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IMPROVING DIMENSIONAL ACCURACY OF PARTS BY PROCESS OPTIMISATION

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ABSTRACT

Fulfilment of dimensional accuracy characteristics is predominantly the first requirement for accepting a manufactured part. In spite of this, in the literature there has been little interest on this important topic. This paper highlights the difficulties associated with this problem and proposes practical measures that can be applied by a user of machine tools. Two methods, namely modelling and statistical methods, have been applied for improving dimensional accuracy of parts by process optimisation. In the first part of the paper, modelling of peripheral end milling operation is presented and it is shown that the specified tolerance levels of a prismatic component part can be achieved by the proper selection of cutting parameters and cutting configurations. In the second part of the paper the dry turning process has been optimised by the application of two statistical methods: Pareto ANOVA and Taguchi methods.

Keywords: Modelling, Pareto ANOVA, Taguchi methods, Peripheral end milling, dry turning

1. Introduction

Dimensional accuracy and predictability of tolerance levels of component parts are two of the most fundamental requirements for today's highly automated manufacturing environment, yet very little research has been reported on this key area. In 1998 the *International Institution for Production Engineering Research* (CIRP) working group on Modelling of Machining Operations in its keynote paper [1] identified this as a priority research area. However, the progress in this vital area has been rather slow due to a lack of fundamental understanding of various machining processes. This problem has been exacerbated by the fact that the dimensional accuracies of component parts are influenced by a host of error sources (see Table 1), for which finding solutions will require a large number of strategies or prediction models. Each error component listed in Table 1 is influenced by a large number of factors and it is estimated that the total number of variables in a dimensional accuracy model would be in the order of one hundred [1].

A closer look at the error components listed in Table 1 reveals that most of them are *machine tool dependent*; therefore, the user has little or no control. Nonetheless, during the last few decades the manufacturers have improved the accuracy of machine tools significantly and the specified accuracy levels of modern CNC machine tools are very high. However, the accuracy levels specified by the manufacturer of machine tools are designed for "ideal" (non-machining) conditions. Therefore, these levels are not achievable in practical machining conditions which cannot be non-productive and ideal. However, a major contributor to the dimensional errors produced on modern CNC machine tools is *process dependent*. The process-dependent error components can be controlled by the user; hence there is great scope for improving dimensional accuracy of component parts by process optimisation.

Since the early twentieth century, the optimisation of machining has attracted the attention of many researchers. In 1907, Taylor [3] showed that the material removal rate of a single-pass turning operation can be maximized through proper selection of cutting speed. A commentary on historical development of various models applied in machining operations can be found in [4]. At present, a number of tools are available for machining optimisation. Of these tools, modelling and the statistical methods are two categories of tools that are relatively popular. These two tools are described briefly in Sections 3 and 4 of this paper.

The main objective of this research is to predict and subsequently optimise the various dimensional accuracy characteristics of simple components

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machined under typical machining conditions. This study has been undertaken from the machine tool user's point of view and, consequently, machine tool errors are taken on an "as is" basis. The independent input parameters over which the user has control are the *cutting conditions*; that is, cutting speed, feed rate and depth of cut and *cutting configurations*; that is, tool material, tool diameter, and tool geometry.

Table 1: Machining error components and their sources in CNC machine tools (adapted from [2])

Sources	Sources	Error Components
Machine Tool, Fixture, Cutting Tool and Workpiece Error	Machine Tool Error	Geometric machine tool Orientation change error of MT moving parts Machine parts deflection
	Fixture Error	Geometric error of the Fixture deflection error
	Tool Error	Dimensional tool error Tool deflection error Tool wear error Tool thermal error
	Workpiece Error	Workpiece geometric error Workpiece thermal error Workpiece inspection error
NC System Error	NC Controller Error	Programming error Interpolator error
		Error of interpolator Errors in forming the 'go to zero instructions
	Servo Drive Error	Drift error of servo drive unit characteristics Drive torque error Dynamic error of the drive Drive velocity error
	Measuring System Error	In-pitch transducer error Cumulative transducer error Forming converter error
	Feed Mechanism Error	Geometric error of the lead Backlash error of the ball bearing screw Error caused by stick-slip
External Factors		Workpiece inspection error Errors caused by other external factors

