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Article

Sustainable Manufacturing and Parametric Analysis of Mild Steel Grade 60 by Deploying CNC Milling Machine and Taguchi Method

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Abstract: Design and manufacturing are the key steps in the sustainable manufacturing of any product to be produced. Within the perspective of injection molds production, increased competitiveness and repeated changes in the design require a complete optimized manufacturing process. Local and minor improvements in the milling process do not generally lead to an optimized manufacturing process. The goal of the new geometry and parametric analysis of the mould is to reduce the quality issues in mild steel grade 60. In this explicit research, the surface roughness (smoothness) of indigenously produced injection moulds in the local market in Pakistan is investigated. The CNC milling machine (five-axis) is used for the manufacturing of an injection mould, and the Taguchi method of the design of the experiment is applied for parameters optimization. Hence, the overall process is assisted in balancing the milling machine parameters to trim down the surface roughness issue in mild steel moulds and increase their sustainability. The spindle speed (rpm), the depth of cut (mm), and the feed rate (mm/rev) are considered as input variables for process optimization, and the experiments are performed on mild steel grade 60. It is deduced that the combination of a spindle speed of 800 rpm, feed rate of 10 mm/rev and depth of cut of 0.5 mm is the best case in case of minimum surface roughness, which leads to sustainable products. It is also deduced from ANOVA, that the spindle speed is a factor that affects the surface roughness of mild steel products, while the feed rate turns out to be insignificant.

Keywords: mild steel grade 60; milling; machining; sustainable manufacturing; taguchi method; parametric analysis

1. Introduction

CNC milling is a non-traditional machining process that makes use of multi-point rotating cutting tools and computerized controls to take away material from the work-part to produce a desired part or product. Explicitly, milling is the process of removing bits and pieces from a workpiece with the help of rotary cutting tools. The specialized cutter often has many cutting points, which usually move upright on the given axis, with the circumference of the tool into the work part. During the machining operation, the edges of the tool engrave minute cuts in the piece to shape its surface. As the machining continues, the chips are produced continuously, which are chipped off the surface as a resut of cutting. This type of machining is efficient for a wide range of materials such as wood, metal, glass, and plastic. A wide variety of shapes can be produced through this process, i.e., holes, slots, notches, pockets, and grooves.

Sustainable production has always been the main factor for economic growth because of its large technological opportunities and status as an economic multiplier. However, manufacturing industries mostly have carbon footprints that raises concerns regarding the sustainability of product development [1–4]. In molding, mould is a term that is used commonly, and it is used to elaborate the process used to make plastic goods. The moulds are essential to produce when production is required at a large scale. Moulds are used to produce products from simple paper clips to complex shapes that are used in complex technologies. Moulds are mostly made from mild steel, aluminum, and beryllium–copper alloys [5]. While manufacturing different moulds, important properies to be taken under consideration in manufacturing and application are good polishing capability, good machining properties, excellent spark erosion properties, easy heat treatment, safe, and good surface finish. Crucial characteristics of injection moulds are uniform composition and liberty from internal damages, toughness, weldability, polishability, and wear resistance.

The design and the production of moulds have a substantial effect on the final product's cost and quality [6]. With the repeated changes in mould design and increasing competitiveness, it is very helpful to estimate the exact production expenses to optimize the manufacturing process [7]. For achieving a good quality product after manufacturing, it is important to design, analyze, and fabricate moulds in the best possible way. If mistakes/errors occur during designing, analysis, and manufacturing, it will lead to quality problems in the final products.

Several researchers carried out research on different materials using the CNC milling process and deployed different optimization methods to reduce quality issues and sustain and improve the final outcome. Thus far, a number of researchers designed and fabricated injection/insertion moulds for diverse products and processes. Jamshed et al. conducted research on the design of an injection mould for making cam bush containing a submarine gate and for analysis of the mold flow, location of the submarine gate, and the filling rate, having auto desk plastic insight was used [8]. Likewise, Alaneme et al. researched on the mould and dies of a punching machine utilized for the making of cable trays, and the failure analysis was done through microstructural examination, visual examination, hardness testing, and chemical reaction determination [9]. The damages and breakdowns were investigated on a copper mold with chromium layered sides where in analysis, it was pointed out that working conditions cause failure origin and a high content of zinc causes the liquid steel copper wear [10].

Xi-Ping and co-researchers published their research on the stress and thermal study of electric heating rotation of a plastic insertion mould for TV panels and buckling of the mould structure, and the source that causes huge thermal stress was investigated by finite element simulation [11]. Research work was done in which the designing of an insertion mould was highlighted for warpage testing sample and to carry out thermal analysis of the mould. In the same way, a mould was designed by using Unigraphics (Software Version 13.0, Siemens NX). Residual stress analysis (thermal) was also performed by means of LUSAS Analyst (Version 13.5) [12–15]. The Taguchi method was deployed for diminishing warpage in the modeling of the injection mould, and it was concluded from the results that the melting temperature is a decisive factor on the phenomena of warpage, while the filling time of a mould affected warpage to some extent [16]. Moulds failures were also analyzed under pressure, and the main reasons of failure of the moulds were found to be the nature of the substance used, cyclical temperature to power intensity, as well as the physical and chemical reaction of the casting alloy. The maximum intensity of stress took place at the joining surfaces for the period of filling and short contact of melt in the mould [17–21].

Multi-response optimization was also addressed all together to reduce the ten-spot roughness (*Rz*), arithmetical roughness (*Ra*), and machining power consumed (P_m). The influence of depth of cut (a_p), spindle speed (*S*), tip radius (*r*), and the feed rate (f_z) were explored though the grey relational analysis (GRA) technique. It was deduced from the results, that processing factors greatly affected the machining power and the radius had a considerable effect on the roughness criteria [22–24]. P20 steel was machined in a CNC milling machine, during which the process parameters that had an impact on the power consumption were investigated. Response surface methodology was deployed, and the cutting speed, the depth of cut, and the feed rate were taken for optimization. ANOVA was applied to find the most influencing factors on power consumption, and it was revealed that the cutting depth/depth of cut slightly influenced the power consumption, while the feed rate and speed of cutting are the considerable parameters in upsetting the power consumption [25].

