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OPTIMIZING SURFACE ROUGHNESS IN DRY-TURNING AISI 1029 STEEL WITH CARBIDE INSERT TOOLS ON THE LATHE MACHINE USING TAGUCHI'S METHOD

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Keywords: *Machining, Turning, Surface roughness, Minimization, Optimal cutting conditions, Taguchi's method, Signal-to-Noise ratio, Smaller-the-Better*

Abstract: *The AISI 1029 carbon steel type is frequently machined by turning operations to produce bolts, nuts, washers, threaded rods, studs, and other fasteners for various engineering applications. The paper demonstrates the use of the Taguchi optimization method in determining the optimum surface finish as a special quality requirement in the turning of the steel on the lathe machine. Taguchi's L-9 Latin-squares orthogonal arrays were designed with cutting speeds of 125, 250, and 500 m/min; feed rates of 0.1, 0.2, and 0.3 mm/rev; and cut depths of 0.5, 1, and 1.5 mm. Dry-turning experiments were conducted on the XL9 400 lathe machine with a 79.6-mm-diameter and 200-mm-length solid rod of the steel under each array of cutting conditions. The produced surface roughness responses from the turning operations were measured and analyzed by generated signal-to-noise ratios, main effect plots, contour plots, surface plots, and analysis of variance on the basis of Taguchi's concept of the smaller the better using the Minitab-17 software. The analyses showed that the 500-mm/min cutting speed, 0.1-mm/rev feed rate, and 1.5-mm depth of cut array produced optimal surface roughness in the turning operations. Analysis of variance at 95% confidence level showed that feed rate variation had the greatest contribution of 61.78% to surface roughness, followed by depth of cut with 26.22%, and cutting speed with 8.865%. The confirmation test at the optimal turning conditions indicated 2.20-µm optimal surface roughness with only 2.3% error against the 2.15-µm value obtained with the Minitab-17-generated regression equation.*

1. INTRODUCTION

Machining is a fast and efficient production process in which a sharp single or multi-edge cutting tool is used to mechanically cut a material in a controlled manner to remove away unwanted stuff from the material in the form of chips so that the remaining solid shape complies with the dimensions and surface finish of desired component or part for engineering application [1]. Turning is the most commonly used machining process in metal cutting industry. It is especially used for finishing machined parts such as shafts, bearings, screw-nuts, and cams in manufacturing industries at high rate with reasonable accuracy and surface finish [2, 3]. Turning is also commonly used as a finishing

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process for products of other manufacturing processes such as casting, rolling, and forging [1]. Turning is accomplished on the lathe machine by removing excess metal from the outside diameter of a cylindrical part with a single-point cutting tool to form desired cylindrical or conical component [4]. In turning, the work-piece is held and rotated in the lathe chuck while the cutting tool is held without rotation on the lathe tool post and used to provide depth of cut on the work-piece in its transverse direction and feed rate in its longitudinal direction [5]. Turning can be done under wet or dry conditions [6]. There are similarities, advantages, and disadvantages in dry and wet turning. Dry turning is more economical because it does not require cutting fluid or its delivery system. It is also less hazardous to workers, non-prone to environmental pollution, and eliminates problems associated with corrosion of machine tools [6, 7]. Notable disadvantages in dry turning include general unsuitability for hard materials, limitation to low process input variables, considerably higher temperatures and excessive heat generation, and ability of the work surface to oxidize or burn under generated heat with attendant poor surface quality [6, 7]. The ultimate target in turning and other machining operations whether under dry or wet conditions is to consistently achieve high product quality and productivity at affordable cost [8]. There are many input variable parameters in turning process such as cutting forces, coolant type and flow rate, tool geometry and orientation, attendant vibrations, cutting speed, depth of cut, and feed rate which need to be properly controlled to achieve high product quality and productivity at affordable cost in turning operations [5, 8]. Cutting speed, depth of cut, and feed rate are however the most influential variable parameters because reducing or increasing them also reduces or increases the extents of the other variable parameters such as cutting forces, and attendant temperatures and vibrations on the tool relative to the work-piece that also need to be controlled [9, 10]. The usual output process control targets in any turning process are maximization of productivity by maximization of metal removal rate, maximization of product quality by minimization of surface roughness and maximization of dimensional accuracy, and minimization of product costs by maximization of tool life and minimization of cutting forces [8, 11, 13]. To achieve all these targets with a given work-piece type and cutting tool type especially in mass production of a component is difficult or impracticable, so the targets are usually prioritized. Depending on which target is a priority, turning and other machining processes require trade-off in the targets to achieve that priority [11]. Theoretical and trial-and-error methods are often used for achieving the desired priority. However, theoretical methods are less accurate than experimental methods; because they are mostly based on ideal conditions by not considering interplay of all involved variables such as attendant vibration levels, cooling extents, effects of chips formed and tool wear, and work-piece structural integrity; while trial and error methods are based on the experience of the machinist and can substantially reduce productivity and increase cost and labor input into the machining process. The most common target priority for the bulk of machined components or parts used in engineering nowadays is maximization of their qualities by minimization of their surface roughness [2, 3. 5, 13].

Surface roughness is the measure of degree of variance of surface topology of a part or component from its ideal form from which there is no variance [14]. It is challenging and costly to control surface roughness to ideal or optimal level in critical production processes such as turning due to wide variability of controllable cutting speed, depth of cut, and feed rate [15]. The need for minimizing surface roughness in machining stems from inimical effects higher surface roughness can have on aesthetic value and mechanical behaviour of applied part or component with regards to crack initiation, wear and corrosion resistance, fatigue life, mating, sealing, bearing, and relative dynamics in fluids. Moreover, surface roughness of a part or component is inversely related to its dimensional accuracy and machining cost [3, 9, 10, 15, & 16]. For components like fasteners, optimization of their surface roughness is crucial for achieving consistent levels of tightening torque clamps with no or minimal wear, minimizing their risks of corrosion deterioration or failure, and enhancing their mating contacts and overall durability in service. The need for minimizing surface roughness is particularly important in finishing production processes such as turning where greater surface roughness control is critical to ensure that the final product looks better with minimal surface roughness and lasts long in service with satisfactory performance [3]. The use of theoretical or trial-and-error approaches in arriving at set of cutting conditions for achieving optimal or required surface roughness in turning operation is therefore considered inappropriate in our today's volatile and fiercely competitive product requirements [3]. It is much more productive and economical if machinists or concerned stake-holders know beforehand, the required surface roughness and optimal setting of cutting variables for every given machinable material for achieving the required surface roughness instead of resorting to theoretical or trial-and-error approaches. However, all such required information has not been documented in machining manuals or standards for easy availability and selection of optimal settings for every machinable material type on every machine tool. This is why there have been continual experimental research efforts with motives of providing settings of cutting variables for achieving optimal or required product surface roughness with all critical machinable materials and different selectable sets of cutting conditions [2, 17]. The typical average surface roughness (R_a) of metallic products by different conventional machining processes under different cutting conditions and cooling levels are in the ranges of 0.4-12 μm for boring and turning, 0.1-1.6 μm for grinding, 1.6-25 μm for sawing, 1.6-12.5 μm for shaping and planning, 1.6-12.5 μm for drilling, 0.8-6.3 μm for milling, and 0.8-3.2 μm for broaching and reaming [18, 19].

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Carbon steel is the most commonly used material in turning operations. No two different types of carbon steel are equally machinable to the same surface roughness under the same cutting condition due to variations in their machinability levels. The greater the machinability level of carbon steel type, the better the surface roughness of products from the steel type; but machinability is very difficult to predict because it depends on many factors such as the composition, microstructure, hardness, and strength level of the steel type. Machinability of carbon steel is also determined by many variable factors such as choice of cutting fluid, cutting tool material and geometry, structural rigidity and vibration extent in the machine tool, feed rate, cutting speed, and depth of cut [8, 20]. The AISI 1029 steel is a carbon steel type that contains carbon in the range of 0.25-0.31% [11, 12]. AISI 1029 steel type is a suitable material for manufacturing forged components that are subjected to low stresses for automotive and general engineering. It is a suitable material for gas turbines, boilers and pressure vessels, nuclear power plants, marine engineering, chemical processing plants, and furnaces. This type of steel frequently requires turning operations to produce components such as bolts, nuts, washers, threaded rods, studs, stud bolts, and other fasteners to desired accuracy specifications for various engineering applications [11, 21]. Metallurgical factors indicate that the AISI 1029 steel is a suitable soft material for dry machining because it has an average BHN of 145, a high iron content of from 98.7 to 99.15%, a low carbon content of only 0.25 to 0.31%, and a finer grain structure than medium carbon steel [11, 21].

Turning of carbon steels can involve cutting speeds as low as a few centimetres per second to as high as 1000cm/s, depths of cut as low as less than 1mm to as much as over 10mm, and feed rates as low as less than 1mm/rev to as high as over 5mm/rev. This wide variability of cutting conditions depends on properties of the steel types and makes it difficult for machinists or stakeholders to know and/or select cutting conditions for optimal turning requirements of carbon steel types without use of optimization methods [8, 22]. Application of optimization techniques in turning of carbon steel is seen as a strategic way of increasing productivity and quality of the bulk of machined products used in engineering. Various optimization methods such as genetic algorithm, Taguchi, Monte Carlo, quasi-Newton, linear programming, finite element, artificial neural network, Fuzzy, ant colony, design of experiment, etc have been found exploited in the literatures to optimize solutions to several and wide cases of cost and quality management problems encountered in production engineering [9, 23]. Taguchi's optimization method is among the best experimental methodologies that are employed to find the minimum number of experiments to be performed within limit of factors and levels to ensure quality of products or processes. The method is based on the principle of determining the best level of process or production control factors to achieve robust products [22]. The best level of control factors is the one that minimizes or maximizes the Signal-to-Noise ratio

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depending on the process requirement. Signal-to-Noise ratios are log functions of desired output characteristics. The significance of Signal-to Noise ratio is that it is a measure of the sensitivity level of a product or process to all factors that can cause its performance variation [12].

