Machining of Inserts with PCD Cutting-Edge Technology and Determination of Optimum Machining Conditions Based on Roundness Deviation and Chip-Cross Section of AW 5083 AL-Alloy Verified with Grey Relation Analysis

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Abstract: This paper describes the important significance of cutting-edge technology in the machining of polycrystalline diamond (PCD) cutting inserts by comparing the evaluation criteria. The LASER technology of cutting-edge machining is compared with grinding and electrical discharge machining (EDM) technologies. To evaluate the data from the experiments, the Grey Relational Analysis (GRA) method was used to optimize the input factors of turning to achieve the required output parameters, namely the deviation of roundness and chip cross-section. The input factors of cutting speed, feed rate, depth of cut and corner radius were applied in the experiment for three different levels (minimum, medium and maximum). The optimal input factors for turning of aluminum alloy (AW 5083) were determined for the factorial plan according to Grey Relational Grade based on the GRA method for the multi-criteria of the output parameters. The results were confirmed by a verification test according to the GRA method and optimal values of input factors were recommended for the machining of Al-alloy (AW 5083) products. This material is currently being developed by engineers for forming selected components for the automotive and railway industries, mainly to reduce weight and energy costs. The best values of the output parameters were obtained at a cutting speed of 870 m/min, feed rate of 0.1 mm/min, depth of cut of 0.5 mm and a corner radius of 1.2 mm.

Keywords: cutting edge; roundness deviation; EDM; laser; grinding; PCD; grey relation analysis; turning; AW 5083

1. Introduction

In machining, the main focus is on reducing machining times while maintaining or improving the quality of the material being machined [1]. To achieve this, cutting tools with the required better properties (e.g., hardness, cutting edge strength, tool life and wear resistance) must be used [2]. The cutting materials that meet the required properties such as hardness and wear resistance include the so-called super hard cutting materials such as polycrystalline cubic diamond (PCD) and polycrystalline cubic boron nitride (PCBN) [3]. PCD can be defined as an artificial material consisting of the transformation of graphite with hexagonal lattice into a cubic lattice of diamond under the influence of high temperature and pressure and using a small amount of catalysts [4]. Super hard cutting materials have become permanently established in the range of global manufacturers who are constantly trying to innovate them and develop new methods in the manufacture of PCD tools [5]. The modern trend is to combine properties of known cutting materials such as coating sintered carbides with synthetic diamond or cubic boron nitride, which is constantly evolving [6]. Replaceable inserts with a cutting edge of PCD material are an essential component in the rational machining of non-ferrous materials and for achieving the required quality of the machined surface for roundness deviation and the performance
of chip cross-section in finishing operations [7]. When using diamond cutting tools for machining ferrous base materials (e.g., steel, cast iron), there is usually a high degree of diffusion between the tool and the material to be machined and thus very rapid wear due to ongoing chemical reactions (especially on the tool edge) [8]. Therefore, we must not use diamond tools for machining ferrous materials.

The applications of PCD cutting materials are mainly in turning all pure nonferrous metals and nonferrous materials with little or no abrasive filler content [9]. Among the most commonly used nonferrous materials are aluminum alloys, which are used not only in mechanical engineering but also in many other industries [10]. Aluminum-manganese alloys have excellent corrosion resistance, good weld ability, and formability—properties that are highly sought after in mechanical engineering [11]. Due to their natural hardness, corrosion resistance and light weight nature, aluminum-based alloys, such as EN AW 5083, are increasingly being used to replace heavy iron-based materials, especially steels, such as in automotive aggregates [12]. By using lightweight aluminum alloys, it is possible to lighten the vehicle by up to one third of the aggregate weight [13]. Another alternative is to turn the ignition flanges from aluminum alloy EN AW 5083 with PCD cutting inserts for off-road engines. This reduces the weight of the engine while increasing the corrosion resistance. The use of the material EN AW 5083 can also be found in shipbuilding or hydraulic lines in aircraft [14–16].

The manufacture and machining of PCD cutting tools has been covered by a number of authors. One of the conventional methods for machining PCD materials is grinding [17]. In their article Wu and Li et al. presented the results that cutting inserts manufactured by grinding have longer tool life than those manufactured by another technology described by him such as electrical discharge machining (EDM) [18]. Rahim et al. in his paper compared tool edge machining by grinding and electrical discharge machining (EDM) for machining PCD material. He presented the research results with the following conclusion and that in terms of achieving the required surface roughness parameter Ra both methods achieved almost the same surface roughness but in EDM technology, the diamond was converted to graphite at elevated temperature which resulted in degradation of the cutting tool [19]. In their article, Li and Rahim et al. analyzed the wear of PCD cutting tools machined by different electrical discharge machining (EDM) methods and then tested them on titanium alloy Ti-6Al-4V with different cutting conditions. The research focused on the analysis of the negative phenomena in the production process and their influence on the change of damage, i.e., wear of the cutting part of the tool [20]. Jia and Li et al. analyzed the machining of PCD tool by EDM technique using different types of cutting wire. The surface properties of the material were studied using X-ray diffraction method [21]. In conventional PCD tool grinding, it is necessary to use a grinding wheel with the same hardness as diamond, and yet significant wear occurs when grading the tool edges. Therefore, You and Fang et al. proposed to use LASER machining when machining the cutting edges of PCD tools. This machining method does not cause mechanical wear, which is an innovative alternative for manufacturing and machining tools made of PCD material [22].

Brecher et al. suggested using LASER to machine the cutting edges of PCD tools. He also suggested using LASER only for finishing operations such as selective sharpening of cutting edges. because the entire machining process with LASER takes much longer than conventional grinding or EDM. By combining grinding and LASER it is possible to save up to 50% of the total time required to machine cutting tools [23]. Dold et al. applied the method of short pico-second pulses in machining cutting edges with LASER, which resulted in better wear resistance of the tools and thus increased tool life in machining carbon fiber materials compared to conventional grinding [24].

On the subject of machining and the use of PCD tools, various publications can be found that analyze the influence of changes in cutting conditions on the wear of the tool cutting edge on tool life or on the quality of machining the workpiece with PCD tools [25]. However, many publications consist of an analysis of only one type of PCD machining such as grinding, EDM or LASER. The machining of innovative materials based on titanium.
and aluminum lightweight alloys for the aerospace and automotive industries is of great importance [26].

