength, Ultimate [N/mm^2]	Elongation at Break A [%]
7.87	310	535	16

This is a general purpose, unalloyed, structural carbon steel. During the experiment, 16 workpieces were machined to the size of ø39.7×50 mm, of which 30 mm length was used for smooth outer boring.

Cylindricity deviation measurements were performed on a Talyrond 365 measuring machine produced by Taylor Hobson (Fig.7). Talyrond 365 is a mid-range roundness geometry-measuring instrument.

a)
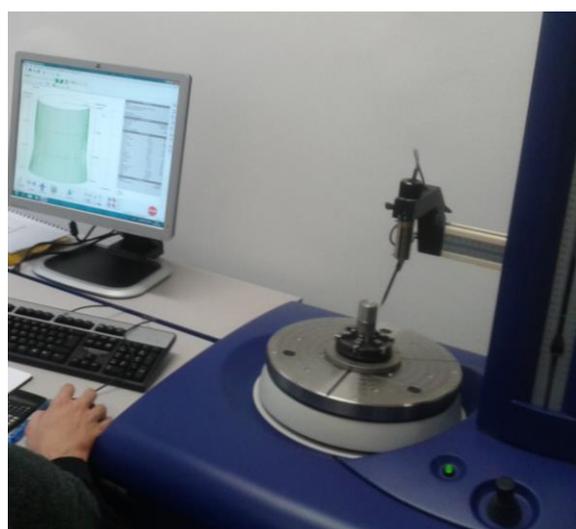
b)

Fig.7, Measurement with Talyrond 365
a) cylindricity and shape error measuring equipment,
b) execution of the measurement

Easily programmed using ultra roundness software, Talyrond 365 is quick and easy to use. Component set-up is fully automatic using motorized centering and levelling. It has built in filtering and data removal options to ensure productivity. This equipment is an integration of a high specification column and air bearing spindle mounted in a stable platform to give unequalled measurement performance. Its characteristic features:

- automated roundness geometry system,

- modular concept - choose the product that meets your requirements,

- automatic centering and levelling capabilities for fast component set up.

This measuring machine is suitable for measuring medium-sized parts (max: ø200× 500 mm). Using easy-to-program "μltra" software, measurements and evaluations can be done quickly and easily. Moving of the fine probe is fully automated in both direction. During the tests, minimal lubrication is used to make eco-efficient machining. Concentricity of the emulsion is 5% from the two basic oils separately. During the experiment one or two nozzles were used. Our goal was to investigate whether minimal lubrication (when one or two nozzles are in operation) will influence the cylindricity error. The viscosity of the emulsions used for the experiments is shown in Table 3.

Table 3, Viscosity of the oils and emulsions

Types of lubricants	Kinematic viscosity of oil, emulsion (at 40°C)
Oil 1	$\nu_{oil\ 1}$=30 mm^2/s
Oil 2	$\nu_{oil\ 2}$=70 mm^2/s
Emulsion made from Oil 1	ν_1=2.4557 mm^2/s
Emulsion made from Oil 2	ν_2=4.4554 mm^2/s

Examined experimental parameters: cutting speed, feed rate and volume of emulsion which parameter ranges are following:

cutting speed: v_{c1} = 125.7 m/min
                                  v_{c2} = 188.5 m/min
volume of emulsion: V_{Em1} = 273 cm^3/min
                                  V_{Em2} = 546 cm^3/min
feed rate: v_{f1} = 0.05 mm/rev
                                  v_{f2} = 0.15 mm/rev

The matrix of the Taguchi type Factorial Experimental Design [51] can be seen in Table 4, which contains the outer boring parameters in natural dimensions and in transformed ones.