2. Dimensional Accuracy of Parts

In current dimensioning and tolerancing standards [5, 6], part accuracy is expressed through: (i) size tolerance, (ii) geometric tolerances, including form, orientation and location tolerances, and (iii) surface texture characteristics. It is worth pointing out that all dimensional accuracy characteristics of a *feature* are related to each other as they are produced by the same manufacturing process although the exact relationships are usually unknown. However, when specifying these characteristics the designer must ensure that these characteristics are compatible with each other.

Size tolerance is the total amount of variation permitted in the actual size of a component part or a feature which controls linear and angular dimensions. In most cases, size tolerance is the first criterion required for acceptance of manufactured parts. A number of authors [7, 8] utilise the following formula to estimate the size tolerance achievable through a manufacturing process:

$$ST = \left(0.45\sqrt[3]{X} + 0.001X\right) 10^{\frac{IT-16}{5}} \quad (1)$$

where ST is the size tolerance (mm), X is the magnitude of size (mm) and IT is the International Tolerance grade number.

This model is based on tolerance standards for cylindrical fits. According to this model, the size tolerance achievable through a manufacturing process depends on the cube root of the magnitude of size and also on the International Tolerance (IT) grade for the process, a number reflecting the precision of the process. This model is more than sixty years old and at that time the main source of machining error was the positioning error of the machine tool, which produced errors proportional to the length of the feature. Thanks to vast improvements in machine tool accuracy over the past few decades other factors, such as tool deflection error in end milling, have become the most dominant factors influencing the achievable size tolerance. Therefore, new models/approaches are necessary to predict achievable size tolerances.

3. Modelling

Modelling is a technique widely used in a variety of fields in science and engineering for analyses of problems by idealisation of real world parts. Although various types of modelling are in use, *mathematical modelling* is the most widely used technique whereby the components of a system are represented by idealised elements and their behaviour is described by mathematical equations. However, construction of a mathematical model requires a thorough understanding of the process. In metal machining models have various applications; the most well known examples are [1]: (i) design of processes, (ii) optimisation of processes, (iii) control of processes, (iv) simulation of processes, and (v) design of equipment. The necessary sophistication of a model depends on its applications.

Modelling methods used in metal machining can be divided into three broad categories: (i) empirical, (ii) analytical, and (iii) numerical. *Empirical models* are purely based on experimental data; Taylor's tool life equation is the most prominent example of this type; other examples are available in [9, 10]. *Analytical models* are science based, for example, Ernst and Merchant's [11] model for predicting the shear plane angle was developed by applying the *minimum energy principle*. More examples of analytical models for machining operations can be found in [12, 13]. *Numerical models* are computation based and the most promising numerical model being developed is the finite element method. One difficulty with analytical models is they often require high-level mathematics; in contrast, the finite element method is based on relatively simple algebraic equations but may require the solution of hundreds of equations simultaneously. With the increase of high-speed digital computers this method is becoming popular over time. Examples of numerical models are [14, 15].

The CIRP working group on Modelling of Machining Operations is playing a vital role in advancing knowledge in this area. The current state-of-the-art in modelling and optimisation of different machining operations may be found in [1, 16]. An application of modelling technique for end milling process is described in Section 5 of this paper.

4. Statistical Methods

Statistical methods are useful tools for the optimisation of machining processes, especially when the basic process is poorly elucidated thus impossible to model. Moreover, in machining the sources of variability are great, which makes it a perfect candidate for application of statistical methods. A number of statistical methods have been applied for process optimisation, of which the Pareto ANOVA and Tanguchi methods are the two most popular choices.

