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Original Article

Optimization of CNC Machining Parameters for Improved Surface Finish

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ABSTRACT
Surface finish Surface finish is one of the most important quality traits in Computer Numerical Control (CNC) machining, which has a direct effect on functional performance, fatigue life, corrosion resistance and aesthetic values of machined parts. In current manufacturing businesses like aerospace, automobile, biomedical and precision engineering, getting high-quality surface finish without compromising productivity and cost is still a significant challenge. Many process parameters such as cutting speed, feed rate, depth of cut, tool geometry, and coolant conditions have a very strong influence on the performance of CNC machining. Unacceptable selection of these parameters usually results in low surface integrity, more wear on the tools and unnecessary machining time. In this paper, the work will provide an in-depth research on how CNC machining parameters can be optimized in order to enhance the level of surface finish. Some of the classical and modern methods of optimization reviewed by the study are the Taguchi method, Response Surface Methodology (RSM), Grey Relational Analysis (GRA), Genetic Algorithms (GA), and the combination of artificial intelligence (hybrid). The experimental methodology is offered, the parameters of which are designed, it is machined, measurement of surface roughness is conducted, and statistical analysis through the analysis of variance (ANOVA). Mathematical models that relate machining parameters and the surface roughness are elaborated and optimization strategies dwelled on. The findings show that the most controlling parameter that influences the roughness of the surface is the feed rate, the next is cutting speed and depth of cut. The parameter combinations which are optimized have a lot of reduction in surface roughness than conventional settings do. The results can be useful to manufacturing engineers and researchers who aim to promote the quality of surfaces, productivity, and sustainability of CNC machining processes.

KEYWORDS
CNC Machining, Surface Roughness, Process Optimization, Taguchi Method, ANOVA, Machining Parameters.

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1. INTRODUCTION

1.1. Background

The Computer Numerical Control (CNC) machining has gained prominence in contemporary manufacturing because it is capable of providing the sought after high degree of precision, repeatability and automation in the provision of material removal processes. The CNC machines use programmed instructions and sophisticated manipulation systems, which result in repeated manufacturing of complicated components with high-dimensional control limits. They are widely utilized in turning, milling, drilling and grinding in various industries like the automotive industry, aerospace industry, medical devices and tool manufacturing. CNC machining is also suitable in both mass production and customized production processes because of the flexibility of the machining process which enables the rapid change in both design and process parameters. Nevertheless, the desired surface finish is still a major challenge in CNC machining especially when handling hard to cut materials, high strength alloys or materials of complex geometry. Surface finish is an aspect of machining which has a direct impact on the functional behavior of the machined component, including the properties of friction, wear resistance, fatigue life and corrosion behavior. The lack of surface quality may contribute to the higher number of assembly problems, shorter life of components and the higher manufacturer costs because of rework or rejection. Surface finish is usually assessed on standard roughness parameters such as arithmetic average roughness (Ra), root mean square roughness (Rq) and maximum height of peak-to-valley (Rz). The most common of these is the parameter that is used in the most common industrial practice due to its simplicity, ease of measurement, and ability to characterize overall surface texture, namely Ra. It gives a consistent reference point on the comparison of machining conditions and evaluation of surface quality. As a result, it is crucial to define and manage the factors that can determine the surface roughness, especially by optimizing CNC machining conditions, in order to obtain the high-quality and low-cost manufacturing results.

1.2. Importance of Optimization of CNC Machining Parameters

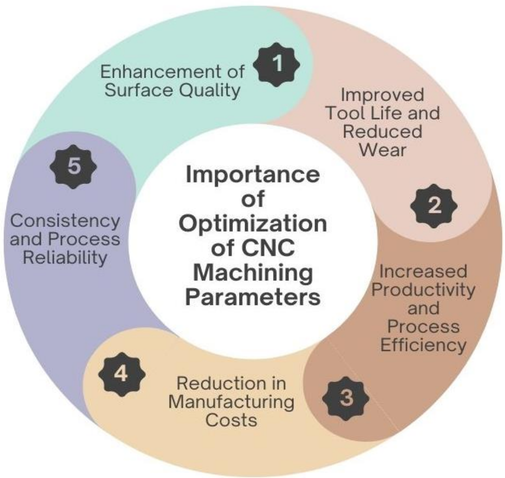

Fig 1 - Importance of Optimization of CNC Machining Parameters

1.2.1. Enhancement of Surface Quality

CNC machining parameter optimization is important in realizing an excellent surface finish which is one of the most demanded traits in the high-precision manufacturing. Adequate choice of parameters including cutting speed, feed rate, and depth of cut reduces the amount of surface irregularity, tool mark and defects on the machined surface. The added value in terms of surface