Table 4, Applied experimental parameters

No.	Cutting speed v_c, $\left[\frac{m}{min}\right]$	Feed rate v_f, $\left[\frac{mm}{rev}\right]$	Volume of emuls. V_{Em}, $\left[\frac{cm^3}{min}\right]$	Transformed parameters		
				X_1	X_2	X_3
1	125.7	0.05	273	-1	-1	-1
2	188.5	0.05	273	+1	-1	-1
3	125.7	0.15	273	-1	+1	-1
4	188.5	0.15	273	+1	+1	-1
5	125.7	0.05	546	-1	-1	+1
6	188.5	0.05	546	+1	-1	+1
7	125.7	0.15	546	-1	+1	+1
8	1885	0.15	546	+1	+1	+1

5 Measurement Results

Measurement of the cylindricity was done with a circularity and shape error measuring machine type Talyrond 365. From among the 16 cylindricity indices 3 were analyzed that mostly determine operating properties: CYLt - peak to valley cylindricity deviation; CYLp – peak to reference cylindricity deviation; and CYLv – reference to valley cylindricity deviation [52]. The definition of CYLt is: "The minimum radial separation of two cylinders, coaxial with the fitted reference axis, which totally enclose the measured data" [53].
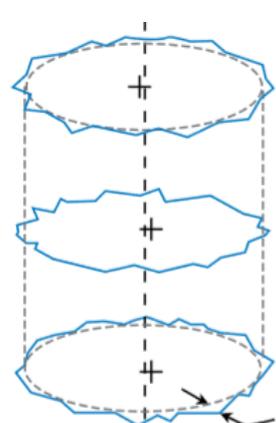
Fig.8 illustrates the minimum zone cylinder, the maximum inscribed cylinder, and the minimum circumscribed cylinder [53]. In Fig.9. another illustration of CYLt can be seen. The above mentioned CYLt, CYLp and CYLv cylindricity parameters are included in the geometrical product specifications (GPS) ISO Standard 12180-1.

The cylindricity error measurements were performed in 5 divisions at 4 mm on all the sixteen test specimens. The measurement results were evaluated using the software of the measuring machine and are contained in Tables 5-8. Table 5 and 6 show the measurement results of the experiments executed with Emulsion 1, while Table 7 and 8 refers to experiments done by Emulsion 2.

Using Factorial Experiment Design empirical formulas (1-6) can be determined. The evaluated results of the measurements done by using MathCAD software can be seen in Figs. 6-11. Figs. 6-8 relate to the results for Emulsion 1, and Figs.8-10 relate to the results for Emulsion 2. In the left-hand side of formulas (1-3) in the index position Em1 can be found, which refers to the use of Emulsion 1, while in formulas (4-6) Em2 similarly refers to Emulsion 2.
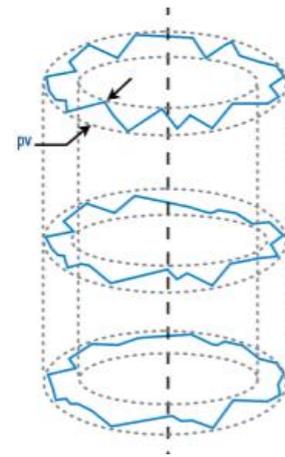
a)
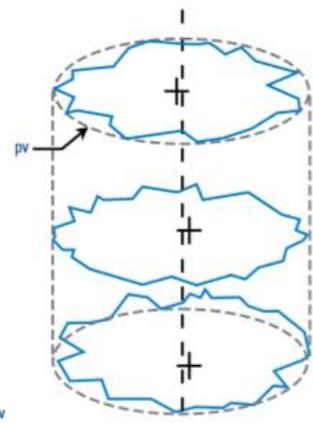
b)   c)

Fig.8. Cylindricity parameters; a) Minimum zone cylinder; b) Maximum inscribed cylinder; c) Minimum circumscribed cylinder [53]
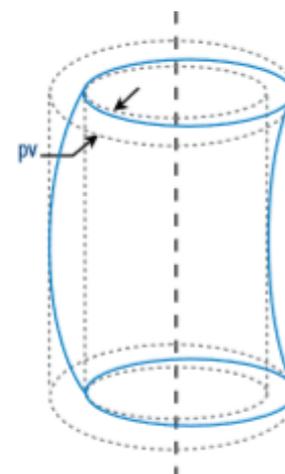

Fig.9. Illustration of cylindricity tolerance, and CYLt

Table 5, Measured values of the cylindricity error values for Emulsion 1

Table 6, Measured values of the cylindricity error values for Emulsion 1

	Emulsion 1		
1	X_1=-1	X_2=-1	X_3=-1
CYLt [µm] 24.78 CYLp [µm] 18.13 CYLv [µm] 6.65			
2	X_1=+1	X_2=-1	X_3=-1
CYLt [µm] 12.42 CYLp [µm] 7.11 CYLv [µm] 5.31			
3	X_1=-1	X_2=+1	X_3=-1
CYLt [µm] 16.75 CYLp [µm] 6.01 CYLv [µm] 10.74			
4	X_1=+1	X_2=+1	X_3=-1
CYLt [µm] 18.19 CYLp [µm] 11.57 CYLv [µm] 6.62			