The experiments that are conducted to determine the best level of control factors are based on Taguchi's "orthogonal arrays", and are balanced with respect to all control factors and yet minimal in number. This in turn implies that the material resources and time required for the experiments are also minimal [22, 24]. Taguchi's method has several applications in different fields of human activities because of its easiness to use to optimize target parameters against input variables by systematically formulating requisite experimental layout, analysing the influence of each experimental parameter using statistical analysis of variance (ANOVA), and all in all; determining the optimal combination of parameters to the best process condition. The method is a great quality control approach used in product design and development in engineering for reducing occurrence of defects and failures in manufactured products [25, 26]. The only setback in Taguchi's method is that optimal results obtained from the method are only relative to the levels of selected input variables but not for the entire range of input variables. The method also does not test the output for all possible combinations of input variables since the combinations of the selected inputs has to be limited [24, 26].

1.1 Aim

This aim of this paper is to illustrate the application of Taguchi's optimization method in orthogonal dry turning of AISI 1029 carbon steel using a carbide insert tool cutter at selected sets of cutting speeds, cut depths, and feed rates with the specific objective of improving the surface roughness of fasteners and other components produced with the steel type by the dry turning process to optimum aesthetic value and mechanical behavior, dimensional accuracy, crack initiation mitigation, wear and corrosion resistance, fatigue life, mating, sealing, and bearing capacities at minimal costs.

1.2 A Review of Research Outputs on Optimization of Operating Variables Using Taguchi's Method

Several studies involving Taguchi optimization of operating variables in many experimental and production processes, such as those of [27], [28], [29], [30], [31], [32], etc., have continued to be used to date in solving several complicated problems in science and engineering. A review of all such research in this narrow band is impossible; however, a review of some more recent works in which Taguchi's method was employed for optimal solution of problems in engineering and scientific processes, especially in metal cutting on the lathe, show that:

Irfaan *et al* [32] investigated surface roughness improvement in the turning of the AISI 1045 steel by using cutting speed of 58.9048 to113.2887 m/min, feed rate 0.1 to 0.3 mm/rev., and depth of cut of 0.4 to 0.8 mm variable parameters. They observed that these parameters are most responsible for surface roughness of machined components and their working range is set. Taguchi's method was used to collect the experimental data in the investigation. An L-9 orthogonal design, signal to noise ratio, and analysis of variance to improve

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surface roughness of the steel were also employed. They found that the feed rate exerted higher effect on surface roughness followed by depth of cut, and They also found that the surface roughness increased with increasing feed rate, depth of cut and decrease with decreasing cutting speed.

Ososomi and Ekhayeme [33] affirmed that quality and productivity play significant role in today's manufacturing market. In their research work, turning operation was performed on mild steel with the aim of evaluating the best process environment which could simultaneously satisfy requirements of both quality and as well as productivity. The experiments were conducted by taking cutting speed, feed rate and depth of cut as process parameters and got the optimized value of surface roughness and cutting temperature. An L9 orthogonal array, the signal-to-noise (S/N) ratio and the analysis of variance (ANOVA) were employed to the study the performance characteristics in the turning on CNC using tungsten coated carbide cutting tool insert with a nose radius of 0.8mm. The analysis of results showed that the combination of process parameters for minimum surface roughness was obtained at 75m/min cutting speed, 0.2 mm/rev feed and 1.0 mm depth of cut for minimum surface roughness. It was observed that feed rate and the speed play important role in minimizing surface roughness. For maximum material removal rate, the optimum values were cutting speed of 75m/min, feed rate of 0.2 mm/rev and depth of cut of 0.6 mm. It was also observed that depth of cut and the speed play important role in minimizing cutting temperature. Finally, the relationship between cutting parameters and responses were developed by using the Minitab 18.1 software and regression equations were developed. For surface roughness and cutting temperature, the values of $2.313\mu m$ and $65.39^{o}C$ were determined using their respective objective functions with their optimum parameters (values).

Krishankant *et al* [34] noted that Taguchi method is a good method for optimization of various machining parameters as it reduces the number of experiments. They also noted that every day scientists are developing new materials and for each new material, economical and efficient machining is needed. They found from the literatures that no work was done on the use of the method for machining EN24 steel. They reported on optimization of turning process by the effects of machining parameters applying Taguchi's methods to improve the quality of manufactured goods, and engineering development of designs for studying variation. They used the EN24 steel as the work piece material for carrying out the experimentation to optimize the material removal rate. They used the steel in bar form of diameter 44mm and length 60mm and three machining parameters; spindle speed, feed rate, and depth of cut. They conducted different experiments by varying one parameter and keeping other two fixed to obtain maximum value of each parameter. They found the operating range by experimenting with top spindle speed and taking the lower levels of other parameters. They designed Taguchi's orthogonal array with three levels of turning parameters with the help of software Minitab 15. They performed nine experiments in the first run and material removal rate (MRR) was calculated. When they repeated experiments in the second run MRR was again calculated. They noted that Taguchi's method stresses the importance of studying the response variation using the signal–

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to–noise (S/N) ratio, resulting in minimization of quality characteristic variation due to uncontrollable parameter. They considered the metal removal rate as the quality characteristic with the concept of "the larger-the-better". They calculated the S/N ratio values by taking into consideration with the help of software Minitab 15. They measured the MRR values from the experiments and their optimum value for maximum material removal rate.

Mishra and Gangele [35] applied Taguchi's techniques to find out the optimum tool flank wear width in turning operation of AISI 1045 steel. They used the Taguchi's L-9 orthogonal array, S/N ratios and analysis of variance (ANOVA) to study the performance characteristics of cutting speed, feed rate and depth of cut as turning parameters with tool flank wear width as response variable. The result and analysis of their study showed that the selected machining parameters significantly affected the tool flank wear width of Tungsten Carbide cutting tool while machining AISI 1045 steel. Their result and analysis also indicated that the cutting speed is the most influencing parameter out of the three parameters under study. They finally confirmed their results by validation experiments or confirmation run.

Nalbant *et al* [36] used the Taguchi's method to find the optimal cutting parameters for surface roughness in turning operations. They employed orthogonal array, the signal-to-noise ratio, and analysis of variance to study the performance characteristics in turning operations of AISI 1030 steel bars using TiN-coated tools. They optimized three cutting parameters namely; insert radius, feed rate, and depth of cut with considerations of surface roughness. They provided experimental results to illustrate the effectiveness of this approach.

Wakjira *et al* [37] conducted research employing Taguchi's approach with the aim to investigate the machinability of CSN 12050 carbon steel bars using carbide insert tool in order to utilize the optimum cutting parameters. They performed experiments under dry cutting condition using an optimization approach according to Taguchi's orthogonal arrays, and signal-to-noise ratio. They performed ANOVA to determine the importance of machining parameters on the material removal rate (MRR). They analysed results using signal-to-noise ratios (S/N) and employed; 3D surface graphs, main effect graphs of mean, and predictive equations to study the performance characteristics. They obtained 275-m/min cutting speed, 0.35-mm depth of cut, and 0.25-mm/rev feed rate results as the optimal cutting parameters. They found an improvement of 5.22 dB at optimal cutting conditions for each significant MRR response parameters such as cutting speed, depth of cut, and feed rate. They concluded that it is possible to optimize machinability for product sustainability with these proposed optimal parameters.

Das *et al* [38], presented an optimization method of cutting speed, depth of cut, and feed machining parameters in dry turning of AISI D2 steel to achieve minimum tool wear, low work piece surface temperature and maximum material removal rate. They used three depths of cut in the range from 0.5 to 1mm, three feed rates in the range from 0.15 to 0.25mm/rev and three cutting speeds in the range from 150 to 250m/min. They concluded from their study results that depth of cut was the most significant parameter by contributing 51.1%, followed by feed by contributing 25.5% to material removal

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rate the turning operation. They reported that the optimal combination of cutting parameters for maximum material removal rate were 250m/min cutting speed, 1mm depth of cut, and 0.25mm/rev feed.

Ghan and Ambekar [39] developed surface roughness and material removal rate prediction model for turning and milling of Al-alloy using multi regression analysis for optimization of the machining parameters. They used Taguchi's L-9 orthogonal arrays for designing and conducting their experiment. They analyzed the experimental data using Minitab16 software. From their study, they concluded that: The most significant parameters on surface roughness of Al-alloy in the machining are cutting speed and depth of cut. In the case of material removal rate, speed is most influencing parameter followed by feed. In case of machining time, speed is most influencing parameter followed by depth of cut.

Gupta and Diwedi [40] investigated the effect of insert nose radius and machining parameters including cutting speed, feed rate, and depth of cut on surface roughness and material removal rate in a turning operation using the Taguchi's optimization method. For the work; they used three cutting speeds from 100 to 200m/min, three feed rates from 0.25 to 0.3mm/rev, three depths of cut from 1 to 2mm and three insert nose radii from 0.4 to 1.2mm and found that for simultaneous optimization of surface roughness and material removal rate, depth of cut is the most significant parameter affecting the performance followed by the nose radius.

Gupta and Kumar [41] investigated surface roughness and material removal rate in the turning of unidirectional glass fiber reinforced-plastics using principal component analysis and Taguchi method. They used three tool rake angles from -6 to 6 degrees, two insert nose radii from 0.4 and 0.8mm, three cutting speeds from 55.42 to 159.66m/min, three feed rates from 0.05 to 0.2mm/rev, three depth of cuts from 0.2 to 1mm under dry, wet and cooled cutting conditions. From this investigation they concluded that surface roughness and material removal rate increase as feed rate increases. They also reported that feed rate is the factor with the greatest influence on surface roughness, followed by cutting speed in turning of the fiber-reinforced plastics.

Jarayaman and Kumar [42] used grey relation analysis to perform multi-objective optimization of surface roughness and material removal rate. They investigated the effect of cutting speed, feed and depth of cut on surface roughness and material removal rate in turning of Al6063 aluminum alloy using uncoated carbide insert under dry condition. They conducted experiments based on Taguchi's orthogonal L-9 array, followed by optimization of result using ANOVA to find out maximum MRR and minimum surface roughness. From this study they concluded that feed rate is most influencing factor in grey relation grade followed by depth of cut. They also reported that lower cutting speed, lower feed rate, and medium depth of cut give minimum surface roughness and maximum material removal rate in turning of the aluminum alloy.

Davim [43] investigated optimal cutting spindle speed, feed rate and depth of cut in dry turning of mild steel of 0.21%-carbon and 0.64%-manganese contents with a HSS cutting tool. He conducted the investigation with Taguchi's L-27 orthogonal array to find out the lowest surface roughness. He utilized ANOVA and signal to noise ratio to find out the performance characteristics. From his results, he found that among the three cutting parameters only feed rate is significant in the turning operation.

