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Research Paper

HIGH SPEED CNC MACHINING OF AISI 304 STAINLESS STEEL; OPTIMIZATION OF PROCESS PARAMETERS

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This study highlights optimization of CNC high speed milling process parameters to provide better surface finish as well as high material removal rate. The surface finish and material removal rate have been identified as quality attributes and are assumed to be directly related to productivity. In order to build up a bridge between quality and productivity, and attempt made to optimize aforesaid quality attributes in small and medium size companies involved with heterogenic product demand. This invites a multi-objective optimization problem which has been solved by DOE based genetic algorithm optimization procedure. The response surface method of Box- Benkhen method has been adapted to get multi objective optimization problem. The methodology found to be useful in simultaneous optimization of more number of responses.

Keywords: CNC milling, Optimization, Surface finish, DOE, ANOVA, Material removal rate, Box-benkhen method, Stainless steel

INTRODUCTION

High speed machining has become increasingly imminent for small and medium scale enterprises to stay in contention of the hectic competition and to get through the agile, lean and heavy demand patterns of today. The usage Alloy steels increasing day to day in fields of engineering especially the stainless steel materials for precision component industries, which demands high accuracy, high quality and frequently varying quantity requirements. In this paper Stainless steel AISI 304 material is taken for the study to determine the parameters and to optimize with Design Of Experiments (DOE) based Response Surface Method (RSM) to find the optimal parameter set as per the requirements of the user of the high speed CNC machine. Accordingly with the suggested technique the process planners can decide on the input parameters to attain the required quality of the product in time to meet the demand. The

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proposed method is found to be most useful for job order type production houses deals with precision components. The study and the results of the experimentation shows improvements in machining input parameters like Speed of the spindle, feed rate, Depth of cut with 12 mm flat bull and ball end milling cutters. The components are with better accuracy and faster production rate with optimal input parameters which minimizes the machining time, while improving the accuracy (Ra) and Material Removal Rate (MRR).

LITERATURE SURVEY

Mike *et al.* (1999), have developed a surface roughness prediction method using regression analysis for CNC end Milling is the first of its kind in development of the importance of precision machining and surface roughness (Mike *et al.*, 1999). The real frame work was developed by the study conducted by Yih-Fong and Fu Chen (2005) on two phased parameter optimization for better accuracy by Taguchi's robust design method, which prompted the two phase analysis technique with Taguchi's DOE and simultaneous optimization procedure to give away the various parameters on surface roughness requirements followed by a case study. The study conducted for turning process with cutting force modeling with tool wear rate by dynamic signal reading procedure was developed, though it is a significant development but failed to recognize the other important factors of real time process. Abele and Frolich (2008) have compiled the case study of high speed milling of titanium alloys have provided base for different metallurgical and machining conditions to be taken into account for the study. The case study conducted for the titanium based alloys were conducted for the high speed milling process for sets of input parameters with moderate cutting speeds and feed rate to get better material removal of aircraft materials. The rapid introduction of the computational intelligence in product data engineering was insisted for computerized solutions for optimality of the CNC environment. Expressions for entry and exit angles and limiting combinations of feed rate, spindle speed, and tool radius for chip formation are also studied to improve cutting conditions in milling. Kaladhar *et al.* (2010) developed the optimized parameters of turning process of AISI 202 Austenitic stainless steel by Taguchi's DOE model with constraints as the material cutting conditions and parameters were optimized with the study ended up at middle point strategy of operator, but provided wide knowledge of the stainless steel 202 and operating conditions to be taken in to consideration. Aman and Hari (2005) reviewed various linear and non linear optimization techniques were studied in detail and relative advantages are also discussed and inferred for the non linear optimization methods are the most suited for the optimization of machining processes. Study on optimization of CNC milling process parameters using PCA based Taguchi method by Sanjit *et al.* (2010) had served the purposes of optimization but not simultaneously optimize the surface roughness and the material removal rate. The study instead used cumulative method to approximate the effect of the parameters to reduce it into single objective problem. Abdullah *et al.* (2006) had conducted the optimization experiments in stainless steel milling but addressed the improvement of Surface roughness for the conventional CNC machine. The paper by Palanisamy *et al.*

(2007) had established cutting parameters are the most valuable in terms of providing high precision and efficient machining and the optimization of parameters for milling is important to minimize the machining time and cutting force, increase productivity and tool life and obtain better surface finish.

