Investigation of Machining Process Parameters in the context of Geometric Dimensioning and Tolerancing (GD & T)

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in

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by

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1. Abstract

Machining attributes to a major channel of manufactured goods. The machined component manufactured should be able to achieve both the geometrical and dimensional requirements. To apply the concept of design for manufacturability, the designer specifies tolerance on the parts in order to meet the functional requirement as well as for cost effective manufacturing. For cost effective manufacturing predictive models need to be developed, which in turn could be used to decide the optimum value of input process parameters. These parameters in the right combination help to achieve the desired output, i.e. to optimize geometrical error on machined components, vis-à-vis functional requirements.

Machining is carried out on a vertical machining center. A case study of dual plate check valve and nozzle check valve is analyzed in the context of GD & T. The range of input parameters such as Cutting Speed, Feed and Depth of Cut are decided by standards and process capability. The response parameters are flatness & surface roughness in face milling operation, while cylindricity & perpendicularity in drilling of WCB (Wrought Cast Steel - Grade B) material. Reliable experiments on the basis of Design of Experiments (DOE) were performed, as DOE is a useful method in identifying the significant parameters and in studying the possible effect of the variables during the machining trials. The parameters related to dimensions and geometry has been measured using Coordinate Measuring Machine (CMM), while surface roughness is measured using surface roughness tester.

The ANOVA was performed to know the significance of the process parameters and its influence on the responses. The data is used to develop predictive models, which in turn helps in deciding the best process parameters for optimizing geometrical error. The models' adequacy has been checked by calculating correlation coefficient. It shows that the developed models are well fitted for the prediction of responses within the specific range of input variables. The soft computing technique fuzzy logic is used to predict the responses and it shows that the predicted and experimental values are very close. This shows the validity of the fuzzy model for further use. Thus the developed models will be very useful to the practicing engineers.

2. Brief description of the state of the art of the research topic

Rigorous work has been carried out by the researchers for the modelling of surface roughness by varying machining and other parameters. Even though the surface roughness is better and within limit; there still exists assembly problems occurring due to various geometrical errors present in the mating parts. Few researchers have reported the reasons of these geometrical error sources in high speed milling by considering machine geometry, thermally induced error, path trajectory planning, clamping force and cutting force etc [10, 39, 48]. Various compensation strategies for these errors have been developed, but it becomes insignificant at different spindle speeds. So, machining parameters plays a vital role in deciding the geometrical tolerances. These geometrical errors must be quantified at the design stage itself to meet the functional requirements and to ensure assembly of mating parts in the most economical manner. For taking such decisions the designer must be aware of the machine capabilities, optimal parameters and the customer specifications. But the machine tool capabilities in the context of geometric tolerances are little investigated. So, here an attempt is made to develop a procedure and later on models of few geometrical errors, which would help in predicting geometric tolerances in context of its machining process parameters.

In today's era of competition GD & T technology has become handy for designers of products to instill right quality through finer geometrical details meant to ensure assembly of parts without compromising the functional requirements. The quest for better quality products and GD & T go hand in hand. These developments prompted in the selection of this topic for research. Automobile industries in variably use GD & T to roll out vehicles with improved satisfaction of customers both functionally and economically. In line with that this work is proposed to be carried out for quality improvement and to fulfill the functional requirement of the customers during valve manufacturing, by incorporating the GD & T concepts. Designs without GD & T are same as the diabetic patient without insulin.

3. Definition of the problem

In the present work the case studies of dual plate check valve and nozzle check valve are considered. The geometrical tolerances of the mating part impact a lot on the assembly and performance of these valves. These tolerances are ensured on machined components through various machine tools according to the process sequence. In order to achieve these capabilities of machine tools vis- a vis tolerance need to be experimentally indentified. Though the designers specify the tolerance to meet functions, the machining parameter values to achieve that tolerance need to be derived. So, predictive models of these geometrical tolerances are derived in the context of machining parameters, which in turn helps to optimize the geometrical error on the machined part. The valves are made of different materials like WCB, CF8, CF8M, CF3, CF3M, INCONEL and Aluminum bronze. But around 80% of the valves are manufactured using WCB due to its low cost along with its functionality, and the same is selected as base material for experimentation.

