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Measurement of the Machined Surface Diameter by a Laser Triangulation Sensor and Optimalization of Turning Conditions Based on the Diameter Deviation and Tool Wear by GRA and ANOVA

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Abstract: One of the most important operations in the technological production process is the inspection of the manufactured product. The gradual wear of the tool affects the achievement of the required quality of the functional surfaces. In this research, we present the results of measuring the diameter deviation with a new generation laser triangulation sensor (LTS). At the same time, we have performed parametric optimization of several multi-responses, such as insert wear on the VB_B flank side of cutting edge and diameter deviation Δ_d for a C45 steel sample during dry turning and using a sintered carbide insert, using the method of grey relational analysis (GRA) in combination with the Taguchi L16 orthogonal array. The optimal setting of input factors for multi-response parameters is a_p 4-f 4-v_c 1 i.e., depth of cut 0.5 mm, feed 0.4 mm per revolution, and a cutting speed of 70 m/min. At the same time, we present an evaluation of the significance of input factors using the method ANOVA.

Keywords: laser triangulation sensor; diameter deviation; tool wear; turning; steel C45; GRA; ANOVA

1. Introduction

The direct contact of the measuring contacts with the machined surface is one of the negative phenomena in measurement. One of the ways to solve this negative phenomenon is to use non-contact methods of measuring the parameters of machined surfaces.

This article describes the suitability and new use of a laser triangulation sensor for measuring the deviation of the cylindrical surface diameter in the context of evaluating tool wear when turning C45 steel and optimizing cutting conditions. In this article, we present a new method for intermediate and final control of the measurement of quality parameters of the machined surface without removing the workpiece from the working area of the machine. In this way, it is possible to eliminate several errors in the inspection of products after machining. Currently, there are several companies in our region that produce various C45 steel shafts for agricultural and garden machinery.

Several authors have used laser scanners in their research. These technologies can be used in different industries and in different applications [1]. Javaid et al. states that laser technology is one of the most advanced technologies and laser scanners are immediately used in industry [2]. Li et al. proposes a pneumatic for laser measurement system [3]. Schmitt et al. state that sensors as information sources determine the quality level of information measurement and control systems [4]. According to Balestrieri et al. advanced systems for measuring parameters are important in terms of their various properties [5].

In selected studies, the authors have used LTS in machining, focusing mainly on the surface roughness parameter and surface defects. Yang et al. describe the use of the laser triangulation method as one of the most modern methods for measuring product diameters [6]. Giganto et al. found that optical measurement systems are suitable for surface roughness evaluation [7]. In their research, Garcia et al. used laser deviation sensors in the evaluated real-time surface quality control based on cutting force, vibration, and acoustic emission signals [8]. The influence of the dynamic aspect of the cutting process on the machined surfaces was analyzed by Kiss et al. in their research [9]. Yuan et al. presented evaluation of surface roughness based on machining process [10]. Syed et al. dealt with the optimization of parameters to predict defects in the manufacturing process [11]. Bose et al. investigated the use of optical systems to identify defects in the production process [12].

Some authors have focused on solving positional accuracy of tools with LTS. Authors such as Chen and Selami et al. dealt with design of algorithms for determining the position of tools with the application of a triangulation sensor [13,14]. Montavon et al. presented deviation measuring between the defined tool comparison position and the actual tool tip position [15]. Miklós et al. proposed a measurement method to determine linear stability for different real spindle speeds and virtual depths of cut using deviation sensors [16]. Ji-Hwan You et al. present that laser sensors are widely used in automotive industry for position measurement [17]. Frommknecht et al. present a 6D multisensor measurement system for drilling robots in their paper [18]. Takushima et al. designed an optical system for measuring the position of tools during drilling [19].

Other authors also dealt with the use of LTS for vibration research and its effects on tool damage during machining. Wojciechowski et al. proposed a new experimental method for estimating the vibrations of the milling cutter with a laser sensor [20]. Bombiński et al. described and proposed an innovative algorithm for early detection of tool damage [21]. In the research, Kossakowska et al. analyzed various signal functions that affect the wear of a tool, filtering out unwanted signals [22]. Wang et al. investigated the possibilities of using sensors to evaluate roundness deviations [23].

By designing the material used and the uncoated cutting insert, we aimed to minimize the effects of degraded machinability of the various materials and the effects of the properties of the cutting insert structures. Zlamal and Peterka et al. point out the effects of cutting the cutting edge of a sintered carbide tool when milling steel C45 to eliminate tool wear and achieve the required surface quality [24,25].

Is the application of a laser beam suitable for checking the quality parameters of the machined surface of products (e.g., diameter deviation) after the end of the cutting process? Based on the experience of machining different materials, we have chosen C45 steel specimens and sintered carbide inserts for dry turning and under the important condition that the vibrations of the machine tool comply with the values certified for the machine tool.

Therefore, in order to eliminate negative phenomena in product control, we proposed to review the application of the new generation LTS to measure the deviation of cylindrical surface diameter (Δ_d) and evaluate the effects of flank wear (VB_B value according to ISO 3685) of the sintered carbide insert on this parameter under different cutting conditions.

2. Optimization of Input Factors Using the GRA Method and Analysis of the Significance of Factors According to ANOVA

When processing data from technological processes with different response parameters, the mutual relationships are complex and very often incomprehensible. We refer to this relationship as grey. For processing selected results from our research, we proposed a method based on GRA [26]. When optimizing with the method GRA we followed Lin [27]. The following values and parameters must be calculated as part of the procedure.

Calculation of the data for the methodology and the smaller the better according to Equation (1):

$$x_i^*(k) = \frac{max\ x_i^0(k) - x_i^0(k)}{max\ x_i^0(k) - min\ x_i^0(k)} \tag{1}$$

where:

$i = 1, \ldots, m$ $k = 1, \ldots, n$,

m	is the number of experimental data,
n	is the number of response characteristics,
$x_i^0(k)$	indicates the original sequence,
$x_i^*(k)$	indicates a sequence after data processing,
$max\ x_i^0(k)$	highest value of $x_i^0(k)$,
$min\ x_i^0(k)$	lowest value of $x_i^0(k)$,
x_i^0	is the required value of $x_i^0(k)$.