	Emulsion 1		
5	X_1=-1	X_2=-1	X_3=+1
CYLt [µm] 15.30 CYLp [µm] 12.36 CYLv [µm] 2.92			
6	X_1=+1	X_2=-1	X_3=+1
CYLt [µm] 13.31 CYLp [µm] 9.22 CYLv [µm] 4.09			
7	X_1=-1	X_2=+1	X_3=+1
CYLt [µm] 18.56 CYLp [µm] 10.29 CYLv [µm] 8.27			
8	X_1=+1	X_2=+1	X_3=+1
CYLt [µm] 20.15 CYLp [µm] 10.45 CYLv [µm] 9.70			

Table 7, Measured values of the cylindricity error values for Emulsion 2

Table 8, Measured values of the cylindricity error values for Emulsion 2

1	Emulsion 2		
	$X_1=-1$	$X_2=-1$	$X_3=-1$
CYLt [µm] 19.56			
CYLp [µm] 17.20			
CYLv [µm] 2.36			
2	$X_1=+1$	$X_2=-1$	$X_3=-1$
CYLt [µm] 29.17			
CYLp [µm] 23.78			
CYLv [µm] 5.39			
3	$X_1=-1$	$X_2=+1$	$X_3=-1$
CYLt [µm] 24.20			
CYLp [µm] 15.12			
CYLv [µm] 9.08			
4	$X_1=+1$	$X_2=+1$	$X_3=-1$
CYLt [µm] 24.07			
CYLp [µm] 10.68			
CYLv [µm] 13.38			

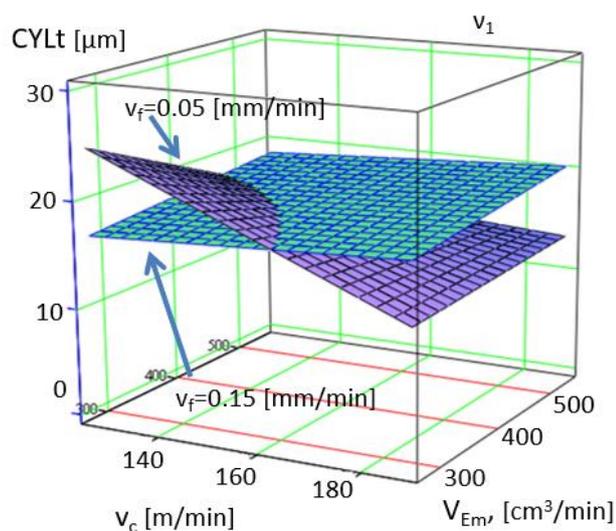| 5	Emulsion 2		
	$X_1=-1$	$X_2=-1$	$X_3=+1$
CYLt [µm] 11.64			
CYLp [µm] 8.94			
CYLv [µm] 2.70			
6	$X_1=+1$	$X_2=-1$	$X_3=+1$
CYLt [µm] 15.94			
CYLp [µm] 11.49			
CYLv [µm] 4.45			
7	$X_1=-1$	$X_2=+1$	$X_3=+1$
CYLt [µm] 19.36			
CYLp [µm] 9.66			
CYLv [µm] 9.69			
8	$X_1=+1$	$X_2=+1$	$X_3=+1$
CYLt [µm] 29.47			
CYLp [µm] 21.30			
CYLv [µm] 8.17			