The flatness on the milling components is of prime importance in dual plate check valve as shown in Fig. 1. Here two matting planar surfaces together create metal to metal seal, for a dual plate check valve. A perfect metal to metal seal without significant rocking can be achieved by desired flatness and proper surface roughness. Researchers have developed a fuzzy logic & regression based model to predict surface roughness during face milling operation [14, 22, 23, 40, 43, 49]. It seems that the investigation of geometrical features along with the surface roughness needs to be addressed to meet the functional requirement of such kind of products produced with face milling operation, as surface roughness and flatness control helps in reduction of leakage and subsequently it helps in meeting the functional requirement of an assembly. So, the investigation of flatness and surface roughness of WCB material creates new scientific domain in the machining. The selection of proper cutting parameters for milling process becomes a vital requirement for reduction of rework and to increase the productivity. Few main parameters like Spindle speed, Feed rate, Depth of Cut are considered for the present investigation. Their right selection may optimize the flatness error and surface roughness during machining.

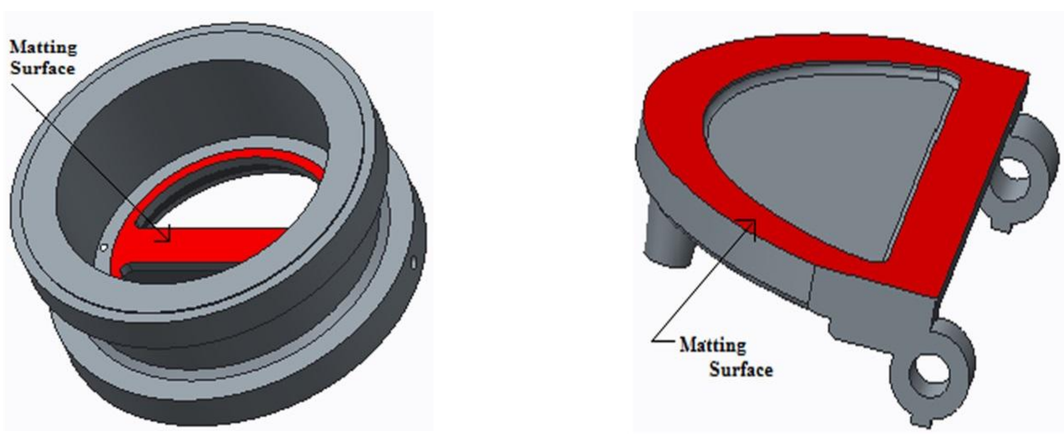
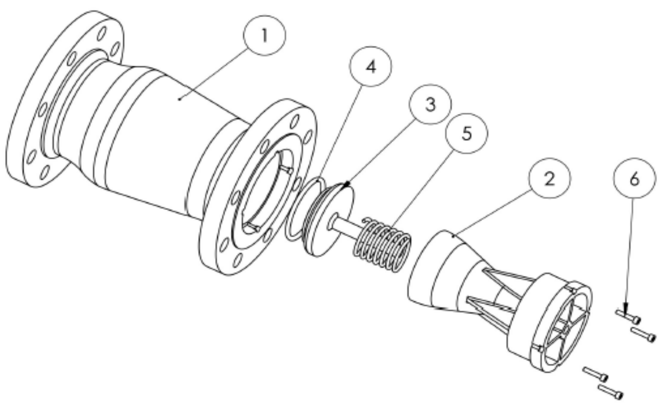


FIGURE 1 Conceptual Sketch of Dual Plate Check Valve

Fig. 2 (a) shows the exploded view of nozzle check valve with different parts. Here part 3, i.e. disc stem, has to slide in the part 2, i.e. diffuser. It seems that the geometry of mating parts play a vital role in assembly, leakage and fluttering at high pressure. So, these two parts have to be produced carefully with proper tolerances for fulfilling the functional requirements. Cylindricity and perpendicularity tolerances are playing vital role in reducing the fluttering at high pressure which can be seen in Fig. 2 (b).