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quality is also experienced in functional performance through lowering friction and wear, raising the level of fatigue strength and tying to the appearance of parts, particularly in aerospace, automotive and medical manufacturing sectors.

1.2.2. Improved Tool Life and Reduced Wear

Optimized machining is useful in management of cutting forces and temperatures of the tool workpiece interface leading to minimization of the tool wear as well as premature tool failure. High cutting speed/feed rate may result in high tool degradation whereas poor parameters may cause accretion of edges and unbalanced loading of the tool. Optimization of parameters assures optimized usage of the tools and accordingly scales up the lifespan of the tools and also minimizes the costs of the tool which is a big portion of the total manufacturing cost.

1.2.3. Increased Productivity and Process Efficiency

Higher machining speeds through material removal optimization allows the manufacturer to have rates that are higher without lowering the quality of the surfaces or the life of the tools. This results to a shorter machining time, better utilization of the machines and greater production throughput. Modern manufacturing environments require efficient machining procedures to ensure punctual production schedules and be competitive.

1.2.4. Reduction in Manufacturing Costs

The optimization decreases the chances of rework, scrap, and component rejection due to inappropriate surface finish or dimensional errors. The minimization of the tool replacement frequency and minimization of energy consumption contribute to cost savings further. Consequently, CNC machining activities are optimized, which results in the more economical and sustainable production processes.

1.2.5. Consistency and Process Reliability

Optimized machining parameters guarantee uniform quality throughout production batches because the machining process is reduced to a minimum variance. It is a requirement in mass production and quality control, and in this respect, manufacturers can easily satisfy a high demand of the industry and consumers.

1.3. Parameters for Improved Surface Finish

Mechanics governing the process of attaining improved surface finish in CNC machining vary greatly depending on the careful choice and regulation of machining parameters since they directly relate to the machining operation. Cutting speed, feed rate and depth of cut are some of the most important parameters where the roughness of surfaces is concerned according to the various parameters. Speed of cutting affects the chip shape and temperature over the cutting area with the increase in cutting speed tending to produce smoother surfaces as the edge formation on the building up edge is reduced and the cutting action tends to remain constant. Nevertheless, high speeds may overload tool wear and thermal damages that may have a negative impact on the quality of the surface. As such, the cutting speed should be chosen in such a way that the balance between the surface finish and the tool life is achieved. The most commonly known parameter that controls the roughness of the surface is the feed rate. It directly controls tool marks distance and height that are left on the machined part. Reduced feed rates also result in finer tool cuts that leave surfaces smooth enough to be finished. Unlike this, high feed rates enhance productivity but usually lead to surface roughness caused by deeper and higher tool marks. Surface finish is also influenced by depth of cut but not so much as feed rate and speed of cutting. Greater depths of cut enhance cutting forces and vibration that may reduce surface quality, whereas smaller depths enhance stable machining and better surface finish. Besides these key parameters, the tool related parameters like tool material, tool geometry and overall tool wear condition also play major role in determining the quality of surfaces. Appropriate tool materials, and optimized tool geometry can be used to minimize the friction and cutting force and thus achieve a better surface finish. When cutting vibration and heat generation are to be minimized, machine tool rigidity, cutting environment and cutting fluids are also important factors. In general, better surface finish in CNC machining is obtained with the synchronous and optimized tool selection mix with machining parameters and process control leading to high-quality and reliable manufacturing results.