Wang et al. applied the method GRA to optimize the input factors in turning according to several criteria. In their research, they showed the importance of the method GRA for integrating multiple output parameters and determining the required input factors [27]. Huh et al. present the results of the evaluation of an aluminum alloy product with a cylindrical surface. The article concludes that the optimum combination of process output parameters was determined from numerical results and confirmed by experiments. The analysis is carried out using fractional model and Taguchi method to evaluate the effects of process parameters, such as chip shape and roundness (curvature) of the aluminum pipe [28]. Zhennan et al. presented in their paper that roundness and surface roughness are important quality characteristics of machined cylindrical products. The optimum output machining parameters were determined by using GRA and the main machining parameters that affect the machining performance. They can be determined by the difference between the maximum and minimum GRG values. The experimental results have shown that the roundness and surface roughness of the machined surfaces can be effectively improved by the proposed approach [29]. Mekid in his article presents the result of a new method for measuring the deviation of roundness, which is an important parameter in the evaluation of quality on cylindrical surfaces of components [30]. Śniegulska et al. presented in their paper an important factor of the chip cross-section by the modeling of the cutting force to solve the problem of complete plastic deformation of the chip cross-section [31]. Both Yalcin and Kundrák et al. in their studies present the results of milling and turning points out the importance of the chip cross-section in designing the cutting conditions and eliminating the stress on the cutting edge of tools [32,33].

This paper presents the results of a research that can be divided into two phases. In the first phase of the research, the results of the influence of three different technologies on the machining quality of the cutting edges of replaceable inserts designated DCGW 11T308 with a cutting edge made of super-hard polycrystalline diamond (PCD) are presented. The inserts were fabricated using three different technologies, namely: grinding, LASER and electroerosive cutting (EDM). The experimental part of the work includes machining the cutting edges, measuring the total time taken to produce the cutting edges, measuring the radius of the cutting edge and measuring the roughness surface of the cutting part below the main cutting edge. Based on the analysis of these parameters, the manufactured cutting insert with the best parameters was recommended and selected for the production process.

The second phase of the research represents the optimization of input factors for machining a semi-finished product of the aluminum bar with a diameter of 160 mm and a length of 200 mm made of the aluminum alloy AW 5083 (AlMg4.5Mn0.7) by DCGW 11T308 cutting insert. To determine the influence of selected input factors (cutting speed, feed rate, depth of cut and corner radius) during turning on the output quality and performance parameters, the Gray Relational Analysis method was applied.

The achievement of the required quality parameter of the roundness deviation and performance parameter of the chip cross-section were designed to increase the quality of the machined surface and to prevent the outgoing chips from damaging the machined surface. The roundness deviation was chosen on the basis of the requirements for the manufacture of certain products.

2. Experimental Conditions and Procedure

The essence of the cutting process performed in the cutting zone is to create a new surface with defined properties. These properties can be evaluated as internal and external properties of the new surface. The new surface can be defined as a function of the interaction between the cutting edge of the tool and the machined surface on the workpiece. The result of this interaction in the cutting zone is a machined surface, the formation of a plastically deformed material in the form of chips and a worn cutting edge. The wear of the cutting edge surface and the chips depends on several factors. Very important are the cutting speed,
the feed rate, depth of cut (or size of allowance) the geometry of the cutting part of the tool
the cutting material and others for external analysis of the quality of the machined surface.
These are mainly the parameters of surface roughness and the dimensional parameters
of the machined surface deviation from the nominal dimension and the deviations of the
shape are important. The basic input factors were cutting speed $V$ (m/min), feed rate $F$
(mm), depth of cut $A_p$ (mm) and corner radius $R_c$ (mm). The input factors were designed
for three different levels, minimum (lower), medium (medium) and maximum (upper),
mainly based on practical experience. These input factors for the three levels are listed in
Table 1.

| Factor Level | A | B | C | D |
|--------------|---|---|---|---|
| Lower (−1)   | 450| 0.1| 0.1| 0.4|
| Medium (0)   | 660| 0.2| 0.3| 0.8|
| Upper (+1)   | 870| 0.5| 0.5| 1.2|

The technological system M-T-O-F by which we define the production process consists
of a machine (M) a tool (T) an object (O) and a fixture (F). This technological system can be
described by the model:

$$TS = M + T(T_H + T_{CI}) + O + F(F_T + F_O)$$

(1)

M (Machine) a high precision lathe was used for the experiments (DMG Mori eco
Turn 450) turning center as shown in Figure 1.

![Figure 1. Working zone of the DMG Mori eco Turn 450 turning center.](image)

T (Tool); the tool consists of a tool holder (TH) and a cutting insert (TCI). Cutting
inserts DCGW 11T308 were used for the experiments. The standard dimensions of the
insert according to the standard ISO are length 19.65 mm and height 3.97 mm. The diameter
of the insert in the axis is 9.525 mm. The changeable cutting inserts made of super hard
cutting materials are manufactured in two layers. A disk of polycrystalline diamond is
brazed onto the carbide substrate. The disk contains a brazed tip made of the material
PCD-CTB 010 with a length of 2.77 mm and a depth of 1.6 mm. The corner radius is 0.8 mm
and the tip angle is 55, as shown in the AutoCAD model in Figure 2.
Figure 2. Cutting insert model DCGW 11T308.

ELementSix brand PCD material characterized by the properties listed in Table 2 was used as a semi-finished product for the manufacture of a plate from PCD (SVJCR 2525 M16-M-A-9024123323) according to ISO norm was used as the blade holder.

Table 2. Basic properties of PCD material [14].

| Basic Properties of PVD-VTB 010 Material | PCD-CTB 010 |
|----------------------------------------|-------------|
| Grain size                             | 10 µm       |
| Density                                | 4.08 g/cm³  |
| Binder                                 | Cobalt      |
| Thermal Conductivity                   | 501 W/m·K   |
| Thermal Diffusion                      | 0.27 × 10⁻³ m²/s |
| Cobalt Content                         | 10.3%       |
| Diamond Share                          | 89.7%       |

O (Object) a round bar semi-finished product was used for the experiments with diameter of 160 mm and length 200 mm, AW 5083 (AlMg4.5Mn0.7—EN 573-3). The chemical composition of the aluminum alloy AW 5083 is shown in Table 3.