PART NO	PART NAME
1	BODY
2	DIFFUSER
3	DISC
4	ORING
5	SPRING
6	SCREW

FIGURE 2 (a) Exploded View of Nozzle Ckeck Valve

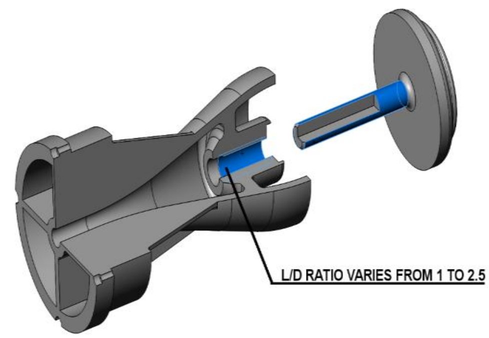


FIGURE 2 (b) Sketch of Mating Geometry

4. Objectives and scope of the problem

- To develop empirical models of geometrical errors for the specific range of input parameters.
- To identify the optimum value (Multi Objective Optimization) of input process parameters in the right combination for the desired output, this in turn minimizes geometrical error on machined components.
- To use the artificial intelligence (Fuzzy logic) in modeling.

5. Original Contribution of the research

5.1 Case of face milling operation

Experiments are carried out on blocks having size of 60 mm x 60mm x 50 mm of WCB material. Spindle speed, Feed and Depth of cut are selected as input variables to perform experiments according to 2^3 full factorial with four center points experimental design. The levels of input variables are shown in Table 1. Machinability tests were carried out on the 3-axis CHIRON FZ 16 L/CNC Milling having spindle motor power of 5.7kw. Miracle coated VP15TF insert is used. WCB block is clamped by using hydraulic vice and all six sides of the block is initially machined and then after that face milling process is carried out on each face of block to create 50 mm wide slot throughout length. Here no. of passes and coolant flow rate are kept constant.

TABLE 1: Factors and levels

FACTORS	CODED FACTORS	Low (-)	Center Point	High (+)
Spindle speed (rpm)	A	500	850	1200
Feed rate (mm/min)	B	150	225	300
Depth of Cut (mm)	C	0.1	0.3	0.5

Inspection of geometrical tolerances is a complex task, because geometric errors are related to three-dimensional features and estimation of this type of error is usually based on a cloud of points that has to be measured on the machined surface. Coordinate Measurement Machines (CMM) are the most common equipment for 3D measurement in the mechanical field, because of their accuracy and flexibility [42]. Here flatness measurement is carried out on hexagon make CNC co-ordinate measuring machine, with temperature compensating probe. Raghunandan et al [34] worked on an optimum sample size for flatness error estimation while using CMM. They have suggested method and strategies for accurate measurement of flatness error at reduced sample size in batch and mass production. For measuring flatness, rectangle grid extraction strategy is used to extract points from the surfaces [35- 37].

Points are extracted from the surfaces having 35 mm x 35 mm cross section with 5 mm grid size. Surface roughness measurement is carried out on Surf test SV-2100. The cut off length (measuring length) is 4.8 mm with probe speed of 0.50 mm/sec. The responses in terms of the coded factors and treatment combinations using 2^3 full factorial with the four center points are shown in Table 2.

TABLE 2: Results of flatness and surface roughness for various treatment combinations

Treatment combination	Coded factors			Responses	
	A	B	C	Flatness (mm)	Surface Roughness (μm)
1	-	-	-	0.027	2.1195
a	+	-	-	0.019	2.1035
b	-	+	-	0.038	5.7466
ab	+	+	-	0.028	4.4532
c	-	-	+	0.026	2.5713
ac	+	-	+	0.023	1.7697
bc	-	+	+	0.040	6.5157
abc	+	+	+	0.028	2.0633
center points	0	0	0	0.021	2.8351
	0	0	0	0.018	2.8004
	0	0	0	0.020	3.0775
	0	0	0	0.018	2.4305

5.2 Case of drilling operation

The test specimen made of WCB, used for drilling operation is having 240 mm x 160 mm x 55 mm size. Machinability tests are carried out on the 3-axis VMC VF2SS machine. The tool insert used is SOMX 050204 DT, which has been produced by ISCAR Ltd. The Block is clamped using a hydraulic vice. The bottom surface is machined to create a qualified datum feature, which acts as a primary datum. Then work piece is located on the qualified datum for further machining & the slot is created on the top surface to generate a new qualified surface, which will be useful for measurement. Holding the plate in the same position all the holes are drilled. Total 54 experimental runs are performed for various combinations of the input factors as 3^3 full factorial designs with 2 replicates are selected. The factors along with its levels are shown in Table 3. Three plates of size 240 mm x 160 mm x 55 mm are drilled with each plate having 18 holes of 20mm diameter and 40mm depth (L/D ratio is 2).