2. LITERATURE SURVEY

2.1. Conventional Studies on Machining Parameters

Initial research on machining performance was mainly based on empirical and experimental research to find out the correlation between the machining parameters and surface roughness. Parameters like cutting speed, feed rate and depth of cut were varied systematically by the researchers to determine their effect on surface integrity. Such parameter as feed rate was repeatedly found to be the most significant parameter influencing the surface roughness since faster feed rates would promote the appearance of tool marks and surface deviations. Reduction in speed was observed to impact the secondary effect which is usually enhancement of surface finish to an optimum level because built-up edge is minimized. Depth of cut was less likely to affect the surface roughness but had a strong effect on cutting forces and wear of the tool. These traditional research works formed the basis of comprehending machining behavior, but they usually were material-dependent and could not extrapolate to the predictive outlook outside of the experimental regime.

2.2. Taguchi-Based Optimization

The Taguchi approach went on to become a standard technique of machining parameter optimization because it was simple, strong, and allowed experimental performance to be minimized. The Taguchi technique allows an orthogonal array to be used to study a large number of parameters in a machining process in a small set of experiments, in contrast to full factorial tests. Signal-to-noise (S/N) ratios enable the researcher to adjust variability due to aspects out of their control, leading to parameter settings less sensitive to noise. This technique has been effectively implemented in order to maximize surface roughness, rate of material removal and the wear of the tools used in the different machining processes. Although it is effective, the Taguchi technique is majorly used in single response optimization and there is a linear relationship between factors and response which may constrain its use in machining environment where the machining factors are complex.

2.3. Response Surface Methodology

Response Surface Methodology (RSM) is an excellent statistical software tool employed to design and assess the connection between multiple processes and a single or more responses. In machining research, RSM has frequently been used to come up with second-order polychromic models or models that express individual and interaction impacts of cutting parameters. According to the more popular designs, like Central Composite Design (CCD) and Box-Behnken Design, are often applicable in order to make an effective exploration of the experimental space. Among the major strengths of RSM are its capability to display the interaction between parameters in the form of contour and three-dimensional surface plot, to gain a better understanding of the processes. Multi objective optimization of surface roughness, cutting forces, and tool life has been popularly used by

RSM. Its usefulness, however, is limited by the sufficiency of the regression model and can reduce with very nonlinear machining processes.

2.4. Evolutionary and AI-Based Methods

The optimization of machining parameters is currently an area that is attracting the interest of evolutionary algorithms and artificial intelligence (AI)-based methods in light of the progress in the computational intelligence. It is especially applicable to Genetic Algorithms (GA) that imitating nature, meaning natural selection, are effective in large and complex solution space search. Due to their effective learning and generalization features, Artificial Neural Networks (ANN) are strongly adopted in the modeling of nonlinear relationships between machining variables and nonlinear performance metrics. Hybrids involving the application of ANN in conjunction with GA or other optimization methods have been shown to be more predictive and efficient during optimization. Such techniques are particularly appropriate in very complicated CNC machining work whose conventional statistical models might fail. Although they have advantages, AI-based approaches need extensive datasets to be trained, and they are usually not interpretable, which might make the implementation in industrial practice difficult.

2.5. Research Gaps

Despite the great achievements in the optimization of the machining parameters, there are still a number of research gaps. A significant difficulty is that optimization findings are usually not generalizable to other workpiece materials, tool designs, and machining conditions. Also, the majority of the available literature is carried out in the laboratory, and little effort is put in the implementation of real-time monitoring systems, like sensors and adaptive control systems. The must-have to strike a balance between the surface quality and productivity and energy consumption and environmental sustainability is another rising issue. Existing optimization methods seldom involve the use of energy efficiency or carbon footprint as objective functions. The solution to these gaps is to design smart, dynamic and sustainable machining schemes, which are able to be utilized in the real-life manufacturing setting.