Fig.6. Change in CYLt cylindricity deviation depending on technological parameters and volume of emulsions for Emulsion 1

$$CYLt_{Em1} = 113.4 - 0.553v_c - 673.6V_{Em} - 0.169v_f + 3.823v_c \cdot V_{Em} + 9.025 \cdot 10^{-4}v_c \cdot v_f + 1.162V_{Em} \cdot v_f - 5.99 \cdot 10^{-3}v_c \cdot V_{Em} \cdot v_f \qquad (1)$$
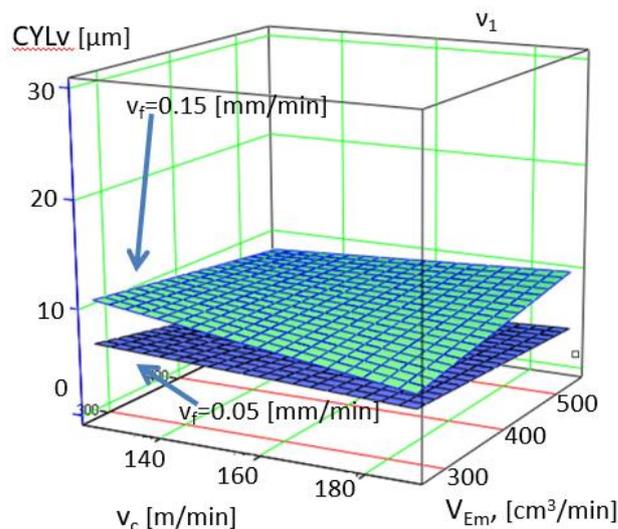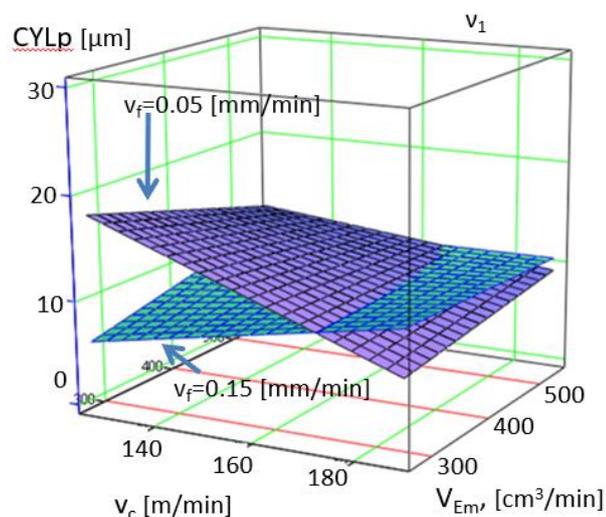

Fig.7. Change in CYLp cylindricity deviation depending on technological parameters and volume of emulsions for Emulsion 1

$$CYLp_{Em1} = 102.555 - 0.538v_c - 818.3V_{Em} - 0.146v_f - 4.749v_c \cdot V_{Em} + 8.456 \cdot 10^{-4}v_c \cdot v_f + 1.34V_{Em} \cdot v_f - 7.736 \cdot 10^{-3}v_c \cdot V_{Em}.v_f \qquad (2)$$

Examining Figs. 6-11 it can be stated that the values of CYLt are the largest while the value of CYLv is the smallest. The nature of CYLt and CYLp is almost the same. When using Emulsion 1 the CYLt, CYLp and CYLv is worse when cutting speed is lower (v_{c1}=125.7 m/min).

Fig.8. Change in CYLv cylindricity deviation depending on technological parameters and volume of emulsions for Emulsion 1

$$CYLv_{Em1} = 10.935 - 0.015v_c - 144.1V_{Em} - 0.023v_f - 0.923v_c \cdot V_{Em} + 5.859 \cdot 10^{-5}v_c \cdot v_f + 0.175V_{Em} \cdot v_f + 1.766 \cdot 10^{-3}v_c \cdot V_{Em} \cdot v_f \qquad (3)$$
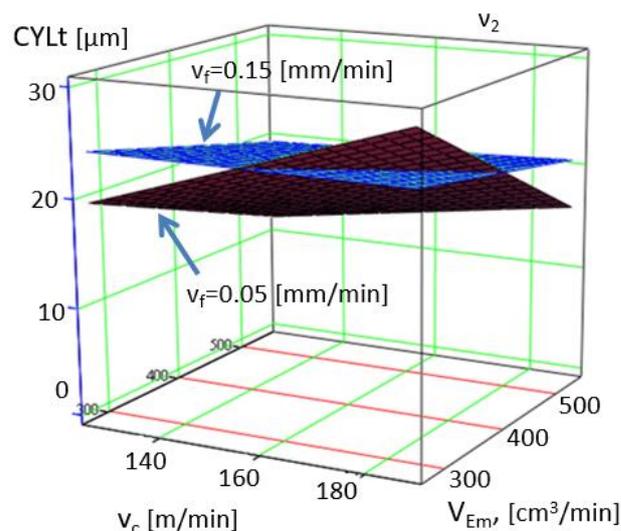