GRC $\xi_i(k)$ according to Equation (2):

$$\begin{aligned} \xi_i(k) &= \tfrac{\Delta_{\min}+\xi.\Delta_{\max}}{\Delta_{oi}(k)+\xi.\Delta_{\max}} \\ \Delta_{oi}(k) &= \left|x_o^*(k) - x_i^*(k)\right| \\ \Delta_{max} &= 1.00\ \Delta_{min} = 0.00 \end{aligned} \tag{2}$$

where:

$\Delta_{oi}(k)$	is the sequence deviation of the reference sequence and the comparison sequence $x_i^*(k)$,
Δ_{min}, Δ_{max}	are the minimum and maximum values of the absolute differences (Δ_{oi}),
ξ	is an identification coefficient, and is defined in scope $0 \le \xi \le 1$ and depends on the needs of the system. Usually, the value of (ξ) is 0.5.

GRG calculation according to Equation (3):

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n} \xi_i(k) \tag{3}$$

where:

γ_i is the GRG required for the i experiment,
n number of response characteristics.

Calculation of the expected value of the optimal GRG level according to Equation (4).

$$\hat{\gamma} = \gamma_m + \sum_{i=1}^{s}(\gamma_i - \gamma_m) \tag{4}$$

where:

γ_m is the total mean of GRG,
γ_i is the mean of GRG at the optimal level of each factor,
s is the number of significant process factors.

Many authors have used the GRA method, the Taguchi method, and the ANOVA method to present the results of their research. Sivalingam et al. and Pervez et al. optimized the process factors in their study and used the Taguchi L27 orthogonal array [28,29]. Mufarrih et al. and Li et al. solved the optimization of parameters in the machining process, using the Taguchi method—GRA [30,31]. Sharma et al. applied the GRA method and Taguchi L18 orthogonal array method to optimize the cutting parameters in drilling AA6082 and analyzed the results using ANOVA [32]. Chelladurai et al. used Taguchi method and GRA method to study the milling parameters in CNC machining of Al-6063 aluminum alloy [33]. Tamizharasan, Sylajakumari, and Puh et al. investigated the influence of turning parameters on chip formation to achieve the required surface quality when machining aluminum composite. Taguchi method was proposed for the design of L9 orthogonal array fields and ANOVA for the experiments [34–36].

In an experimental study, Kilickap et al. investigated the influence of various cutting parameters on cutting force, surface roughness, and tool wear during milling of the alloy Ti-6242S [37].

After analyzing the design of the optimal combination, we perform analysis of variance (ANOVA) to evaluate the significance of the factors affecting multiple responses at 95% confidence level and recommend significant information on the experimental data. To evaluate the significance of the response parameter, the *p* value (probability of significance) is analyzed. After determining the optimal combination of process factors, the confirmation test must be performed.

2.1. Experimental Design—Technological System

Two technological systems TS-A and TS-B (according to Table 1) were designed for the experiments, which are shown in Figure 1 and described by the following model.

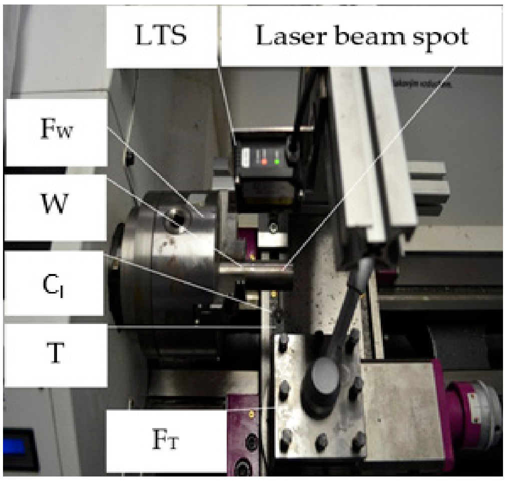
$$TS = M + T\ (T_H + C_I) + W + F\ (F_T + F_W)$$

where:

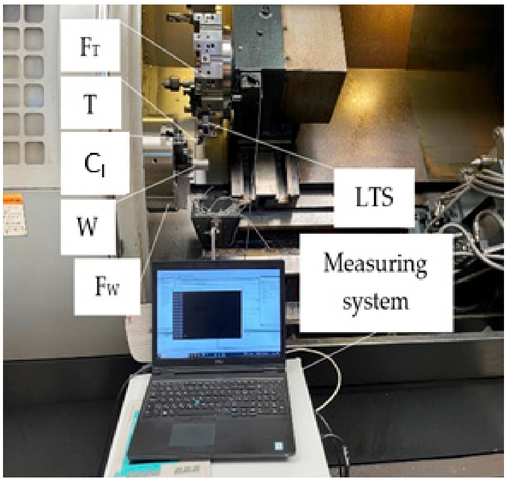
M is (machine),
T is cutting tool (consisting of tool holder—T_H and cutting insert—C_I),
W is workpiece,
F is fixture (consisting of fixture for cutting tool—F_T, and fixture for workpiece—F_W).

Table 1. Description of technological systems (TS-A-laboratory conditions, TS-B-practical conditions).

Components	TS—A	TS—B
M	Optimum TU 2807	Viper VT-28BL-1500s
W	Steel C45 EN 10083-2-91	Steel C45 EN 10083-2-91
C_I	SCMT09T308 TTR	SCMT09T308 TTR
T_H	SSDCN1212K12 M-A	SSDCN1212K12 M-A
F_T	Tool holder	Tool holder
F_w	Workpiece holder (chuck)	Workpiece holder (chuck)
LTS	Laser triangulation sensor	Laser triangulation sensor



(**a**)



(**b**)

Figure 1. (**a**) Working zone and general view of the Optimum TU 2807 machine; (**b**) working zone and general view of the Viper VT-28BL-1500s with FANUC Series 21i—TB control system.

In the case of TS-A, the lathe TU 2807 was used. This lathe has a certified hardened spindle surface (DIN 55021 standard) with a concentricity of less than 0.009 mm. The cutting tool used was an uncoated cemented carbide cutting insert with a geometry corner angle ε_r = 90°, main cutting edge setting angle κ_r = 45°, clearance angle major α_o = 7°, corner radius r_ε = 0.8 mm. TS-B consisted of machining lathe center Viper VT-28BL-1500s. This lathe has a certified maximum radial runout of 0.035 mm and a maximum axial runout of 0.025 mm. The cutting tool used was the same insert as in TS-A.