3. METHODOLOGY

3.1. Selection of Workpiece and Tool Material

The choice of suitable materials in workpieces and cutting tools is one of the relevant areas of machining studies because this directly impacts machinability, surface integrity, tool wear and efficiency of the whole process. Medium carbon steel AISI 1045 is chosen as an exemplar material of the workpiece in this research because a great percentage of industrial and production works use the material. AISI 1045 steel is usually composed of about 0.45% carbon which is a good balance of strength, hardness, toughness, and machinability. These qualities have resulted in its popularity as a material in components like shafts, gears, bolts, axles, and automotive parts where moderate strength and good wear resistance is needed. Moreover, AISI 1045 is capable of stable mechanical behavior at machining conditions and, therefore, consistency of cutting performance and surface quality can be evaluated. It is also significantly useful in comparison of experimental findings with literature, owing to its wide usage in the earlier studies on machining. In the case of the cutting tool, a standard geometry carbide insert is used in this study. In contemporary machining processes, carbide cutting tools have gained great popularity because of their high level of hardness, good hot strengths and high levels of wear resistances as opposed to the conventional high-speed steel tools. All these properties enable the carbide tools to retain sharp cutting edges at high temperatures; hence suitability in high-speed and high-feed machining environment. The tool geometry is standardized to

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provide consistency in cutting behavior, or to reduce variation in experiment results, and to provide improved reproducibility in results. Moreover, the carbide tools can be used on a very wide variety of workpiece materials, such as medium carbon steels, and offer an acceptable cutting performance to tool life ratio. AISI 1045 steel combined with a carbide cutting tool provides a convenient and industrial object of interest in data gathering on machining parameters and surface quality. Such a choice allows not only to guarantee high-quality experimental observations but also to further increase the relevance of the results to practical production conditions.

3.2. Identification of Machining Parameters

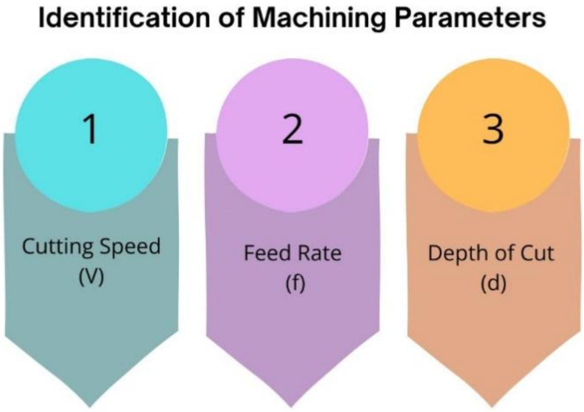

Fig 2 - Identification of Machining Parameters

3.2.1. Cutting Speed (V)

The cutting speed can be one of the most significant machining parameters, which is described as the relative velocity of the workpiece surface and cutting tool. It is important in the determination of machining efficiency, surface finish and tool life. Increased cutting speeds typically enhance surface quality by decreasing the formation of built-up edges as well as create more smooth material removal although extreme speeds may also cause a higher cutting temperature and faster tool wear. One should thus make the right choice of cutting speed to produce an ideal combination between surface finish and durability of the tool.

3.2.2. Feed Rate (f)

Feed rate Measures the distance the cutting tool travels with respect to the work piece in relation to one unit period of time or per revolution. It dominates the surface roughness because with increased feed rate, the markings and irregularities of the tool on the machined surface are increased. Although an increment of the feed rate increases productivity, by lowering machining time, it may lead to the compromise of surface quality and augment cutting forces. Therefore, feed rate should be controlled well to achieve a desired surface finish without impacting negatively on the tool life and dimension.

3.2.3. Depth of Cut (d)

Depth of cut is the amount of material flowing away with each succession of the cutting tool. It has a great impact on cutting forces, power consumption and removal rate of material. The greater the depth of cut, the greater the productivity, however the mechanical loads on the tool and the machine increase and this may cause vibration, tool deflection, and poor surface quality. On the other hand, a shallow depth of cut is more easily machined and gives a superior surface finish and

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dimensional control, but at the cost of machining efficiency. That is why depth of cut should be chosen wisely to create a stable process and reach maximum machining results.