4.1 Pareto ANOVA

Pareto ANOVA is a simplified analysis of the variance (ANOVA) analysis method that does not require an ANOVA table therefore does not use *F*-tests, unlike the regression analysis method. It enables the significance of factors and interactions to be evaluated by Pareto-type analysis. It also allows the optimum levels of factors to be obtained; further details of Pareto ANOVA are available in [17]. Application of this method in relation to metal machining can be found in [18, 19].

4.2 Taguchi Methods

The *Taguchi method* is a powerful tool for process optimisation which selects the optimum values of the input parameters and their combinations. It is most appropriate when design parameters are qualitative and discrete in nature. The method utilises *signal-to-noise* (S/N) ratio for evaluating the robustness of a process; the higher the value of S/N ratio, the better the result. Details of Taguchi methods are available in [20]. Taguchi methods are applied in various fields including metal machining [19, 21].

Applications of Pareto ANOVA and Taguchi methods for optimisation of a turning operation are described in Section 6 of this paper.

5. End Milling Optimisation

End milling is one of the most universal metal removal processes used in today's industry. With the advent of CNC machining centres, the application of end mills has grown tremendously, particularly in the aerospace and turbo machine industries. Accordingly, attention needs to be paid to the accuracy of end milling operations to guarantee high quality of the finished products thus reducing the number of rejects.

The objective of this project is to develop a predictive model for size tolerance of a prismatic component machined through peripheral end milling under typical machining conditions. Subsequently, the model will be employed for predicting the size tolerances of a prismatic component by varying one controllable variable at a time and the relationship between the size tolerance and the variable changed will be monitored. When a distinct relationship is noted it will be further analysed both analytically and experimentally. Finally, the model will be used for solving inverse problems, i.e., for selection of optimum cutting conditions based on the specific size tolerance of component parts.

5.1 Cutting Force Model

The cutting force model used [22-24] is based on the mechanics of the cutting process and is, therefore, commonly known as the *mechanistic force model*. The underlying assumption behind such models is that the cutting forces are proportional to the uncut chip area. However, these models are not entirely analytical and their accuracy depends heavily on empirically determined *cutting force coefficients*, which are a function of cutting conditions and, as a result, cannot be applied readily to a variety of cutting conditions. The adopted cutting force model has overcome this shortcoming by providing a method, details of which are available in [23], for determining *cutting-condition-independent cutting force coefficients*. For accurate prediction of the cutting force, the model also takes into account the *variable depth of cut* caused by the tool deflection and tool runout as well as the *ploughing effect* resulting from the rounded cutting edge.

The schematic view of the end milling process and the adopted coordinate system for modelling are illustrated in Fig. 1, where *x* is the direction parallel to the feed in the plane perpendicular to tool axis, *y* is the direction perpendicular to *x* (in the same plane), and *z* is the direction of the tool axis that is perpendicular to both *x* and y. Each cutting force component is calculated in the manner described below.

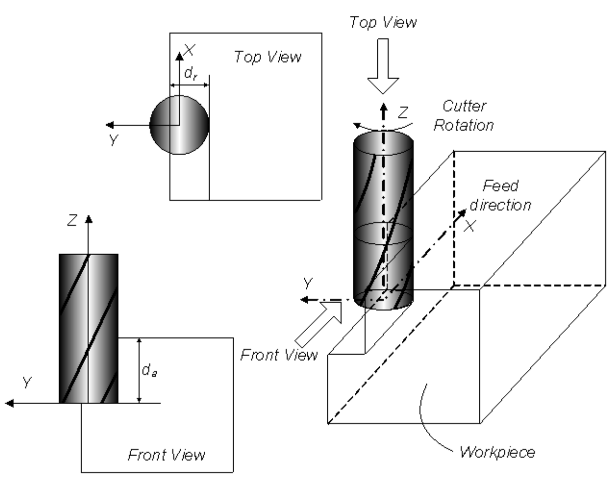

Fig 1 Schematic view of the end milling process geometry and coordinate system

Firstly, the end milling cutter is divided into a finite number of coaxial disk elements and then the *x*, *y* and *z* components of force acting on a flute at a particular instant are obtained by summing up the force components acting on each individual disk element. Finally, the total force acting on the cutter is obtained by adding the force components acting on all flutes.

