## Examination of Shape Error of Outer Cylindrical Surfaces Machined by Environmentally Friendly Way

GYULA VARGA<sup>1</sup>, TIBOR PUSKÁS<sup>2</sup>, ISTVÁN DEBRECENI<sup>3</sup> Institute of Manufacturing Science University of Miskolc Miskolc, Egyetemvaros HUNGARY <sup>1</sup>gyulavarga@uni-miskolc.hu, <sup>2</sup>puskas91@outlook.hu, <sup>3</sup>debrec.istvan@gmail.com

*Abstract:* - The paper deals with experimental examination of the machining of the cylindrical workpieces. The purpose of this paper was to obtain a comprehensive understanding of the relation between cutting data (cutting speed, feed rate), parameters of coolants and lubricants (viscosity, volume per minute), and error of machined cylindrical workpiece in terms of peak to valley cylindricity deviation, peak to reference cylindricity deviation, and reference to valley cylindricity deviation during "outer boring" with a carbide insert in AISI 1045 steel. Full factorial experiment design was used in the study. The kinematics and rigidity of the machining examined here differs from the usual machining. In our study, the cylindrical workpiece is standing on the milling machine, and a cutting tool having single point cutting edge makes the rotating movement and the feed as well. Our aim is to determine empirical expressions between the technological parameters set at machining and the geometrical shapes error. Based on the examinations, the appropriate parameter combination can be selected.

Key-Words: - Environmentally conscious machining, cylindricity error, Factorial Experiment Design

### **1** Introduction

The paper contains the examination of machining standing cylindrical surfaces by a rotating cutting tool having defined edge geometry on a milling machine. The task was to determine the parameters of the experiments, the choice of oils of which the different emulsions could be prepared, and the determination of the different volumes of the emulsions. The experiments were done based on the Taguchi type full factorial experiment design. After machining, the different cylindricity error indicators were determined by measurement. The aim of the experiments was the choice of the type (kinematic viscosity) and volume of the lubricating emulsion which results in minimal defects shape error. These tests determine the relationship among the shape error, the mode of lubrication and the volume of Thus, a technological parameter lubricants. combination can be determined which minimizes the shape error 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 the best parameter combination.

Because our experiments involve the use of a small amount of coolants and lubricants with different volumes, in the following a summary of the various modes of low-pressure machining is given.

## 2 Main features of low environmental load lubrication modes

Cloud computing, the Internet of Things, Big Data, and Artificial Intelligence have gradually leaked into the manufacturing industry and allow the integration of physical and virtual worlds into cyber-physical systems (CPS), which show the appearance of Industry 4.0 [1]. Widespread use of cyber-physical systems in manufacturing environments makes production systems more intelligent. That is how it is related to sustainable, environmentally friendly production.

According to Hegab et al., [2] a detailed and general evaluation model of machining processes can be used to determine optimal cutting conditions, to analyze energy and material flows. In this work, a general sustainability algorithm for machining processes was developed. The use of coolant lubricants has generally been applied to increase the performance of metal cutting. Advantages of coolants and lubricants include removing frictional heat occurring during machining [3]. Even when hard machining the hardened AISI H-13 steel, a great amount of heat is produced. High temperature dramatically reduces the tool life of the cutting tool [4]. Therefore, during machining, a coolant and lubricant is used to reduce the cutting temperature. The conventional cooling-lubricating fluid application techniques are least effective when removing heat from the chip-tool interfaces [5].

Extreme pressure-resistant additives are added to the coolants and lubricants for getting better cooling and lubrication effect [6]. Pressurized, oil-based coolant-lubricating fluid flows may reduce the cutting force and improve surface roughness [7]. Therefore, coolants and lubricants increase the tool life, improve surface roughness, and facilitate the transportation of chips [8]. 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 [3]. For example, a worker who is exposed to the harmful effects of the cooling-lubricating fluid for a long time may suffer from respiratory and skin problems [9]. In addition, coolants and lubricants can contaminate water and soil. Consequently, environmental legislation must be observed when handling and disposing of coolants and lubricants. Experiments by Gajrani et al. [10] aimed at reducing or completely abandoning coolants and lubricants. They dealt with sustainable dry or near-dry machining. Vegetable-based coolants and lubricants are biodegradable, and their handling costs are low as well [11]; thus, vegetable-based coolants and lubricants are environmentally friendly liquids [12].