3.3. Measurement of Surface Roughness

Surface roughness is another important measure of the quality of machined surface because it is directly related to functional properties like friction, wear resistance, fatigue strength as well as aesthetic appearance of components manufactured. Surface roughness in the given study is measured via the use of a stylus-type surface roughness tester that is highly regarded in remote practicality as well as in academia because of its reliability, simpleness and the high level of measurement accuracy. One of the guitar instruments that are played using a stylus is the stylus-type instrument, which works by moving along a diamond-tipped stylus over the machined area in a fixed speed. The irregularities of the surfaces that cause vertical deviations of the stylus are transformed into electrical signals, which are processed to compute surface roughness standard parameters. Among many other parameters of surface texture, one of the most common parameters is arithmetic average roughness value (Ra) which is also used to measure surface finish in common and is therefore adopted in this study to compare and create a uniform result. To recreate the actual profile of the surface at the cutting operation, measurements are made across the machining direction. To reduce the effects of localized surface defects, vibration or measurement noises, three trials of every experiment are performed on the same machined surface, at different places. These three readings are averaged and taken to be the representative value of the surface roughness in the case of the machining condition. This method enhances the consistency and the reproducibility of experimental data and minimizes the influence of random errors. Measurement accuracy and consistency are ensured by calibration of the surface roughness tester before measurements on the necessary samples are measured. Special precautions are observed to keep that of measurement in uniformity, including the stylus force, the length of traverse and the length of cutoff as it is suggested in international standards. The environment conditions like temperature and surface purity as well as external vibrations are also regulated so as to avoid the deviations in measurements. The methodological accuracy of this study can be attributed to the systematic measurement process that makes the data of the surface roughness of high quality that allows evaluating the effect of machining parameters clearly on the surface finish and it provides a credible foundation to further analysis and optimization.

3.4. Mathematical Modeling

In the current study, mathematical modeling is used to develop a quantitative correlation between the surface roughness and the machining parameters, i.e. cutting speed, feed rate and depth of cut, which are the parameters of the selected machining process. The model adopted is the second-order poly regression, it is extensively applied in machining driven researches because it can determine the impact of both linear and nonlinear impacts as well as interplay of impacts of various process variables. The surface roughness expressed in terms of the arithmetic average roughness value (RA) is a quadratic equation containing the machining parameters. The constant term, in this model, is the regression equation intercept that indicates the minimum allowed surface roughness in the case as all machining parameters are not at reference level. The linear terms cutting speed, feed rate and depth of cut explain the separate effect of each parameter on the surface roughness. The terms are used to determine the relative contribution to machine variable changes as well as the sensitivity of Ra. The interaction terms explain the same two parameters operating together e.g. cutting speed and feed rate, cutting speed and depth of cut and feed rate and depth of cut. These relations are especially essential in machining operations, whereby the influence of a single parameter is usually a factor of another level. The quadratic terms arculate the curvature influences

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of the machining parameters whereby, the model is capable of forecasting the non-linearity tendencies in the surface roughness. The terms raise the qualification of the best machining circumstances since they enable the determination of the least or maximum values of answers in the experimental field. Experimental evidence is used to estimate regression coefficients in the model based on the least-squares regression analysis. The meaning of the validation of the developed model and its sufficiency are done using the statistical tools like the analysis of variance. In general, the second-order poly representation gives a more complete mathematical model of machining process, which makes it possible to predict well the surface roughness as well as optimize machining parameters within the range of studies.

3.5. Statistical Analysis

An essential part is the statistical analysis that will help to verify the results of the experiment and explain the effect of the machining parameters on the surface roughness. Analysis of Variance (ANOVA) is used in this research paper as a powerful statistical to assess the level of significance of separate machining parameters such as cutting speed, feed rate, and depth of cut and their interaction effects on the response of the surface roughness. ANOVA and removes the trivial contribution of each input factor and that of the error in the experimentation, thus making it possible to objectively determine the significance of the parameter. ANOVA process entails the computation of the sum of squares, mean squares, F-values, and probability (p) value per factor and interaction item in the regression equation. The F-value is used to determine the comparative effect of a factor as the variance is compared with the variance of errors whereas the p-value is used to assess the significance statistically. Parameters that have a p-value that is less than a desired level of significance, normally 0.05 are statistically significant and are said to have a significant impact on surface roughness. This analysis assists in determining all the most dominating machining parameters and important interactions that affect the quality of surfaces. Besides the significance test, ANOVA is employed to test the sufficiency of mathematical model developed. Statistical measures are studied and this includes coefficient of determination and adjusted coefficient of determination which determine the extent to which the model explains the variability of the experimental data. The lack-of-fit test is also conducted to ascertain whether the model is adequate to capture the model observations of the experiment in the parameter range of study. Normal probability plot, residual-versus-predicted value plot, and residual analysis are performed to test the assumptions of normality, independence and the assumption of constant variance. On the whole, ANOVA application is a strict and systematic method of analyzing the results of the experiment, confirming the predictive model, and making credible conclusions about the impacts of machining parameters on the surface roughness.