A method was proposed to perk up the entire cycle of milling and polishing in view of limitations from the machine tool and polishing process. Hence, the complete process is analyzed for balancing the milling as well as polishing times to lessen the total production time. The designed experiments were conducted on an aluminum mould for plastic bottles [26]. Mehdi Moayyedian et al. made the new shape of the entire runner system in the plastic injection molding, and the aim of this geometry was to decrease the cycle time and scrap and also to eject the runner system from the moulds easily. As the contact face of the runner system is reduced with the mould walls, this improved the opening of the runner system from the cavity/drag as well [27]. The designing of a mould in injection molding is a key task with considerable implications to yield productivity and quality. Bush conduit spreading extensively influences injection molding, and it was revealed that the injectant's polymeric property offers a substantial advantage in the designing of sprue bush [28]. Likewise, Failure Mode and Effect Analysis were used in order to make out the conditions in which a mould for plastic injection can make scrap parts [29]. Similarly, many other researchers conducted research on different materials while machining on CNC milling and were able to reduce quality problems and make the desired outcome sustainable [30–33].

So far, significant research studies have been executed on CNC milling. However, research studies on specific grades of steel are still not enough. Adel Taha et al. found optimized cutting conditions for face-milling on grade-H steel using the Edgeworth–Pareto method and artificial neural networks. The combination of parameters was adjusted to minimize the surface roughness, improving the accuracy and lessening production costs [34]. Energy consumption and surface quality associated with the material removal rate and costs were investigated for AISI 1045 steel during face milling. It was revealed that the optimized milling performance for fast manufacturing is possible through gray relational analysis [35]. Experimental research was performed to flatten the material using the face mill wear effect by various cutting conditions of steel 45 [36].

Manufacturing sectors are striving hard to achieve sustainability by making changes in systems, products, and processes. Likewise, local manufacturers and industrialists in Peshawar (Pakistan) were coming across an issue of surface unevenness in the moulds of mild steel grade 60 due to the limitations of applications of scientific optimization techniques on particular issues, and there was no consideration of applying optimized parameters in the local market [37–40]. In this research, the issue of surface roughness has been tackled and optimized with selected process parameters, while optimization of the selected material is carried out using a CNC milling machine. The results suggested that the optimized process parameters of the milling machine optimized the surface roughness in the final outcome, and the desired products with superior quality have been achieved. Ultimately, sustainability in the form of less surface roughness has been achieved. This would lead to less waste material and increased productivity.

2. Materials and Methods

To achieve the desired output, it is imperative to plan an acceptable and suitable methodology for the research work. Hence, a proper methodology has been planned and designed. It was observed from the literature review and local market surveys in Peshawar that there are limited skilled people and advanced machines that cause quality issues in the form of surface roughness, wastage of materials, time, and power consumption in final manufactured moulds. More specifically, mild steel grade 60 is selected, as manufacturers were facing problems in moulds of this specific material, and the limitation of the application of optimization techniques leads to difficulties in the machining process and surface roughness issues. This material is ductile, low cost, easily available, and not as hard compared to other types of steel.

The mould is modeled in PTC CREO 3.0 software, and the experimental setup is done for mould manufacturing. After designing it in CREO, it is fabricated using a CNC five-axis machine. Parameters such asthe depth of cut, the speed of the spindle, and the feed rate are optimized to reduce the surface roughness in grade 60 mild steel moulds.

2.1. Mould's Modeling

Surface roughness is a serious issue, and it is important to reduce it in final products/moulds of mild steel. It is deduced from the literature that the modeling (designing) of each and every component of mould [41–44] plays a vital role in the quality of products. Hence, these parts are modeled in CREO software instead of machining the mouldparts directly. Modeling of mould is also carried out to complete the overall product development process. Generally, mould has a core, cavity, and mounting bosses. The core shows the internal surface of the mould, and the cavity shows the outer surface of the mould, while mounting bosses keep the core and cavity in fixed positions. In this research, mould is made in several parts and modeled in CREO software. Drawings of drag and cope and other smaller parts are also created and are shown in Figures 1 and 2 respectively.

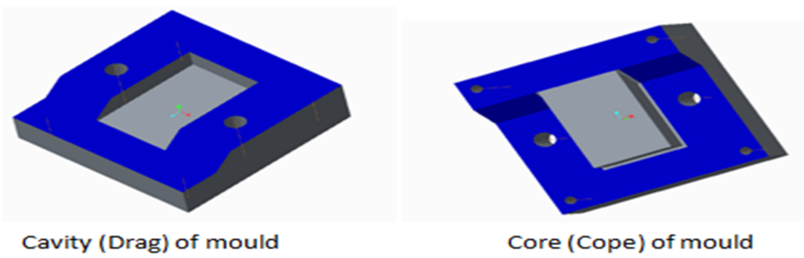

Figure 1. Cavity and core of mould.

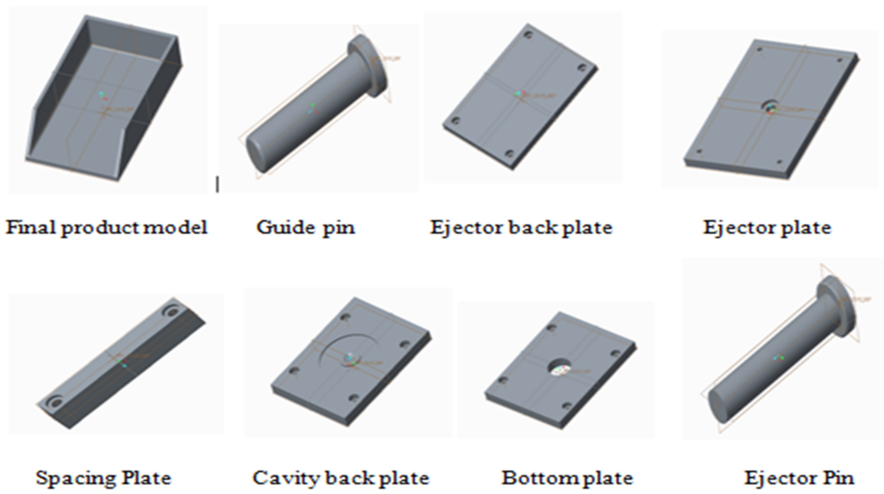

Figure 2. Models of different parts of a mould.

The final part to be made inside the cavity of the mould is 20 mm high and 65 mm in breadth. The revolve command and the extrude command are used in modeling of the cavity in CREO software, while some other commands are also used in the modeling of different parts. Slight changes are made in the cavity, core, and other plates for further processing and can also be seen in Figure 2.

After separately modeling the core and cavity and different parts, they are assembled using different assembling commands to form a complete mould. Then, the same parts are communicated through software with the milling machine for fabrication.