TABLE 3: Factors and levels

FACTORS	CODED FACTORS	LOW(1)	MEDIUM(2)	HIGH(3)
Spindle speed (rpm)	A	1200	1400	1600
Feed rate (mm/min)	B	100	150	170
DOC / CAN cycle (mm)	C	1	1.5	2

Measurement of cylindricity and Perpendicularity

The four cylindricity measuring strategies are: a) the strategy for measurement of roundness profiles b) the strategy for measurement of generatrix lines c) the bird-cage strategy (which is a combination of measurement of roundness profiles & generatrix lines) d) point strategy [19]. Here measurement of cylindricity was carried out by moving a probe into the spiral fashion for 720^0 rotation which covered 30 mm depth [20, 51]. The intermediate points during the measurement of one hole are measured with 15^0 angular pitch and 30/48 mm linear pitch. The centre axis of the cylinder has been obtained by measuring cylindricity. The perpendicularity is measured in the context of top plane/ surface. As minimum three points on the top surface decide the datum plane, so here three distant boundary points on the machined surface are used to decide the datum. Table 4 show the results of the measured cylindricity and perpendicularity.

TABLE 4: Results of cylindricity and perpendicularity for various treatment combinations

Run Order	**Treatment combinations**			**Responses**			
				Cylindricity (mm)		**Perpendicularity (mm)**	
	A	B	C	Replicate 1	Replicate 2	Replicate 1	Replicate 2
1	1	1	1	0.057	0.055	0.088	0.093
2	1	1	2	0.053	0.052	0.100	0.101
3	1	1	3	0.061	0.066	0.102	0.127
4	1	2	1	0.055	0.060	0.093	0.125
5	1	2	2	0.048	0.050	0.125	0.138
6	1	2	3	0.059	0.063	0.134	0.144
7	1	3	1	0.06	0.063	0.138	0.140
8	1	3	2	0.056	0.057	0.147	0.150
9	1	3	3	0.063	0.068	0.153	0.151
10	2	1	1	0.056	0.050	0.049	0.050
11	2	1	2	0.051	0.052	0.064	0.067
12	2	1	3	0.067	0.061	0.079	0.080
13	2	2	1	0.067	0.070	0.067	0.068
14	2	2	2	0.061	0.059	0.082	0.081
15	2	2	3	0.07	0.067	0.091	0.099
16	2	3	1	0.082	0.083	0.075	0.080
17	2	3	2	0.08	0.081	0.082	0.088

18	2	3	3	0.09	0.091	0.093	0.091
19	3	1	1	0.059	0.057	0.025	0.035
20	3	1	2	0.057	0.058	0.046	0.045
21	3	1	3	0.068	0.070	0.059	0.057
22	3	2	1	0.073	0.093	0.036	0.047
23	3	2	2	0.078	0.080	0.052	0.054
24	3	2	3	0.094	0.095	0.060	0.062
25	3	3	1	0.124	0.122	0.044	0.046
26	3	3	2	0.121	0.123	0.056	0.054
27	3	3	3	0.132	0.134	0.062	0.060

6. Methodology of research and Result analysis

6.1 Analysis of variance (ANOVA)

Analysis of variance (ANOVA) assesses the importance of one or more factors by comparing the response variable mean at the different factor levels. It helps to know the significant factors, how each individual factor affects on response and percentage contribution of each factor. The percentage contribution of spindle speed, feed rate and depth of cut/ canned cycle is summarized in Table 5 for various responses.

Table 5: % contribution of machining parameters on various responses

Responses	Spindle Speed	Feed Rate	Depth of cut/ Canned cycle (drilling)
Surface roughness	22.95	32.06	0.52
Flatness	20.67	50.06	1.08
Cylindricity	37.35	35.77	4.31
Perpendicularity	78.89	8.56	6.98

The presence of curvature effect in ANOVA of surface roughness and flatness implies that a higher order regression model is better to represent the situation. More no of experiments in accordance with a rotatable central composite design are performed. This model is relatively more accurate in prediction of responses flatness and surface roughness.