4. RESULT AND DISCUSSION

4.1. Effect of Cutting Speed

Cutting speed has a prominent role in defining surface finish during machining process because it has direct impacts on the formation of the chips, temperature of cutting and the association between the tools and the works. Overall, a rise in cutting speed results in a rise in surface finish, which may be ascribed to the decrease in the formation of built-up edge (BUE) in the cutting tool edge. Lower cutting speed causes the material to stick to the tool tip because of friction and lack of balance in material flow, which leads to irregular surface marks and roughness. The faster the cutting rate, the higher the temperature in the cutting area will be which during the process will cause the material to adhere less hence making separation of the chips to proceed smoothly hence improving the quality of the surface. Also, increased cutting speed allows the cutting process to be more stable

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as cutting forces are reduced, and other overall vibration is minimized, which also leads to better surface finish. Shearing action is made more monotonous, giving finer textures of surfaces and lessening surface defect like tearing and smearing. The effect is especially observable machining medium carbon steels, in which the optimum cutting speeds are used to accommodate the trade-off between the thermal softening of material and the controlled material removal. Increases in cutting speed have a limiting point, however, with respect to benefits. Unrealistically high cutting speeds also lead to a drastically high increase in cutting temperature that accelerates cutting tool wear mechanisms in abrasion, diffusion and oxidation. There is also rapid wear of the tool that results in dulling of edges, friction, and possible tool failure, which negatively trigger surface finish. Furthermore, in long machining processes, excessive heat is likely to cause thermal damage of machined surface such as cracking of micro-cracks or burning of the surface. Higher cutting speeds therefore do tend to improve the surface finish however it is necessary to choose an optimum range of cutting speed which will give an optimum surface finish without deteriorating the life of the tool used. Experimental findings of this paper draw attention to the need to balance the cutting speed in order to provide a uniform surface finish and performance efficiency of machining.

4.2. Effect of Feed Rate

Feed rate this machining parameter is widely recognized as the most hegemonic factor of surface roughness in that it directly controls the type of geometric profile to be left on the machined surface. Feeds rate specifies how far the cutting tool travels within each turn or unit period thus it affects the spacing and heights of tool scars produced in the cutting process. As observed experimentally, there is a sharp increase in the level of surface roughness as the feed rate increases because of the appearance of deeper and more pronounced feed marks. These tool marks put more surface irregularities leading to a relatively bad surface finish. Lower feed rates cause the cutting tool to cut material into finer steps generating closer tool tracks and less pronounced surface profiles. An advantage of this condition is that it is conducive to surface integrity and favored where finishing of operation is in demand and high surface quality is needed. Higher feed rates, in turn, improve productivity without the need to turn to surface finish because they improve material removal on each pass that improves productivity, though at the expense of surface finish. The higher feed level increases cutting forces that results to an increase in tool deflection and vibration hence further compromising the quality of the surface. Also, high feed rates increase friction at the toolworkpiece interface and hasten the wear of tools as well as encouraging nonconstancy in surface textures. A feed rate also affects chip thickness and further cutting mechanics and surface generation. On increasing the feed rate, heavier chips are formed and cutting resistance and thermal load in the cutting zone is increased. Such states can lead to a gouging effect, accumulation of edges, and micro-tearing of the piece of work. The combined effect of these effects is roughness of the surface. Findings of this research prove the importance of a tight feed rate control to attain the desired surface finish. Although increasing feed rates enhances efficiency and shorter cycle time, it has to be adjusted in order to achieve productivity and also quality of the surface. Thus, the choice of feed rate is very important in the optimization of machining parameters, especially when the primary performance criterion of machining is surface finish.