2.2. Experimental Setup

As the modeling process is completed, the whole process of manufacturing the same mould is executed through a milling machine (CNC five-axes). Each and every step of this specific research, i.e., from machining to surface roughness measurment, is shown via the experimental setup/scheme given in Figure 3. In Figure 3, 1 shows different parts of the machine, 2 shows the machining of parts, 3 shows the desktop that helps in guiding and controlling the machining process, 4 represents the scanning electron microscope for taking micrographs, and 5 represents the roughness tester for finding the surface roughness. The optimization of data is explained in Table 3 in the results and discussion section in detail.

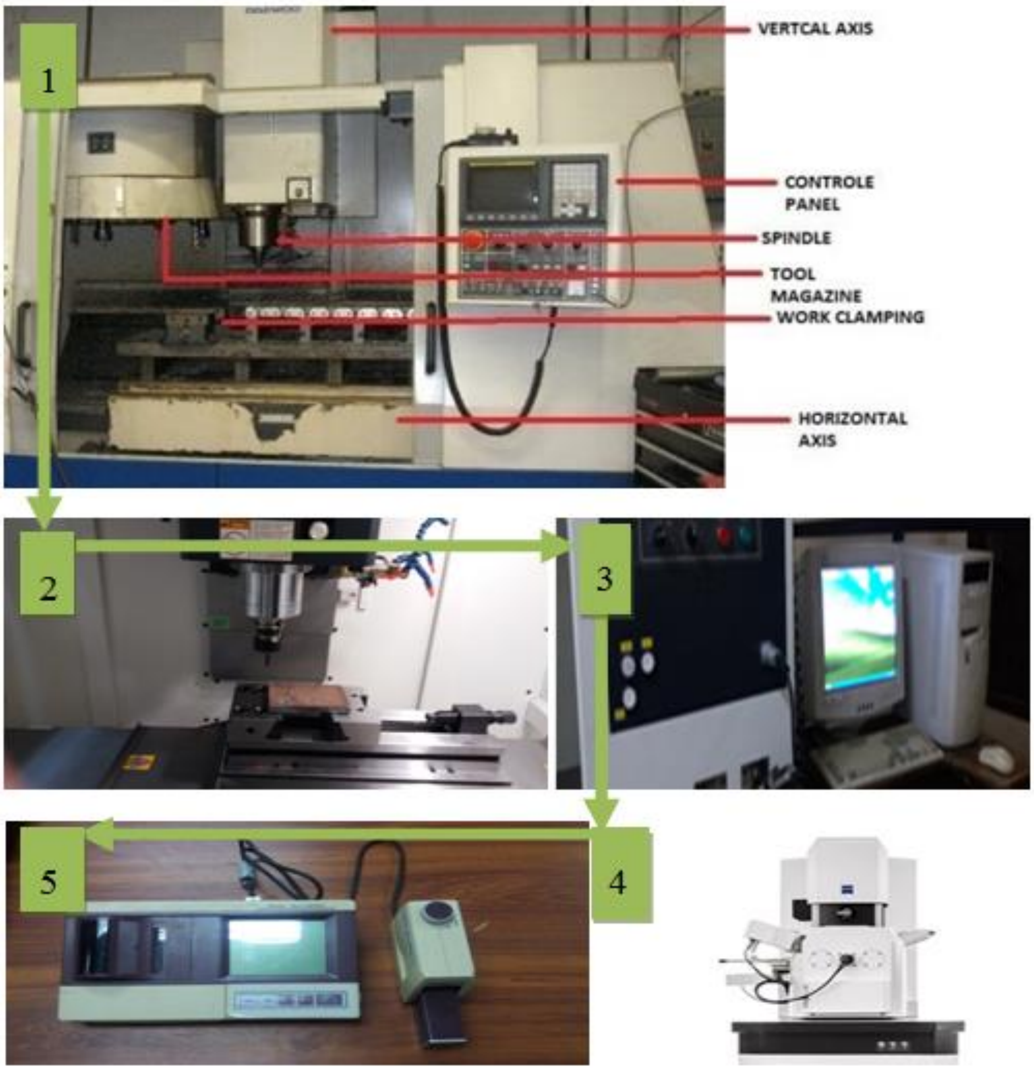

Figure 3. Scheme/experimental setup for surface roughness optimization.

The model of this specific machine is LG-500, Taichung city, Taiwan, power of 15 kVA, 3520 kg weight, frequency of (50/60) Hz, the air taken is 6.5 Kg/cm^2 (92 Psi) for pressure operation, and ISO-VG 68 oil lubricator is used.

For the machining of any part through a CNC machine, initially, a program is written, which is then communicated to the machine through a computer. The tools and the workpiece are attached to the machine, which operates as per the program. After the whole setup, machining is executed on actual basis. The cutter assembly of the CNC milling machine is given in Figure 4a. Figure 4b shows the engagement of tool on the workpiece. A sliding motion occurs between the workpiece and the cutter during machining.

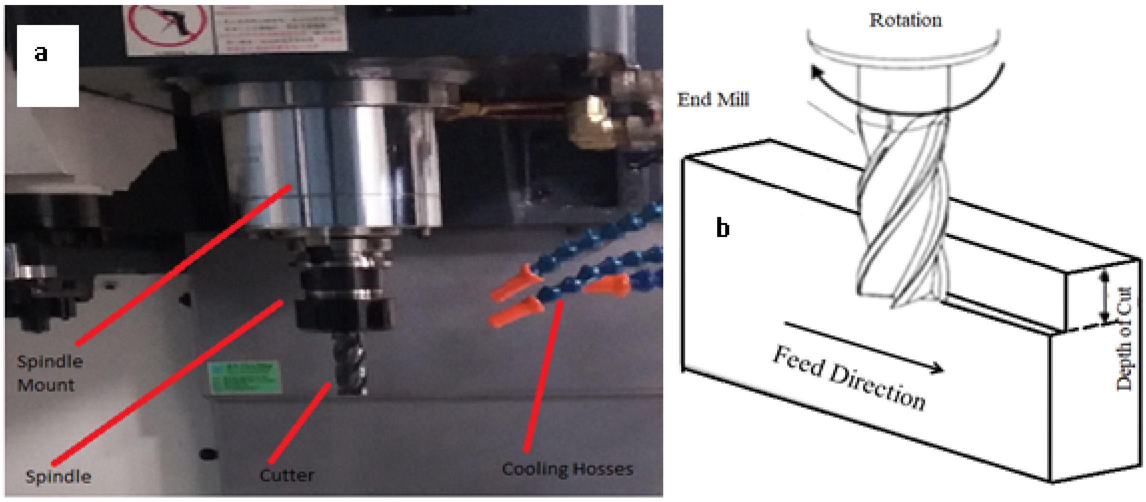

Figure 4. (**a**) Assembly of end mill cutter and (**b**) engagement and basic tool motion on workpiece.