Table 3. Chemical composition of aluminum alloy AW 5083 [15].

| Al Alloy | %    |
|----------|------|
| Si       | 0.40 |
| Fe       | 0.4  |
| Cu       | 0.10 |
| Mn       | 0.4–0.10 |
| Mg       | 4.0–4.9 |
| Cr       | 0.05–0.25 |
| Zn       | 0.25 |
| Ti       | 0.15 |
| Others.  | 0.35 |
| Al       | balance |

Table 4 Shows the mechanical and physical properties of the aluminum alloy AW 5083. F (Fixture = FT +FO) the fixture is for the tool (FT) and the fixture is for the object (FO). A cutter head (FT) was used for the tool fixture and a chuck (FO) was used for the object fixture. As the process medium Cimcool Cimstar 40B, which contains semi-synthetic type of oil and water was used in all experiments. It is a semi-transparent process medium suitable for applications requiring long life and cleanliness.
Table 4. Physical and mechanical properties of aluminum alloy AW 5083 [16].

| Al Alloy                      | Value   |
|-------------------------------|---------|
| Yield stress Rp 0.2 (MPa)     | 110     |
| Tensile strength Rm (MPa)     | 270     |
| Density [kg/m³]               | 2660    |
| Melting range [°C]            | 575–683 |
| Electrical Conductivity (MS/m)| 16–19   |
| Thermal Conductivity (W/m K)  | 110–140|
| Modulus of Elasticity (GPa)   | 70      |

3. Manufacturing Process of PCD Cutting Inserts

The cutting insert of Figure 3 was made in the following successive steps. Production of the cutting insert DCGW 11T308 from sintered carbide. Cutting the mold on a cutting insert DCGW 11T308 for mounting the PCD plate and blade as shown in Figure 3a by electrical discharge machining on Fanuc 31 i/W, using a 0.25 mm brass wire with a strength of 900 N.

![Figure 3](image-url) (a) Shape of the cutting insert with PCD blade before sharpening; (b) Cutting insert after sharpening.

The EDM cutting process shown in Figure 4 was carried out under the following conditions 4 erosion process, voltage 78 V and current of 0.8 A. Distilled water was used as the dielectric fluid. The cut was set up for two cycles with a cutting speed of 4.8 mm/min.

The process took 247 s. When using EDM technology, there is often a problem in controlling the parameters and the machining process. This causes the brass wire to break, resulting in lost time in the production cycle. This problem can be eliminated by optimizing the manufacturing conditions of EDM technology.

Cutting the shape of the blade from PCD using EDM technology. The following conditions were applied, cutting speed 3.1 m/min. and voltage 49 V. In order not to turn the diamond into graphite which is caused by the high temperature during cutting [34]. The single cutting cycle took about 480 s and consist joining the carbide disk and the cutting blade made of PCD by induction brazing, sharpening the cutting edges made of PCD material according to the selected technical documentation and testing of the cutting insert with a PCD cutting edge.
3.1. Sharpening Process

Three technologies were used in sharpening process of the DCGW 11T308 insert with PCD cutting edge, grinding on a Coborn R9 NC grinder, electrical discharge machining (EDM) on a Fanuc 31 i/W machining center and LASER cutting on a CNC Lasertec 20. To sharpen the cutting edges by grinding, as shown in Figure 5, grinding wheel Tyrolit Skytec XD-1 with 150 mm diameter and a high percentage of diamond grit was used to machine the PCD material. The spindle speed was set at 2000 rpm, feed rate of 12.5 mm per second and a depth of cut of 0.1 mm. The grinding wheel was water sprayed directly onto the tool throughout the machining cycle. The average sharpening time per plate was 852 s.

Figure 4. (a) Calibration of the machine before EDM sharpening of the cutting insert; (b) Cutting process of PCD insert with EDM machining technology.

Figure 5. Sharpening of insert with PCD grinding in NC Coborn R9 (working zone).
Sharpening the cutting edges with LASER as seen in Figure 6 has the advantage of being a non-contact technology so this process does not require the use of additional tools that wear out over time. The sharpening cycle was performed on a Lasertec 20 machine at a cutting speed of 591 mm/min, which is an incomparable difference to grinding. Despite the high speed the resulting sharpening time for one plate was 2160 s.

![Figure 6](image1)

**Figure 6.** (a) Calibration of the machine before LASER sharpening of the cutting insert; (b) Sharpening of the cutting insert with LASER CNC Lasertec 20.

The EDM of the cutting edges has a double sharpening cycle and was performed on a Fanuc 31/WA Figure 7 at a cutting speed of 2.2 mm per minute and a voltage of 42 V in two stages as specified by the manufacturer Element SIX. The machining time for one plate was 480 s.

![Figure 7](image2)

**Figure 7.** Sharpening of the cutting insert with EDM machining on Fanuc 31/WA.
Based on the results of the analysis of the comparison of three technological methods the evaluation output parameters were established on the basis of practical experience by article of Židek et al. [34]. With the help of a 3D light microscope from Alicona Edge Master G4 in Figures 8a,b and 9 the parameters on the cutting insert namely the radius of curvature of the cutting edge and the surface roughness were evaluated. The measurement results are shown in Table 5 for machining by grinding. EDM and LASER. This device is used for microscopic 3D measurement of roughness and shape of components with output to a computer monitor. All-important surface properties are measured with only one multifunctional measuring sensor.

![Alicona 3D optical microscope](image1)

**Figure 8.** (a) Measuring the radius of curvature of the cutting edge on Alicona 3D optical microscope; (b) Cutting edge display measuring with Alicona 3D software.

| Name     | Value (µm) | Description                                      |
|----------|------------|--------------------------------------------------|
| Lc       | 800.0000   | Cutting wavelength for chipping measurement      |
| Ra       | 1.3433     | Average roughness of profile                     |
| Rz       | 1.6733     | Root Mean Square roughness of profile            |
| Rn       | 4.0730     | Mean peak to valley height of profile            |
| Rp       | 2.3089     | Maximum peak height of profile                   |
| Rv       | 0.6167     | Maximum valley depth of profile                  |

**Figure 9.** Example of measured parameters of cutting edge arithmetic mean deviation of the assessed profile Ra (EDM sharpening).
Table 5. Experimental plan matrix.