4.3. Effect of Depth of Cut

Depth of cut is a significant machining parameter and one that determines the speed of material removal, the cutting forces and the stability of the process thus determining the surface roughness to a moderate degree relative to cutting speed and feed rate. The experimental data points out that the depth of cut usually worsens the surface finish condition as the cutting forces and

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dynamic instability during machining increases with an increase in depth of cut. With a larger depth of cut used it means more material can be removed at once and this leads to increased mechanical loads on the machine structure and cutting tool. The higher forces related to depths of cut that define the cutting force may lead to tool deflection, chatter, and vibration which have adverse effect on the quality of the surface. The contact between the tool and the workpiece becomes irregular because of vibrations creating a rough profile on the surface and varying values of roughness. There are also cases of over deflection of tools that changes the actual geometry of the cutting leading to uncontrolled removal of material and surface waviness. These effects are increased when machining at increased depths of cut at less rigid machining conditions. In thermal terms, a greater depth of cut is another determinant of high heat production in the cutting zone because it leads to more friction and energy usage. Increased temperatures hasten the process of wear (flank wear and edge rounding) on tools and this eventually worsens surface finish at a later stage. A comparison of the feed rate and the direct effect of depth of cut on surface roughness however shows that the effect of depth of cut is of comparatively lesser importance since the surface generation is mostly controlled by feed-induced tool marks. Smaller depths of cut, on the contrary, allow steady operations to be cut with less force, and less vibration, to achieve better surface finish and dimensional accuracy. This type of condition is normally desired in operations where a finish is required and other times huge depths of cut are desired in operations where one seeks more productivity than appearance. Hence, it is critical to determine a suitable depth of cut to establish efficiency in machining, tool life, and surface integrity that guarantee uniform and acceptable surface finish within the tolerable operational range.

4.4. ANOVA Results

Table 1: ANOVA Results

Parameter	Contribution (%)
Feed Rate	55.4
Cutting Speed	28.7
Depth of Cut	10.6
Error	5.3

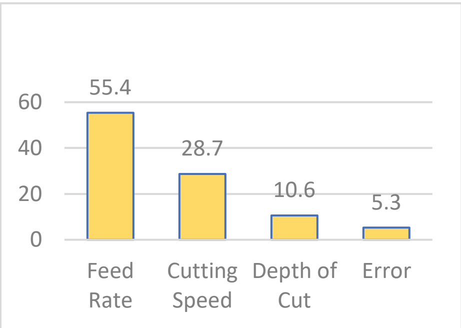

Fig 3 - Graph representing ANOVA Results

4.4.1. Feed Rate (55.4%)

According to the results of ANOVA, feed rate is the most important parameter affecting surface roughness as it contributes 55.4 percent of the overall variation. This is a high percentage that indeed proves that surface generation in machining is to a great extent determined by tool marks produced by the feed. The height and spacing of these tool marks is more pronounced with increase in the feed rate resulting in the observable destruction of surface finish. Suppression of feed rate emphasizes the fact that this parameter should be chosen and regulated with particular care, particularly in finishing processes when quality of the surface is a major factor.

4.4.2. Cutting Speed (28.7%)

The second factor, which also has 28.7% impact on roughness surfaces variation, is cutting speed. Its influence is majorly related to modification of cutting temperature, chip formation and cumulative edge behavior. A rise in cutting speed normally enhances a surface finish because it lowers stickiness in material, and facilitates the ease of cut. But, the optimum tolerance limit will exist after which cutting speeds can increase rapidly as a result of tool wear, which has an indirect influence on surface quality. The high value attached to cutting speed brings out its importance in establishing a balance between the surface finish as well as the tool life.

4.4.3. Depth of Cut (10.6%)

Depth of cut contributes 10.6 percent of differences in surface roughness which is moderate compared to other factors such as feed rate and cut speed. It has an indirect effect preponderantly because higher depths-of-cut raise cutting forces and vibration and may consequently lower the quality of the surface. Although depth of cut is more essential in defining the productivity and material removal rate, its output on the surface roughness is very secondary. Adequate selection of depth of cut is thus significant to ensure stability of processes and good surface finish is achieved.