The work is to provide a comprehensive solution to the optimal output of the lowest average surface roughness with optimally high rate of material removal for the finish operation of the stainless steel with the best of the high speed machining operation (Zolfaghariy and Liang, 2002; Yih-Fong and Fu Chen, 2005; and Sanjit *et al.*, 2010). The literatures have generally discussed the factors and parameters with single objective and the same have given us the base idea of the various factors involved and the parameters to be studied with this case study. The improvements and strides of the earlier researchers are taken as benchmark for the start up of the work, and one of the relevant areas of improvement at simultaneous optimization of the parameters is studied in this paper. The need for optimized parameter set for best roughness measures with improved metal removal rate by controlling the relevant parameters. This study excludes and fixes less influencing tool wear, cooling method, Cutting force, tool geometry and tool metallurgy and many other factors as they were discussed in detail by the researchers and got optimized earlier, hence the contributions by the researchers are considered as best suited and kept as constant and referred as least influencing factors for the simultaneous optimization. The contribution of researchers on the factors and parameters considered in this study taken based on the bench mark studies. The chemical composition of the machined work piece material is shown

Chemical composition (wt. %) of AISI 304

Element	C-	Si-	Mn-	Cr-
wt %	0.02-	0.32-	1.31-	16.38-
Mo-	P-	S-	Ni	
2.03-	0.30-	0.20-	12.17	

PROBLEM DESCRIPTION

After the detailed study of the literature and a on the job study conducted at advanced manufacturing Technology laboratory of Coimbatore Institute of Technology, Coimbatore, and SME grade companies of 3 PPM level of quality assurance to their clients of Japan and Germany, when considering with surface roughness deviations, are Sri Gowrish CNC (P) Ltd., Sri Parthasarathi CNC (P) Limited, Genuine CNC consultants, Chinnavedampatti, Ganapathi, COINDIA tool room at Coimbatore 641006, South India. The CNC based job order companies involved in precision components manufacturing to equipment manufacturers of Japan and Germany and to the local market inside India. The study reveals the surface roughness is the most important requirement along with geometrical and dimensional qualities with its tolerance levels. The choice of High speed CNC manufacturing process is based on cost, productivity and quality requirements to attain best possible surface quality within the given constraints for precision components. The indicator of surface quality on machined parts is the value of surface roughness or the waviness. The surface roughness is mainly a result of various controllable or uncontrollable process parameters (Figure 1) and it is harder to attain and track than physical dimensions. A considerable number of studies have researched the effects of the cutting speed, feed, depth of cut, nose radius and other factors on the surface roughness (Zolfaghariy and Liang, 2002). In recent studies, the effects of some factors on surface roughness have been evaluated and models are developed but failed to address the requirements of the end operator, who decides on the input parameters and ground realities. The goal of this study is to obtain a mathematical model that relates the surface roughness to three cutting parameters in face milling, precisely to the cutting speed, feed rate and depth of cut. In this work DOE based approach is used to get the mathematical model and Box Behnken model analysis used for the optimized parameter set. Case study method is adopted for parameter study and Design Of Experiment (DOE) with analysis and Regression Analysis (RA).

Surface Roughness

The surface parameter used to evaluate surface roughness in this study is the roughness average (Ra). The roughness average is the area between the roughness profile and its central line, or the integral of the absolute value of the roughness profile height over the evaluation length. There are a large number of factors influencing the surface roughness and Figure 2 shows all influential factors on machined surface roughness (Lin, 2002). The roughness component of surface