| Number of Experiment | A  | B  | C  | D  | ∆d (mm) | S_{ch} (mm²) |
|----------------------|----|----|----|----|---------|-------------|
| 1                    | −1 | −1 | −1 | −1 | 0.0112  | 0.2194      |
| 2                    | −1 | −1 | −1 |  1 | 0.0106  | 0.2082      |
| 3                    | −1 | −1 |  1 | −1 | 0.0124  | 0.2193      |
| 4                    | −1 | −1 |  1 |  1 | 0.0114  | 0.2105      |
| 5                    | −1 |  1 | −1 | −1 | 0.0131  | 0.2088      |
| 6                    | −1 |  1 | −1 |  1 | 0.0106  | 0.3841      |
| 7                    | −1 |  1 |  1 |  −1| 0.0142  | 0.2238      |
| 8                    |  1 |  1 |  1 |  1 | 0.0124  | 0.3917      |
| 9                    |  1 | −1 | −1 |  −1| 0.0116  | 0.2345      |
| 10                   |  1 |−1  |  1 |  1 | 0.0108  | 0.2453      |
| 11                   |  1 |−1  |  1 | −1 | 0.0104  | 0.2153      |
| 12                   |  1 |−1  |  1 |  1 | 0.0102  | 0.2316      |
| 13                   |  1 |  1 |−1  |  1 | 0.0147  | 0.2162      |
| 14                   |  1 |  1 |−1  |  1 | 0.0115  | 0.2644      |
| 15                   |  1 |  1 |  1 |−1  | 0.0117  | 0.2592      |
| 16                   |  1 |  1 |  1 |  1 | 0.0103  | 0.2458      |
| 17                   |  0 |  0 |  0 |  0 | 0.0126  | 0.2652      |
| 18                   |  0 |  0 |  0 |  0 | 0.0117  | 0.2388      |
| 19                   |  0 |  0 |  0 |  0 | 0.0104  | 0.3943      |
| 20                   |  0 |  0 |  0 |  0 | 0.0119  | 0.2715      |
| 21                   |  0 |  0 |  0 |  0 | 0.0128  | 0.2225      |
| 22                   |  0 |  0 |  0 |  0 | 0.0106  | 0.2263      |
| 23                   |  0 |  0 |  0 |  0 | 0.0105  | 0.2844      |
| 24                   |  0 |  0 |  0 |  0 | 0.0129  | 0.2135      |

Figure 10 shows a comparison of the values obtained for the cutting edge radius Rn. We have recorded the smallest radius in the technology LASER. Figure 11 shows a comparison of the parameters of surface roughness Ra and Rz. The best parameters Ra and Rz were measured using the technology LASER. The parameters Ra and Rz were measured with a measuring device MarSurf PS 10. We measured as the shortest cutting edge sharpening time using EDM technology. Based on the above comparison of the parameter evaluation results after applying the three technologies, the machined cutting inserts LASER were used to optimize the output parameters for Al alloy turning and the results will be presented in the next part of the paper.
3.2. Optimization of Input Factors for AW 5083 Processing

All 24 experiments were conducted to determine the influence of four input factors on the results of the two output parameters, roundness deviation (Δd) and chip cross-section (S_{ch}). To make the results of the factors verifiably accurate we performed 5 replicate measurements for each combination of input factors. In addition, the inserts were replaced after 5 replicate measurements for each experiment. The matrix of experiments is shown in Table 5. This matrix of experiments was created from a composite factorial design which contains 24 defined experiments for specific conditions and the results of the experiments for the responses of the dependent variables Δd and S_{ch}. All the information obtained from the process of manufacturing cutting inserts and inserts as well as information obtained from turning was analyzed and evaluated in detail in order to achieve the desired result of the experiments and the optimal input factors to achieve the specified technical require-
ments. The parameter of roundness deviation of the machined surface was measured with a Round Test R-120 measuring device and the chip cross-section (thickness—$h_{sch}$ and width—$b_{sch}$) were measured with a micrometer. The measurement was made around the circumference of the workpiece in five positions and the results were statistically analyzed for each test. The chip cross-section was calculated from the measured values of chip thickness and width according to Equation (2) statistically evaluated and the values are given in Table 6.

$$S_{ch} = b_{sch} \cdot h_{sch} \left( mm^2 \right)$$  \hspace{1cm} (2)

Table 6. The sequence after data preprocessing.

| Reference Comparability Sequence | $\Delta d$ (mm) | $S_{ch}$ (mm$^2$) |
|----------------------------------|-----------------|-------------------|
| Reference sequence comparability sequence | 1.000 | 1.000 |
| E1                               | 0.778           | 0.940             |
| E2                               | 0.911           | 1.000             |
| E3                               | 0.511           | 0.940             |
| E4                               | 0.733           | 0.988             |
| E5                               | 0.356           | 0.997             |
| E6                               | 0.911           | 0.055             |
| E7                               | 0.111           | 0.916             |
| E8                               | 0.511           | 0.014             |
| E9                               | 0.689           | 0.859             |
| E10                              | 0.867           | 0.801             |
| E11                              | 0.956           | 0.962             |
| E12                              | 1.000           | 0.874             |
| E13                              | 0.000           | 0.957             |
| E14                              | 0.711           | 0.698             |
| E15                              | 0.667           | 0.726             |
| E16                              | 0.978           | 0.798             |
| E17                              | 0.467           | 0.694             |
| E18                              | 0.667           | 0.836             |
| E19                              | 0.956           | 0.000             |
| E20                              | 0.622           | 0.660             |
| E21                              | 0.422           | 0.923             |
| E22                              | 0.911           | 0.903             |
| E23                              | 0.933           | 0.591             |
| E24                              | 0.400           | 0.972             |
For factorial design, the variables are multilevel and their output effects are nonlinear. Therefore, it was decided to use a three-level experiment for each factor. Process medium was designed as a constant factor. In Full Factorial Design (FFD) the number of factors as well as their levels increases exponentially with the number of experiments. This number of experiments has a significant impact on the duration of the research and the amount of costs. The FFD consisting of four input factors at three levels would have a form of $3^4$ which means conducting 81 experiments. If we include the repeatability of each experiment, for example for repeatability 5 it is 405 experiments. To reduce the number of experiments performed we assumed a trade-off design for two unfavorable factors—the choice of optimal cutting conditions and a limited number of experiments. We designed a composite factorial $2^4 + 8$ with a content of 24 experiments. These were selected to optimize performance and quality characteristics for the turning process. The experiments were conducted according to the process input factors listed in Table 1.

The chip cross-section is an important parameter for the performance evaluation of the cutting process, also based on the interrelationship between the technological parameters (feed rate and depth of cut) and the physical parameters (chip thickness and width) of the cutting process. Furthermore, it is the physical and technological parameters of the chip that are important for the productivity of the cutting process.

The cross-section of the removed layer (or the cutting cross-section) during turning is determined from the input variables by the feed rate, the depth of cut and the setting angle of the main cutting edge. This cross-section of the removed layer (or cross-section) is evaluated in the tool ground plane $Pr$. The actual real cross-section of the chip is determined by measuring the chip, i.e., after turning. The chip cross-section is a parameter that can be used to evaluate the performance factors of turning as: (performance parameter, due to the change in the actual cross-section of the chip, evaluation of chip shape, chip compression, chip formation and chip root, evaluation of loading—especially pressure and its influence on internal energy of elements in the cutting zone, friction and tribological properties of the machining process).