The type of cutter used in the machining process is an end mill cutter, and it is specifically called a tungsten carbide end mill cutter. The direction of the movement of the cutter can be in five different directions. However, in this experimental setup, the motion of a tool is restricted in three directions depending upon the requirements. The approximate hardness and chemical composition of a workpiece and a cutter are given in Table 1.

Table 1. Hardness and chemical composition of workpiece and cutter.

Materials	Hardness	Chemical Composition				
Mild Steel (Workpiece)	71 HRC	Manganese	Silicon	Carbon	Sulfur	Phosphorus
		0.70%	0.40%	0.16%	0.040%	0.040%
Tungsten Carbide (Cutter)	75 HRC	Tungsten	Carbon	Iron	Impurities	
		96%	3.9%	0.02%	0.02%	

2.3. Manufacturing of Mild Steel Mould

The milling process follows similar fundamental production steps to those of every other computerized machining process that includes modeling a CAD model, altering the model to the CNC program, running the computerized milling machine, and performing the milling operation. During the machining process on a CNC machine, a wide range of tools are utilized for machining a workpiece or any part. A suitable selection of tools is very necessary for the proper machining of a product, and for this purpose, the tool length compensation function is used [45]. According to this particular function, machining is executed automatically without any interruption, even a tool is changed mechanically as per the program cutter path. For good quality milling, a cutter should have many teeth and perfect sharpness, the rpm of tool should be high enough to cut a material significantly, and some other parameters should be taken into consideration.

Mould manufacturing is a complex job [46,47]. In this research, the machining was made possible through three axes of the milling machine, while the fourth and fifth axes were disabled. As the materials brought from the market were not in exact sizes that is why extra material was removed by cutting. After cutting extra materials from the plates, a facing process was carried out on each plate for absolute machining. The speed of the spindle, the feed rate and the depth of cut were changed as per the size and shape of the part while using the same tool during the facing operation. Figure 5 depicts the removal of extra material and facing operation during machining. As this is facing process that is why it is different from Figure 1. Few changes were made in the machining to achieve the final dimensions of the plates.

Figure 5. Various phases of mould manufacturing.

After a few machining processes, each and every part is completed and then assembled to construct a complete designed mould. During this machining process, an optimization technique is applied on different parameters for sustainable manufacturing which will be discussed in Sections 2.4 and 3. Complete fabricated mould can be seen in Figure 5.

After fabrication, the same manufactured mould is mounted in a vertical injection/insertion molding machine. There was no scientific knowledge applied on the mild steel moulds by the local manufacturers, which led to the surface roughness issue in products produced during injection molding. Hence, an optimization of parameters for plastic products can be done using this mould. The installed mould in the molding machine is also shown in Figure 5.

2.4. Application of Optimization Technique

The design of experiment is a method that is deployed to unearth a relationship among a number of factors. Input parameters are selected for the desired output [48]. Out of the input/process parameters, some of the factors are controlled by the operators, while other factors are not in the control of the worker.

In this explicit research, three controllable input parameters, the feed rate, the speed of the spindle and the depth of cutare chosen and are processed during the manufacturing process of a mould on a milling machine (CNC five-axes) to get an optimized result for surface roughness. For obtaining the expected results, the Taguchi technique of optimization is applied to optimize the parameters. The Taguchi method is selected because it is an optimization technique that determines the finest levels of factors, and it is based on planning, performing, and evaluating results of matrix experiments.

After choosing the parameters such as the spindle speed (rpm), the feed rate (mm/rev) and the depth of cut (mm), three additional different stages of all parameters were considered. The factors and their respective levels are given in Table 2.

Table 2. Chosen process parameters and their respective levels.

S.NO	Process Parameters	Level/Stage 1	Level/Stage 2	Level/Stage 3
I	Speed of spindle (rpm)	800 rpm	2000 rpm	3000 rpm
II	Feed rate (mm/rev)	10 mm/rev	80 mm/rev	120 mm/rev
III	Depth of cut (mm)	0.05 mm	0.5 mm	1.00 mm

The numbers of experiments obtained by applying the Taguchi method of optimization were twenty-seven (27). The obtained combinations in those twenty-seven experiments are given in Appendix A Table A1.

The objective of the selection of the above mentioned parameters in Table 2 was to optimize them to optimize the surface roughness. The surface roughness was calculated through a surface roughness tester (portable). The topology of the machined surfaces is also measured and will be discussed in the results and discussion section.

After measuring the surface roughness for each experiment through a surface roughness tester, analysis of variance was deployed to determine the significant process parameters from the chosen parameters.

3. Results and Discussion

The Taguchi optimization technique from the design of experiments was deployed to find the optimum number of experiments between the input parameters (depth of cut, speed of spindle and feed rate) and an output parameter (surface roughness). The topography and surface roughness have also been measured through an electron microscope and profilometer. The Taguchi method recognizes proper control factors for the optimum findings of the process. Analysis of variance is also used to find the significant factors from the preferred parameters that affect the surface roughness the most. Normality test is deployed to find the normal distribution.

Different instruments are used to find the topography and optimized surface roughness. Scanning electron microscopic images are used for the verification of the morphology and surface integrity of the machined surfaces. The beam of electrons is focused on scanning the surface for producing images of samples. The obtained images of workpiece surfaces from the scanning electron microscope are given in Figure 6. It is evident that brittle and sharp fractures of fibers point out the failure modes.

Figure 6a shows the profile obtained from high, medium and low spindle speed. The surface roughness is enhanced rapidly at the maximum spindle speed. The increase of spindle speed leads to the higher generation of heat and tool wear, which ultimately led to the greater surface roughness. The maximum spindle speed also results in incomplete machining and causes a maximum surface roughness.

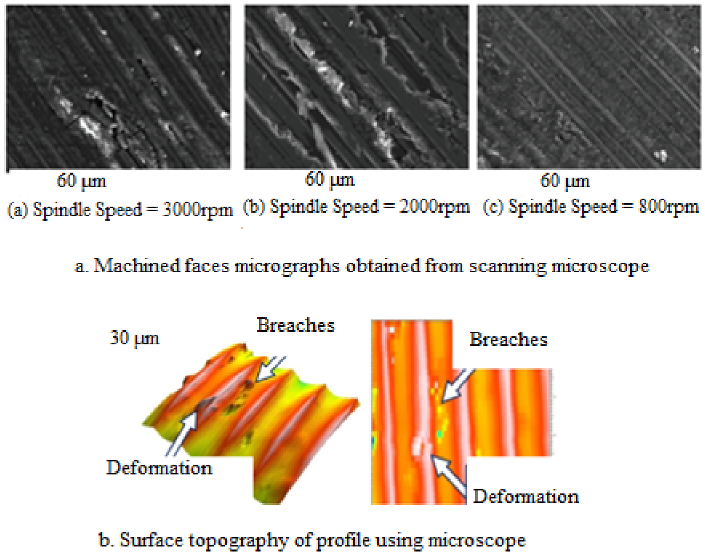

Figure 6. (**a**) Machined faces micrographs and (**b**) surface topography of the profile.