The cross-section of the cutter, cutter rotation, feed direction and cutting edge location angles is illustrated in Fig. 2. In down milling, the cutter engages with the maximum uncut chip thickness. As the cutter rotates, the uncut chip thickness reduces, thus resulting in a reduction in the force components. However, the actual profile of the force graph is greatly influenced by entry and exit angles, which are a function of the radial and axial depth of cuts, cutter diameter and helix angle.

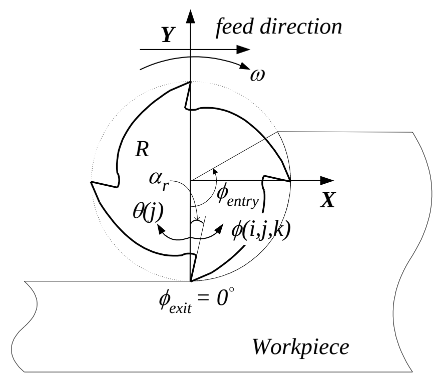

Fig 2 Cross-section of the cutter

5.2 Tool Deflection Model

The end mill is modelled as a cantilever beam, rigidly gripped by the tool holder, where the cutting force is applied near the non-supported end (Fig. 3). Due to the helical profile of the cutting edge, the point of application of the cutting force varies from the non-supported end to the axial depth of the cut. The amount of tool deflection for each disk element in the *y* direction (direction of interest for generating surface error) can be calculated by summing the defection of all disk elements.

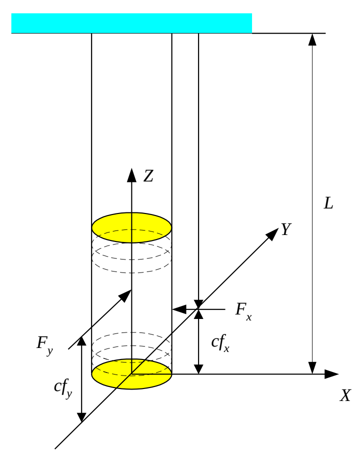

Fig 3 Tool deflection model

5.3 Cutter Diameter Estimation Procedure

The dimensional repetition and predictability of workpiece size tolerances is closely related to the correct tool diameter supplied to the CNC controller during machining operations. Traditionally, the nominal size of the cutter is provided to the controller, thus resulting in significant machining errors. This is because the cutter itself has a tolerance; for example, a ϕ*16.000* end mill used in the present machining experiments had a -0/+ 0.030 mm tool manufacturer's specified size tolerance. This problem is compounded by the fact that the cutter usually has runout errors. We also need to consider other forms of tool errors, such as, tool wear error and tool thermal error. Hence, the actual cutter diameter during cutting is unknown. Experienced machinists are aware of this problem and adopt various approaches to rectify it. For example, they take measurements prior to the final cut and compensate for the error during the final cut.

At Curtin University, a research project has been undertaken to come up with a viable solution for this problem. Different options were under investigation including the use of a non-contact measuring system such as a laser scan micrometer for on-machine measurement of the cutter diameter. Until an acceptable solution was found, the problem was solved by determining the tool diameter during machining by cutting a soft material (paraffin block) to avoid tool deflection error. Initially, a slot was cut and was then enlarged on both sides by 1 mm. The feed directions were chosen so that both cuts were executed through down milling. Special measures were taken to keep the tool runout to its minimum of around 5 microns. More than 50 measurements of the slot width were taken and, as a result, the revised cutter diameter supplied to the controller was *16.102* mm. Consequently, the differences between the measured and simulated averages were reduced to 7 microns, or the prediction error was about 19.4%.