6.2 Regression modeling

The regression model for flatness (Eqn. 1), surface roughness (Eqn. 2), cylindricity (Eqn. 3) and perpendicularity (Eqn. 4) is developed with the help of MINITAB software. Here x1, x2, x3 are the predictor variables corresponding to the spindle speed, feed rate and depth of cut/canned cycle respectively in terms of the coded factors.

Flatness = 0.01925 - 0.004125 x_1 + 0.004875 x_2 + 0.000625 x_3 + 0.009375 x_1^2 - 0.001375 x_1x_2 + 0.000375 x_1x_3 - 0.000125 x_2x_3 - 0.000875$x_1x_2x_3$ (R-Sq = 98.86%) [1]

Surface Roughness = 2.78587 - 0.820425 x_1 + 1.27685 x_2 - 0.18785 x_3 + 0.631975x_1^2 - 0.616025 x_1x_2 - 0.493075 x_1x_3 - 0.21735 x_2x_3 - 0.296675 $x_1x_2x_3$ (R-Sq = 99.18%) [2]

Cylindricity = 0.12413 - 0.0386667x_1 - 0.0335x_2 - 0.0268333x_3 + 0.00577778x_1^2+ 0.0145417x_1x_2 + 0.00544444x_2^2- 0.00125x_2x_3 + 0.000833333x_1x_3+ 0.00752778 x_3^2 + 0.0003125 $x_1x_2x_3$ (R-Sq = 98.04%) [3]

Perpendicularity = 0.0797037 - 0.0615278x_1 + 0.0514167x_2 + 0.0245278x_3 + 0.0104722x_1^2 - 0.008625x_1x_2- 0.00386111x_2^2 - 0.00295833x_2x_3 - 4.16667e-005x_1x_3 - 0.00169444x_3^2 + 0.000125$x_1x_2x_3$ (R-Sq = 97.71%) [4]

R-Sq is the co-efficient of determination, which helps to judge the adequacy of the developed regression model. R-Sq (adj) values for all the models is very much close to R-Sq value, which indicates that non-significant terms are not present in all the models. The R-Sq (pred) value is the variability in the data accounted by the model in percentage. The R-Sq (pred) value obtained for all the models is near to 1, which indicates that high correlation exists between experimental and predicted values.

In order to validate the models of flatness and surface roughness, four new experiments are conducted at different levels with different combinations other than that used to develop the model. Table 6 shows the error of prediction associate with this four new experiments. While to validate the models of cylindricity and perpendicularity, the values predicted by the regression model are compared with the experimental one, which are very close to one another. Error between the predicted and experimental readings for each run is shown in Fig. 3 (a) and (b) for cylindricity and perpendicularity respectively. From this it can be observed that maximum error in predicting cylindricity is 6.62% and minimum error is 0.21%, while predicting perpendicularity maximum error is 5.88% and minimum error is 0.36%.

Table 6: Error of flatness and surface roughness during validation experiments

No. of Experiment	Parameters (Inputs)			Measured Flatness (mm)	Measured Surface Roughness (μm)	Predicted Flatness (mm)	Predicted Surface Roughness (μm)	% Error Flatness	% Error Surface Roughness
	A	B	C						
1	-1	0	1	0.032	4.112	0.033	4.5434	3.125	10.49
2	1	0	-1	0.022	3.683	0.0235	3.2783	6.81	10.98
3	0	1	1	0.023	3.496	0.024625	3.6575	7.06	4.62
4	1	1	0	0.027	3.303	0.028	3.2582	3.70	1.35