2.2. Experimental Design—Measuring System LTS

In this experiment, the LTS IL100 (Keyence) was used. Its technical characteristics are measuring range 70–130 mm, measuring spot diameter (0.400 × 1.350 mm) depending on the distance to the workpiece, linearity ±0.03 mm, repeatability 0.004 mm and accuracy of 0.001 mm. For the experiment, we developed a measurement system, the schematic of which is shown in Figure 2 and which contains these elements as shown in Figure 3.

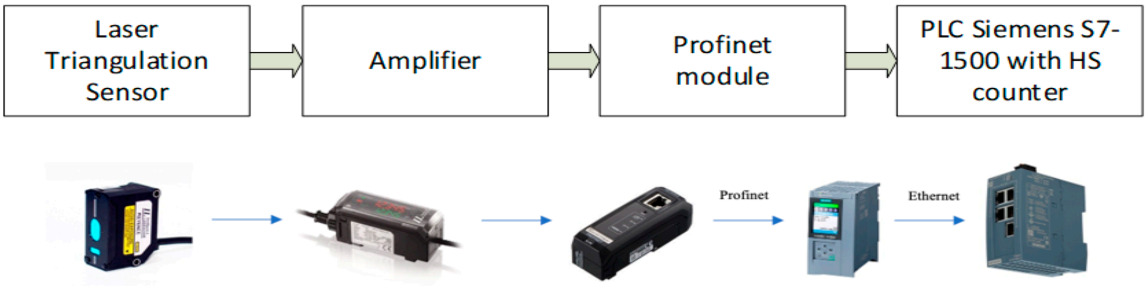


Figure 2. Measuring system LTS (Keyence—IL 100).

Figure 3. Measuring scheme of LTS, containing amplifier IL-1000, profinet module DL-PN1, PLC module Siemens 1511C.

The measurement system also consists of a communication unit (DL-PN1 type DIN rail mount) with an amplifier (IL-1000, type for communication speed 500 kbps). The switch (Siemens-XB005) is used to connect the PLC via ethernet to a PC with software.

For the PLC device, software was developed in the TIA portal program. As reported by Filipescu et al. TIA Portal is also intended for the development of operator interfaces for machines and plants with operator panels (HMI) and for dispatching systems [38]. Profinet communication has been configured in Siemens TIA Portal (Figure 4).

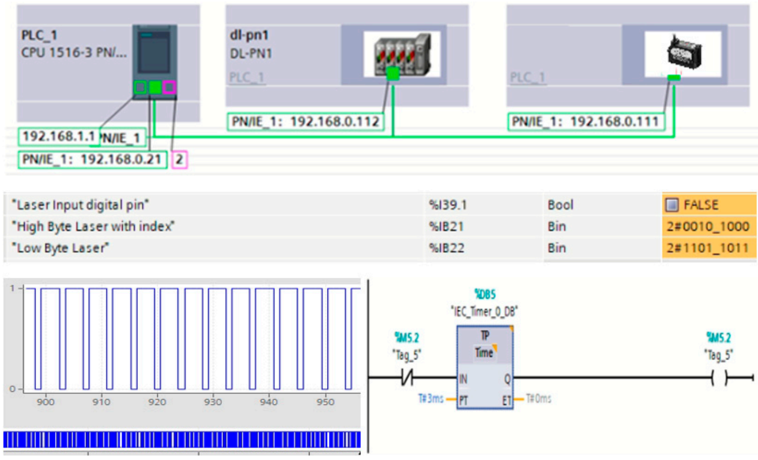


Figure 4. TIA portal configuration and graph for experimental setup for stable pulses generation.

It is very important that the data transfer from the PLC to PC is done via TCP communication with the TCP server and the client. The principle of data transfer is shown in Figure 5 also with the TCP communication part for data transfer from PLC to C#.

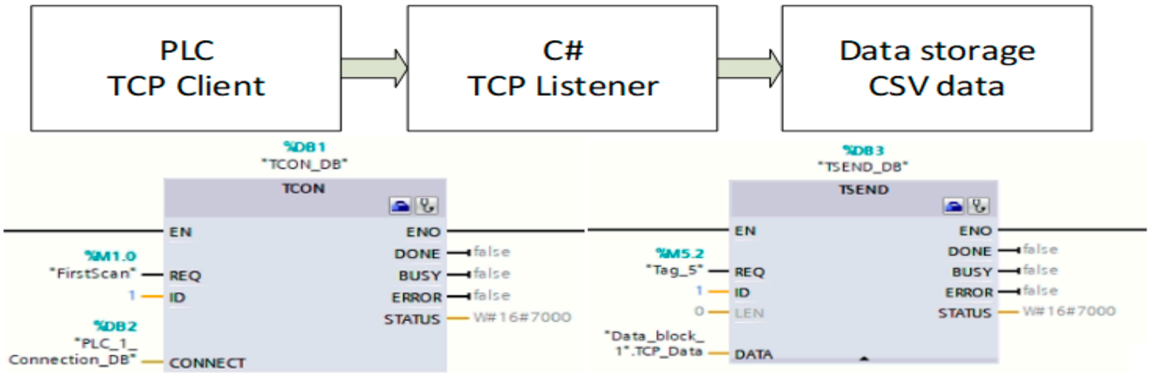


Figure 5. Client communication in PLC system.

An example of the main loop of the algorithm with an explanation of the basic principle can be found in Figure 6. The measurement data from the measurement process is stored in a PC as structured data in CSV format same as in articles by Židek et al. [39,40].

```
//Laser data
Byte[] laser = new Byte[2];
laser[0] = bytes[3];
laser[1] = bytes[2];
uint result = (BitConverter.ToUInt16(laser,0));
double result2 = result*0.001;
if(result > 60000)
result2 = result2 - 65.536;

//Spindle index
Byte[] index = new byte[2];
index[0] = bytes[7];
index[1] = bytes[6];
uint resultindex = (BitConverter.ToUInt16(index,0));
double resultindex2 = resultindex;

//write to file
string filepath = @"C:\\Users\\kpiia\\Documents\\laserdata.txt"; //sample file name & location
using (StreamWriter writer = new StreamWriter(filepath,true))
```

Figure 6. Main loop example for data transfer to value in mm.