5.4 Simulation Results

The effect of cutting speed and feed rate on size tolerance is shown in Fig. 4. The figure shows that size tolerance is always directly proportional to feed rate and inversely proportional to cutting speed. The influence of cutting speed at low feed rates appears to be greater than the influence of cutting speed at higher feed rates. Fig. 5 demonstrates that size tolerance is always proportional to the feed rate but not to the radial depth of cut. Therefore, there is a possibility of achieving a required size tolerance through proper selection of radial depth of cut. Minimum and maximum levels, respectively, are noted near the radial depth of cut equal to a quarter and a half of the cutter diameter. Indeed, we are able to determine the cutting conditions producing the maximum and minimum tolerance levels and formulas are developed, the details of which are available in [22]. This knowledge will be applied to develop a cutting conditions optimisation strategy.

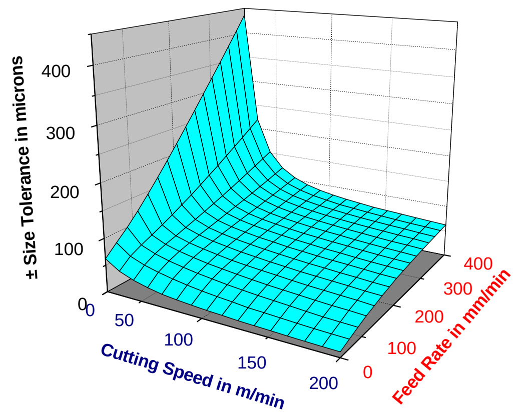

Fig 4 Effect of cutting speed and feed rate on size tolerance (radial depth of cut = 2 mm)

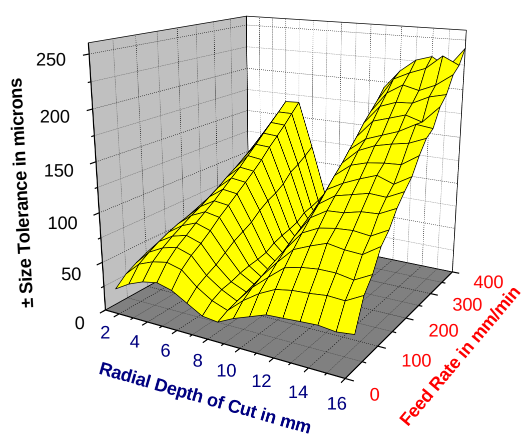

Fig 5 Effect of radial depth of cut and feed rate on size tolerance (cutting speed = 50 m/min)

5.5 Selection of Optimum Cutting Conditions

Based on the knowledge acquired through simulation, an optimisation strategy for a single pass peripheral end milling has been developed, details of which can be found in [25]. Two variations of the strategies are available: (i) technical optimisation and (ii) technical and economical optimisation.

In the case of technical optimisation, the cutting conditions are optimised only on the basis of specified part tolerance, which is a technical parameter. A 3D search strategy similar to *lattice search* has been adopted in which the search ranges for cutting speed and feed rate are nominated by the user and are usually based on machine tool specifications. The minimum depth of cut is selected on the basis of the accuracy of the workpiece prior to machining and the maximum is calculated applying a formula which is available in [22].

In the case of technical and economical optimisation, the cutting conditions are optimised on the basis of both technical and economical parameters, namely, specified part tolerance and economical cutting speed. Formulae are available for calculation of economical cutting speed. For example, the economical cutting speed for minimum cost may be calculated using the following formula [26]:

$$V_{c\min} = \frac{C_v}{\left[\left(\frac{1}{n}-1\right)\frac{C_w + C_d T_c}{C_d}\right]^n} \qquad (2)$$

The cutting speed that yields the maximum production rate may be calculated using the following formula [26]:

$$V_{p\max} = \frac{C_v}{\left[\left(\frac{1}{n}-1\right)\times T_c\right]^n} \qquad (3)$$

The coefficients used in Eq. (2) and (3) such as C_w (tooling cost) and C_d (direct operation cost) are site dependent, while C_v (cutting speed constant in Taylor's tool life equation), which is numerically equal to the cutting speed that gives a tool life of 1 minute, depends on all the input parameters for the cutting operation such as tool material and workpiece material. Therefore, we propose the economical cutting speed be selected using Eq. (2) or (3) at the shop floor level on a case by case basis. Then a 2D search should be carried out in the feed rate and radial depth of cut domain using a lattice search strategy. This method is faster in that the technical optimisation method as cutting speed is kept constant throughout the optimisation search.