Figure 1: Fish Bone Diagram for Surface Roughness Parameters

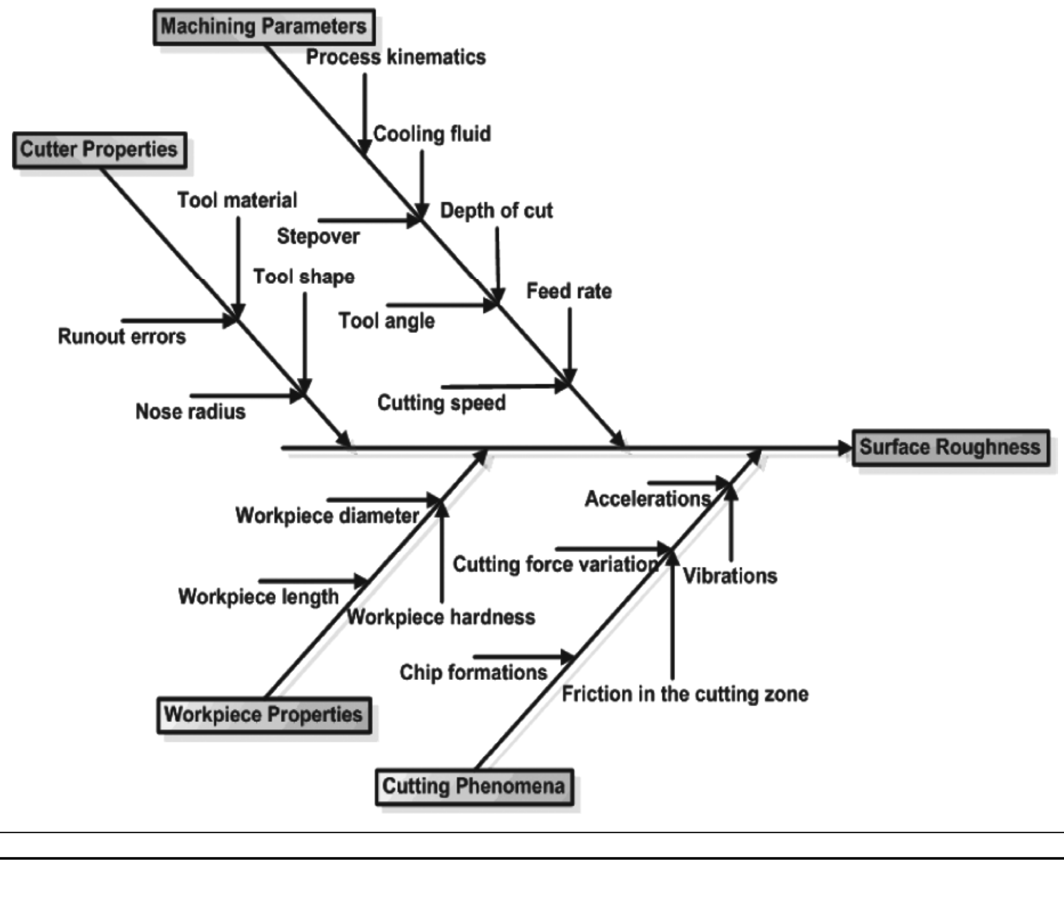
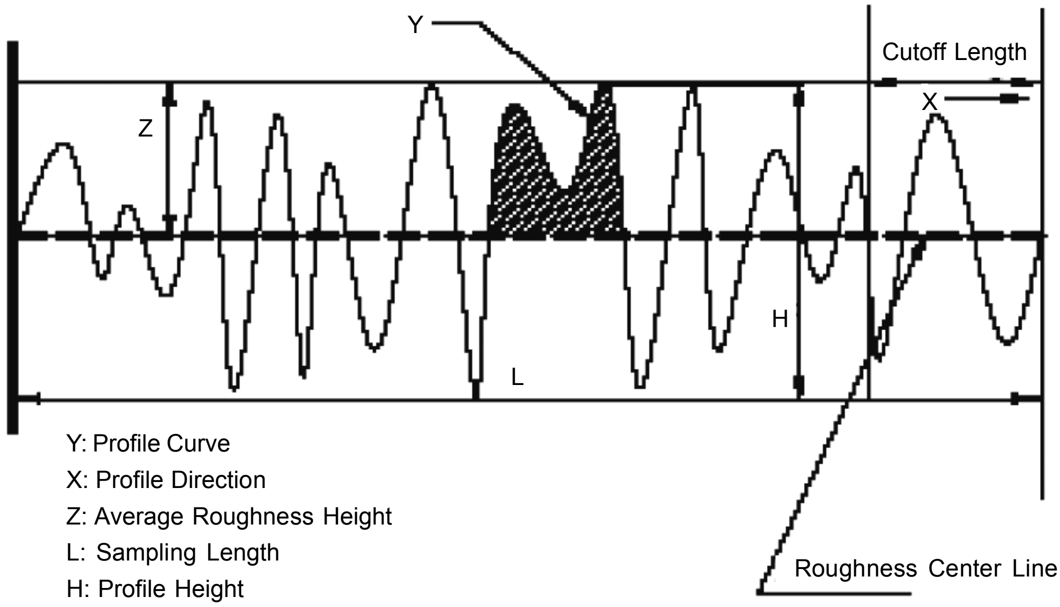


Figure 2: Surface Roughness Profile



is generally quantified by the parameter roughness average (Ra), is an effective parameter representing the quality of machined surface. Ra is the area between the roughness profile and its mean line, or the integral of the absolute profile height over the evaluation length as shown in Figure 2.

Therefore, the *Ra* is specified by this equation:

$$Ra = \frac{1}{L}\int_0^L |Y(x)|\, dx \qquad ...(1)$$

Material Removal Rate

From this equation, *Ra* is the arithmetic average deviation from the mean line, *L* is the sampling length, and *Y* is the ordinate of the profile curve. Material Removal Rate (MRR) has been calculated from the difference of weight of work piece before and after the experiment (Yih-Fong and Fu Chen, 2005).

$$MRR = W_i - W_f / r_s t \qquad ...(2)$$

W_i – The initial weight of the work piece in grams;

W_f – Final weight of the work piece in grams;

r_s – Density of the material in grams/mm^3;

t – Time taken for machining (cutting).