Breaches and deformations have also been measured using a microscope. Figure 6b shows the topographies of the surface of one of the plates of the mould obtained from the microscope. After the milling process on the profile, there are several breaches on the faces of mild steel. There is unevenness in the distribution of burrs and breaches. The number of breaches, dimensions of breaches, burrs on the profiles, and material deformations affects the dimension, shape preciseness, and performance of the workpieces. The source of breaches on the machined profile is due to the composition of the exterior layer of the mild steel.

The machined surface was also scanned by using the profilometer and is as given in Figure 7. Roughness measurements are performed on the machined surfaces. The readings are measured in the longitudinal and lateral direction. Figure 7a suggests the line path for finding the roughness values in the perpendicular direction whereas Figure 7b suggests the line path direction parallel to the grooves. Figure 7c shows that the depth of the groove is calculated as a path length function. The line path measures the width and depth of the grooves.

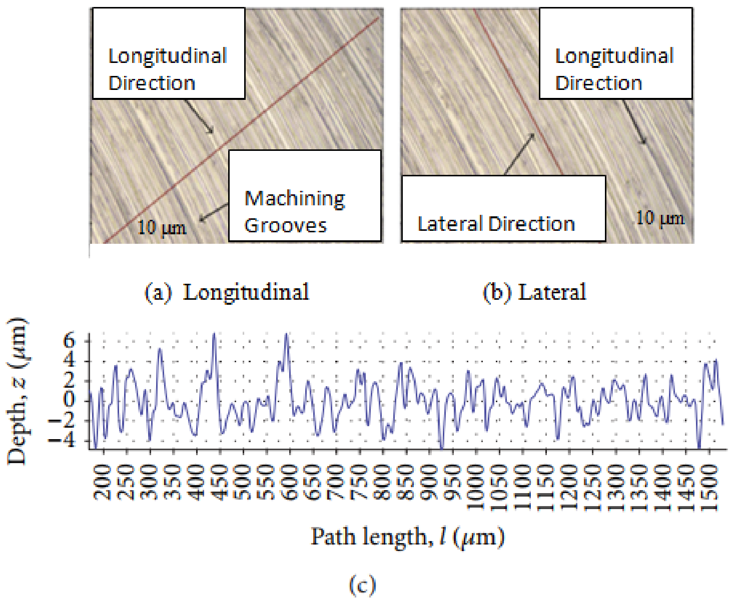

Figure 7. Measurement of surface roughness in (**a**) longitudinal direction, (**b**) lateral direction and (**c**) representation of path length.

After finding the topography and viewing different sections, a chart is drawn for process parameters against the surface roughness where different combinations of process parameters (experiments) are taken on the x-axis, while surface roughness is taken on the y-axis and is shown in Figure 8.

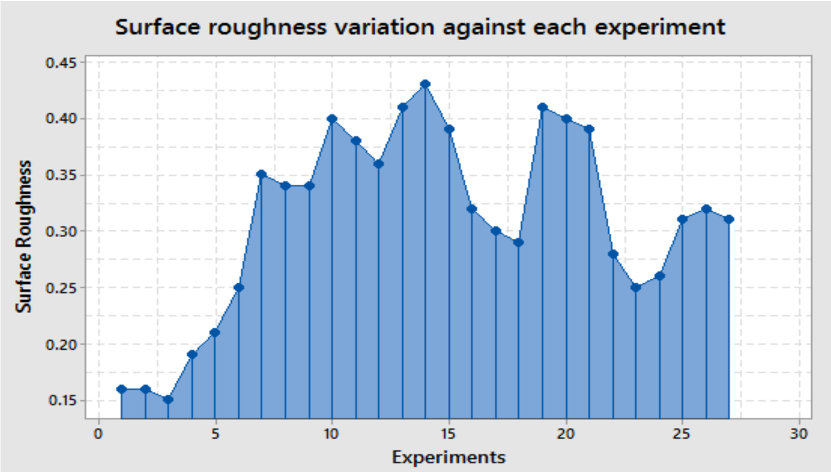

Figure 8. Scatterplot of surface roughness (*Ra*) against experiments.

The highest and the lowest surface roughness calculated from plates by using the Surftest/surface roughness tester are 0.43 µm and 0.15 µm respectively. The respective experiments for the highest and the lowest measured surface roughness are experiments 14 and 3, as shown in Figure 8 and also depicted in Table 3. The highest measured value is the worst case, while the lowest measured value is the best case for mild steel using a CNC 5-axis milling machine.

Table 3. Maximum and minimum surface roughness.

Experiment	Speed of Spindle (rpm)	Feed Rate (mm/rev)	Depth of Cut (mm)	Surface Roughness (*Ra*)	Conclusion
3	800 rpm	10 mm/rev	0.5 mm	0.15 µm	Best case
14	3000 rpm	120 mm/rev	0.05 mm	0.43 µm	Worst case

Hence, it is concluded that a 10 mm/rev feed rate, 800 rpm spindle speed, and 0.05 mm depth of cut (experiment 3) give the lowest and optimized surface roughness, which leads to sustainable manufacturing. ANOVA is also deployed on the chosen parameters to find their significance. It is observed during the analysis of variance from the chosen parameters that the speed of the spindle is the significant and vital factor in changing the surface roughness of the manufactured goods. The *p*-values for three process parameters are given in Table 4.

Table 4. *p*-values for three process parameters.

S. NO	Parameters	*p*-Value	Conclusion
1	Spindle speed (rpm)	0.003	Significant
2	Feed rate (mm/rev)	0.766	Insignificant
3	Depth of cut (mm)	Not estimated	Removed

The *p*-value obtained from ANOVA for the spindle speed is 0.003 and it is less than 0.05, which suggests that it is a significant factor. The *p*-value obtained for the feed rate is 0.766, which shows its insignificance. The depth of cut is not estimated in ANOVA, hence it is removed. Referring to the *p*-value of the spindle speed which is below 0.05, we can litigate with more than 95% confidence that spindle speed is the significant factor and the response variable changes abruptly by making changes in this factor. Hence, we reject the null hypothesis and p is the probability that justifies the acceptance or rejection of the null hypothesis.The confidence interval taken in this research is 95%. The regression equation shows the relationship between the data if any exists. Future events can also be forcasted from this equation.