Fig.9. Change in CYLt cylindricity deviation depending on technological parameters and volume of emulsions for Emulsion 2

$$CYLt_{Em2} = -19.43 + 0.367v_c + 0.028V_{Em} + 341.4v_f - 5.005 \cdot 10^{-4}v_c \cdot V_{Em} - 2.593v_c \cdot v_f - 0.367V_{Em} \cdot v_f + 3.819 \cdot 10^{-3}v_c \cdot V_{Em} \cdot v_f \qquad (4)$$

When using Emulsion 2 the highest value of CYLt, CYLp and CYLv can be achieved when value of the cutting speed is lower (v_{c1}=188.5 m/min). When examining CYLv it can be stated that CYLv is lower, so better, when feed rate is smaller (v_{f1}=0.05 mm/rev) related to both Emulsions.
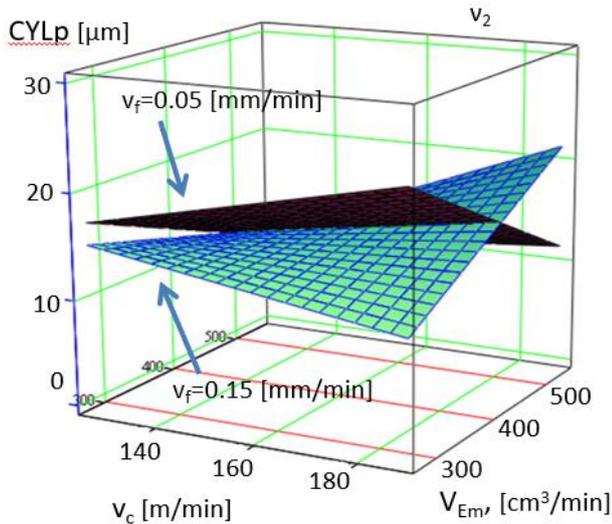
Fig.10. Change in CYLp cylindricity deviation depending on technological parameters and volume of emulsions for Emulsion 2

$$CYLp_{Em2} = -24.45 + 0.417v_c + 0.068V_{Em} + 573.8v_f - 8.211 \cdot 10^{-4}v_c \cdot V_{Em} - 4.954v_c \cdot v_f - 1.371V_{Em} \cdot v_f + 0.012 \cdot v_c \cdot V_{Em} \cdot v_f \quad (5)$$
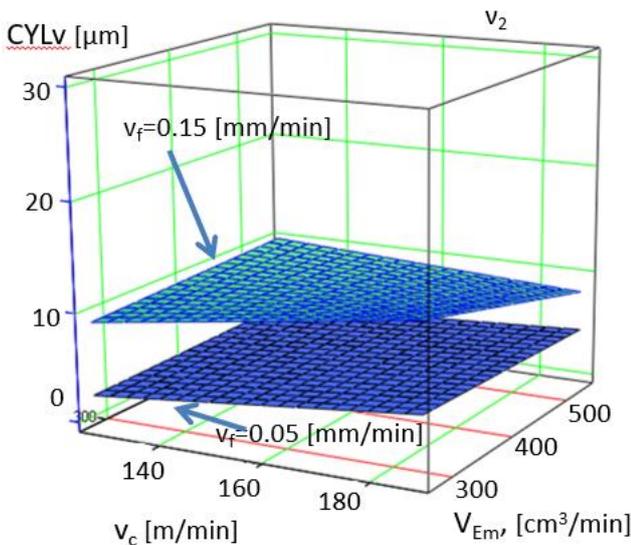

Fig.11. Change in CYLv cylindricity deviation depending on technological parameters and volume of emulsions for Emulsion 2

$$CYLv_{Em2} = -3.945 + 0.022v_c - 6.758 \cdot 10^{-3}V_{Em} - 53.1v_f + 5.976 \cdot 10^{-3}v_c \cdot V_{Em} + 0.936v_c \cdot v_f + 0.348V_{Em} \cdot v_f - 2.688 \cdot 10^{-3}v_c \cdot V_{Em} \cdot v_f \quad (6)$$

When studying Figs.5-10, the improvement values of the minimum cylindricity deviations can be calculated by (7).