The theoretical calculation of material removal done to verify the values obtained from volumetric measurements.

$$MRR = \frac{D_c \times F_r \times Dia\ of\ Cutter \times Length\ of\ Cut\ on}{Total\ No.\ of\ Seconds\ for\ the\ Cutting} \qquad ...(3)$$

Tangential force component for the cutting operation is given by

$$F_t = Ks\ D_c\ f_r \sin\theta + D_c \times Edge\ Force\ Constant \times Flank\ Wear\ Width \qquad ...(4)$$

Axial force component for the cutting operation is given by

$F_r = R_1 Ks\, D_c\, St \sin\theta + R2\, D_c \times Edge\ Force\ Constant \times Flank\ Wear\ Width$ ...(5)

EXPERIMENTAL METHOD

Stainless steel 304 the frequently used material for precision products, is studied for the high speed milling characteristics. The samples were annealed at 800 °C for 30 min to relieve stress. Hardness of material was also recorded at room temp of 25 °C. The roughness parameters were analyzed in the feed direction using a Mitutoyo roughness control instrument. Measuring parameters are as listed and studied include the average (R_a) and the maximum (R_t) height of surface profile and MRR. The Cutting speed (V_c) m/min and Feed per tooth (F_r) mm/rev/tooth, Depth of Cut (D_c), Hardness (H), type of tool used are taken as variables (Zolfaghariy and Liang, 2002; and Sanjit *et al.*, 2010). The above are considered after careful study of the literature and based on the listed small and medium companies around Coimbatore for about Two years of their production systems, manufacturing, products and customers. The proved DOE method for 4 nos of factors with 4 nos of blocks proposed by George P Box and Donald Behnken experimental method for response surface methodology. An L27 array (Total numbers of experiments with extra center points) is considered to conduct the experiment as the other DOE method does not facilitate the simultaneous optimization of two responses.

The experiments were conducted in standardized equipment listed in the machine configuration. DECKEL MAHO, a 4 axis milling center is used for the study and with the parameters and ranges stainless steel 304, the commonly used material for precision products, used to study the high speed milling characteristics. The roughness parameters were analyzed in the feed direction using a Mitutoyo roughness control instrument. The Cutting speed (V_c) m/min and Feed per tooth (f_r) mm/rev/tooth, Depth of Cut (D_c), type of insert used are taken as variables. The above are considered after the keen study on the listed small and medium companies around Coimbatore for about Two years of their production systems, manufacturing, products and customers. A DOE of L27 array was taken to conduct the experiment and the experiments were conducted in standardized equipment listed in the machine configuration. DECKEL MAHO, a 4 axis milling center is used for the study and with the parameters and its ranges. Machined surface finish and material removal rate are two important aspects of CNC milling, which require attention both from industry as well as in research and development. The high speed CNC machines are considered most suitable for these manufacturing systems and capable of achieving reasonable accuracy and surface finish. The need for a soft computing tool that evaluates the surface roughness and material removal rate value before the machining of the part, which can easily be used in the production-floor contributing to the minimization of machining time and cost of production for the desired surface quality.

Factors and Their Ranges

The input parameters of Spindle speed, Feed, depth of cut and insert type were taken as factors (Table 1) for the experimentation of the design of experiment stage. The correlation between the input parameters and the responses Ra and MRR are ascertained and the deviations with respect to the input

Table 1: Factors and Range

Factor	Range
Spindle speed (V_c) rpm	3000-12000 rpm
Feed rate (f_r) mm/s/teeth	600-1800 mm/s
Depth of cut (D_c) mm	0.40-1.00 mm
Depth of cut (D_c) mm	0.40-1.00 mm
Cutter type	Bull, Flat and Ball of 12 mm diameter

Table 2: L27 Array with Values of Ra and MRR

Speed (rpm)	Feed (mm/s)	Depth of Cut (mm)	Ra (mm × 10^{-5})	MRR (mm^3/s)
3000	1800	0.2	1.57	84.9256
3000	1200	0.3	1.24	161.2903
3000	1200	0.1	1.32	50.50505
3000	600	0.2	1.26	105.8201
7500	1800	0.3	0.93	215.0538
7500	1800	0.1	0.24	277.7778
7500	1200	0.2	0.68	196.0784
7500	600	0.3	0.34	588.2353
7500	600	0.1	0.21	317.4603
12000	1800	0.2	0.63	211.6402
12000	1200	0.3	0.58	344.8276
12000	1200	0.1	0.55	121.2121
12000	600	0.2	0.53	251.5723
3000	1200	0.2	0.35	380.9524
7500	1800	0.2	0.39	341.8803
7500	1200	0.3	0.29	689.6552
7500	1200	0.1	0.35	190.4762
7500	600	0.2	0.29	459.7701
12000	1200	0.2	0.29	459.7701
3000	1200	0.2	0.26	512.8205
7500	1800	0.2	0.32	416.6667
7500	1200	0.3	0.34	588.2353
7500	1200	0.1	0.56	119.0476
7500	600	0.2	0.20	666.6667
12000	1200	0.2	0.26	512.8205
7500	600	0.3	0.43	568.2353
12000	1200	0.3	0.68	354.8276

parameters are also analysed using Design Expert R8 software package. The factors and its range is listed in Table 2.