Regression Equation

Surface roughness (µm) = −0.0942 + 0.000240 Spindle speed (rpm) + 0.001398 Feed rate (mm/rev) + 0.2964 Depth of cut (mm) − 0.000000 Spindle speed (rpm) * Spindle speed (rpm) − 0.000001 Spindle speed (rpm) * Feed rate (mm/rev) − 0.000142 Spindle speed (rpm) * Depth of cut (mm)

The main effects and interacted plots for surface roughness are graphically given below for output response variables (surface roughness). Figure 9 depicts how the data of three different levels of each parameter, i.e., the speed of spindle, the feed rate, and the depth of cutare varyingand affect the response in the milling process. The following results are deduced from Figure 9. The surface roughness is 0.24 µm at level 1 of the spindle speed, and at level 2, it is almost 0.36 µm, while at level 3, the surface roughness is 0.31 µm. Hence, the lesser surface roughness is at level 1, and the spindle speed turns out to be significant in minimizing the surface roughness, and its significance has also been deduced from the ANOVA. The measured surface roughness is 0.305 µm at level 1 of the feed rate, and at level 2, it is 0.29 µm, while at level 3, the measured surface roughness is 0.31 µm. Hence, the lesser surface roughness is at level 2. Similarly, the measured surface roughness is 0.245 µm at level 1 of the depth of cut, and at level 2, it is 0.29 µm, while 0.37 µm is the measured surface roughness at level 3. Hence, the lesser surface roughness is at level 1.

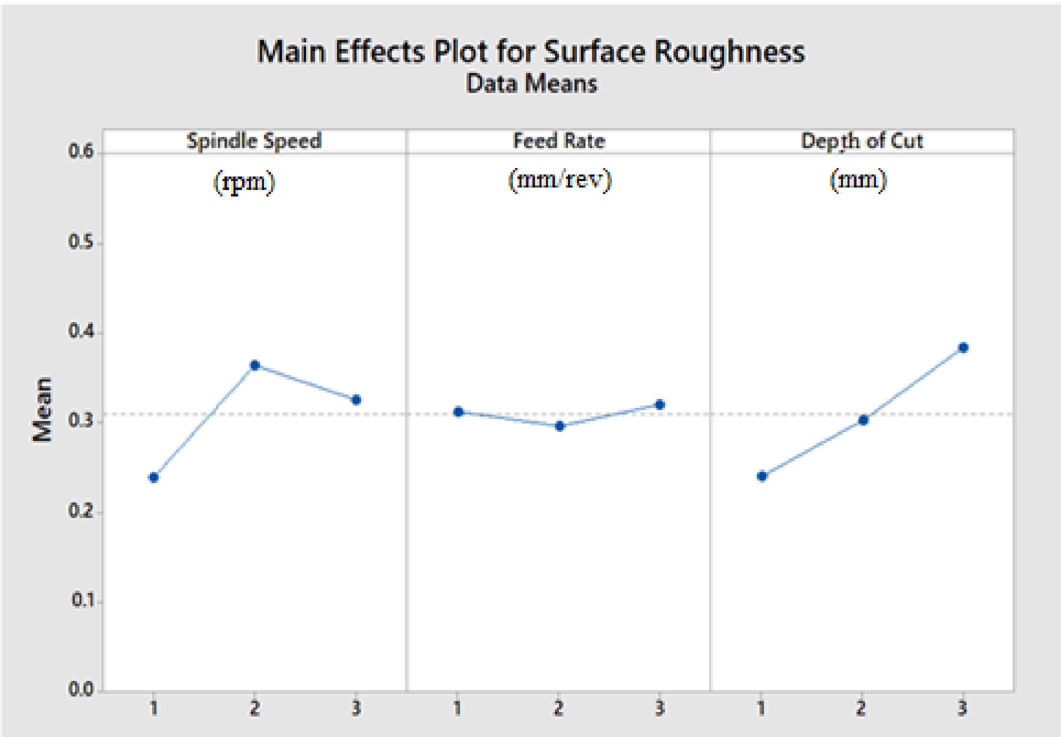

Figure 9. Main effects plot/graph for *Ra*.

Figure 10 depicts the interaction plot/graph for the surface roughness of mild steel grade 60 and shows thatthe interaction among the different levels of each parameter (the speed of the spindle, the feed rate and the depth of cut) affects the response variable in the milling process. The effect of the interaction of different levels of parameters is different for every different grade of material. It is clearly presented that how the spindle speed, the feed rate and the depth of cut vary and interact at three different levels. The interaction plot shows that if level 1 of the feed rate is taken, i.e., 10 mm/rev, then the surface roughness of the mould against level 1, i.e., 800 rpm of spindle speed, will be minimum. If level 1 of the depth of cut is taken, i.e., 0.05 mm, then the surface roughness of the mould against level 1, i.e., 10 mm/rev of the feed rate, will be minimum and maximum in case of level 3. If level 1 of the spindle speed is taken, i.e., 800 rpm, then the surface roughness of the mould against level 2, i.e., 0.05 mm of the depth of cut, will be minimum and maximum in case of level 1.