We have, therefore, chosen the chip cross-section for the evaluation, because in our research of several years we have focused on the study of the pressure fields in the cutting zone under changing cutting conditions.

To evaluate the values of the results of the experiments, we used the GRA method according to Deng et al. [35]. GRA is a method by which we measure the degree of approximation between sequences according to the Grey relational grade (GRG). This method has been applied by several researchers [35–37].

Kumar et al., in their publication, defined the ideal machining conditions using the GRA method and the Taguchi model based on the ANOVA method by varying the machining conditions of the material composite of WC-Co during drilling [38]. Another author who used GRA method to optimize machining conditions was Sahu et al. who used various machining parameters with EDM parameters such as material removal rate (MRR), tool wear rate (TWR) and radial over cut (ROC) in machining titanium alloys [39]. Garg et al. used characteristics and process optimization of the ECDM process of Carbon Fibre Reinforced Polymer machining performed by the Grey Relational Analysis (GRA) method in Taguchi’s $L9$ orthogonal array method by using the applied voltage, electrolyte concentration, and inter-electrode distance as process parameters [40]. Akepati et al. used an idea of machining the polypropylene composite with a Laser technology and determined the optimum processing conditions by GRA method, which were confirmed by the method ANOVA [41].
In order to arrive at the correct results, it is necessary to initially preprocess the experimental results of the deviation of the roundness and cross-section of the chip and to arrange them in sequences ranging from 0 to 1. This is also called Grey Relational Generation. An important indicator of the method is GRG, which we calculate as an average for each resulting parameter. The total result for multiple output parameters is determined using GRG. Optimizing complex multiple input factors can result in conversion to a single Grey Relational Grade. Based on the GRA method, we can design different combinations of factors for the optimal cutting process. Optimization of input factors of turning to achieve quality and performance parameters using the GRA method requires the following procedure according to [35]:

1. Identify the input factors and the parameters for evaluating the output quality and performance of the cutting process;
2. Determination of the number of levels for the input factors of the cutting process;
3. Design of the factorial matrix of the experiment and assignment of the factors of the cutting process;
4. Results of experiments for roundness deviation and chip cross-section;
5. GRG generation and calculation of GRC coefficients;
6. Calculation of GRGrades based on GRC results;
7. Analysis of experimental results with GRGrade;
8. Design of optimum levels of cutting process parameters.

3.3. Data Pre-Processing

Data preprocessing must be performed because the range and unit in a data sequence may differ from the others. Data preprocessing is a means of converting the original sequence into a comparable sequence. Depending on the characteristics of the data sequence. There are different methods for data preprocessing that are recommended for GRA [35].

Input experiments were conducted to design the input factors. Initially, roundness deviations in the range of 0.001 to 0.05 mm were obtained. Based on these input experiments, adjusted input factors (A, B, C, D) were set according to Table 1, assuming that we achieve the required initial values of the parameters. Manufacturers required (mainly in terms of product function and production cost) to achieve roundness deviations in the range of 0.01 to 0.05 mm with the highest output (largest chip cross-section). Therefore, in the optimization of the method GRA, the methodology chosen was the larger the better, i.e., to approach larger but required values.

We applied the methodology, if the sequence is infinite and has the property “the higher is better”. The original sequence can be normalized according to Equation (3).

$$x_i^{+}(k) = \frac{x_i^0(k) - \min x_i^0(k)}{\max x_i^0(k) - \min x_i^0(k)}$$  \hspace{1cm} (3)

where \(i = 1, \ldots, m, k = 1, \ldots, n, m\) is the number of experimental data \(n\) is the number of parameters, \(x_i^0(k)\) denotes the original sequence, \(x_i^{+}(k)\) denotes the sequence after data processing, \(x_i^0(k)\) the highest value of the smallest value of \(x_i^0(k), \min x_i^0(k)\) smallest value of \(x_i^0(k), x_i^0\) is the required value of \(x_i^0(k)\). GRA is a method based on the study of importance between two sequences defined by the Grey relational grade (GRG) indicator. When only one sequence is available as a reference sequence and all other sequences serve as reference sequences this method is called Local Grey Relational Measurement. After preprocessing the data, we perform the GRC calculation according to Equation (4).
\[ \xi_w(k) = \frac{\Delta_{\text{min}} + \xi \cdot \Delta_{\text{max}}}{\Delta_{iv}(k) + \xi \cdot \Delta_{\text{max}}} \]  

(4)

where \( \Delta_{iv}(k) \) is the sequence divergence of the reference sequence \( x_0^i(k) \) and the reference sequence \( x_1^i(k) \). The \( \xi \) is the identification coefficient and is defined in the range \( 0 \leq \xi \leq 1 \).

This value can be set by the system as required. For smaller values \( \xi \) the resolution is higher. The determination of this coefficient is important to show the degree of the relationship between the reference sequence \( x_0^i(k) \) and the 24 comparison sequences \( x_j^i(k) \). Where \( i = 1, 2, \ldots, m \) and \( k = 1, 2, \ldots, n \). For the experiment we determined \( m = 24 \) and \( n = 2 \).

The determination of GRG in the procedure GRA is to define the degree of influence between the 24 sequences \( [x_0^i(k) \text{ and } x_j^i(k), i = 1, 2, 3 \ldots 24] \). After determining the GRC we then determine the GRG value as the mean of the GRC values. Calculate GRG according to Equation (5).

\[ \gamma_i = \frac{1}{n} \sum_{k=1}^{n} \xi_i(k) \]  

(5)

In real processes, the relative importance of the different factors varies. Deng and Lin et al. recommend changing Equation (4) to the form of Equation (6) [35].

\[ \gamma_i = \frac{1}{p} \sum_{k=1}^{r} w_k \xi_i(k) \sum_{k=1}^{r} w_k = 1 \]  

(6)

where \( w_k \) denotes the normalized weight of the factor \( k \). If the weight is the same Equations (5) and (6) are the same. The Grey relational degree expresses the degree of correlation between a reference sequence and a comparable sequence. If the two sequences are identical due to the circumstances, then the GRG value is 1. GRG also expresses the degree of influence of the possibility of using a comparable sequence compared to the reference sequence.

In the presented experiment we have identified two output parameters, namely the performance parameter chip cross-section and the qualitative parameter roundness deviation which is influenced by the formation of BUE, when turning Al alloy for cutting edge factors on a plate of LASER. These two different output parameters are listed in Table 5. Therefore, we applied the “higher is better” methodology for data preprocessing and used Equation (3).