Another variation of this approach may be to generate contour plots similar to the one shown in Fig. 6. The cutting speeds required for these contour plots are determined by using the economical cutting speed formulas expressed in Eq. (2) or (3). These plots can be very useful tools at the shop floor level because they allow the machinist to select the suitable feed rate and depth of cut combinations based on the specified size tolerance without any calculation and the decision will be based on both technical and economical parameters.

6. Turning Optimisation

Turning is one of the most basic material removal processes in which material is removed from the external surface of a rotating workpiece. Turning is the first choice for machining cylindrical parts and is performed in both dry and wet conditions. In wet tuning, *cutting fluid* is applied for a number of reasons, such as to reduce the cutting temperature, to lengthen the tool life, to produce a better surface finish, to gain an acceptable dimensional accuracy and to facilitate chip disposal. However, in recent years, the application of cutting fluids in machining operations has attracted immense scrutiny due to its adverse effects on the environment. Consequently, dry turning has gained renewed interest for its potential environmental and economic benefits. However, the dimensional accuracy of component parts may suffer due to the application of this technique. The objective of this project was to investigate the effects of the cutting parameters on the dimensional accuracy of dry turned parts and to optimise the cutting parameters for achieving specified dimensional accuracy.

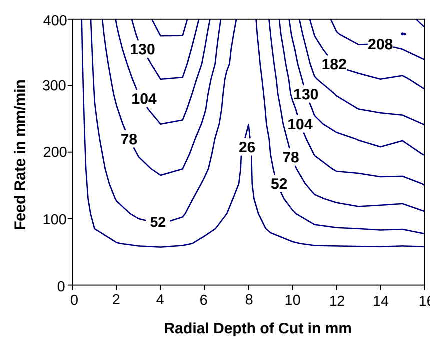

Fig 6 Contour plot showing constant tolerance values in ± microns

6.1 Experimental Work

The experiments were planned using Taguchi's orthogonal array methodology [20] and a three-level L_{27} orthogonal array was selected for our experiments. A total of 27 experimental runs were conducted using the dry turning technique. The values of the three cutting parameters (cutting speed, feed rate and depth of cut) were selected on the basis of the capacity and the limiting cutting conditions of the lathe machine used.

Bars of AISI 4340 with hardness value of 30 HRC were used in this experimental work. Test parts were produced on a Harrison 13 inch conventional lathe machine. The nominal diameter of the test parts was 40 mm and a three-jaw chuck supported by the dead centre was used to hold the workpiece. For a turning operation, size tolerance (or diameter error), circularity and surface roughness are the three most important dimensional accuracy characteristics, thus they were selected for monitoring the dimensional accuracy of parts. A general purpose co-ordinate measuring machine (CMM) manufactured by Brown & Sharpe, USA was used for precision measurements. The surface roughness (arithmetic average or R_a values) was measured by a surface measuring instrument manufactured by Mitutoya, Japan.

6.2 Analysis of Experimental Work

Each dimensional accuracy characteristic of the turned part was analysed applying the Pareto ANOVA and Taguchi method and numerous graphs and tables were constructed. However, due to space constraints, only a few representative ones are included here. Full details of this analysis can be found in [27].

The Pareto ANOVA analysis for dimensional error given in Table 2 shows that parameter A (cutting speed) had the most significant effect on dimensional error of the parameters, followed by C (depth of cut) and B (feed rate). The interaction between BxC (feed rate and depth of cut) also played a role in this cutting process. The medium cutting speed, A1, was the best cutting speed for achieving a low value of dimension error. Since the interaction of BxC was also significant, the BxC *two-way table* was applied to select their levels (see Table 3). From the BxC two-way table, it can be seen that the optimum combination for factor B and factor C, in order to achieve a low value of dimension error, was B_0C_0. Thus, the optimal combination to achieve low value of dimensional error was $A_1B_0C_0$.