RESULTS

Case study was conducted and the parameters were chosen from the factors involved in the process and the impact of the factors on the final result was taken to account and the results were taken for regression and correlation analysis using design expert-commercially used mathematical analysis software. The experiment is designed in such a way to represent all the possible operations and conditions in the entire range of the parameter to give better insight on each of the parameter and its influence on the results of the Surface roughness (Ra) and the Material Removal Rate (MRR). The experimental result of L27 array as listed and reveals that the coded factors are very much relevant and enough to decide on the optimum cutting parameters vide Spindle speed, Feed per tooth, Depth of cut and insert types as bull, flat and ball nose cutter of all 12 mm diameter. The following quadratic equations inclusive of the design parameters were obtained from the software package .

Prediction Equation for Computing the Value of Ra with Actual Factors

Minimize $Ra = +\,0.68 - 0.26A + 0.10B + 0.023C + 0.017D - 0.052AB + 0.027AC - 0.020AD + 0.14BC - 5.000 \times 10^{-0.3}BD - 0.012CD + 0.2A^2 - 0.040B^2 - 8.750 \times 10^{-0.3}C^2 - 0.39D^2$ ...(6)

Prediction Equation for Computing the Value of MRR with Actual Factors

Maximize $MRR = +\,196.07 + 47.41A - 4.63B + 127.35C - 27.38D - 4.76AB + 28.21AC +$

$28.86AD - 69.88BC + 33.03BD + 25.36CD - 36.80A^2 + 66.94B^2 + 23.80C^2 + 221.84D^2$ ...(7)

When the parameters obtained are optimum and can be treated as the desired set. The surface roughness and Material removal rate are completely controlled by the above factors and by keeping the Spindle speed as high, moderate feed rate and above moderate value of depth of cut for bull and flat type cutters of 12 mm diameter is suggested for the stainless steel material of AISI 304 grade. This is because all surface roughness characteristics follow Lower-the-Better criteria at the same time the objective is to improve surface finish. In this computation it has been assumed that all quality features are equally important (same priority weightage).

DISCUSSION

The input values are also listed and the MRR values were computed to find the maximum among the listed values. The list of inputs and the responses were analyzed using the graphs shown below. The enlisted values gives us the sets of operating parameters for the optimum surface finish for the precision machining of the AISI 304 stainless steel material. This method is giving the best set of parameters by which the end user, i.e. The small and medium scale companies involved with job order type production of precision parts.

The Figures 3, 4 and 5 shows the values of *Ra* and *MRR* are mainly dependent of the input parameters and relatively has the complexity of suggesting a particular factor is more dominating. The general idea that can be derived is that the input parameters are equally vital and has a cumulative effect on the responses. Thus it is to be noted the domain space of the feasible solution is wide ranged inside the confirmed domain surrounded by the parameter ranges. The planner has to decide based on the above