To optimize the input factors (cutting speed, feed rate, tip radius and depth of cut) and to evaluate the two required output parameters (roughness deviation and chip cross-section), we applied the methodology according to the method GRA. For the performance parameter chip cross-section, it is important that its size ensures the required turning performance, and for the surface quality parameter (deviation of roundness) that the required value of the machined surface is achieved. We have determined the input factors experimentally in order to achieve the highest possible performance parameter and, at the same time, to achieve the required value of the deviation of roundness, which results from the function of the machined surface on the product. Therefore, the “higher is better” method was chosen. The smallest parameter values or the largest parameter values are not always correct. It is important to develop optimum input factors to achieve the required output parameters resulting from real operating conditions. Thus, even roundness values close to 0.0 mm may not be correct in practice.

The results of the sequence deviations for \( i = 1 \) to 24 and \( k = 1 \) for 24 experiments are shown in Table 7. The results of labeled reference sequences and labeled reference sequences for \( i = 1 \) to 24 and \( k = 1 \) for 24 experiments are shown in Table 8. The sequence deviations can be calculated according to Equation (3).

Values:

\[ \Delta_{\text{max}} = \Delta_{11}(1) = \Delta_{24}(2) = 1.00, \Delta_{\text{min}} = \Delta_{11}(1) = \Delta_{24}(2) = 0.00 \]
Table 7. The deviation sequence.

| Deviation Sequence | $\Delta_{oi}(\Delta d)$ | $\Delta_{oi}(S_{ch})$ |
|--------------------|------------------------|----------------------|
| E1                 | 0.222                  | 0.060                |
| E2                 | 0.089                  | 0.000                |
| E3                 | 0.489                  | 0.060                |
| E4                 | 0.267                  | 0.012                |
| E5                 | 0.644                  | 0.003                |
| E6                 | 0.089                  | 0.945                |
| E7                 | 0.889                  | 0.084                |
| E8                 | 0.489                  | 0.968                |
| E9                 | 0.311                  | 0.141                |
| E10                | 0.133                  | 0.199                |
| E11                | 0.044                  | 0.038                |
| E12                | 0.000                  | 0.126                |
| E13                | 1.000                  | 0.043                |
| E14                | 0.289                  | 0.302                |
| E15                | 0.333                  | 0.274                |
| E16                | 0.022                  | 0.202                |
| E17                | 0.533                  | 0.306                |
| E18                | 0.333                  | 0.164                |
| E19                | 0.044                  | 1.000                |
| E20                | 0.378                  | 0.340                |
| E21                | 0.578                  | 0.077                |
| E22                | 0.089                  | 0.097                |
| E23                | 0.067                  | 0.409                |
| E24                | 0.600                  | 0.028                |

The coefficient $\xi$ can be replaced by the procedure of Equation (4) for GRG coefficient. We consider the value of the coefficient $\xi$ as 0.5 since both initial parameters have the same weight. The GRC and GRG values for each factorial design experiment were calculated according to Equations (4)–(6). Table 8 shows the GRG for each factorial experimental design experiment. Higher GRG values represent the corresponding experimental values and are more indicative of the standard values. According to the GRG values in Table 8 experiment E2 out of 24 experiments expresses the best results for both output parameters as the GRG value is the highest.

Chips after turning were examined for shape after turning (tangled chips with varying lump sizes predominated and for possible side effects of cutting). Samples (about 3 to 8 cm long) were taken for measurement, following the principle that chips should not be taken at the beginning and end of the turned area. The thickness and width of the chips were measured with a micrometer, according to the Figure 12. The repeatability was 5 for each chip. Calculation of particle cross-section from the average values obtained by measurement according to the equation presented in the content of the article. An example of the measurement of chip width and thickness is shown in Figure 12. From the presented results of the study in Table 8 and Figure 13 the optimization of two output parameters in turning an Al alloy can be seen, which is replaced by the GRG optimization. At the same time the optimal turning parameters for the deviation of the roundness and the chip
cross-section were determined. In Table 9 for the factorial design method the calculated GRG value for each level of input factors was used.

**Table 8.** Calculated Grey relational coefficient and Grey relational grade values for 24 comparable sequences.

| Number of Experiment | GRC (Δd) | GRC (S') | GRG |
|----------------------|----------|----------|-----|
| E1                   | 0.692    | 0.893    | 0.792|
| E2                   | 0.849    | 1.000    | 0.925|
| E3                   | 0.506    | 0.893    | 0.700|
| E4                   | 0.652    | 0.976    | 0.814|
| E5                   | 0.437    | 0.994    | 0.715|
| E6                   | 0.849    | 0.346    | 0.598|
| E7                   | 0.360    | 0.856    | 0.608|
| E8                   | 0.506    | 0.336    | 0.421|
| E9                   | 0.616    | 0.780    | 0.698|
| E10                  | 0.789    | 0.715    | 0.752|
| E11                  | 0.918    | 0.929    | 0.924|
| E12                  | 1.000    | 0.799    | 0.900|
| E13                  | 0.333    | 0.921    | 0.627|
| E14                  | 0.634    | 0.623    | 0.629|
| E15                  | 0.600    | 0.646    | 0.623|
| E16                  | 0.957    | 0.712    | 0.835|
| E17                  | 0.484    | 0.620    | 0.552|
| E18                  | 0.600    | 0.753    | 0.676|
| E19                  | 0.918    | 0.333    | 0.626|
| E20                  | 0.570    | 0.595    | 0.582|
| E21                  | 0.464    | 0.867    | 0.665|
| E22                  | 0.849    | 0.837    | 0.843|
| E23                  | 0.882    | 0.550    | 0.716|
| E24                  | 0.455    | 0.946    | 0.700|

**Table 9.** Response table for Grey relational grade.

|        | −1     | 0     | 1     | Max-Min |
|--------|--------|-------|-------|---------|
| A      | 0.697  | 0.670 | **0.749** | 0.079  |
| B      | **0.813** | 0.670 | 0.632 | 0.181  |
| C      | 0.717  | 0.670 | **0.728** | 0.058  |
| D      | 0.717  | 0.670 | **0.734** | 0.064  |
Figure 12. (a) Sample of the resulting chip from turning process of AW 5083; (b) Chip width measurement in (mm); (c) Chip thickness measurement; (d) Another sample of chip width measurement.

Figure 13. Grey Relational Grade for the section of chip and roundness deviation.
GRG values for each level of turning factors were calculated as average values. The GRG can be characterized as a method in which we examine the degree of correlation between the reference sequence and the comparison sequence. The higher value of the average GRG of the reference sequence is more meaningful than the average value of the GRG of the comparison sequence.