Based on the design of the software for transformation and data processing, we can recommend the use of LTS directly in the manufacture of products on CNC machines. Part of the research was the design of the holder for LTS, its production on a 3D printer (as seen in Figure 7.)

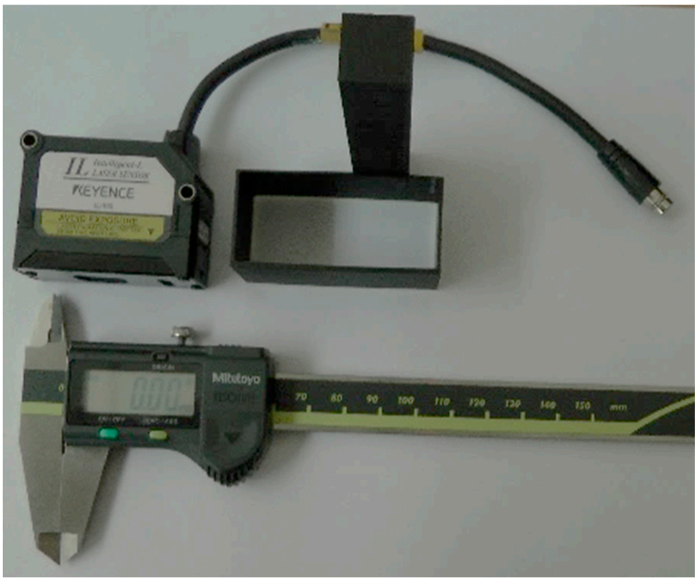


Figure 7. LTS with 3D-printed sensor holder.

3. Description, Implementation and Results of Experiments

An input experiment to test the LTS application for parameter measurement was conducted for cylindrical surface turning. For the experiment, we selected steel C45 with a specimen of 40 mm diameter and 150 mm length, shown as Table 2.

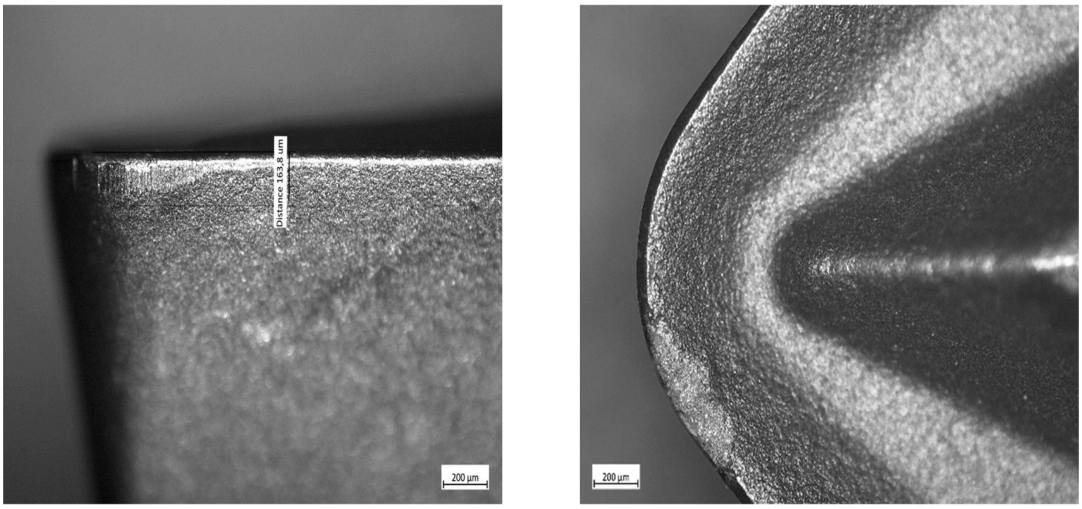
Table 2. Chemical composition of steel C45 [41].

Steel C45	%
C	0.48
Mn	0.70
Si	0.20
Cr	max 0.25
Ni	max 0.30
P	0.040
S	0.040

After verification of the selected LTS on TS-A, the experiments could be continued, as it was shown that this LTS is suitable for measuring the deviation of geometrical parameters of the machined surface. In the next step, the experiments were performed on TS-B according to Table 1, and the results of the experiments are reported in this section. The deviation of the diameter Δ_d and the wear of the flank side of the cutting insert (VB_B) were measured after each experiment. Each value of the diameter deviation and the value of the wear of the flank side of the cutting insert is a value obtained from eight repetitions (with two cutting insert). The diameter deviation was measured directly in the working zone of the machine tool with LTS, i.e., after machining the surface of the workpiece without switching it off. The measurement system for the LTS is shown in Figure 2. The surface wear of the cutting insert was measured and analyzed using a Carl Zeiss Primotech D/A ESD microscope, as shown in Figure 8.

Figure 8. Measurement and analysis of flank wear on the cutting insert by Carl Zeiss Primotech D/A ESD microscope.

In all experiments, regular wear was observed on the flank side of cutting insert, so VB_B values were measured according to ISO 3685. This parameter was important for the analysis of the impact on the next studied parameter diameter deviation for steel C45. An example of a VB_B measurement is shown in Figure 9.



(**a**) (**b**)

Figure 9. (**a**) Cutting insert wear, VB_B—flank wear 163.8 µm; (**b**) another view from face part of the damage on cutting insert.

The experiments were planned according to the Taguchi L16 orthogonal array for three input factors such as depth of cut (a_p), feed (f), and cutting speed (v_c) in four levels, as shown in Table 3. The Taguchi L16 orthogonal array represents 16 experiments, which were always turned with a new cutting edge on a 210 mm long experimental piece (3 cuts with a length of 70 mm). After turning, the machined area was measured with the LTS. The diameter deviation was measured for a defined start and reference point (with a diameter deviation value of 0 mm), which was defined in the specimen axis.

Table 3. Cutting process conditions for Taguchi L16 orthogonal array.