The analyses for circularity and surface roughness were repeated using the same procedure and the final outcome is summarised in Table 4. The response graphs from S/N ratio analysis for the three-dimensional accuracy characteristics are shown in Fig. 7. It is clear from the information shown in Table 4 and Fig. 7 that different cutting parameters are required to be kept at different levels in order to optimise each quality characteristic. As a result, it is difficult to optimise all three quality characteristics all at once. A hybrid predictive model, recently proposed by Jawahir and Wang [16] for optimum cutting parameter selection, can be a viable alternative. Nevertheless, further analysis reveals that the utilisation of low feed rate can optimise the dimensional error, surface roughness and circularity of cylindrical component parts, simultaneously.

7. Concluding Remarks

This paper demonstrates that dimensional accuracies of parts produced by various machining operations can be improved by process optimisation. A modelling method is presented which can predict the size tolerance of a prismatic component machined through peripheral end milling. The method provides better control of dimensional accuracy of products by achieving a required size tolerance through proper selection of input parameters.

Two statistical methods, namely Pareto ANOVA analysis and Taguchi methods, were applied for optimising dry turning operation and the results show that cutting parameters such as cutting speed, feed rate and depth of cut have significant influences on the three dimensional accuracy characteristics (diameter error, surface roughness and circularity). However, different cutting parameters are required to be kept at different levels for optimising each dimensional accuracy characteristic, which highlights the problem of optimising a number of dimensional accuracy characteristics simultaneously. A hybrid predictive model recently proposed by Jawahir and Wang can be a viable option.

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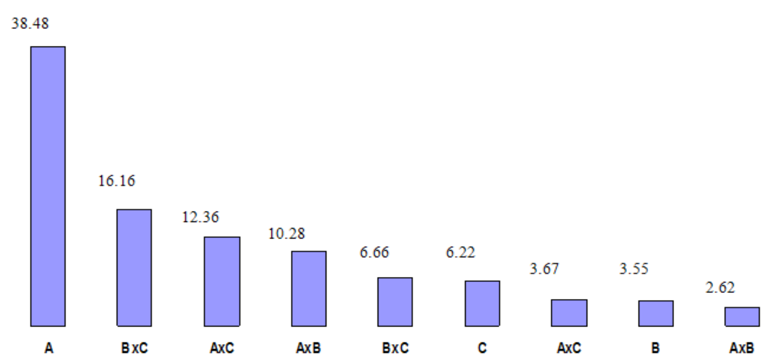
Table 2: Pareto ANOVA analvsis for dimensional error

Sum at factor level	Factor and Interaction								
	A	B	AxB	AxB	C	AxC	AxC	BxC	BxC
0	137.41	145.88	136.16	139.21	144.23	133.82	135.82	151.51	144.00
1	158.52	136.09	132.59	144.49	143.29	144.83	151.11	139.00	143.83
2	122.92	136.88	150.10	135.16	131.33	140.20	131.92	128.33	131.01
Sum of squares of difference (S)	1923.45	177.19	513.69	131.42	310.70	183.26	617.72	807.62	333.01
Contribution ratio (%)	38.48	3.55	10.28	2.63	6.22	3.67	12.36	16.16	6.66



Cumulative contribution	38.48	54.64	67.00	77.28	83.94	90.16	93.83	97.37	100.00
Check on signification interaction	BC two-way table								
Optimum combination of signification factor level	$A_1B_0C_0$								

Table 3: BC two-wav table for dimensional error

	B_0				B_1				B_2				Total
C_0	16.344	18.862	20.385	**55.591**	12.905	16.440	14.486	**43.831**	14.895	18.249	11.667	**44.811**	**144.23**
C_1	18.913	17.098	15.041	**51.052**	15.459	18.108	10.722	**44.290**	18.225	17.788	11.938	**47.951**	**143.29**
C_2	11.341	15.139	12.753	**39.233**	15.546	20.476	11.949	**47.971**	13.779	16.363	13.979	**44.122**	**131.33**
Total				**145.88**				**136.09**				**136.88**	**418.85**