4.4.4. Error (5.3%)

The contribution error of 5.3 percent represents the difference in the roughness of a surface which is not described by the machining parameters chosen. Such a comparatively low value suggests that there was a good control of the experiment and sufficiency of the developed model. The error can be due to small errors in measurements, changes in the condition of the tools, and uncontrollable environmental changes. In general, the consistency of the experimental findings and statistical analysis can be trusted to the low percentage of errors.

4.5. Optimal Parameter Combination

The combination of machining parameters, which was the best according to the results of this study, is based on a cutting speed of 200 m/min, a feed rate of 0.1 mm/rev, and an 0.5-mm depth of cut. The combination is a compromise cluster of circumstances resulting in the least amount of roughness on the surface at the same time keeping machining stable and effective. The chosen cutting speed of 200 m/min is in the preferential range of cutting speed whereby the built-up edge development is reduced and leading to the chip flow and surface finish of the part is enhanced without debasing the cutting tool with excessive heat. The cutting temperature at this speed is high enough not to produce adhesion of materials yet not allowing quick tool wear. The feed rate of 0.1 mm/rev is important in the attainment of high quality surfaces. Since the feed rate is the most critical factor that influences the roughness level of surface, using a relatively small value of feed will guarantee that the tool marks are finer, and the surface profile is smoother. It is a feed rate especially used in finishing, where material removal rate is not as important as surface integrity and dimensional accuracy. Also, the lower feed rates also decrease cutting forces and vibration, which can contribute to the stability of the processes and the long life of the tool. The 0.5 mm cut depth is used to balance the chosen cutting speed and feed rate of the machine through moderate material removal rate to ensure the cutting forces are not too high. The given depth of cut comes in handy to avoid too much tool deflection and vibration, so that the tool and workpiece are in constant contact. The synergistic combination of these parameters will yield an optimal balance between surface finish, tool

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life and productivity. On balance, the choice of optimal parameters that was identified indicates the effectiveness of the experimental/statistic optimization strategy being used. These machining conditions may be suggested to provide high quality surface finish in machining of medium carbon steel under the use of carbide tools, and may be used in practical reference in industrial machining processes.

5. CONCLUSION

This paper involves a thorough research on optimization of CNC machining factors with aim of obtaining better surface finish and greater machining rates. The study, through the methodical examination of how improving speed of cut, the feed rate, and depth of cut affect the roughness of surface, provides important data on how medium carbon steel behaves when machine with carbide cutting tools. The outcomes of the experimental study provide a clear indication that the aspect that exerts the greatest effect on the surface roughness is the feed rate, which explains the greatest impact on the variation of the surface quality. Cutting speed is numbered as the second biggest factor as it predominantly affects surface finish as it is related to chip formation and a decrease in built-up is significant as it influences the surface roughness rather moderately. Statistical optimization methods, specifically, the Taguchi method and Analysis of Variance (ANOVA), have been found useful in the determination of the optimal machining conditions using a much smaller experimental sample. Orthogonal arrays also allowed systematic experimentation and ANOVA allowed a clear insight into the relative importance of machining parameters and their interaction. This method helped to reduce the cost and time of experiment as well as provide reliable and statistically validated results. The designed mathematical model and the correct prediction of the surface roughness in the range of machining parameters of choice also contributed to the strength of the optimization process. The parameter combination with optimization led to a significant change in the quality of the surface, which proved the practical efficiency of parameter optimization in CNC machining activities. Better surface finish will provide better component performance in terms of friction, wear, and chances of early failure as well as dimensional accuracy and appeal. Moreover, it may also result in long tool life, less reworking and less overall costs of manufacturing since optimized machining conditions are of great importance in industrial use. In general, this study can offer some useful principles to engineers working in the field of manufacturing to enhance the surface finish by optimizing the parameters systematically. Another key source of future research is the results of the study since it will be possible to use modern technologies, including artificial intelligence, machine learning, and a real-time monitoring system. A combination of such technologies and traditional statistical procedures may be used to facilitate adaptive and intelligent machining tasks that can react dynamically to new machining environments and would eventually promote sustainable and high-performance manufacturing systems.

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