In conventional fluid application methods 15-17% of the production cost is related to the cost of coolant and lubricant fluid [13]. Research has shown that the cost of cooling oil is often higher than the cost of cutting tools [14]. The negative features of coolants and lubricants can be eliminated in various ways. The abandonment or minimization of coolants and lubricants is desirable both economically and environmentally reasons. Its advantages include eliminating the purchase cost of coolants and lubricants, reducing manufacturing costs, reducing disposal costs, a lower environmental load and improving healthcare conditions [15]. The use of environmentally friendly coolants and lubricants further reduces the harmful environmental impacts. Dry machining is expected to be necessary soon for manufacturing companies to comply with legislation on environmental, safety and health at work [8].

The advantages of dry machining are shown by Jaharah et al. [16]. In their experiment, AISI H13

tool steels were milled dry using P10 carbide insert coated by TiN and P20 uncoated cermet tools. Their results have shown that dry machining is not suitable for cutting very hard materials. Results obtained by turning stainless steel AISI 422 showed that dry machining can achieve values comparable to wet cutting [17]. Khan and Maity [18] investigated the impact of cutting speed and the effect of environmentally friendly cooling technology when finishing turning special titanium alloy. The experiments were performed using three different machining methods using carbide inserts with dry cutting, flood cooling and minimum quantity lubrication. The results of the different cooling and lubricating modes were compared, and it was found that the very good improvement in process parameters was achieved with in case of minimum quantity lubrication within the examined range.

Dry machining applications depend to a large extent on the choice of cutting tools, technological parameters, and workpiece material [19]. In machine industrial machining the application of dry machining is an effective method for reducing the environmental problems in connection with cooling and lubrication, because obviously all negative effects caused by coolants and lubricants can be eliminated [20]. There are several ways to improve the performance of dry machining, one of which is the development of coatings on cutting tools. Statistics show that four-fifths of all machining operations are performed using coated cutting tools [21]. 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 [22]. Most problems occur due to the microstructure change during the machining process [23]. Dry machining is not effective related to tool life and getting better surface quality [24]. Near-dry machining or minimum quantity lubrication or micro-lubrication, applying a minimum amount of coolant lubricating fluid, offers an alternative solution for reducing adverse environmental impacts [25]. In the case of a minimum amount of coolant lubricating fluid applications, a cooling fluid is used at a flow rate of 500-600 ml/h. This has the advantage that the resulting atomized fog goes directly to the cutting tool-workpiece interface of the cutting area [26]. The minimum amount of coolant lubricating fluid reduces occupational hazards and manages environmental issues.

For abrasive machining, a new trend is the use of nano-fluids as cooling-lubricating fluids [27]. The machining of hardened bore holes can be performed by using environmentally friendly hard turning instead of grinding [28]. Of course, we know from our experience that use of minimum quantity lubrication influences the wear of the cutting tool as well [24]; however, its examination is not the topic of this paper. Now, we intend to determine whether there any effect of the different amount of coolant applied and the change of kinematic viscosity on the cylindricity error of the machined cylindrical surface.

# **3** Features of machining of cylindrical surfaces

The machine tool is a milling machine on which the cylindrical workpiece to be machined is standing and the cutting tool, having single point defined edge geometry, performs the rotating movement (main cutting movement) and the feed (auxiliary cutting movement) (Fig. 1). This machining is called "outer boring". The rigidity of the Workpiece - Fixture - Machine tool - Cutting tool system of the examined machining differs from the conventional one, which influences cylindricity error, 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 error of the machined workpiece.



Fig.1, Outer boring with single point cutting tool having defined edge geometry

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 tool Z-axis feed is required, so this process can be considered more productive.

## 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 [29].

Table 1, Chemical composition of AISI 1045 [%][29]

	С	Fe	Mn	Р	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 [29]

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

This is a general purpose, unalloyed, structural carbon steel. Applications can include parts of the machine and automotive industry where the load is not too high, abrasion-resistant components, parts of pressure vessels, etc. After the product is manufactured, the material quality mentioned above is excellent for heat treatment.

During the experiment, 16 workpieces were machined to the size of  $\emptyset$ 39.7×50 mm, of which 30 mm length was used for smooth outer boring.

Shape error measurements were performed on a Talyrond 365 measuring machine produced by Taylor Hobson. This measuring machine is suitable for measuring medium-sized parts (max:  $\phi 200 \times 500$  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.

The system for cooling and lubrication was developed at the Institute of Manufacturing Science because the CNC machine tool cooling system was suitable for flood cooling only. The 5% emulsion was delivered to the working area by two tubes, where it was sprayed onto the workpiece and cutting tool. Two different volumes were set. The method of lubrication is shown in Fig. 2.



Fig.2. The position of the spraying heads relative to the workpiece in the machining area

The viscosity of the emulsions used for the experiments is shown in Table 3.