Factor Level	a_p Depth of Cut (mm)	f Feed (mm per Rev.)	v_c Cutting Speed (m/min)
1.	0.01	0.1	70
2.	0.05	0.2	120
3.	0.1	0.3	170
4.	0.5	0.4	220

The experimental results of the wear of the flank side and the diameter deviation are listed in Table 4.

Table 4. Experimental results for parameters—flank wear (VB_B) and diameter deviation (Δ_d) according to Taguchi L16 orthogonal array.

Number of Experiment	a_p	f	v_c	VB_B (mm)	Δ_d (mm)
1	0.01	0.1	70	0.0601	0.0526
2	0.01	0.2	120	0.1254	0.0020
3	0.01	0.3	170	0.0518	0.1460
4	0.01	0.4	220	0.1239	0.0627
5	0.05	0.1	120	0.1141	0.0589
6	0.05	0.2	70	0.0260	0.0923
7	0.05	0.3	220	0.1638	0.0704
8	0.05	0.4	170	0.1181	0.0614
9	0.10	0.1	170	0.1843	0.0476
10	0.10	0.2	220	0.1839	0.1062
11	0.10	0.3	70	0.0698	0.0344
12	0.10	0.4	120	0.1136	0.0662
13	0.50	0.1	220	0.1990	0.1148
14	0.50	0.2	170	0.1301	0.0792
15	0.50	0.3	120	0.1073	0.0589
16	0.50	0.4	70	0.0284	0.0036

The results of the experiments and the diagrams of the main effects are presented in Figure 10 (Δ_d and VB_B), showing that the resulting parameter VB_B wear of flank gradually increases with increasing depth of cut, feed, and cutting speed.

The greatest influence of the input factors was found in the order of cutting speed, depth of cut, and feed. The deviation of the diameter increases significantly when the depth of cut changes from level 1 to 2 of the depth of cut, but it is also reversed from level 2 to 3 of the depth of cut and increases gradually from level 3 to 4 of the depth of cut. The lowest value was displayed at a depth of cut of level 1. During the feed, lower values were measured from level 3 to 4. The lowest value of diameter deviation was measured at a feed of 0.4 mm. The influence of the cutting speed is significant to obtaining lower deviations of the average from level 1 to 2 of the cutting speed.

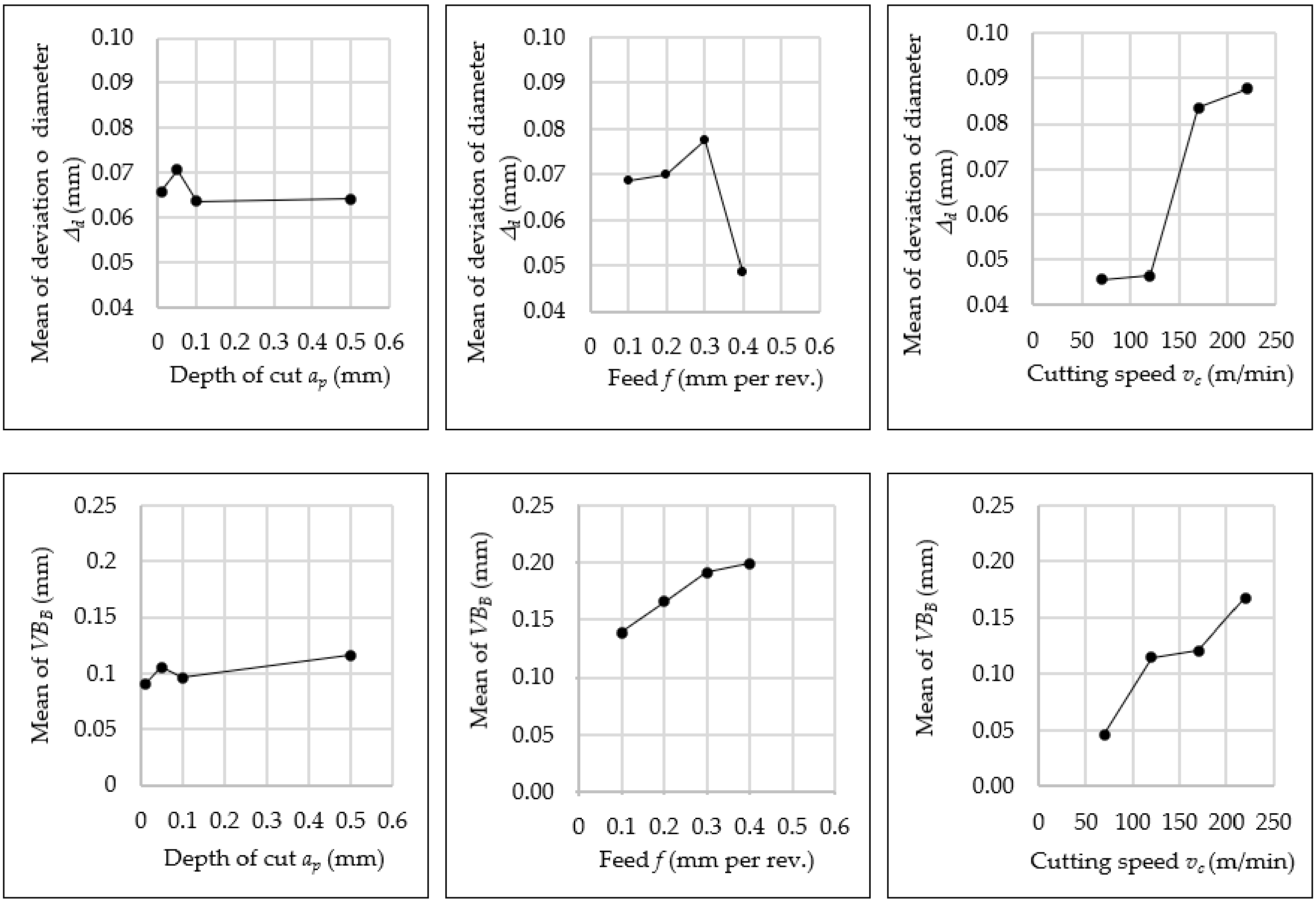


Figure 10. Main effect plot of diameter deviation Δ_d and flank wear VB_B.