Kumar *et al* [44] investigated by regression analysis the optimum cutting conditions to get the lowest surface roughness in face turning of EN8 alloy. The cutting parameters they used in the investigation were spindle speed, feed rate, and depth of cut. They determined the performance and the effect of the cutting parameters on surface roughness by multiple regression analysis and ANOVA using MINITAB software. They conducted the experiments on the lathe by taking three levels of parameters and using coated ceramic cutting tool. To analyze the performance and effect, they formed an empirical equation. From their study results, they concluded that cutting speed and feed were the significant factors affecting surface roughness in face turning of EN8 alloy.

Rodrigues *et al* [45] studied the effect of feed rate, cutting speed and depth of cut on the surface roughness as well as cutting force in turning mild steel with HSS cutting tool. They carried out experiments using high precision lathe machine. They used full factorial design with two repetitions to find the optimal solution. They found that; feed rate and the interaction between feed rate and cutting speed were the main influencing factors on surface roughness. They also reported that; the feed rate, depth of cut, and interaction between feed rate and depth of cut influenced the variance of cutting force significantly. They concluded that feed rate and depth of cut have significant effect on surface roughness and cutting force in the turning operation.

Somashekara and Lakshmana [13] investigated the setting conditions for turning Al6351-T6 alloy for minimal surface roughness. They generated a model for optimal surface roughness using regression technique. The turning parameters they considered were cutting speed, feed rate, and depth of cut with three levels each. They implemented the L-9 orthogonal array for the experiment, and conducted the surface roughness measurements with three repetitions. The results they obtained for the regression model and experimental values were having errors of less than 2%, thus confirming one another. They also found from ANOVA and S/N ratio that cutting speed is the highest significant parameter followed by feed rate and depth of cut in the turning operation.

Davim [46] inquired into the effect of cutting speed, feed rate, and depth of cut machining parameters on optimization of surface roughness in turning AISI 1045 steel alloy. He conducted experiments of the study on stallion 100HS CNC lathe using Taguchi's L-27 orthogonal array. From ANOVA he found that feed rate has the maximum contribution of 95.23% on the surface roughness of products from the turning operation than cutting speed. Using predictive equation, his predicted value of optimum surface roughness at the optimal conditions was found to be 0.89 μm whereas the calculated response was 0.93 μm with only 4.4% as the error between them. He evaluated the results using MINITAB 16 software. He also investigated the effect of cutting parameters such as cutting speed, feed rate and depth of cut in turning mild steel and aluminum using HSS cutting tool. He carried out the investigation to achieve better surface finish and to decrease power requirement by reducing cutting force in the turning operation. He conducted the experiments based on 2k factorial techniques and used ANOVA to find out the

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effect of cutting parameters on surface roughness and multiple regression analysis to develop cutting forces required for machining. He found that, the feed rate has significant effect on both surface roughness and cutting force of the materials in the turning operations.

Shunmugesh *et al.* [47] studied the machining variables in the process of turning 11SMn30 alloy using carbide tip inserts under dry conditions. They obtained optimal settings for the cutting parameters. Their three-level cutting parameters were cutting speed, feed rate, and depth of cut. The turning experiment was conducted using an L-27 orthogonal array in CNC turning centre stallion 200. They measured roughness values Ra and Rz with a surface roughness tester. They did statistical analysis using MINITAB 17. They found that the feed rate is the most significant factor to affect surface roughness other than cutting speed and depth of cut in the turning operation.

Kartal [48] employed Taguchi's L-9 orthogonal arrays, signal-to-noise ratio (S/N), and analysis of variance (ANOVA) to investigate the cutting characteristics of St 33 and St52 steel bars using a hard-mine-tipped pen cutting tool in CNC turning operations. Controlled factors were cutting speed (120, 150, and 180 m/min), feed rate (0.1, 0.2, and 0.3 mm/rev), and depth of cut (0.5, 1.0, and 1.5 mm). Performance characteristics considered were amount of tool wear and surface roughness. After analyzing the collected data, he found out that cutting speed was the most effective parameter for tool life, and feed rate has a smaller effect compared with cutting speed. The most effective parameter was feed rate for surface roughness; cutting speed and depth of cut had smaller effects when compared with feed rate.

Guma and Onoja [11] noted that machining is essentially a finishing production process and an economic activity that requires maximization of productivity and quality of products at minimal costs. In their paper, an experimental investigation of cutting variables for optimal metal removal rate (MRR) as a measure of optimal productivity in the turning process was conducted with 125, 250, and 500-m/min cutting speeds; 0.1, 0.2, and 0.3-mm/rev feed rates; and 0.5, 1, and 1.5-mm depths of cut. Taguchi's L-9 Latin square orthogonal arrays were designed with the cutting variables. Turning operations were conducted on the XL 400 lathe with a 79.6-mm diameter and 200-mm-length solid cylindrical AISI 1029 steel rod using the array variables as inputs and MRR as the response variable. The input variables and the MRR values obtained from the experimental turning process were analyzed with the Minitab-17 software using generated signal-to-noise ratios, main effect plots, contour plots, surface plots, and analysis of variance by imbibing Taguchi's concept of "the larger, the better." Results obtained from all the analyses jointly showed that the cutting speed of 500 m/min, depth of cut of 1.5 mm, and feed rate of 0.3 mm/rev were turning conditions for optimal MRR in the turning operation. Analysis of variance of their collated data showed that feed rate had the highest contribution of 45.634%, followed by depth of cut with 23.0234%, and cutting speed with 22.0033% in the MRR. The confirmation test at optimal conditions indicated 225 cc/min MRR against the 222.41 cc/min value obtained from the Minitab-17 predictive regression equation. This put the experimental value in error by only 1.2%. The confirmation tests and percentage errors revealed the accuracy

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of the conducted turning experiments at a 95% confidence level.

Guma and Onoja [12] also noted that the AISI 1029 steel type is often used in the turning process to manufacture fasteners, studs, and other engineering components under the costly effects of high temperatures. Their paper exemplifies the use of Taguchi's optimization method in selecting cutting conditions and determining at which condition the optimal tool-workpiece interface temperature occurs in dry-turning the steel type on the lathe with a carbide-insert tool. Turning experiments were performed on an XL 400 lathe with the steel type in accordance with the L-9 Latin squares arrays designed with 0.5, 1, and 1.5 mm depths of cut; 0.1, 0.2, and 0.3 mm/rev-feed rates; and 125, 250, and 500 m/min cutting speeds as selected inputs and measured tool-workpiece interface temperatures as the outputs. The inputs and outputs were analyzed using the Minitab-17 software-generated signal-to-noise ratios, main effect plots, contour and surface plots, and variance analysis by imbibing Taguchi's philosophy of the smaller, the better. The result showed that the optimal interface temperature within the turning conditions was 29.5 ^{o}C at 125 m/min cutting speed, 0.1 mm/rev feed rate, and 1.5 mm depth of cut. The variance analysis at a 95% confidence level showed that the cutting speed contributed most to the temperature with an 88.15% value, followed by depth of cut with 5.33%, and feed rate with 33.33%. A validation test at the optimal cutting condition indicated 30.31 ^{o}C as the optimal interface temperature with an error of only 2.7% relative to the 29.5 ^{o}C value obtained with the software's predictive regression equation.

Zhujani et al. [49] asserted that to remain competitive, machining processes must be optimized to provide increased productivity and higher-quality products. The aim of most efforts in machining processes is to establish the optimal parameters to obtain the maximum material removal rate with minimum surface roughness, which represents two of the main quality responses. Their paper focuses on the optimization of process parameters in dry turning of Inconel 718, a nickel-based superalloy with PVD-coated carbide inserts based on the single-objective optimization using Taguchi technique and the desirability function approach combined with response surface methodology (RSM), which is known as the multi-objective Desirability Optimization Methodology (DOM). Taguchi's orthogonal-array design L9 (3^3) and analysis of variance (ANOVA) were used to study the relationship between cutting parameters (cutting speed, feed rate, and depth of cut) and the dependent output variables, i.e., the arithmetic mean deviation of the profile's surface roughness (Ra) and material removal rate (MRR). A regression analysis was used to develop a mathematical model based on the first-order model to predict the Ra and MRR models. Using multiple regression analysis, a first-order linear prediction model was obtained to find the correlation between surface roughness and MRR with independent variables. In the range of parameters investigated, the obtained mathematical models accurately represented the response index, and the results of the experiments demonstrate that the feed rate and the depth of cut are the most important factors influencing Ra and MRR, respectively in the dry turning of Inconel 718 with PVD-coated carbide inserts. Finally, confirmatory tests proved that

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Taguchi's method, the desirability function approach combined with linear regression models, was successful in optimizing turning parameters for minimum surface roughness and maximum MRR.

Elshaer et al. [50] noted that TC21 alloy is a high-strength titanium alloy that has been gaining attention in various industries for its excellent combination of strength, toughness, and corrosion resistance. Given that this alloy is a hard-to-cut material, their study aimed to optimize the process parameters of turning the alloy under different conditions, such as a received alloy and a heat-treated alloy. The L9 Taguchi approach-base orthogonal array was used to determine the optimum cutting parameters with the least number of experimental trials required. For the achievement of this target, three different cutting parameters were used in the experimental work; each cutting parameter had three levels. The cutting speeds were chosen as 120, 100, and 80 m/min. The feed rates' values were 0.15, 0.1, and 0.05 mm/rev, and the depth of cut values were 0.6, 0.4, and 0.2 mm. After applying three steps of heat treatment (the first step was by heating the sample to 920 °C for 1 h, then decreasing to 820 °C also for 1 h; the second step was cooling the sample to room temperature by water quenching (WQ); the third step was holding the sample at 600 °C for 4 h (the aging process). The results revealed that the triple heat treatment led to the change in the microstructure from (α + β) to (α + β) with secondary α platelets (α s) formed in the residual β matrix, leading to a decreased surface roughness of 56.25% and tool wear of 24.18%. It was found that the two most critical factors that affect the tool insert wear and surface roughness are the death of cut and cutting speed, which contribute 46.6% and 46.7% of the total, respectively. Feed rate, on the other hand, has the least importance, contributing 20.2% and 31.9%, respectively, to the parameters.