Figure 3: Ra vs. Depth of Cut, Feed Rate

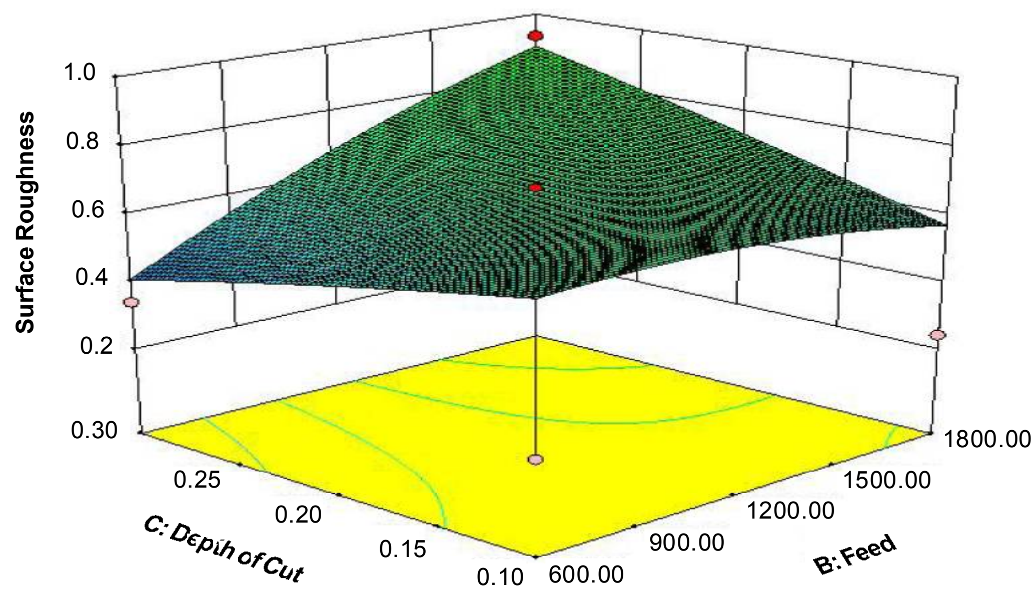


Figure 4: Ra vs. Depth of Cut, Speed

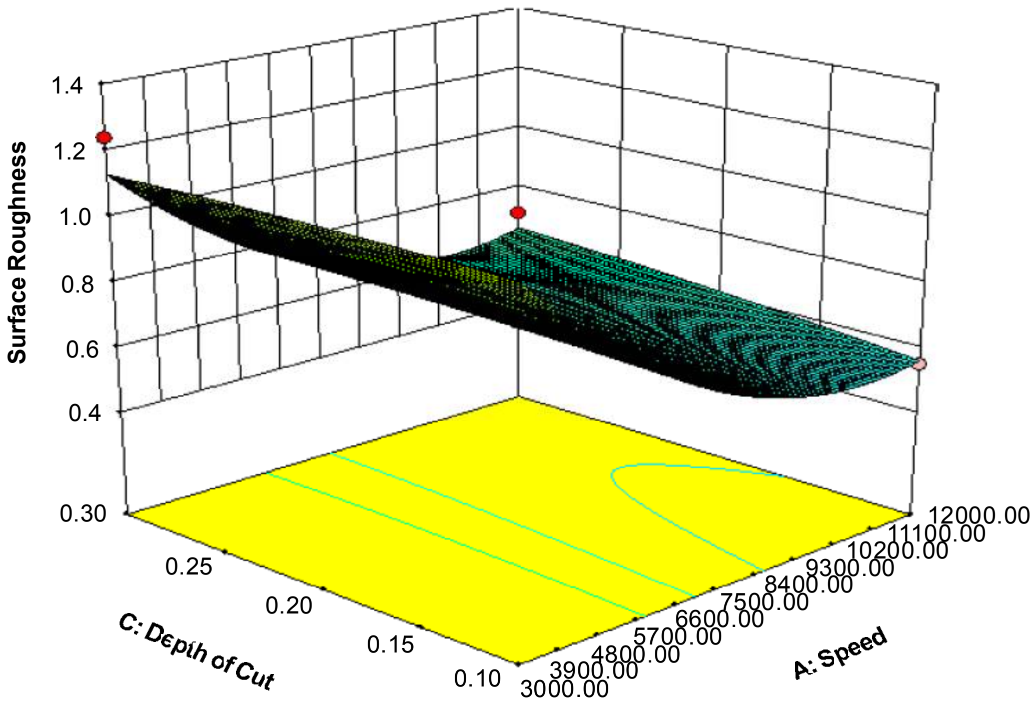
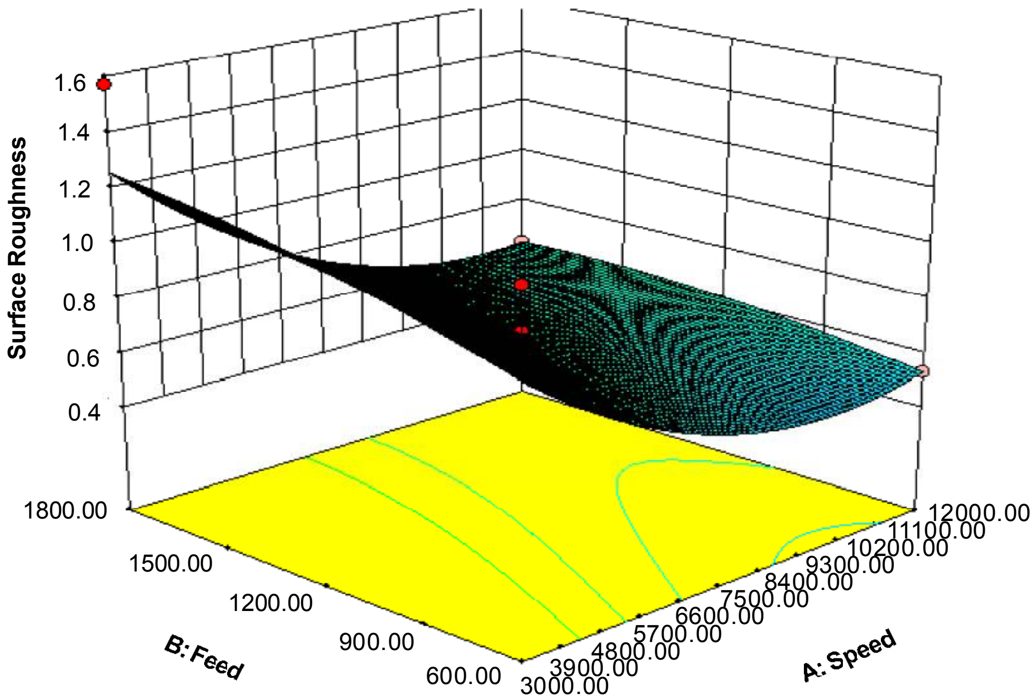


Figure 5: Ra vs. Feed, Speed



graph that the required level of R_a say 20-40 micron finish, it is recommended to choose higher depth of cut(D_c) say 0.9 -0.95 × Max value of the cutting tool manufacturer specified parameter range instead of the mid value to get the best values of MRR, where the Speed of the spindle and feed rate may also be taken more than the mid value to get the desired levels of Ra and MRR.