Table 4: Summary of Pareto ANOVA analysis for dry turning operation

Dimensional Accuracy	Optimum Combination			Contribution Ratio (%)					
Characteristics	A	B	C	A	B	C	AxB	BxC	AxC
Diameter Error	1	0	0	38.48	3.55	6.22	10.28	16.16	12.36
Surface Roughness	1	0	1	0.54	98.15	0.16	0.48	0.21	0.22
Circularity	0	0	2	42.89	2.63	1.17	32.68	4.17	2.70

A = Cutting speed B = Feed Rate C = Depth of Cut

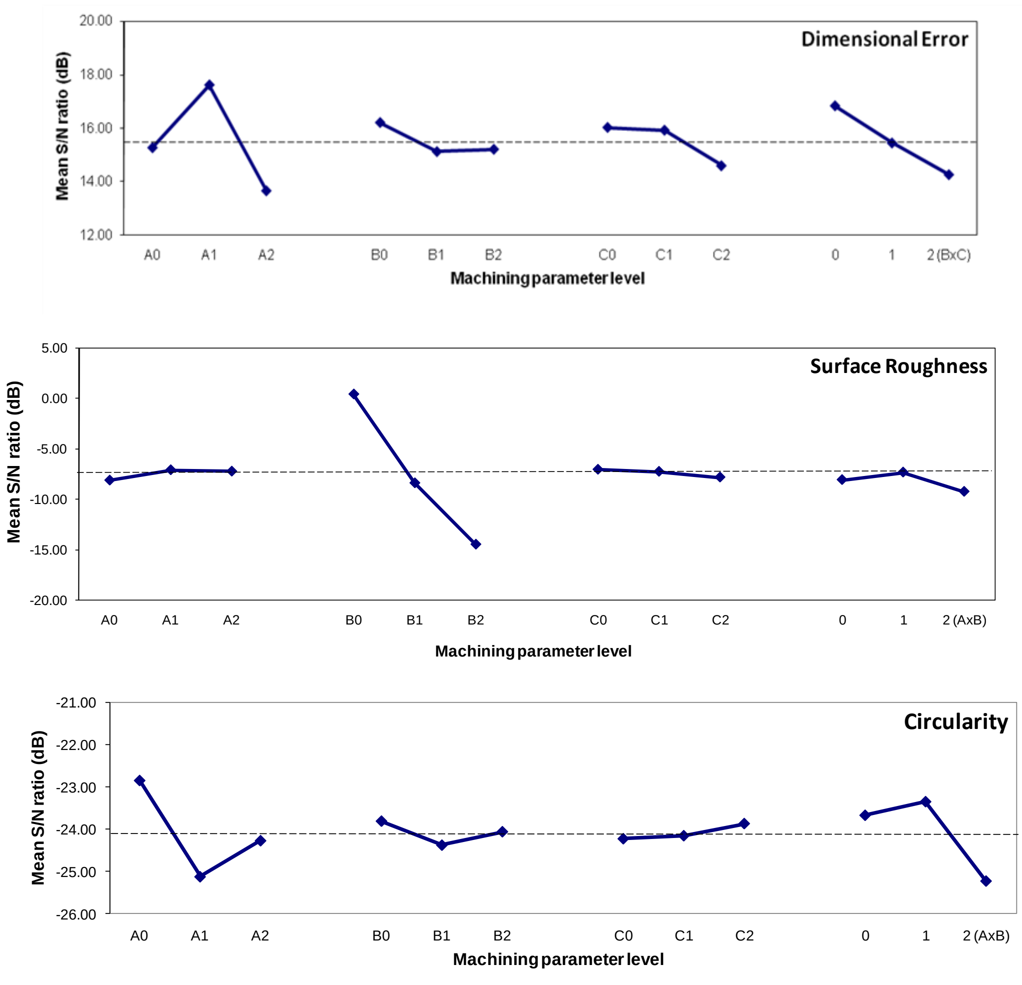


Fig 7 Response graphs for dry turning operation