Patel et al. [51] noted that in the new era of manufacturing science, day by day, evaluation of machining processes occurs. To achieve a high level of surface finish is a very crucial part of all machining processes. Their paper was a literature review on parametric optimization of numerous machining processes such as drilling, reaming, milling, turning, etc. by use of the Taguchi method, Analysis of Variance (ANOVA), Response Surface Methodology (RSM), and others. An extensive literature survey on databases of Elsevier, Taylor & Francis, Springer, IOPscience, Emerald, etc. was used to investigate the importance of parametric optimization in machining processes. Various researchers' works were found on different parameters such as cutting speed, feed, and depth of cut with different types of materials to improve machining processes, essentially surface finish, or reduce surface roughness. From the review, they inferred that to improve machining processes or aspects of the surface finish, it is essential to develop a cost-effective method. The paper represents a review of various approaches to improve the machining processes, which will help the researchers/industrialists find out the new way of machining.

Zaidi et al. [52] affirmed that modern machining requires reductions in energy usage, surface roughness, and burr width to produce finished or near-finished parts. To ensure high surface quality in machining processes, it is crucial to minimize surface finish and minimize burr width, which are considered significant parameters as specific cutting energy. The

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objective of their study was to identify the optimal machining parameters for milling in order to minimize surface roughness, burr width, and specific cutting energy. To achieve this, their research investigated the impact of feed per tooth, cutting speed, depth of cut, and number of inserts on the responses across three intervals using the Taguchi L9 array. Observing the responses by varying these parameters underlined the need for Mult-objective optimization. Machining conditions of 0.14 mm/tooth f_z350 m/min *Vc,*and 2 mm *ap*Using 1 cutting insert (exp no. 9) was identified as the best machining run using grey relational analysis owing to its highest grey relational grade of 0.936. ANOVA examination identified cutting speed as the leading factor impacting the grey relational grade with a 31.07% contribution ratio, with the number of inserts, depth of cut, and feed per tooth also making notable contributions. They concluded that machining parameters identified through response surface optimization resulted in a 21.69% improvement in surface finish, a 11.39% reduction in specific energy consumption, and a 6.2% decrease in burr width on the down milling side, albeit with an increase of 9% in burr width on the up-milling side.

Mohanta et al. [53] asserted, “manufacturers are facing challenges in achieving high productivity and quality in manufacturing through machining. PVD-coated tools can control several machining challenges by enhancing the hardness and abrasion resistance of the cutting tool. These tools facilitate turning operations in terms of efficiency, accuracy, and productivity by extending cutting performance and tool life. Aluminum bronze, a copper alloy valued for its mechanical, thermal, corrosion, and wear-resistant properties, finds application in diverse industries such as aerospace, automobile, marine, and electrical engineering, as well as in the creation of sculptures, decorative elements, and thermal devices. However, machining aluminum bronze presents common challenges, including achieving a smooth surface finish and minimizing high cutting force due to its inherent strength and abrasiveness.” Their research was aimed at identifying the optimal levels of cutting velocity, feed, and depth of cut to minimize surface roughness and cutting force during dry turning of wear-resistant high-strength CuAl10Fe5Ni5-C. They utilized PVD AlTiN-coated tools, which offer many advantages over other tool types, and conducted experiments through Taguchi’s L27 OA (orthogonal array) of factors. The study results indicate that coated tools have superior performance in reducing surface roughness and cutting force, and when it comes to designing and optimizing experiments, integrating PCA with the Taguchi method is a potent strategy. Moreover, they observed that feed is the most influential factor affecting production responses.

Tamizharasan et al. [54] studied the effect of turning parameters on chip generation during machining aluminum composite in their work. Turning of Al-4%Cu-7.5% SiC composite material prepared through powder metallurgy procedure was chosen as the workpiece, machined using uncoated carbide insert TNMG 120404. Chips produced during machining were studied by measuring their thickness and were used along with uncut chip thickness to determine the chip thickness ratio. 99.85% pure aluminum was added with 4% volume fractions of copper and with silicon carbide particulates of 7.5%. To visualize the distribution of reinforcement phases in the matrix, a scanning

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electron microscope was used. Taguchi's methodology of design of experiments was adopted for designing a L_9 (Latin square) orthogonal array for experimental investigation, and from analysis of variance, cutting speed influenced the formation of chip by 64.13%, followed with depth of cut by 35.26%. A confirmation test accomplished with ideal conditions produced a better chip condition.

Shivade et al. [55] asserted that modern manufacturers, seeking to remain competitive in the market, rely on their manufacturing engineers and production personnel to quickly and effectively set up manufacturing processes for new products. Their paper presented the single-response optimization of turning parameters for turning on EN8 steel. Experiments were designed and conducted based on Taguchi's L9 orthogonal array design. Their paper discussed an investigation into the use of Taguchi parameter design to optimize the surface roughness and tool tip temperature in turning operations using a single-point carbide cutting tool. They employed Analysis of Variance (ANOVA) to analyze the influence of process parameters during turning. They obtained useful results of their research for other similar types of studies that can be helpful for further research works on the tool life.

Sumaila et al. [56] have reaffirmed that in machining operations, the quality of the surface finish is very important. Thus, the choice of optimum cutting parameters is necessary. Their study investigated the effects of some machining parameters in turning mild steel with a high-speed steel cutting tool. The objective of their study was to determine the optimum parameter levels that will give the lowest surface roughness using the Taguchi robust optimization technique. Three machining parameters, cutting speed, feed rate, and depth of cut, were each investigated at three levels. The Taguchi orthogonal array, signal-to-noise (S/N) ratio, and analysis of variance (ANOVA) were employed to investigate the effect of these machining parameters. From the ANOVA result, it was established that the cutting speed had the greatest influence on surface roughness with 66.6% significance, followed by feed rate with 22.32%, and depth of cut with 4.81%. From the S/N ratio, their investigation established that the optimum combination of cutting parameters to produce a high surface finish was 80-m/min cutting speed, 0.1-mm/rev feed rate, and 2.0-mm depth of cut of the orthogonal array.

Syed Mohd Fadly Bin Syed Hassan et al. [57] noted that "high-speed machining (HSM) in milling is one of the known technologies in rapid tooling and manufacturing applications. The cutting mechanism, spindle speed, and feed rate are not the same for HSM compared to traditional machining. Coated carbide cutting tools are widely used in high-speed and cutting temperature situations. It is more efficient and provides a lower surface roughness in HSM. Throughout these days, the demand for standard surface roughness is very high aligned to achieve quality in the product." Their paper demonstrated an optimization method of machining parameters in the milling process for high-speed machining of glass fiber reinforced polymer (GFRP) using a coated carbide cutting tool to achieve better surface roughness. They used and reported the Taguchi method as the best method to optimize a parameter where a response variable can be determined. A standard orthogonal array of L9 (3^2) was applied in their research using signal-to-noise (S/N) ratio

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response analysis from optimization process results and analysis of variance (ANOVA) to identify the most significant parameters affecting surface roughness. They reported that the common machining parameters that significantly affect surface roughness are spindle speed and feed rate, and executed conformation tests to analyze the optimization improvement. Their results showed that the feed rate parameter is significant for affecting the surface roughness and 93.3% improvement on the surface roughness performance of the milling process for glass fiber reinforced polymer (GFRP).

Ribeiro et al. [58] presented a study of the Taguchi design application to optimize surface quality in a CNC end milling operation. The study included feed per tooth, cutting speed, and radial depth of cut as control factors, use of an orthogonal array of L9, and carrying out the ANOVA analyses to identify the significant factors affecting the surface roughness. Optimal cutting combination was determined by seeking the best surface roughness (response) and signal-to-noise ratio. The study was carried out by machining a hardened steel block (steel 1.2738) with tungsten carbide-coated tools. Their results led to the minimum arithmetic mean surface roughness of 1.662 µm as the most influent radial depth of cut parameter, with 64%-contribution to the workpiece surface finishing.

Tayisepi et al. [59] noted that during metal machining, the satisfactoriness of cost-quality-time matrix convergence effectively depends on the supreme selection of cutting parameters. Their study investigated the energy use minimization and surface quality generation through optimized cutting parameters application as sustainability enhancement during dry turning of EN19 material. They contended that "cutting parameter optimization is a serious challenge confronting the machining industry as they strive to achieve low energy use and better component quality generation from their operations. The utility material, EN19, is a medium-carbon low alloy steel that typically gets applied in the manufacturing of multiple profiled cylindrical machine tools, rail locomotives, and motor vehicle component parts, inter alia." They used Taguchi full factorial experimental plan to organize the empirical experiments. ANOVA and the main effects plot signal-to-noise ratio optimization analysis were utilized in the study to establish the influence of process parameters on the response parameters—surface roughness and energy use. The aim of their study was to investigate and determine the correlation of the machining strategy parameters with the outcome of low energy use and quality surface texture of the components as the cutting parameters were varied and optimized for minimum surface roughness and energy use. Results of their extensive experimental study produced optimum cutting speed, rake angle variation, and feed rate, which respectively influence the response parameters positively for energy use minimization and improved surface quality. Validation experiments confirmed their model findings.

Samleti and Potdar [60] aimed their research work to utilize the Taguchi method to investigate the effects of drilling parameters such as spindle speed, feed rate, and drill diameter on surface roughness and material removal rate in drilling of grey cast iron using a solid carbide tool. They noted that the Taguchi method is a powerful tool to design optimization for quality and used it to find optimal cutting parameters and used orthogonal arrays, the signal-to-noise ratio, and

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the analysis of variance to analyze the effect of drilling parameters on the quality of drilled holes. Their number of experiments based on the L-9 orthogonal array was conducted using a CNC vertical machining center. A statistical software, Minitab18.1 was used to analyze experiment results. ANOVA was used to determine the most significant control factors affecting the surface roughness and material removal rate. The ANOVA showed that the drill diameter has a significant role to play in producing a higher material removal rate and lower surface roughness in drilling the cast iron. The optimum levels of various parameters obtained in their work for MRR were spindle speed of 800 rpm, feed rate of 90 mm/min, and drill diameter of 12.7 mm. The optimum levels of various parameters obtained in their work for surface roughness were spindle speed of 1000 rpm, feed rate of 70 mm/min, and drill diameter of 10 mm. In their research work, Sulaiman et al. [61] explained the application of dry machining as part of contributions for the development of a sustainable environment in the machining industry. They reported that "achieving a good surface roughness product is one of the most important factors that must be considered in the metal machining process. Surface quality control is a complicated process, and a reliable technique is required during machining operations. Currently, appropriate cutting conditions in most machining cases are determined by trial and error, which leads to time increased, energy consumption, and manufacturing costs. Most of the previous studies have investigated factors that affect surface roughness, but different machining conditions require the control of different factors." In their study, experiments were conducted to optimize cutting parameters and determine the factors significant for the surface roughness quality. Machining experiments were conducted on a vertical milling machine using a square non-coated two-flute HSS Co end mill with selected cutting parameters on aluminum 6061. Their study focused on the surface roughness in one direction and combined it with the Taguchi design method. Signal-to-noise (S/N) ratio and analysis of variance (ANOVA) were employed to examine and reveal the factors that are significant in affecting surface roughness quality. The analysis result revealed that cutting speed exerts the highest effect on surface roughness, followed by feed rate and depth of cut. They concluded the combination of dry machining performance and an eco-friendly environment would result in competitive, sustainable growth of the machining industry.