The Figures 6 and 7 shown in clearly indicates the variation of R_a with respect to the

Figure 6: MRR vs. Depth of Cut, Feed

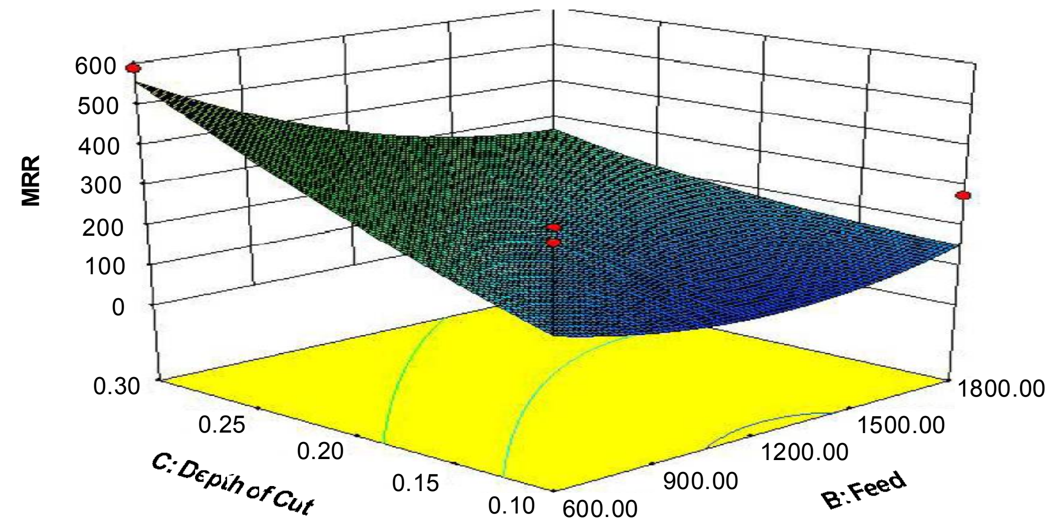


Figure 7: MRR vs. Depth of Cut, Speed

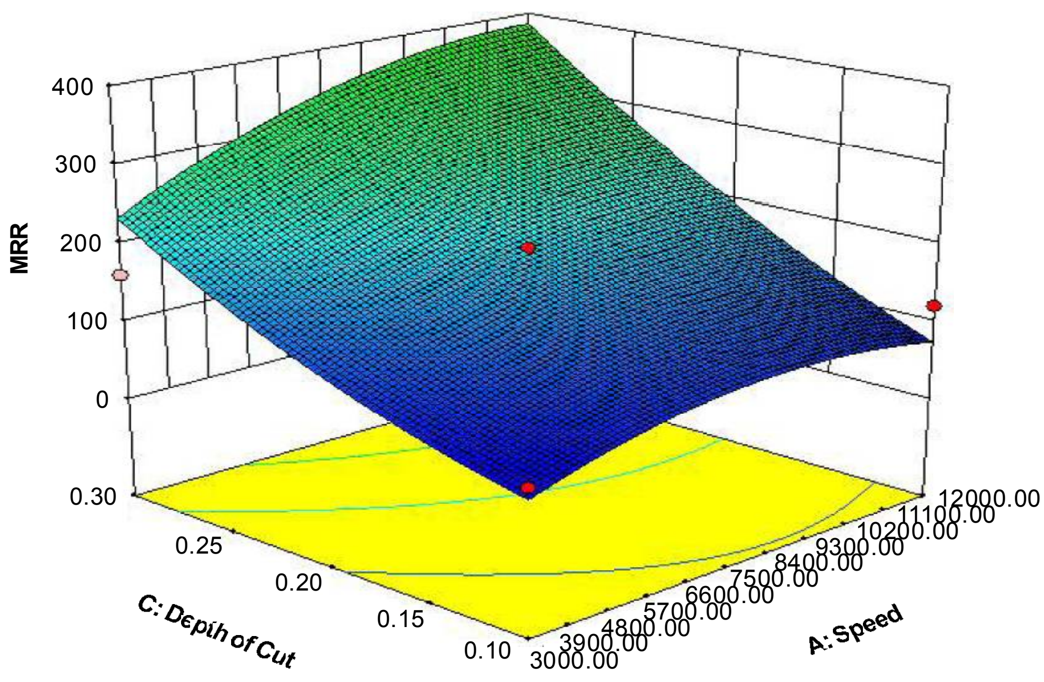
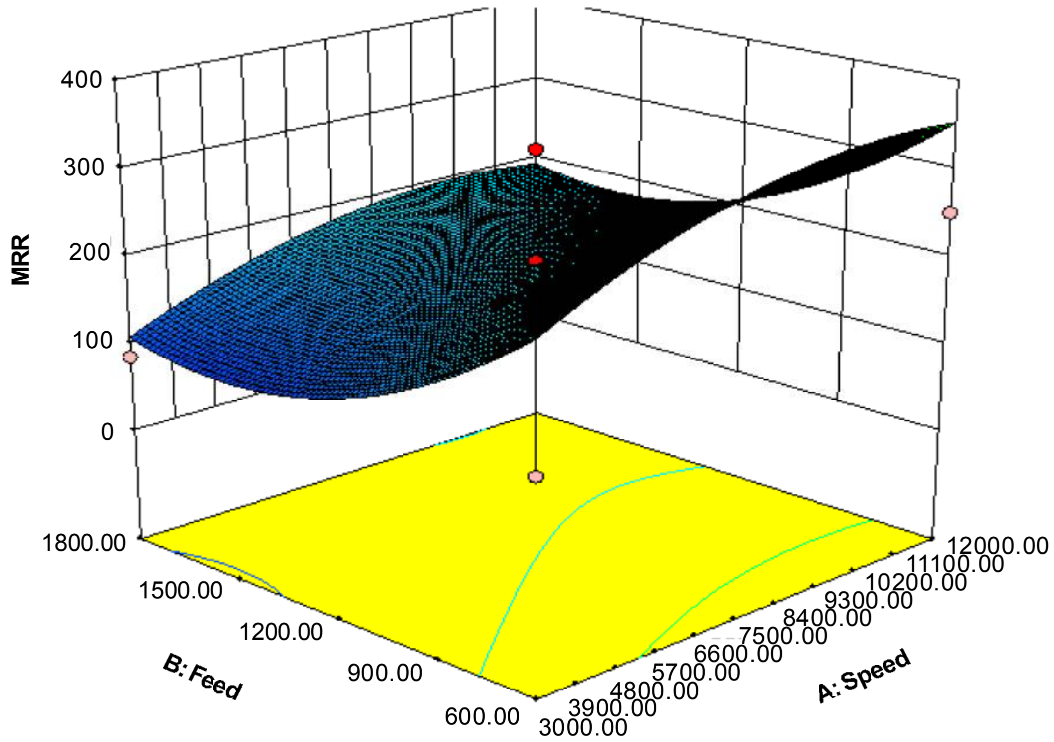