The lowest average value of diameter deviation was measured at a cutting speed of 70 m/min, namely 0.0046 mm, the highest average value of the diameter deviation was measured at a cutting speed of 220 m/min (0.0877 mm). The main effect graphs show the uncertainty of the process parameter levels to be developed for turning steel C45 as a steel group standard, and they also show that for certain lower parameter levels the flank wear is lower, but at the same time a change in the size deviation of the diameter occurs. The measurement results show that level 3 of cutting depth, level 4 of feed, and level 1 of cutting speed are factors for achieving the smallest diameter deviation. The dependence is important for the defined initial parameters, because the wear of the flank side of the cutting insert influences the deviation of the diameter. Therefore, the study of this dependence and the development of optimal input factors is important, also with regard to the use of LTS in the measurement of qualitative parameters.

Application Results of GRA and ANOVA Methods

The experimental data were normalized for the response parameters of flank wear and diameter deviation according to Equation (1) and are shown in Table 4. From the normalized data set in Table 5 the GRC relation coefficients using Equation (2) was calculated. We chose the value of the identification coefficient 0.5 because equal weight was given to response parameters. The statement is based on experience from various tests. The lower the wear value of the cutting part of the tool, the better the quality of the response parameter of the machined surface. The results are shown in Table 4. Next, the GRG was determined using Equation (3) and the GRC results. The GRG result is shown in Table 5.

Table 5. Grey relational values.

Number of Experiment	Grey Relational Generation Values		Deviation Sequence		GRC		GRG	Rank
Ideal sequence	VB_B	Δ_d	VB_B	Δ_d	VB_B	Δ_d		
	1	1	1	1				
1.	0.8029	0.6486	0.1971	0.3514	0.7172	0.5873	0.6523	5
2.	0.4254	1.0000	0.5746	0.0000	0.4653	1.0000	0.7327	2
3.	0.8509	0.0000	0.1491	1.0000	0.7703	0.3333	0.5518	6
4.	0.4341	0.5785	0.5659	0.4215	0.4691	0.5426	0.5058	11
5.	0.4908	0.6049	0.5092	0.3951	0.4954	0.5586	0.5270	8
6.	1.0000	0.3729	0.0000	0.6271	1.0000	0.4436	0.7218	3
7.	0.2035	0.5250	0.7965	0.4750	0.3856	0.5128	0.4492	14
8.	0.4676	0.5875	0.5324	0.4125	0.4843	0.5479	0.5161	9
9.	0.0850	0.6833	0.9150	0.3167	0.3533	0.6122	0.4828	12
10.	0.0873	0.2764	0.9127	0.7236	0.3539	0.4086	0.3813	15
11.	0.7468	0.7750	0.2532	0.2250	0.6639	0.6897	0.6768	4
12.	0.4936	0.5542	0.5064	0.4458	0.4968	0.5286	0.5127	10
13.	0.0000	0.2167	1.0000	0.7833	0.3333	0.3896	0.3615	16
14.	0.3983	0.4639	0.6017	0.5361	0.4538	0.4826	0.4682	13
15.	0.5301	0.6049	0.4699	0.3951	0.5155	0.5586	0.5370	7
16.	0.9861	0.9889	0.0139	0.0111	0.9730	0.9783	0.9756	1

This result is used to optimize the factors when they are converted to a degree. The influence of GRG for the defined experimental conditions is shown in Figure 11. From the figure, we can define experiment No. 13 for the input factors a_p 4-f 1-v_c 4 as the input experiment. For the calculated GRG values, the effects of each process factor at the different levels are shown in Figure 12.

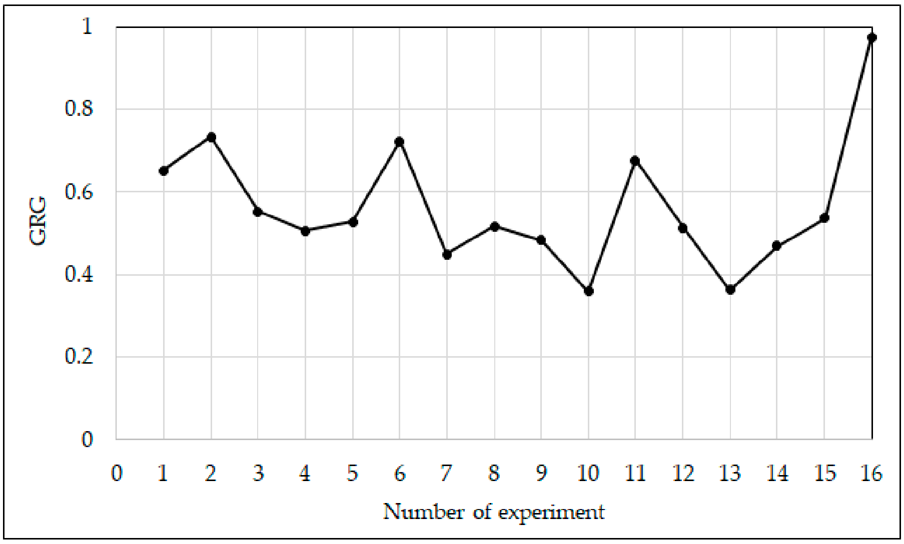


Figure 11. Grade relational grades for response parameters of cutting insert flank wear surface and diameter deviation.