Soori and Asmael [62] asserted that the optimization process is applied to the machining operations in order to provide continual improvement in accuracy and quality of produced parts. The effects of machining parameters in milling operations, such as spindle speed, depth of cut, and feed rate, are investigated in order to minimize the surface roughness as well as the time of the machining process. The effective machining parameters, such as depth of cut, feed rate, and spindle speed, in turning operations are investigated to minimize the surface roughness as well as the time of the machining process. Also, machining parameters, such as peak current, gap voltage, duty cycle, and pulse on time in Electro Discharge Machining (EDM) operations, can be optimized in order to obtain the optimized material removal rate, tool wear, and surface roughness in the part production process. To

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improve material removal rate, surface roughness, and spark gap in the part production process using the wire EDM operations, machining parameters such as spark on time, spark off time, and input current are studied and optimized. To calculate optimized machining parameters, different optimization methods, such as the Taguchi method, fuzzy logic algorithm, artificial intelligence, genetic algorithm, artificial neural networks, artificial bee colony algorithm, ant colony optimization, and harmony search algorithm, are used. As a result, time and cost of accurate production can be reduced to increase productivity in part production processes using machining operations. In this paper, a review of machining parameter optimization is presented, and future research works are also suggested. The main aim of the study is to review the challenges and limitations of the optimization techniques used in optimizing machining parameters. It has been observed that the research field can be moved forward by reviewing and analyzing recent achievements in the published papers.

In their study, Akkuş and Yaka [63] machined AISI 1040 steel on CNC lathes using Taguchi L16 orthogonal array as an experimental design. Experiments were carried out with the three cutting parameters. These parameters were determined as feed rate, cutting speed, and cutting depth. The turning operation was carried out in dry conditions with diamond-cutting tools. At the end of experiments, the values of surface roughness (Rz) on samples were found. Signal/noise (S/N) rates were found using the Taguchi method. According to the results, feed rate had the most significant effect on Rz among three factors. In ANOVA analysis, respectively feed rate, cutting depth, and cutting speed are effective at 95% confidence level at Rz value. In repetition experiments carried out for parameters chosen in Taguchi prediction, it was identified that Taguchi works with nearly 94% accuracy.

According to Sureja et al. [64], the automotive and aerospace sectors have a strong demand for Nitinol alloy machined parts; therefore, optimizing machining parameters is essential to achieving better process performance results in terms of cost and product quality. In general, the process variables that influence machining include feed (f), depth of cut (t), and spindle speed (S). Material removal rate (MRR), tool wear (TW), and surface roughness (Ra) are pertinent output performance indicators. An analysis of variance was performed to assess the effect of process variables on the aforesaid output performance. It was found that feed has a significant effect on MRR and surface roughness with a contribution of 50.65 and 33.62%, respectively, whereas spindle speed has a major contribution on TW with a contribution of 51.9%. The study assessed how well the Nitinol 56 machining process works overall. In their work, the Taguchi method was used to determine the effect of the aforesaid process variables on the output performance indices. To satisfy previously stated conflicting performance indices, a variety of multi-attribute decision-making approaches were used, such as utility, TOPSIS, and grey, to determine the optimal process variables. The optimal process variable combination was achieved as f = 0.133 mm·rev^{-1}, d = 0.06, and S = 835 RPM. This combination was achieved using all methods.

Venkateswarlu and Devara [65] asserted that wire electro-discharge machining is one of the non-traditional machining processes used for

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machining complex-shape components and hard materials like composites and intermetallic materials. Their paper presents the optimization of wire electrical discharge machining (WEDM) process parameters such as pulse on time (T_{on}), pulse off time (Toff), and wire tension (WT) to yield maximum material removal rate (MRR) and minimum surface roughness (Ra) of copper. The machining experiments were carried out according to the Taguchi parametric design (L_9) using 0.25 mm diameter brass wire as a cutting tool. Analysis of variance (ANOVA) was used to find the significance of each process parameter. The optimal results were verified through confirmation experiments. In addition, the regression equations were also established between the process parameters and responses. The results indicate that pulse on time is the most significant factor influencing the MRR and Ra, followed by pulse off time and wire tension.

Yadav and Kumar [66] remarked that aluminum is the second most used metal after steel, largely because it is so versatile. It has been widely used in industries, aerospace industries, building and construction industries, packaging industries, etc. Machining is the removal of metal in the form of chips to produce a workpiece. The quality of machining is generally specified by surface roughness. The lower the value of surface roughness, the higher will be the quality. The optimization of input parameters was conducted for improvement of quality of the product of the milling operation on the CNC machine. Feed rate, spindle speed, and depth of cut were taken as the input parameters, and the surface roughness was taken as the output parameter. In the reduction of performance characteristics and quality measures, Taguchi's approach is very useful in the design of experiments. In their present work, an L9 array was used in the design of the experiment for optimization of input parameters. Their study attempted to introduce and thus verify experimentally as to how the Taguchi parameter design could be used in identifying the significant processing parameters and optimizing the surface roughness of the milling operation.

Şahin et al. [67] investigated the machinability of boron alloy steel by electrical discharge machining (EDM) method using Taguchi L27 vertical knee test set in the experimental study. Discharge current, pulse on time, and pulse of time were selected as processing parameters. As a result of the experiments, average surface roughness, material removal rate, and electrode wear rate values were investigated. The Taguchi method was used to decide on the optimal machining parameters. The effect of control factors on experimental results was calculated using analysis of variance. In the results of the experimental studies, the discharge current was found to be the most effective parameter on the electrode wear rate (EWR), average surface roughness (Ra), and material removal rate (MRR). It has been shown that increasing the discharge current (I) value will have a negative effect on Ra. The factors affecting the average surface roughness after calculation are 86.51% discharge current, 6.17% pulse on time, and 0.2% pulse off time. It was concluded that the effects of the impact time and the impact waiting time on the average surface roughness were insignificant. For MRR, the discharge current was 75.56%, the pulse on time was 9.54%, and the pulse off time was 2.03%. For EWR, the discharge current was 52.87%, toff with 6.25%, and ton with 3.25%.

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Patil et al. [68] studied different review papers with different input and output parameters so as to conclude which input parameter is most beneficial for their particular output parameter. They observed that nowadays the most important process is turning for the manufacturing industry. It helps to increase production rate with high quality. In CNC turning operations, the surface roughness (SR), material removal rate (MRR), power consumption, nose radius, etc. are the output parameters. To evaluate process parameters, surface roughness and material removal rate are too important. There are some process parameters for turning purposes that are more important and considered as input parameters to measure SR and MRR. The input parameters are cutting speed, feed, and depth of cut.

Asavarutpokin et al. [69] aimed to study the effects of cutting conditions on power consumption and surface quality in the tuning process on mild steel S50C. The machine used in the study was a CNC turning and carbide cutting tool. The optimized process parameters by means of the utility concept and Taguchi technique were applied to identify the machinability and energy efficiency. The three types of process parameters with five different levels, including cutting speed, feed rate, and depth of cut, were used in the work. The selection of these parameters was based on a literature review and tool manufacturing recommendations. The Taguchi orthogonal array $L_{25}(5^3)$ was used for conducting the experiments. The results show that the most significant factor for power consumption is depth of cut (60.58%), followed by feed rate (30.27%) and cutting speed (4.36%). For surface roughness, the most significant factor is feed rate (98.49%), followed by depth of cut (0.99%), and cutting speed (0.02%). Nevertheless, the minimum power consumption of the machine condition is in contrast to the surface roughness quality. Therefore, this technique can be applied for production planning to control the product quality and machining cost.

In their review paper, Mohan et al [70] explored systematic optimization of surface roughness and material removal rate (MRR) in the CNC turning process of Al5083/SiCp composite material using the Taguchi Method. The study critically examines relevant literature to provide a comprehensive overview of the key factors influencing surface quality and machining efficiency in this specific machining operation. Various parameters such as cutting speed, feed rate, depth of cut, and tool geometry were analyzed in the context of their impact on surface roughness and MRR. The Taguchi Method, known for its efficiency in experimental design and optimization, was highlighted as a valuable approach to systematically enhance CNC turning processes for Al5083/SiCp. The review identifies trends, challenges, and gaps in existing research, offering insights into potential avenues for future investigations to further refine and optimize the machining parameters for improved surface quality and enhanced material removal rates in CNC turning of Al5083/SiCp composites.

2. MATERIALS AND METHODS

2.1 Material

2.1.1 AISI 1029 steel

The AISI 1029 steel was procured in rod form of diameter 79.6mm and length 2m from a commercial dealer named Hartzog Nig. limited at Kakuri business area in Kaduna metropolis for the experiments.

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2.2Methods

2.2.1 Confirmation of the procured AISI 1029 steel

The basic physical properties of the AISI 1029 steel type at about 25-35^{o}C room temperature are 7850-kg/m^{3} density, 992.85-MPa ultimate tensile strength (UTS), 579.16-MPa yield strength at 0.2%-offset, 145-Brinell Hardness Number (BHN), 190 to 210-GPa Young's modulus, 0.27 to 0.3-Poisson ratio, and 44-% elongation [11, 21]. The nominal composition of the procured AISI 1029 steel rod was determined using the handheld S1 TITAN 500 alloy analysers. The composition showed that the steel rod contained 0.30%-C, 0.10%-Si, 0.790%-Mn, 0.040%-P, 0.050%S, and 98.72%-Fe by nominal compositions. Comparison of the compositions with the AISI standard specifications of 0.25 to 0.31%-C, 0.07-0.6%-Si, 0.6-0.9%-Mn, 0.0-0.040%-P, 0.0-0.050%S, and 98.7-99.15%-Fe for the steel type confirmed the procured steel as AISI 1029 carbon steel type [11, 12, 29].