Figure 8: MRR vs. Feed, Speed



input parameters in the 3 dimentinal mode to accommodate comparison of more than one factor at a time and draws a conclusive non mid point optimum for the different input parameter. Thus it could be inferred such that the mid point strategy of these SME's can be replaced with our methods of deciding the optimum parameter values to improve their performance without affecting the quality, i.e., surface roughness requirements.

Similarly from the 3 dimentional graphical illustrations the broadly used mid point selection of the input parameters were proved non optimum but generally serves the purpose by increased spending of time and effort. Thus the mid point strategy of choosing the input parameters and thump rule based selection procedure can be restructed with scientifically proved and easy method provided by this study. The higher the depth of cut (0.28 mm) and feed rate (1360 mm/s) would yield better material removal rate with relatively good surface roughness values using a spindle speed (12280 rpm) more than the mid value, which improves productivity.

The multi objective simultaneous optimization methodology yielded the results with Min of Ra 0.0167 mm or 16.7 microns at material removal rate of 272 mm^3/s. To validate the results the machining operation is carried out to confirm the results for the input parametric values of Spindle speed 12280 rpm, Feed rate of 1290 mm/s, with 0.29 mm of depth of cut for the bull type cutter performed and found with a variation of 3.16% from the predicted values according to the given input. The results were encouraging and found useful in performance improvement and optimized operation to reduce time of cutting and to improve the material removal rate while getting improved surface roughness values.

CONCLUSION AND FUTURE WORK

The experiments and analysis of the experimental data in connection with multi RSM optimization of high speed CNC end milling operation has been found useful to get optimum parameter setting. Referring to the Figures 3, 4 and 5 the values of Ra is more affected by the upward variation of the depth of cut and feed rate than that of the spindle speed but has a significant influence over the responses. Hence the parameters considered are vital and decisive towards responses. Hence it is to be noted that the depth of cut is the most critical factor for attaining the desired MRR while reducing the value of Ra. While comparing the results of the Figures 3-8 the material removal rate in the range of 200-600 could be achieved with a surface roughness value of less than 0.6-0.2 microns. The operator is now free to choose any of the parameter set to achieve the required MRR while maintaining the quality surface finish. This approach is efficient enough to solve a multi-response optimization problem. Test run conducted for validation, the parametric setting determined by the method yielded about 11.83% of improvement in productivity on implementation in the companies of field study.

The said approach can be recommended for continuous quality improvement when compounded with intelligent process controller of a process/product. The efforts are on for getting even better solution and compatibility by further optimizing the process parameters by a meta heuristic algorithm based solver and a on line process optimizer in the same machine. The possibility of including more numbers of variables and objectives as fitness functions being explored. A holistic solution approach is also proposed for intelligent module for parameter setting of the machine according to the requirement of the company.

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