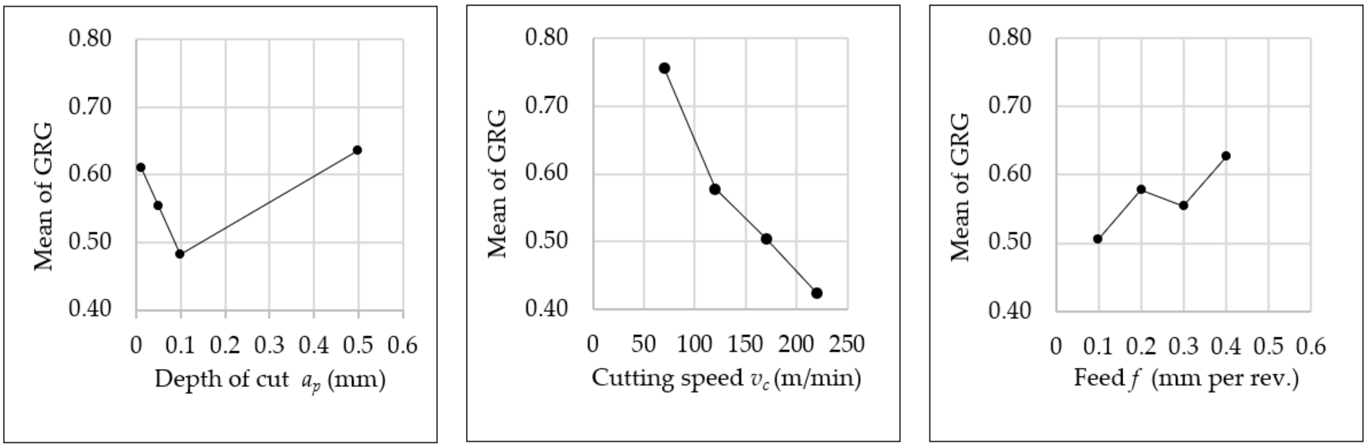


Figure 12. Main effect plot of mean grey relational grade.

The optimal combination of input factors is selected based on higher mean GRG values according to Table 6. A higher GRG value expresses stronger correlation with the reference sequence, i.e., the optimal factor setting for several output parameters is the combination of factors a_p 4-f 4-v_c 1, i.e., cutting depth 0.5 mm, feed 0.4 mm per revolution, and cutting speed 70 m/min.

Table 6. Main effect on mean grey relational grade (total mean 0.5677).

Factors	Mean Grey Relational Grade				Max-Min	Rank
	Level 1	Level 2	Level 3	Level 4		
a_p	0.6107	0.5536	0.4831	0.6367	0.1276	2
f	0.5060	0.5760	0.5537	0.6276	0.1216	3
v_c	0.7566	0.5774	0.5048	0.4245	0.3321	1

The higher values of the average GRG (according to Figure 12) express the minimum values of the wear of the flank side of the cutting insert VB_B and the deviation of the diameter Δ_d. Table 6 shows the GRG values as differences between the maximum and minimum values of the four levels for each factor. This result can be interpreted to mean that cutting speed (0.3321) has the greatest influence on several output parameters compared to depth of cut (0.1276) and feed (0.1216) according to Table 6, when turning steel C45. The significance of each process input factor on the response parameters can be stated in the order of cutting speed > depth of cut > feed. Table 7 formulates the analysis of variance in terms of GRG. This table shows the significance of the process factors on several output parameters. Table 7 shows that cutting speed is a significant process factor affecting several output parameters, as its p-value is less than 0.05 at 95% confidence level. No significance was demonstrated for the feed and depth of cut factors with respect to multiple parameters simultaneously.

Table 7. Results of ANOVA on grey relational grade.

Source	DF	Seq SS	Adj SS	Adj MS	F-Value	p-Value	Remarks
a_p	3	0.0205	0.0205	0.0068	0.6286	0.6231	Insignificant
f	3	0.0329	0.0329	0.0110	1.0075	0.4521	Insignificant
v_c	3	0.2463	0.2463	0.0821	7.5460	0.0181	Significant
Error	6	0.0653	0.0653	0.0109			
Total	15	0.3650					

At the end of the applied methods, confirmatory tests must be performed to determine the improvement in GRG from the initial setting of input factors to the optimum factors obtained when turning steel C45 while measuring the machined surface with LTS. The predicted GRG can be calculated using Equation (4). For the optimal setting of the input factors a_p 4-f 4-v_c 1, GRG has a value of 0.7473, which is very close to the expected value, i.e., 0.8855. To validate the test result, we repeated the experiment for the optimal setting of the input factors a_p 4-f 4-v_c 1. The results of the validation test were produced with repeatability 8 for the optimal level of input factors as shown in Table 8.

Table 8. Confirmation experiment (improvement in GRG = 0.3858).

	Initial Factor Settings	**Optimal Cutting Factors**	
		Prediction	**Experiment**
Level	a_p 4-f 1-v_c 4	a_p 4-f 4-v_c 1	a_p 4-f 4-v_c 1
VB_B	0.1990		0.0983
Δ_d	0.1148		0.0058
GRG	0.3615	0.8855	0.7473

From the confirmation experiment Table 8, GRG for several response parameters, such as flank wear and diameter deviation, was significantly improved (by 0.3858) by setting the optimal parameter combination. These results confirm the resulting response parameters, diameter deviation, and flank wear, performed under operating conditions on a CNC machine. Based on the above analysis, the input factors for the minimum values of flank wear and diameter deviation studied in the turning of steel C45 by GRA based on the Taguchi method are investigated.

Some positive and negative experiences in the study of the application of a laser triangulation sensor to measure the diameter deviation after turning steel C45 standard:

1. Ensure compliance with the certified deviations of some dynamic modules of CNC machines (e.g., spindle);
2. Limit the use of process media or provide suitable constructive protection of the sensor in the working area of the machine;
3. The results may be distorted by red light: this did not affect the results in the experiments;
4. Non-contact measurement method and speed of acquired data: high efficiency;
5. Can be used for static and dynamic measurements;
6. Since we always work with an electrical output signal of the sensor, it is necessary to solve the problem of interference of the sensor by electric or magnetic fields;
7. Program can process, analyze, filter the acquired data according to Figure 13 and decide about the product, whether it was manufactured according to the specified technical requirements.

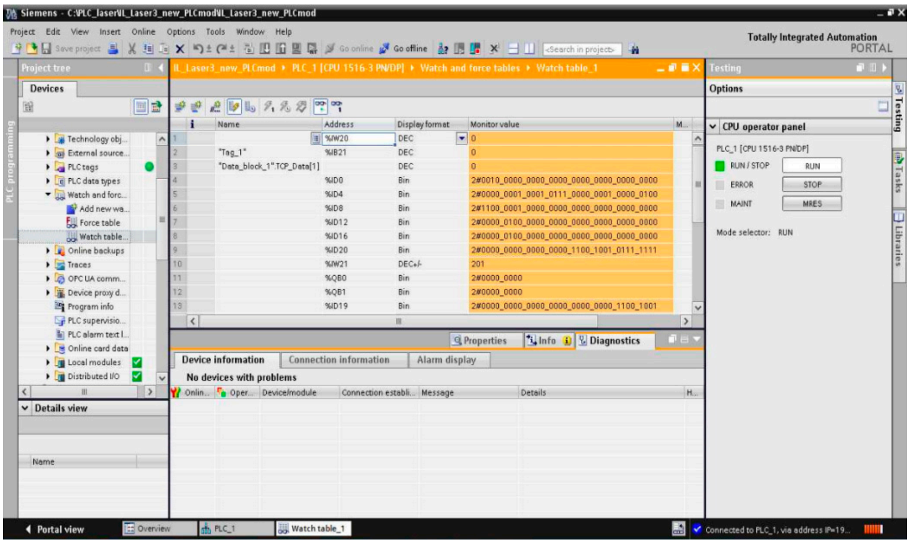


Figure 13. Recording of the measurement of the diameter deviation with a laser triangulation sensor.