2.2.2 Experimental design

Three machining input variables of cutting speed, feed rate, and depth of cut were chosen with each variable designed to have three levels; denoted as L1, L2, and L3 as shown in Table 1. Surface roughness was chosen as the response factor. The experimental design was according to the L9 orthogonal array based on Taguchi's optimization method. The Taguchi orthogonal array provided the number of experiments to be carried out. A set of experiments based on the Taguchi's optimization method was conducted to investigate the relationship between the orthogonal turning parameters of the 1029 steel and the response factors

Table 1: Machining Variables and Levels

	Levels		
Variables	L1	L2	L3
Cutting Speed (m/min)	125	250	500
Feed Rate (mm/rev)	0.1	0.2	0.3
Depth of Cut (mm)	0.5	1.0	1.5

Table 2: Coded and actual process design variables using Taguchi's L9 design with 3 levels and the 3 factors

Coded process variable	Actual process variable					
Experiment No	Cutting speed (mm/min)	Feed rate (mm/rev)	Depth of cut (mm)	Cutting speed (m/min)	Feed rate (mm/rev)	Depth of cut (mm)
1	1	1	1	250	0.1	0.5
2	1	2	2	125	0.2	1.0
3	1	3	3	125	0.3	1.5
4	2	1	2	250	0.1	1.0
5	2	2	3	250	0.2	1.5
6	2	3	1	250	0.3	0.5
7	3	1	3	500	0.1	1.5
8	3	2	1	500	0.2	0.5
9	3	3	2	500	0.3	1.0

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2.2.3 The turning experimentation

The experimental turning operations were conducted with facilities in the production workshop of the Department of Mechanical Engineering, Nigerian Defence Academy, Kaduna, Nigeria. Nine turning test operations were conducted under dry conditions on the XL 400 lathe machine using a solid cylindrical AISI-1029 steel work-piece of diameter 79.6 mm and length 208 mm, and the grade 25 single point cutting tool in each case. The work-pieces were mechanically sawn out from the parent procured AISI 1029 steel rod. Separate work-pieces were used for different sets of cutting conditions. The cutting tool used had four cutting insert edges, an inscribed circle diameter of 12.7 mm, an effective cutting-edge length of 12.7 mm, a corner radius of 0.794 mm, an insert thickness of 4.763 mm, and a 0-degree clearance angle. The inserts used were of CNMG 12 04 08-QM 425 standard specifications. For each set of cutting conditions, one end of the workpiece was rigidly held in the lathe's chuck and its other end was supported by the lathe's tail stock. The cutting tool was rigidly mounted in position on the lathe's tool holder and cutting speed, feed rate, and depth of cut were selected and used according to the experimental design with Taguchi's L-9 orthogonal arrays shown in Table 3. For each turning experiment, the lathe machine was switched on and the work-piece was first faced at both ends to make its length accurate to 200 mm. In each experimental case, the turned length of the work-piece was 140 mm. Also, one insert cutting edge was used for each set of turning experiments, and the inserts were replaced with new ones after all four insert edges of the tool had been used. The cutting speed was determined in accordance with equation 1, given as [71, 72],

$$v = \frac{\pi D N}{1000} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (1)$$

Where, D = diameter of the work-piece in millimetres (79.6mm), and N = the selected spindle speed in revolutions per minute (rpm). Spindle speeds of 500, 1000, and 2000 rpm were used to provide low, middle, and high cutting speeds of 125, 250, and 500 m/min respectively for the turning operations on the lathe. Plate I shows an instance of a turning experiment in the workshop. In each experiment, the surface roughness of the turned work-piece was measured in microns (μm) using the CVR-135 surface roughness analyzer. The analyzer had a measuring range of 0.03μm to 6.35μm. Surface roughness measurements were obtained for each set of experiment in terms of R_a values at three different points of the turned work-piece and average value of the three R_a values were tabulated as SR. Plate I shows a view of a turned work-piece in an experimental process while Plate II shows the process of measuring the R_a values with the CVR-135 surface roughness analyzer in an experimental process and Plate III shows the front view of the CVR-135 analyzer used for the measurements.

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Plate I: A view of turned work-piece in the experimental processes


Plate II: The process of measuring surface roughness of turned work piece in an experiment


Plate III: Front view of the CVR-135 surface roughness analyzer used for the measurements

The Minitab-17 software was used to analyze Signal-to-Noise ratios of the collated input cutting variables and the response surface roughness values (SRs). The Minitab-17 generated Signal-to-Noise ratio alongside main effect plots, contour plots, surface plots, and analysis of variance that were analysed by imbibing Taguchi's concept of the 'Smaller-the-Better' according to equation 2 [24].

$$\frac{S}{N} = -10\,\mathrm{og}_{10}\left[\frac{1}{n}\sum y^2\right] \qquad (2)$$

Where, y was the measured value of surface roughness and n was the number of measurements.

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The relative importance of each turning variable was also provided in the order of its percentage contribution to the turning process by analysis of variance (ANOVA) using the Minitab-17 software at a level of significance α = 0.05 or 95% confidence level. After data analysis to determine cutting condition for optimum surface roughness (SR), a confirmation experiment was carried out using the set of cutting variables that yielded SR as obtained from the analyses. The optimum result obtained from the Minitab-17 generated regression equation was then compared with the results obtained from the confirmation experiment.

3. RESULTS AND DISCUSSION

3.1 Results

Results of the experimentally measured R_a surface roughness values named SR1, SR2 and SR3 at three different points of the turned work-pieces and the corresponding average values of the three (SRs) under various specified conditions of cutting speed, depth of cut, and feed rate are shown in Table 3. The obtained Signal-to-Noise ratio results for the surface roughness responses with the Minitab-17 statistical software is presented in Table 4. The obtained main effect plots for surface roughness under different cutting conditions with Signal-to-Noise ratio values using the Minitab-17 software are depicted in Fig 1.The generated contour plots of surface roughness for cutting speed (m/min) and feed rate (mm/rev) variations, cutting speed (m/min) and depth of cut (mm) variations, and depth of cut (mm) and feed rate (mm/rev) variations using the Minitab-17 software are presented in Figs. 2, 3, and 4 respectively. The produced surface plots for surface roughness due to variations in cutting speed and feed rate, cutting speed and depth of cut, and feed rate and depth with the Minitab-17 software are presented in Figs. 5, 6, and 7 respectively. ANOVA of results for the surface roughness and percentage contribution of the cutting speed, feed rate and depth of cut to surface roughness in the experimental turning operations as obtained with the Minitab-17 software is presented in Table 5. The confirmation test result for the surface analysis is shown in Table 6.

Table 3: Obtained surface roughness for various cutting conditions in the turning experiments

Run	Cutting speed (m/min)	Feed rate (mm/rev)	Depth of cut (mm)	R_a surface roughness (μm)			
				SR1	SR2	SR3	Average (SR)
1	125	0.1	0.5	3.68	3.09	3.37	3.38
2	125	0.2	1.0	4.30	3.80	5.20	4.40
3	125	0.3	1.5	6.03	6.00	6.00	6.01
4	250	0.1	1.0	2.36	3.04	4.20	3.14
5	250	0.2	1.5	3.42	4.20	5.10	4.21
6	250	0.3	0.5	6.13	6.20	6.30	6.21
7	500	0.1	1.5	2.88	2.87	2.89	2.88
8	500	0.2	0.5	4.06	4.03	4.00	4.03
9	500	0.3	1.0	6.30	6.28	6.29	6.29

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Table 4: Signal to Noise ratio from the measured surface roughness

Run	Surface roughness(μm)	Signal-to-Noise Ratio
1	3.38	-10.5783
2	4.40	-12.8691
3	6.01	-15.5775
4	3.14	-9.9386
5	4.21	-12.4856
6	6.21	-15.8618
7	2.88	-9.1878
8	4.03	-12.1061
9	6.29	-16.4825

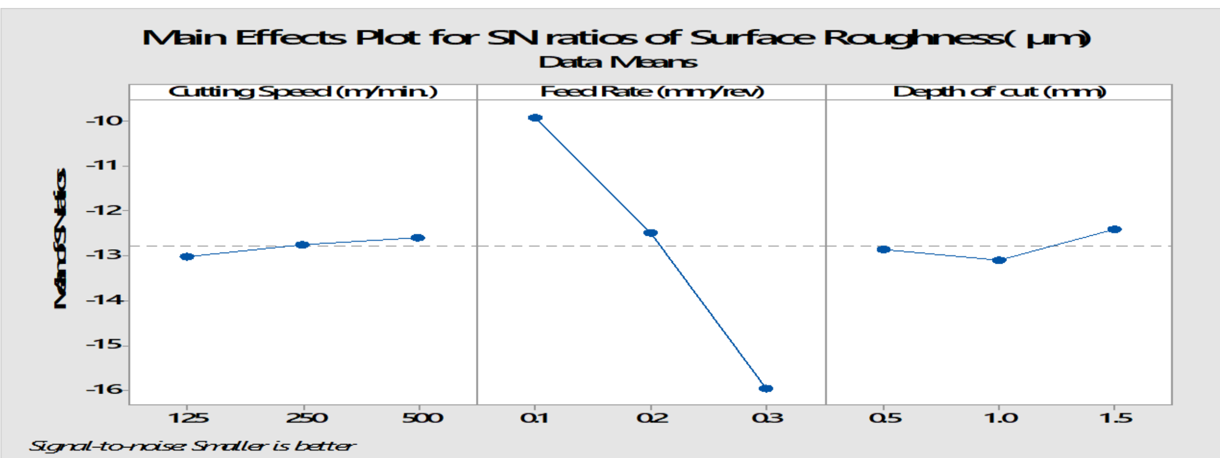

Fig 1: The obtained main effect plot for surface roughness under different cutting conditions of cutting speed, feed rate, and depth of cut