Types of lubricants	Kinematic viscosity of oil, emulsion (at 40°C)
Oil 1	$v_{oil 1}=30 \text{ mm}^2/\text{s}$
Oil 2	$v_{oil 2} = 70 \text{ mm}^2/\text{s}$
Emulsion made from Oil 1	$v_1$ =2.4557 mm <sup>2</sup> /s
Emulsion made from Oil 2	$v_2$ =4.4554 mm <sup>2</sup> /s

Table 3, Viscosity of the oils and emulsions

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.

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

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

The matrix of the Taguchi type Factorial Experimental Design [30] can be seen in Table 4, which contains the outer boring parameters in natural dimensions and in transformed ones.

No.	Cutting	Feed	Volume	Transformed		ned
	speed	rate	of	parameters		ers
	v <sub>c</sub> ,	v <sub>f</sub> ,	emuls.			
	$\left[\frac{m}{min}\right]$	$\left[\frac{mm}{rev}\right]$	$V_{Em},$ $\left[ rac{cm^3}{min}  ight]$	X <sub>1</sub>	X <sub>2</sub>	X <sub>3</sub>
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

#### Table 4, Applied experimental parameters

## **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 [31]. Results can be seen in Fig. 3 [32]. The above- mentioned cylindricity parameters are included in ISO Standard 12180-1.



Fig.3. Cylindricity parameters: CYLt, CYLp and CYLv [32]

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

Emulsion 1, $v_1$ =2.4557 mm <sup>2</sup> /s							
No.	Transformed parameters			Measured values			
	$\mathbf{X}_1$	X <sub>2</sub>	<b>X</b> <sub>3</sub>	CYLt [µm]	CYLp [µm]	CYLv [µm]	
1	-1	-1	-1	24.78	18.12	6.66	
2	+1	-1	-1	12.42	7.11	5.31	
3	-1	+1	-1	16.75	6.01	10.74	
4	+1	+1	-1	18.19	11.57	6.62	
5	-1	-1	+1	15.30	12.36	2.92	
6	+1	-1	+1	13.31	9.22	4.09	
7	-1	+1	+1	18.56	10.29	8.27	
8	+1	+1	+1	20.15	10.45	9.70	

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

Table 6, Measured values of the cylindricity error values for Emulsion 2

Emulsion 2, $v_2$ =4.4554 mm <sup>2</sup> /s							
No.	Transformed parameters			Measured values			
	$\mathbf{X}_1$	$X_2$	<b>X</b> <sub>3</sub>	CYLt [µm]	CYLp [µm]	CYLv [µm]	
9	-1	-1	-1	19.56	17.20	2.36	
10	+1	-1	-1	29.17	23.78	5.39	
11	-1	+1	-1	24.20	15.12	9.08	
12	+1	+1	-1	24.07	10.68	13.38	
13	-1	-1	+1	11.64	8.94	2.70	
14	+1	-1	+1	15.94	11.49	4.45	
15	-1	+1	+1	19.36	9.66	9.69	
16	+1	+1	+1	29.47	21.30	8.17	

A set of measuring results of the cylindricity error can be seen in Fig. 4 in axonometric view. From Fig.4 at the bottom of the cylinder the size is larger (3%), because the deflection of the cutting tool is increasing, which results in larger dimensions of the specimen. 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.5-10. Figs.5-7 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.



Fig.4. Characterizing measurement results of cylindricity for Emulsion 2 for measuring set up No. 16, parameter combination ( $v_{c2}$ ,  $v_{f2}$ ,  $V_{Em2}$ )



Fig.5. Change in CYLt cylindricity error depending on technological parameters and volume of emulsions for Emulsion 1

 $\begin{aligned} CYLt_{Em1} &= 113.4 - 0.553v_c - 673.6v_f - 0.169V_{Em} + \\ 3.823v_c \cdot v_f + 9.025 \cdot 10^{-4}v_c \cdot V_{Em} + 1.162v_f \cdot V_{Em} - \\ 5.99 \cdot 10^{-3}v_c \cdot v_f \cdot V_{Em} \end{aligned} \tag{1}$ 



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

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



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

 $\begin{aligned} CYLv_{Em1} &= 10.935 - 0.015v_c - 144.1v_f - \\ 0.023V_{Em} &- 0.923v_c \cdot v_f + 5.859 \cdot 10^{-5}v_c \cdot V_{Em} + \\ 0.175v_f \cdot V_{Em} + 1.766 \cdot 10^{-3}v_c \cdot v_f \cdot V_{Em} \end{aligned} \tag{3}$ 

Examining Figs. 5-10 it can be stated that the values of CYLt are the largest.