The defects on the machined surface documented according to Figure 14 were imaged using a Carl Zeiss Primotech D/A ESD microscope.

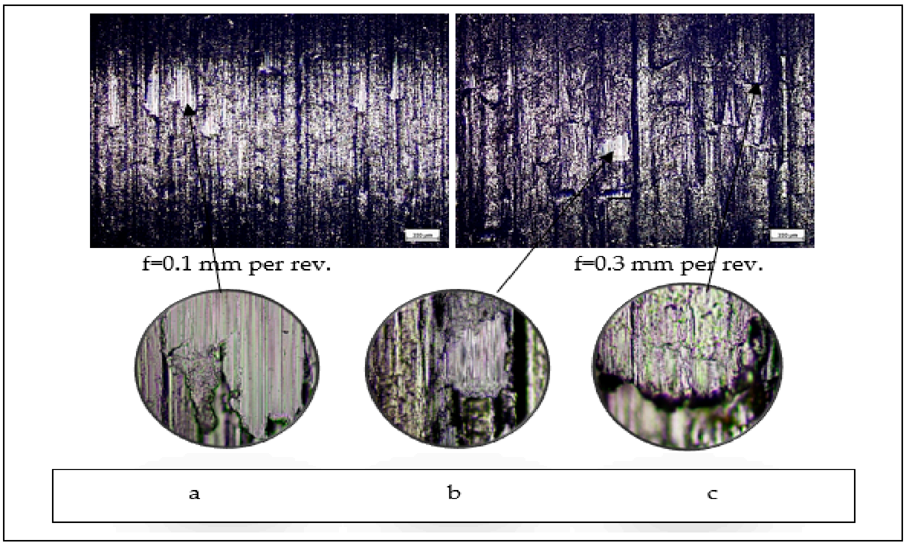


Figure 14. Examples of negative phenomena on the machined surface after turning steel C45 at a feed of f = 0.1 mm per revolution. **a**: f = 0.3 mm per revolution (**a**: spreading of material on the machined surface, **b**: surface after breakage of the material element, **c**: crack on the machined surface).

4. Discussion

In this paper, the suitability of using a laser triangulation sensor for evaluating the quality of the machined surface, in particular, measuring the accuracy of the diameter of the cylindrical surface, was demonstrated. The integration of the initial parameters, namely the data from the measurement of the deviation of the diameter of the cylindrical surface and their harmonization with the data of the wear of the back surface of the cutting insert, proved to be complicated and often very incomprehensible. The use of the GRG characteristic curve according to the method GRA is a suitable parameter to solve this problematic relationship. The method GRA was also used to optimize the conditions for turning steel C45 (as a reference material for the group of steel materials) in terms of two problematic response parameters (Δ_d and VB_B). The experimental conditions were chosen to improve the quality of the machined surface. The average GRG values were found for the GR coefficients of the parameters, as shown in Table 4. These values are the recommended values for determining the rotation factors. The order of the factors according to GRG is as follows (cutting speed, depth of cut and feed). This paper presents the optimization of input factors in dry turning of steel C45 and the measurement of wear parameters of the cutting surface of the insert with a microscope, and the measurement of the deviation of the cylindrical surface diameter with a new generation Keyence laser triangulation sensor IL100 using Taguchi L16 orthogonal array and method GRA. The measurement system was designed for laboratory and operational conditions, a device for clamping the sensor and its production on a 3D printer with verification on a CNC machine was designed. Creation and verification of a program whose task is to communicate the PLC in the measurement system with the software for recording the data obtained from the laser triangulation sensor.

5. Conclusions

The following conclusions of this article are drawn from the research analysis. We can clearly answer the questions we mentioned in the content of the article. Yes, this type of sensor is suitable for measuring the diameter deviation parameter for the machined surface. The information obtained for steel C45 can be used in further research by a comparative method for checking other types of steel. The values of the deviation of the diameter on the cylindrical surface were measured and evaluated in intervals (0.002–0.2 mm) with LTS. The limit (specified by the manufacturers) for a diameter deviation of up to 0.15 mm was observed, although the 0.3 mm criterion (according to ISO 3685) was not exceeded in the wear of the back side of the VB_B cutting plate in all tests. Creation and verification of a program whose task is to communicate the PLC in the measuring system with the software for recording the data obtained from the laser triangulation sensor. The optimal setting of the input factors for multi-responses is a_p 4-f 4-v_c 1. Depth of cut 0.5 mm, feed 0.4 mm per revolution, and cutting speed 70 m/min. The meaning of the input factors of each process for multi-responses can be given in the order cutting speed > depth of cut > feed, which follows from the table for GRG. The table ANOVA shows that cutting speed is an important factor influencing multi-responses with 95% confidence, in turning steel C45 as a case study of the effect of cutting insert flank wear on average diameter deviation studied by LTS for use in CNC machine tools. Other input factors showed less significance for multiple responses by both GRG and ANOVA. The GRG degree is significantly improved by setting the optimal combination of factors (0.3858). Therefore, the results of optimization of input factors for turning technology can be used in production plants to reduce production costs in the production process and product control. The proposed GRA methodology using the Taguchi L16 orthogonal array has proven to be effective in studying the relationship between the input factors of the process and the various response parameters, such as in the case study of turning. At the end of the paper, some negative and positive experiences with the application of a new generation laser triangulation sensor are presented, the verification of which will be presented in future publications.

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