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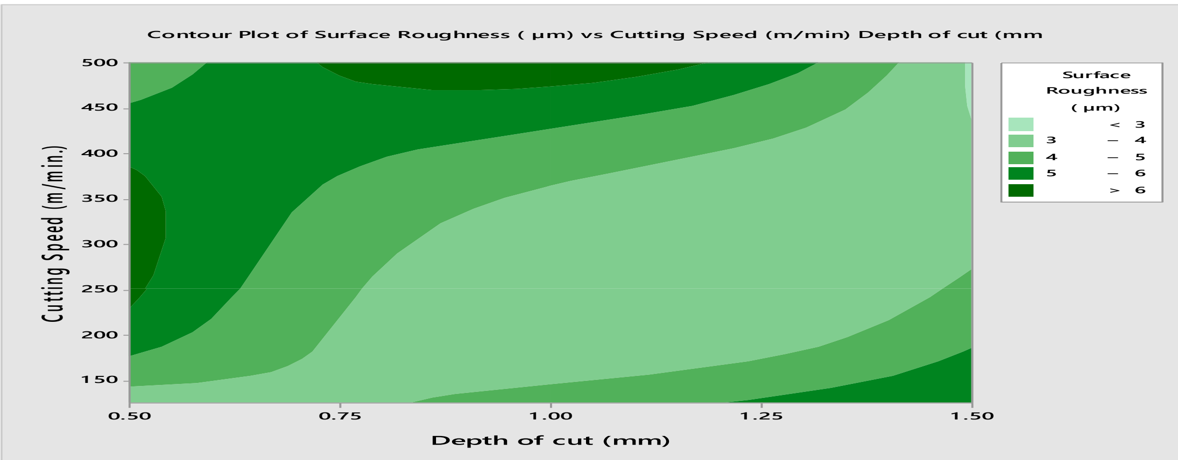

Fig. 2: The obtained contour plot of surface roughness (µm) by varying cutting speed (m/min) and depth of cut (mm)

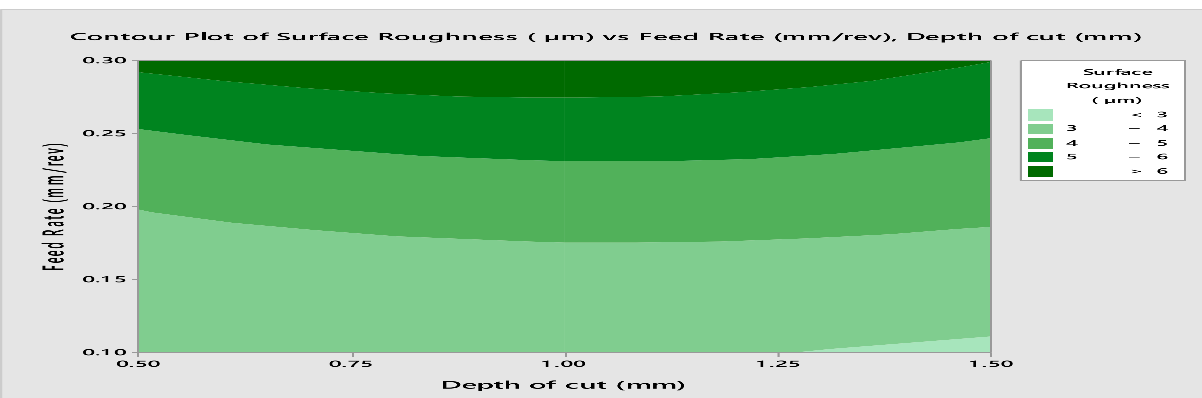

Fig. 3: The obtained contour plot of surface roughness (µm) by varying feed rate (mm/rev) and depth of cut (mm)

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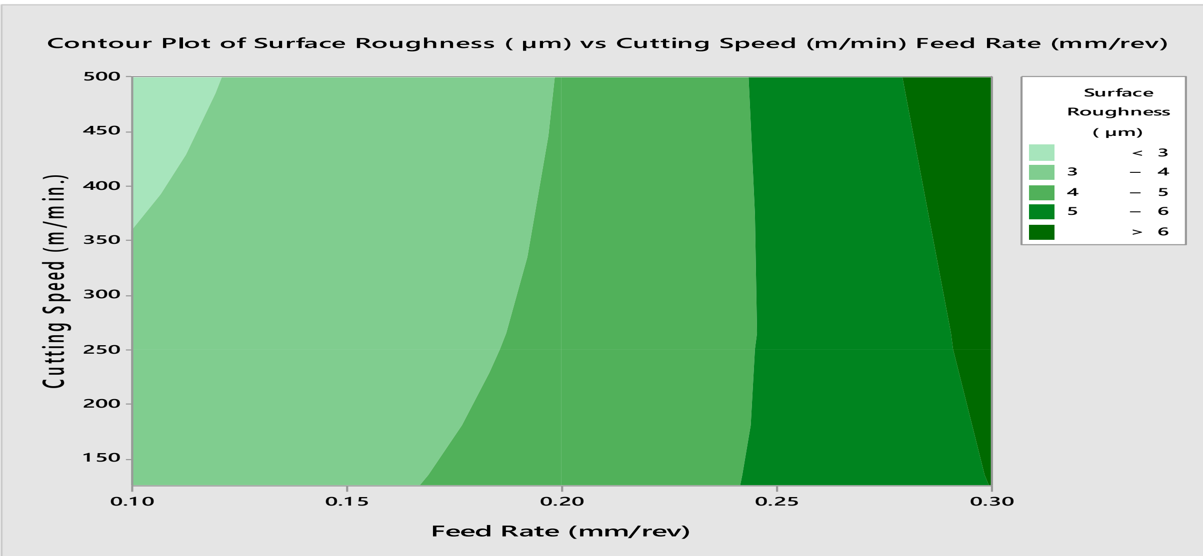

Fig. 4: The obtained contour plot of surface roughness (μm) by varying cutting speed (m/min) and feed rate (mm/rev)

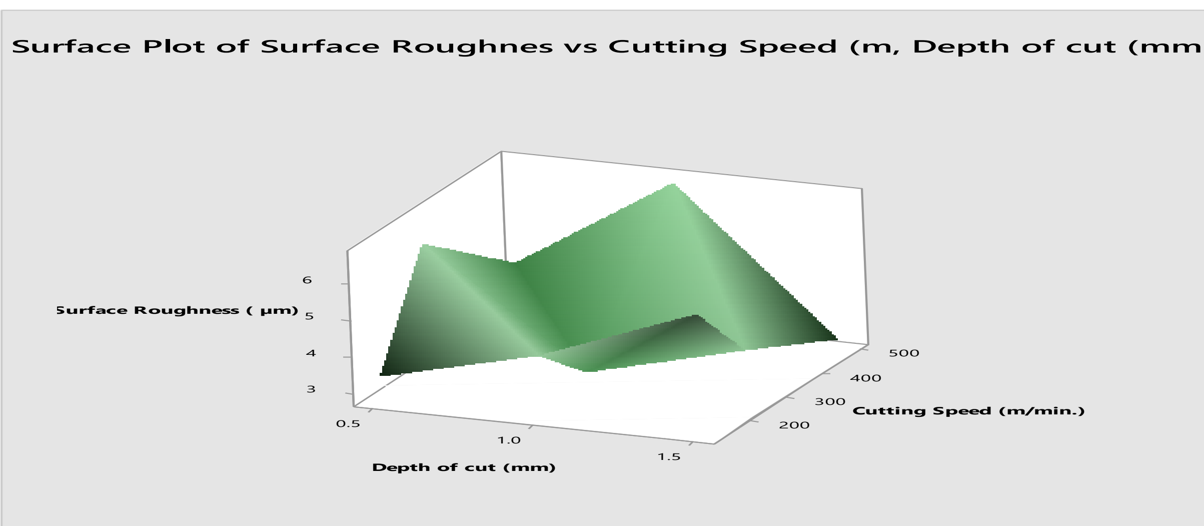

Fig. 5: The obtained surface plot of surface roughness by varying cutting speed (m/min) and depth of cut (mm)

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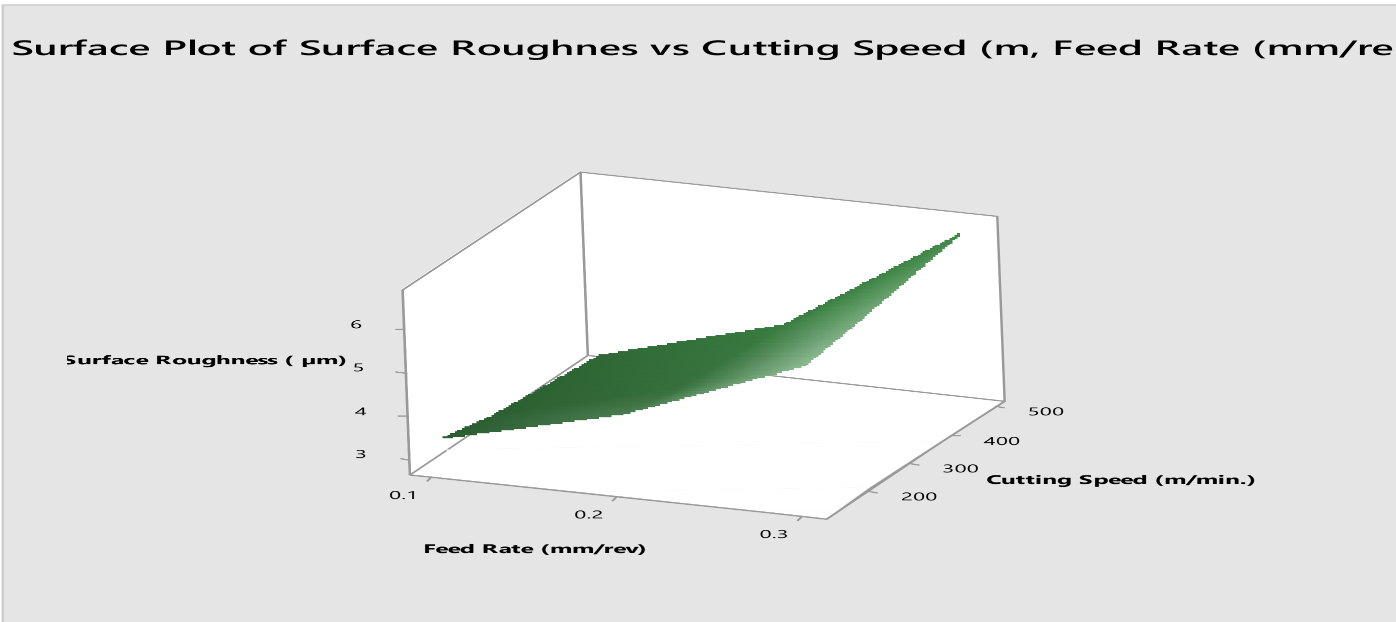

Fig. 6: The obtained surface plot of surface roughness by varying cutting speed (m/min) and feed rate (mm/rev)