The resulting average GRG values for each level of rotation factors are shown in Table 9 and express the performance behavior of the multifactor.

The underlined values indicate the optimal values of the factors for rotation. Figure 14 shows the dependence of the obtained GRG values on different levels of the rotation factors A, B, C and D. The higher the GRG value is, the closer the performance is to the ideal value. A higher GRG value is required for the optimum turning process. Thus, the design of the optimum turning factors corresponds to the highest GRG values according to Table 9, we can conclude that the optimum conditions for turning to achieve required cross-section and deviation of roundness are: cutting speed \( V = 870 \text{ m/min} \) (Level 3), feed rate \( F = 0.1 \text{ mm} \) (Level 1), depth of cut \( A_{p} = 0.1 \text{ mm} \) (Level 3) and corner radius \( R_{e} = 1.2 \text{ mm} \) (Level 3) and obtained by combining them. The values for experiment number E12 according to Figure 14 and Table 8 can be considered very close to the optimal process conditions. As shown in Table 9, the differences between the maximum and minimum values of GRG turning factors are as follows 0.079 for cutting speed, 0.181 mm for feed rate, 0.058 mm for depth of cut and 0.064 mm for radius of tool cutting edge. For the analysis of power turning, we can use a comparison of these factor values and determine the degree of influence of each factor. Based on this, we can determine the order of the output parameters that have a significant influence on the additional performance characteristics of the turning parameters. The order of the input factors is factor B (feed rate), A (cutting speed), D (corner radius) and C (depth of cut). Factor B was an effective performance factor.

![Figure 14](image)

**Figure 14.** Effect of turning factors on the multi-characteristic.

Figure 15a,b shows the influence of the machined surface for the combination of the effects of input factors A, B, C and D on the cross-sectional value of the chip (plastically deformed layer) for defined levels. The results show that an increase in cross-sectional area is significantly affected by an increase in feed rate and an increase in cross-sectional area is significantly affected by an increase in cutting speed. It was shown that the effect of depth of cut in combination with the value of corner radius has a greater influence on the formation of an built up edge shown in Figure 15a,b, which is indirectly shown by the change in chip cross-section and roundness deviation from Figures 16 and 17.
Figure 15. (a) Sample of measuring the angle of the cutting edge on insert before use; (b) Measuring the angle of the cutting edge of the insert after use (angle changed due to BUE); (c) 3D figure of the new insert before use; (d) 3D figure of the used insert with BUE.

Figure 16. (a) Influence of rotation factors on multi-characteristics; (b) The effect of input factors A, B, C and D on the values of roundness deviation.
In order to achieve lower values of roundness deviation and thus approach the optimum circular cross-section it is necessary to apply higher speeds (level 3) or lower feeds (level 1) with greater depth of cut (level 3) and higher corner radius (level 3). The variance of roundness deviation values is small for different values of depth of cut (factor C). Values of corner radius from 0.8 mm to 1.2 mm are more significant and we obtain lower values of roundness deviation. This can be considered as the optimum values of inserts for turning this Al alloy. The effect of input factors A, B, C and D on the values of roundness deviation is shown in Figure 16b.

It was found that the properties of GRG are significantly affected by the input factors (cutting speed, feed rate, depth of cut and corner radius). Figure 17a–d show the influence of input factors on the quality performance characteristics output parameters (chip cross-section and chip accuracy, defined by the deviation of roundness and response) for each level of the factor. Figures 17a and 18a show the effect of cutting speed and Figures 17b and 18b show the effect of feed rate, which have a significant effect on GRG increases and an increase in feed rate leads to a decrease in GRG.
Figure 18. (a) Effect of cutting speed factor on the roundness deviation qualitative parameters; (b) Effect of feed rate factor on the roundness deviation qualitative parameters; (c) Effect of depth of cut factor on the roundness deviation qualitative parameters; (d) Effect of corner radius factor on the roundness deviation qualitative parameters.

Figure 18 shows the effect of a machined surface for a combination of the effects of input factors A, B, C and D on the value of roundness deviation for defined levels. By combining a low feed rate and a high cutting speed, it is possible to achieve a reduction in roundness deviation values and a reduction in roundness deviation values is shown even at a lower level of allowance (depth of cut $A_p = 0.3 \text{ mm}$) and a corner radius value $R_c = 0.8 \text{ mm}$ to $1.2 \text{ mm}$ (this follows from Figure 18c,d). As it turned out, the formation of Built up Edge (BUE) at the tip and at the active cutting edge defined by the cutting edge radius $R_n$ is important for the roundness deviation values, which can be indirectly shown from the change of the chip cross-section and the roundness deviation from Figure 18c,d. Machining the cutting edge with the technology LASER with a radius $R_n$ proved to be correct. With a smaller radius of the corner radius from 0.4 to 0.8 mm the formation of an BUE is greater. The dimensional accuracy of the machined surface tends to deteriorate and the values of roundness deviation become larger. For example, the chip cross-section shows (Figure 17a) $\text{GRG} = 0.697–0.749$, at cutting speeds from 450–660 m/min, chip cross-section increases, but $\text{GRG} = 0.670–0.749$, at cutting speed from 660–870 m/min, chip cross-section decreases. For the deviation of roundness, it follows (Figure 18d), $\text{GRG} = 0.711–0.670$ with a corner...
radius of 0.4–0.8 mm the roundness deviation section decreases. GRG = 0.670–0.734 at a cutting depth of 0.8–1.2 mm the roundness deviation section decreases. By comparing the analyzes from Figures 17 and 18, we can determine the optimal output turning parameters based on the results of the analysis of factors using the GRG.

By applying the method GRA, these statements could be proved and thus a prerequisite for the actual positive application in practice in the turning of products made of Al alloys was created. The depth of cut and feed rate affect the final chip formation mainly in terms of the direct effect of the chip (plastically deformed material) on the machined surface and in conjunction with the size Rn also on the formation of the BUE.