The results of the calculations of the improvements can be found in Table 7. Calculations were made with the measured values of Tables 4-5.

$$I_{CYLx} = \frac{CYLx,g - CYLx,l}{CYLx,g} \cdot 100 \ , \ \% \quad (7)$$

where:

CYLx	x can be: t, p or v
CYLx,l	lower value of the CYLx
CYLx,g	greater value of CYLx, next to the lower value

Table 7, Improvements of cylindricity errors

Improvements	Changes	Applied parameters		Emulsion
I_{CYLt}=49.88%	$v_{c2} \rightarrow v_{c1}$	v_{f1}	V_{Em1}	Emulsion 1
I_{CYLp}=66.83%	$v_{f1} \rightarrow v_{f2}$	v_{c1}	V_{Em1}	
I_{CYLv}=56.16%	$V_{Em2} \rightarrow V_{Em1}$	v_{c1}	v_{f1}	
I_{CYLt}=40.49%	$V_{Em2} \rightarrow V_{Em1}$	v_{c1}	v_{f1}	Emulsion 2
I_{CYLp}=62.41%	$V_{Em2} \rightarrow V_{Em1}$	v_{c2}	v_{f2}	
I_{CYLv}=56.21%	$v_{c2} \rightarrow v_{c1}$	v_{f1}	V_{Em1}	

Table 7 shows improvements in cylindricity errors when reducing the value of one parameter while retaining the others on the same level. The first row of Table 7, for instance, means in the case of a v_1 = 2.4557 mm²/s kinematic viscosity emulsion (Emulsion 1), if the cutting speed is reduced from v_{c2} = 188.5 m/min to v_{c1} = 125.7 m/min, while the feed rate v_{f1} = 0.05 mm/rev and V_{Em1} = 273 cm³/min remain unchanged, the CYLt cylindrical deviation is reduced by 49.88%. The other lines in Table 7 can be interpreted similarly.

There are no big differences between values of the total cylindricity error (CYLt) for the lubricants having different kinematic viscosity:
Emulsion1 CYLt$_{min}$ =13.31 μm, V_{Em1}=273 cm³/min
Emulsion2 CYLt$_{min}$ =11.64 μm, V_{Em2}=546 cm³/min.
Table 8 summarises the results of the experiments. In the columns the minimum values of cylindricity deviations can be found for Emulsion 1 and Emulsion 2 respectively.

Table 8, Minimum values of cylindricity deviations

	Minimum value of		
	CYLt [μm]	CYLp [μm]	CYLv [μm]
Emulsion 1	12.42	7.11	2.92
	(V_{Em1})	(V_{Em1})	(V_{Em2})
Emulsion 2	11.64	8.94	2.36
	(V_{Em2})	(V_{Em2})	(V_{Em1})

Yellow background is put to the smaller amount of the emulsion (V_{Em1}=273 cm^3/min) and green background where the cylindricity error is smaller related to Emulsion 1 and Emulsion 2.

In case of Emulsion 2 the CYLt - peak to valley cylindricity deviation is 0.78 μm smaller than when application of Emulsion 1. This difference is very little; however, it requires the application the larger flowrate (V_{Em2}=546 cm^3/min) of Emulsion 2. With the use of V_{Em1}=273 cm^3/min flow rate, the ambient environment load is lower than when using double flow rate. Thus, the recommended parameter combination is:

- Emulsion 1
  (kinematic viscosity is $v_1 = 2.4557$ mm^2/s),
- $V_{Em1} = 273$ cm^3/min flow rate,
- $v_{c1} = 188.5$ m/min cutting speed,
- $v_{f1} = 0.05$ mm/rev feed rate.

6 Conclusion

The paper deals with the experimental examination of outer boring. Using the measurement data of the experiments carried out based on the parameter combinations determined by the Factorial Experiment Design, empirical formulas were created to examine how the cylindricity error of the machined surfaces is influenced by the changes in the technological parameters. It was also examined how sundry coolants and lubricants (emulsions having different kinematic viscosities) and different flow rates influence the values of the different cylindricity errors CYLt, CYLp and CYLv.

7 Acknowledgements

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