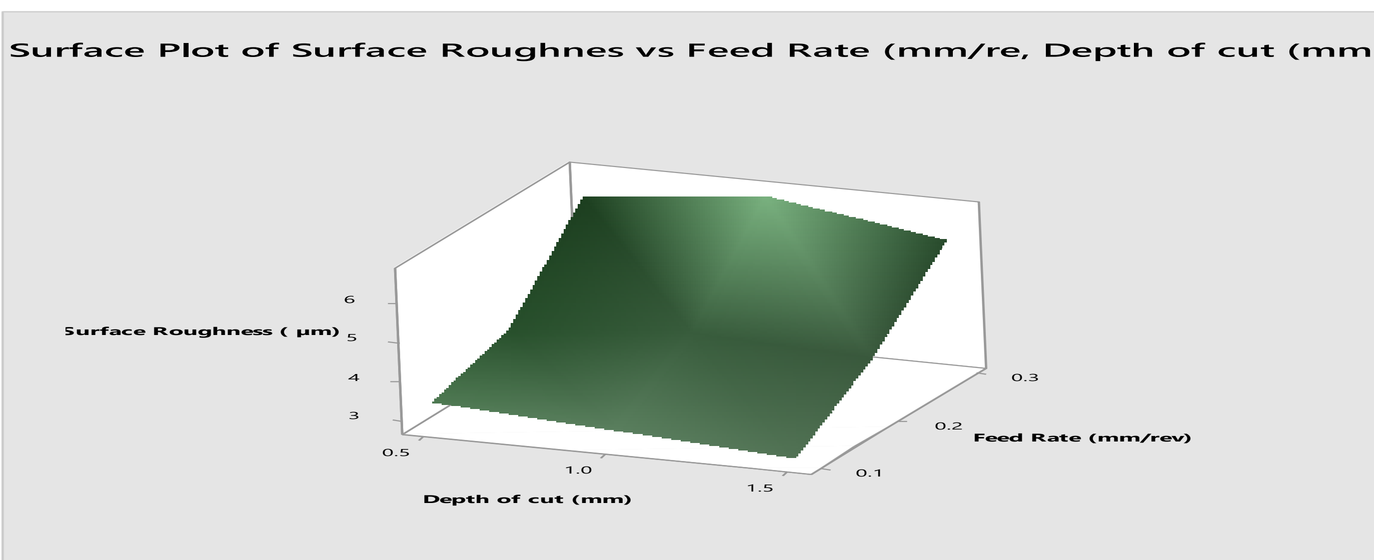

Fig. 7: The obtained surface plot of surface roughness by varying feed rate (mm/rev) and depth of cut (mm)

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Table 5 ANOVA for the surface roughness at 95% confidence level

Factor	DOF	SS	MS	F	P
Cutting speed	2	0.0053	0.0053	0.03	8.86
Feed rate	2	15.0100	15.0100	85.72	61.78
Depth of cut	2	0.0451	0.0451	0.26	26.22
Error	2	0.8755	0.1751	0.00	3.14
Total	8	15.9360	15.2355	0.00	100

Table 6: Confirmation test

Parameter	Estimated value	Experimental Value	Percentage error (%)
Surface roughness (μm)	2.15	2.20	2.3

3.2 Discussion

It can be seen from results presented in Table 3 that the experimentally measured average surface roughness of the turned AISI 1029 steel rods varied in values with Taguchi's orthogonal arrays from 2.88 to 6.29 μm. From the results of the generated signal-to-noise ratios for the experimental runs presented in Table 4, the signal-to-noise ratio value corresponding to Taguchi's concept of the smaller the better is -9.1878. The corresponding orthogonal array of cutting conditions that yielded the smaller-the-better signal-to-noise ratio and hence optimal surface roughness is at experimental run 7 with 500 m/min cutting speed, 0.1 mm/rev feed rate, and 1.5 mm depth of cut, as can be observed from Table 4.

From the main effects results depicted in Fig. 1, it is observable that the signal-to-noise ratios of the produced surface roughness in the turning operations varied at the highest rate from about -10 to -16 with 0.1 to 0.3 mm/rev feed rate variation, respectively, followed by about -12.6 to -13.0 with 0.5 to 1.5 mm depth of cut variation, respectively, and about -12.85 to -13.3 changes in cutting speed from 125 m/s to 500 m/s, respectively. In the case of feed rate variation, the signal-to-noise ratio is highest at the 0.3-mm feed rate and least at the 0.1-mm feed rate. Whereas in the case of depth of cut variation, the signal-to-noise ratio is highest at the 1 mm depth of cut and least at the 1.5 mm depth of cut; and highest at the 125 m/min cutting speed and least at the 500 m/min cutting speed in case of cutting speed variation. These show that feed rate had the greatest effects on the surface roughness of products in the turning operations, and the cutting speed had the least effects. On the basis of Taguchi's concept of the smaller-the-better, product surface roughness in the turning operations was optimal when signal-to-noise ratios due to cutting speed, feed rate, and depth of cut variations were each minimum. These minimum Signal-to-Noise ratios were about -12.85 at 500-m/min cutting speed for cutting speed variation, -10 at 0.1-mm/rev feed rate for

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feed rate variation, and about -12.6 at 1.5-mm depth of cut for depth of cut variation, as can be observed from Fig. 1. The analysis from the signal-to-noise ratio results presented in Table 4 is also upheld by the analysis of the main effects plots shown in Fig. 1.

The predictive empirical regression equation of Ra average surface roughness in the turning operations as obtained with the Minitab-17 software is given by equation 3.

$$Ra = 1.603 - 0.00156CS + 15.82FR - 0.173DC \quad (3)$$

Where; CS = cutting speed, FR = feed rate, and DC = depth of cut.

Substituting the values of the 500-m/min cutting speed, 0.1-mm/rev feed rate, and 1.5-mm depth of cut obtained for optimal surface roughness into equation 3; we obtained the predictive optimal value of surface roughness in the turning operation as;

Ra =1.603 – 0.00156(500) + 15.827(0.1) – 0.173(1.5) =2.15 µm

From the surface roughness contour plot shown in Fig. 2 shows the surface roughness contour plot for cutting speed and depth of cut variation. As can be observed from Fig. 2, there are colour matchings from the faintest green for surface roughness of less than 3µm to the deepest green colour for surface roughness of less than it is observable that the least product surface roughness in the turning operations was less than 3 µm as the depth of cut varied from 0.5 to 1.5 mm and cutting speed varied from 125 to 500 mm/min. Fig. 3 also shows that the least product surface roughness in the turning operations was less than 3µm as the depth of cut varied from about 0.5 to 1.50mm and feed rate varied from 0.10 to 0.2 mm/rev. Furthermore, the least product surface roughness was also less than 3µm in the turning operations as the feed rate varied from 0.1 to about 0.12 and cutting speed varied from about 350 to 500 m/min, as can be observed from the contour plot shown in Fig. 4.

From the surface plot results depicted in Fig. 5, the peak of the plot corresponds to the highest surface roughness value and its lowest depression corresponds to the lowest surface roughness value in the turning operations. A combination of 0.1-mm/rev feed rate and 500-m/min cutting speed gives the lowest surface roughness value as can also be observed from Fig 5. In the same way, the observed cutting conditions for lowest surface roughness value in the turning operations according to the contour plot shown in Fig. 6 are 500-m/min cutting speed and 1.5-mm depth of cut. On the other hand, the contour plot depicted in Fig.7 shows that the lowest point on the plot which corresponds the lowest surface roughness value is at 1.5-mm depth of cut and 0.1-mm/rev feed rate. This analysis also upholds conclusions from the foregoing analyses

From the ANOVA of surface roughness in the turning operations presented in Table 5, it is clear that the feed rate had the highest effect on surface roughness. At 95% confidence level of ANOVA; the percentage contributions of cutting speed, feed rate, and depth of cut to surface roughness in the turning operations were 8.865%, 61.78% and 26.22% respectively. These findings from the ANOVA are in perfect agreement with the analysis of Signal-to-Noise ratio results presented in Table 4 and analysis of main effects plots shown in Fig. 1.

From the conducted confirmation test result shown in Table 6, an experimental confirmation optimal surface roughness value of 2.20 µm was recorded against the Minitab-17 predicted

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regression value of 2.15 µm as can be observed from Table 6. The determined percentage error in the experimental surface roughness was 2.3% as can also be seen from Table 6. From that the reviewed literatures in section 1.2, it can be observed that the obtained optimal result values from the study follow a comparable pattern with many other results from the works of [11, 12, 26-70] in which Taguchi's method has been applied in the last two decades to find optimal solutions to several complicated experimental and practical problems in all areas of science and engineering, especially metal cutting. The optimal result values obtained in this work are however distinct for the dry-turning operation with the AISI 1029 steel on the lathe machine, using the carbide-insert tool.

4. CONCLUSION

A literature review indicates several applications of Taguchi's method in the last two decades to find optimal solutions to many complicated experimental and practical problems in all areas of science and engineering, including metal cutting. The method has systematically been applied to investigate the optimization of product surface roughness in the dry-turning of AISI 1029 steel with carbide insert tools on the lathe machine, a commonly used machining operation for producing fasteners and many other types of engineering-serviceable parts of vast importance with minimal surface roughness. Taguchi's L-9 Latin squares orthogonal arrays of cutting variables formed with 125, 250, and 500-m/min cutting speeds; 0.1, 0.2, and 0.3-mm/rev feed rates; and 0.5, 1.0, and 1.5-mm depths of cut have been used to conduct the optimization investigation. Results show that within the ranges of the cutting variables, the 500-m/min cutting speed, 0.1-mm/rev feed rate, and 1.5-mm depth of cut would yield optimal surface roughness of the steel products in the turning operations. Analysis of variance at 95% confidence level indicates that feed rate has the greatest contribution of 61.78% to surface roughness, followed by depth of cut with 26.22% and cutting speed with 8.865% in the turning operations. The confirmation test at the optimal cutting conditions of the turning operations indicated a 2.20-µm optimal surface roughness against the 2.15-µm value obtained from the Minitab-17 predictive regression equation. This indicated that at the 95% confidence level, the experimental value was in error by only 2.3% against the predictive regression equation value. The specified values of the cutting variables are therefore recommended to be used for optimizing the surface roughness of the steel components in the dry-turning operation on the lathe machine. The work exemplifies the use of Taguchi's method to optimize the surface roughness of the steel components with various other selectable sets of cutting conditions for dry-turning of the steel on the lathe machine with carbide insert tools.

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