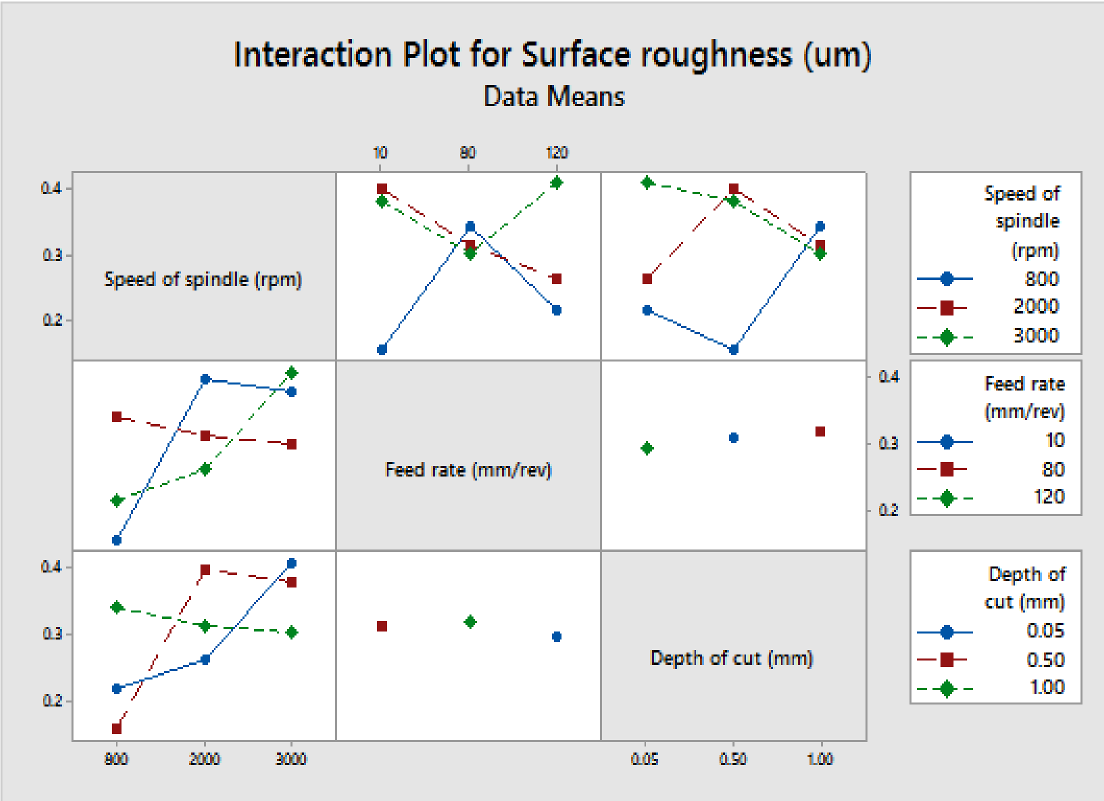

Figure 10. Interaction plot for *Ra*.

The surface plots of surface roughness are also made against different combinations of process parameters and are shown in Figure 11. It is observed in Figure 11a that if changes are made in a combination of spindle speed and feed rate, the surface roughness changes abruptly. This is because of the significance of the spindle speed, as it has been already observed in ANOVA that the spindle speed affects the surface roughness the most. Figure 11b shows that a combination of feed rate and depth of cut has an almost negligible effect on the surface roughness because of the insignificance of the feed rate and no estimation of the depth of cut. Likewise, Figure 11c suggests that if the feed rate is taken in combination with spindle speed, it will affect the surface roughness but will be better than the first case due to no estimation of depth of cut. Hence, similar to ANOVA, the significance of each parameter has been highlighted, and their combination with each other has been analyzed [35–40]. Hence, it is clear from the interaction plot as well that the spindle speed is the main factor affecting the surface roughness, which would ultimately lead to less productivity and increased cost due to extra waste material. Spindle speed was also found to be significant in the machining of stainless steel and end milling of duplex stainless steel [49,50].

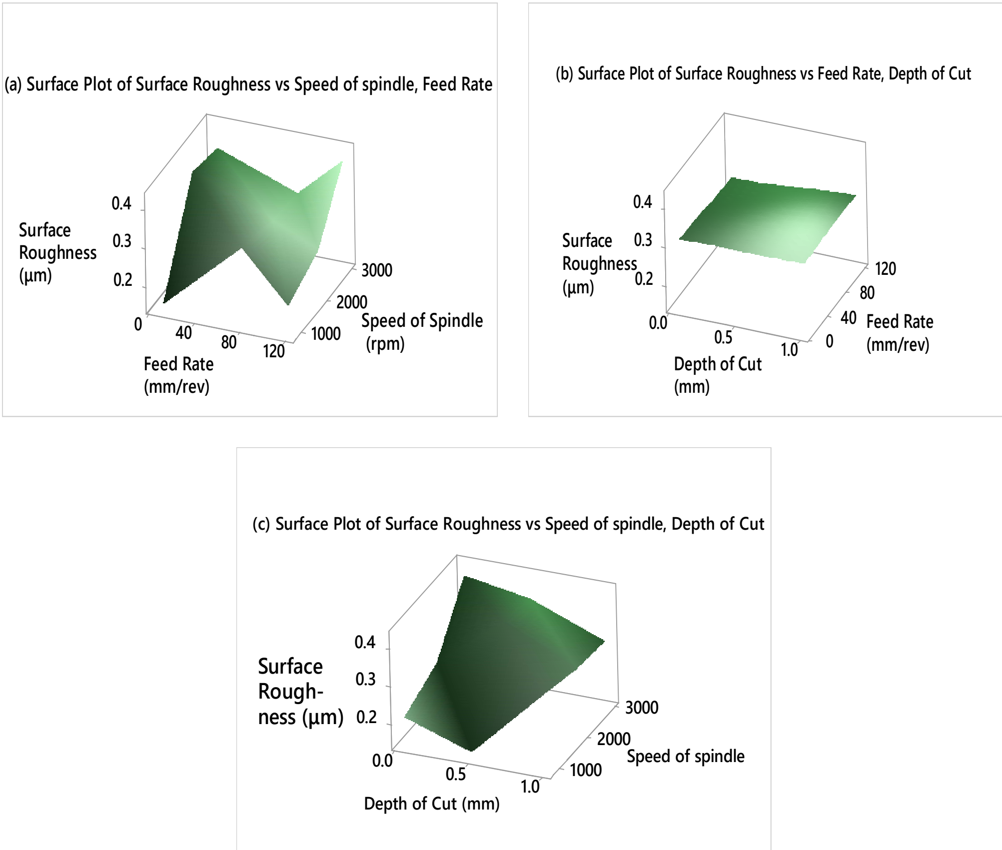

Figure 11. Surface plots of surface roughness against different combinations of process parameters (**a**)surface roughness vs. spindle speed and feed rate, (**b**) surface plot of surface roughness vs. feed rate and depth of cut, (**c**) surface plot of surface roughness vs. spindle speed and depth of cut.

Determining the significance of process variables, finding the main effect plot, interaction plot, and surface plots are vital stages in the whole process. After these stages, it is important to find whether the data follow any distribution or not. A normality test is conducted on the chosen data in MINITAB software to find their normal distribution. For normal distribution, sample data is taken from normally distributed data. ANOVA shows the significance of each parameter, while a normality test shows the significance of the overall data. Figure 12 shows the results of normality test.