3.4. Confirmation Test

After determining the optimal levels of the rotation input factors, the next process was to verify these factors to improve the output parameters by using only the optimal combination. The lowest roundness deviation (0.0102 mm) was obtained in experiment E12. The highest roundness deviation (0.0147 mm) was obtained in experiment E13. As Table 10 shows the comparison of the results from the experiments with the optimal input factors (A3, B1, C3 and D3) determined in the design and the original input factors (A2, B2, C2 and D2) which often result from plotting the experiments. These results are the optimal input factors for turning. The results of the validation experiments were performed with repeatability 5 for the optimal level of the input factors. These results validate the resulting output parameters of roundness deviation and chip cross-section (as the average of 5 repetitions) performed under operating conditions on a CNC machine.

| Name of Experiment | Factor Combination | Deviation of Roundness (mm) | Chip Cross-Section (mm²) |
|--------------------|--------------------|----------------------------|--------------------------|
| Initial plan       | A2.B2.C2.D2        | 0.0117                     | 0.2646                   |
| Optimal plan       | A3.B1.C3.D3        | 0.0102                     | 0.2316                   |

As shown in Table 10 the roundness deviation was reduced from 0.0117 mm to 0.0102 mm and the chip thickness was reduced from 0.2646 mm² to 0.2316 mm². We can interpret this result by a comparison test. We confirmed the improvement of the values of roundness deviation by 12.83% and chip cross-section by 12.48%. So, this comparison test showed that the proposed solution improves the accuracy of workpiece diameter and chip cross-section by the optimal combination of rotation input factors in this study. At the same time, it can be said that the overall quality and performance of turning has improved, which was also observed in the machined surface.

During the confirmatory test, we obtained the lowest values for A3, B1, C3 and D3. The analysis of the obtained results is very important for their recommendation for practical application. The smallest achieved values of the output parameters are not the best values for our research. With the chosen methodology of the applied GRA method, higher values of performance parameters and qualitative parameters are better. If we achieve higher values of the chip section with the chosen input factors, the turning process will be more efficient, but it is necessary to consider the required quality assurance (roundness deviation parameter).

4. Discussion

The essence of the method GRA was to design a multi factorial plan of the response matrix (effects) of Table 1. As a research method for optimizing the rotation of input factors, a table was designed. The initial parameters deviation of roundness and chip cross-section (Δd and Sch) were designed to achieve quality improvement of machined
surface. From the value Table 9, the average GRG values for the GR coefficients of turning parameters were found. These values are recommended values for determining the turning output parameters and achieving the required machining performance. In other words, very important factor is the feed rate. The order of input factors to achieve the required performance output parameters are (feed rate, cutting speed, depth of cut and corner radius).

Experimental results have shown that the roundness deviation and chip cross-section during turning can be effectively improved by the proposed approach. The result can be effectively simplified by the proposed method by optimizing the complex factors. This is proven by the fact that the turning performance factors, such as the roundness deviation and the chip cross-section, are improved based on the proposed method used in this study.

5. Conclusions

The results of the study from the values in Figures 17 and 18 show what the optimum values are for cutting speed, feed rate, tip radius and depth of cut. This is determined by the GRA method and mainly by the value of the parameter GRG. From the number of tests performed, the range of values for the initial parameters (deviation of roundness and chip cross-section) cannot yet be clearly confirmed. Therefore, we have not mentioned any specific requirements from the manufacturers in the study. In the experiments, we measured the largest value of roundness deviation of 0.0147 mm. This value corresponds to the requirements of the manufacturers, i.e., the value is not the smallest and at the same time that we do not exceed the upper required value. Based on the results of the comparison of the three methods for sharpening a cutting insert made of PCD material, we can conclude that the best results were obtained when machining the cutting edge using the method Laser Machining, which is confirmed by the measured values of Ra, Rz and Rn in chapter 3. Based on these results, we decided to use a cutting insert produced by this method for machining the aluminum alloy AW 5083. Based on the results of the GRA method, we selected the optimum machining conditions from the selected criteria of depth of cut, cutting speed and feed rate. We evaluated two output parameters using the GRA method using the GRG parameter. Figure 17a–d show how the cross-section of the chip changes and this is confirmed by the GRG. By analyzing the GRG values from Figures 17 and 18, we can see the effect of the change in the deformed removed layer (chip cross-section) and then the effect of the size of the chip cross-section on the roundness deviation for input factors A, B, C and D.

Optimal turning input factors to achieve the required quality of the machined surface for roundness deviation and the required power for the chip cross-section must be selected with a cutting speed of 870 m/min, feed rate of 0.1 mm and a corner radius of 1.2 mm and a depth of cut of 0.5 mm. The results of the experiment showed a percentage reduction in roundness deviation of 12.83% and a chip cross-section of 12.48% for the optimum combination of input factors. The effectiveness of these conclusions was successfully confirmed and verified by a confirmation experiment. From the experimental results and their processing by the method GRA we can give recommendations for practice.

From Figure 17 the smallest value of the chip cross-section was obtained with factor (A1). The highest value of the chip cross-section was obtained for factor (A2). The smallest value of the chip cross-section was achieved with (B3) factor. The highest value of the chip cross-section was reached with (B1) factor. The smallest value of the chip cross-section was reached with (C3) factor and the highest value of the chip cross-section was reached with (C1) factor. The highest value of the chip cross-section has been reached at (D1) and the smallest value of the chip cross-section was reached with (D3) factor. From Figure 18 the smallest value of the deviation of the roundness was reached at (A1). The highest value of roundness deviation was reached at (A3). The smallest value of the deviation of roundness was reached at (B3). The highest value of the roundness deviation was reached at (B1). The smallest value of the roundness deviation was reached at (C1). The highest value of the
roundness deviation was reached at (C3). The smallest value of the roundness deviation was reached at (D1). The highest value of the roundness deviation was reached at (D3).

Whether we have chosen the right methodological approach “higher is better” in the study was also confirmed to us after reviewing the manufactured products and at the same time their functionality in operation. It should be noted that despite the limitations of the initial factors (number of stages, number of experiments), the results were correctly determined. By establishing the “higher is better” method, we have achieved a reduction in the cost of mergers, mainly by optimizing the input factors.

The changes in engineering production are mainly connected with the development of the elements of the M-T-O-F technological system. The presented solution can be applied by technologists in the production of newly designed products, where the intention is to replace steel with other materials in order to reduce weight and, thus, subsequently search for optimal conditions for processing new materials. This study can be applied to various methods of metal processing and a defined composition of the technological system.

Author Contributions: Conceptualization, J.J. and M.M.-P.; methodology, J.J.; formal analysis, J.J.; resources, M.M.-P.; data processing, M.M.-P.; writing—original draft preparation, M.M.-P.; writing—review and editing, J.J.; supervision, J.J.; funding acquisition, M.M.-P. Both authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Slovak Research and Development Agency under the contract No. APVV-19-0590 and also by the projects VEGA 1/0700/20, 055TUKE-4/2020 granted by the Ministry of Education, Science, Research and Sport of the Slovak Republic.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: As the author of the article, I would like to thank the research team of progressive production technologies, AMTRteam, the grant agency for the support of research works and the co-financing of the VEGA 1/0440/18 project.

Conflicts of Interest: The authors declare no conflict of interest.

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