Fig.8. Change in CYLt cylindricity error depending on technological parameters and volume of emulsions for Emulsion 2

 $CYLt_{Em2} = -28.43 + 0.439v_c + 521.4v_f + 0.061V_{Em} - 4.025v_c \cdot v_f - 7.628 \cdot 10^{-4}v_c \cdot V_{Em} - 1.026v_f \cdot V_{Em} + 9.065 \cdot 10^{-3}v_c \cdot v_f \cdot V_{Em}$ (4)



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

$$\begin{aligned} CYLp_{Em2} &= -24.45 + 0.417v_c + 573.8v_f + \\ 0.068V_{Em} - 4.954v_c \cdot v_f - 8.211 \cdot 10^{-4}v_c \cdot V_{Em} - \\ 1.371v_f \cdot V_{Em} + 0.012 \cdot v_c \cdot v_f \cdot V_{Em} \end{aligned} \tag{5}$$

The nature of CYLt and CYLp is the same. When studying Figs.5-10, the improvement values of the

minimum cylindricity errors can be calculated by (7).



Fig.10. Change in CYLv cylindricity error depending on technological parameters and volume of emulsions for Emulsion 2

$$\begin{aligned} CYLv_{Em2} &= -4.015 + 0.022v_c - 51.7v_f - 6.502 \cdot \\ 10^{-3}V_{Em} + 0.925v_c \cdot v_f + 5.772 \cdot 10^{-5}v_c \cdot V_{Em} + \\ 0.342v_f \cdot V_{Em} - 2.647 \cdot 10^{-3}v_c \cdot v_f \cdot V_{Em} \end{aligned} \tag{6}$$

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

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.

Table 7, Improvements of cylindricity errors

Improvements	Changes	Applied parameters		Emulsion
I <sub>CYLt</sub> =49.88%	$v_{c2} \rightarrow v_{c1}$	$v_{f1}$	$V_{Em1}$	n 1
I <sub>CYLp</sub> =60.76%	$v_{c2} \rightarrow v_{c1}$	$v_{f1}$	$V_{Em1}$	ulsio
I <sub>CYLv</sub> =64.69%	$v_{f2} \rightarrow v_{f1}$	v <sub>c1</sub>	$V_{\text{Em2}}$	Em
I <sub>CYLt</sub> =39.88%	$v_{f2} \rightarrow v_{f1}$	v <sub>c1</sub>	$V_{\text{Em2}}$	n 2
I <sub>CYLp</sub> =13.49%	$v_{c2} \rightarrow v_{c1}$	$v_{f1}$	$V_{\text{Em2}}$	ulsio
I <sub>CYLv</sub> =74.01%	$v_{f2} \rightarrow v_{f1}$	v <sub>c1</sub>	V <sub>Em1</sub>	Em

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  $v_1 = 2.4557 \text{ mm}^2/\text{s}$  kinematic viscosity emulsion (Emulsion 1), if the cutting speed is reduced to  $v_{c1} = 25.7 \text{ m/min}$  from  $v_{c2} = 188.5 \text{ m/min}$ , while the feed rate  $v_{f1} = 0.05 \text{ mm/rev}$  and  $V_{Em1} = 273 \text{ cm}^3/\text{min}$  remain unchanged, the CYLt cylinder error will be 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<sub>min</sub> =12.42  $\mu$ m, V<sub>Em1</sub>=273 cm<sup>3</sup>/min Emulsion2 CYLt<sub>min</sub> =11.64  $\mu$ m, V<sub>Em2</sub>=546 cm<sup>3</sup>/min. The outer boring is strongly influenced by the cutting speed and feed rate. So, in selecting the parameter combination recommended for use, the volume flow rate of the coolant and lubricant was crucial. With the use of V<sub>Em1</sub>=273 cm<sup>3</sup>/min flow rate, the ambient environment load is lower than when using double flow rate. Thus, the recommended parameter combination is:

- Emulsion 1 ( $v_1 = 2.4557 \text{ mm}^2/\text{s}$  kinematic viscosity),
- $V_{Em1} = 273 \text{ cm}^3/\text{min flow rate}$ ,
- $v_{c1} = 188.5$  m/min cutting speed,
- $v_{f1} = 0.05 \text{ mm/rev}$  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 determined to examine how the cylindricity error of the machined surfaces is influenced by the changes in the technological parameters. It was also examined how the various coolants and lubricants (emulsions having different kinematic viscosities) and different flow rates influence the values of the different cylindricity errors CYLt, CYLp and CYLv.

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