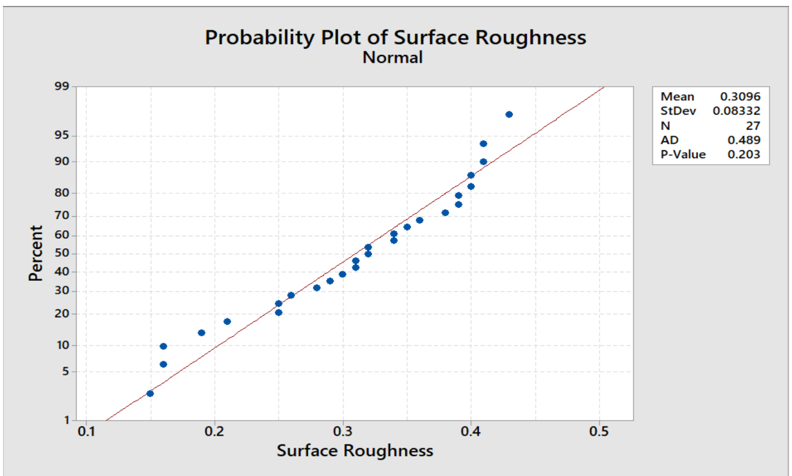

Figure 12. Normality plot of surface roughness.

After conducting a normality test, it is obvious from Figure 12 that the *p*-value is 0.203, which is greater than 0.05. Hence, the *p*-value depicts that the data is following a normal distribution and there are not immense errors in data collection.

4. Conclusion and Future Work

It was observed that the local industry does not have the facility of using scientific tools and optimization methods for their moulds. Local manufacturers and dealers in Peshawar (Pakistan) were facing an issue of surface finish specifically in the moulds of mild steel grade 60, and there was no consideration of applying optimized parameters and sustainable manufacturing in the local market. The mould material surely had an impact on the qualities of the products. Every material works in its own way during machining, and if the mould's cavity is not well made during machining, it wold surely lead to quality issues during its use in molding machines.

In this research, an essential challenge was the design and fabrication of an injection mould, which is achieved successfully through CREO software and a CNC milling machine respectively. After the design and fabrication of an injection mould, the process parameters (the spindle speed, the depth of cut and the feed rate) were optimized with the help of design of experiments (DOE) for mild steel grade 60, which is the novelty of this research. These parameters have not been optimized for mild steel grade 60 before this research using a CNC five-axis milling machine. The Taguchi optimization method is applied successfully to optimize the process variables for a response. The Taguchi method determines the finest levels of factors, and it is based on planning, performing, and evaluating results of matrix experiments. It is concluded from the results that experiment 3 had the best combination of input process parameters (i.e., 800 rpm speed of spindle, 10 mm/rev the feed rate and 0.5 mm the depth of cut) in order to get the minimum surface roughness in the mould of mild steel grade 60, which would surely lead to sustainable manufacturing.

After the designing and manufacturing process, it was vital to find the significance of each factor. Through the analysis of variance, the significant factor from the chosen factors has been identified through statistical analysis in MINITAB software. A normality test was also conducted on the data in MINITAB software to find its normal distribution. The *p*-value illustrated that the data was following a normal distribution, and there were no huge errors in the data collection. In short, parameters have been optimized for mild steel grade through the complete product development process. Hence, an issue of surface roughness in mild steel mould originated from a local market has been resolved and a mould of mild steel grade 60 has been made sustainable. The local market can use the same optimized parameters for the manufacturing of sustainable moulds of mild grade 60. The limitation of this specific research is that it focuses only mild steel grade 60, and only three input variables are taken for optimization of the milling process.

Due to the distinctive properties of every material, different researchers have selected different parameters during machining. This specific optimization research has been carried out on mild steel grade 60 using a milling machine (CNC 5-axis) to get an optimized and sustainable product. In the same manner, in the future, research can be carried out for multi-response optimization, as production time might have been affected due to surface roughness optimization. However, the overall process has been improved. Research can also be carried out on the sustainable manufacturing of moulds made from different materials by balancing the required parameters. In addition, a mild steel mould can be made through any other CNC machine for the comparison of its result with the mould made using a CNC 5-axis milling machine. Likewise, new parameters for mild steel grade 60 and other grades of this specific material can also be optimized using different CNC machines. More advanced techniques such as response surface methodology and gray relational analysis can be applied for parameters optimization for mild steel grade 60.

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Nomenclature

CNC	Computer Numerical Control
ANOVA	Analysis of Variance
DOE	Design of Experiments
Rpm	Revolution per Minute
mm/rev	Millimeter per Revolution
mm	Millimeter
Ra	Roughness Average
3D	Three Dimensional

Appendix A

Table A1. Experiments obtained from Taguchi optimization method.

Run Order	Variable/Factor 1	Variable/Factor 2	Variable/Factor 3
	Speed of Spindle (rpm)	Feed Rate (mm/rev)	Depth of Cut (mm)
1	800	10	0.50
2	800	10	0.50
3	800	10	0.50
4	800	120	0.05
5	800	120	0.05
6	800	120	0.05
7	800	80	1.00
8	800	80	1.00
9	800	80	1.00
10	3000	10	0.50
11	3000	10	0.50
12	3000	10	0.50
13	3000	120	0.05
14	3000	120	0.05
15	3000	120	0.05
16	3000	80	1.00
17	3000	80	1.00
18	3000	80	1.00
19	2000	10	0.50
20	2000	10	0.50
21	2000	10	0.50
22	2000	120	0.05
23	2000	120	0.05
24	2000	120	0.05
25	2000	80	1.00
26	2000	80	1.00
27	2000	80	1.00

Table A2. Experiments and their respective response (surface roughness).

Run Order	Variable 1	Variable 2	Variable 3	Response
	Speed of Spindle (rpm)	Feed Rate (mm/rev)	Depth of Cut (mm)	Surface Roughness (um)
1	800	10	0.50	0.16
2	800	10	0.50	0.16
3	800	10	0.50	0.15
4	800	120	0.05	0.19
5	800	120	0.05	0.21
6	800	120	0.05	0.25
7	800	80	1.00	0.35
8	800	80	1.00	0.34
9	800	80	1.00	0.34
10	3000	10	0.50	0.40
11	3000	10	0.50	0.38
12	3000	10	0.50	0.36
13	3000	120	0.05	0.41
14	3000	120	0.05	0.43
15	3000	120	0.05	0.39
16	3000	80	1.00	0.32
17	3000	80	1.00	0.30
18	3000	80	1.00	0.29
19	2000	10	0.50	0.41
20	2000	10	0.50	0.40
21	2000	10	0.50	0.39
22	2000	120	0.05	0.28
23	2000	120	0.05	0.25
24	2000	120	0.05	0.26
25	2000	80	1.00	0.31
26	2000	80	1.00	0.32
27	2000	80	1.00	0.31

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