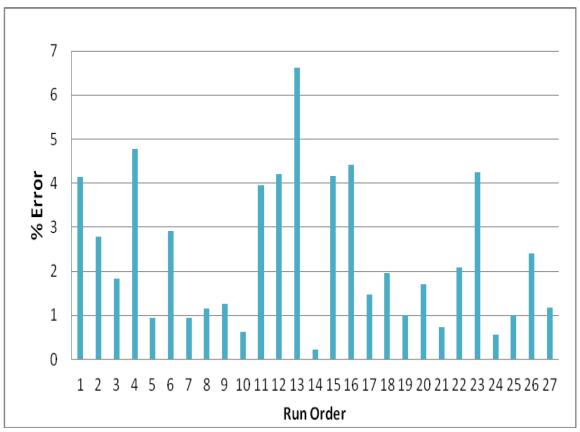


FIGURE 3(a) Error in prediction of cylindricity

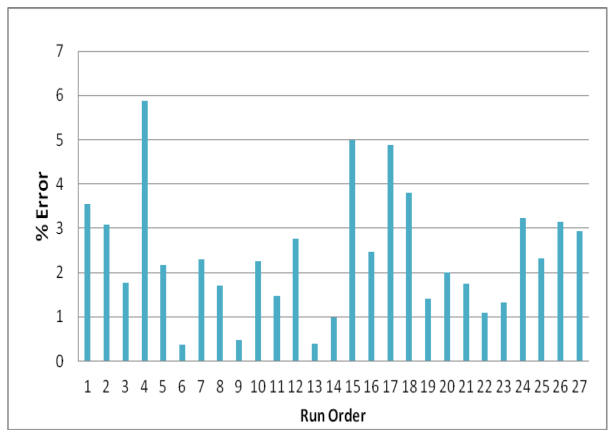


FIGURE 3(b) Error in prediction of perpendicularity

6.3 Grey Relational Analysis (GRA)

GRA gives the optimum process parameters to get the desire responses in multi objective optimization. The steps of normalizing the data, calculating the grey relational co efficient and grey relational grade is followed for both the case studies. ξ is distinguishing coefficient and is used to adjust the difference of relational co efficient: ξ ϵ [0, 1]. ξ = 0.5 is considered for the present analysis. Higher grade relational grade indicates that the experimental value to the ideal normalized values is closer. Thus, higher grey relational grade means that the corresponding parameter combination is closer to the optimal. Table 7 shows the GRA analysis for face milling operation. It can be seen that for 2nd run order one can get the optimize values of process parameters for the surface roughness and flatness. While Fig. 4 shows the run order vs. grey relational grade for drilling operation. It shows that 19^{th} run order gives optimum values of process parameters for the cylindricity and perpendicularity.

Table 7: Values associated with Grey Relational Analysis for flatness and surface roughness

Run Order	Normalized Values		Grey relational coefficients		Grey relational grade
	Surface roughness smaller the better	Flatness smaller the better	Surface Roughness	Flatness	
1	0.926295828	0.5909	0.871529	0.55	0.710765
2	0.929667088	0.9545	0.876681	0.916667	**0.896674**
3	0.162052255	0.0909	0.373707	0.354839	0.364273
4	0.434576485	0.5455	0.469297	0.52381	0.496553
5	0.831099874	0.6364	0.747496	0.578947	0.663222
6	1	0.7727	1	0.6875	0.84375
7	0	0.0000	0.333333	0.333333	0.333333
8	0.938137379	0.5455	0.889897	0.52381	0.706853
9	0.775516224	0.8636	0.690147	0.785714	0.73793
10	0.782827644	1.0000	0.697182	1	0.848591
11	0.724441635	0.9091	0.644697	0.846154	0.745425
12	0.860766962	1.0000	0.782187	1	0.891094

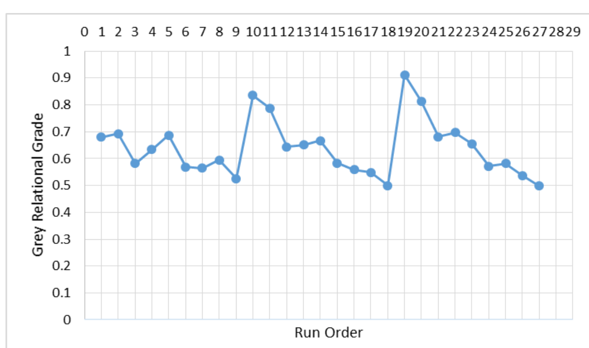


FIGURE 4 Run order vs. Grey Relational Grade

6.4 Fuzzy Logic Based Modeling

Mathematical and empirical modeling are generally used for predicting machining parameters, however, these techniques are time-consuming and complicated. So, here an artificial intelligence based method called fuzzy logic is applied for modeling task. Fuzzy logic is a mathematical theory of imprecise reasoning, which allows modeling of the human thinking by using linguistic terms. MAMDANI type Fuzzy Inference System (FIS) is used for modeling using MATLAB. Triangular membership is used for input and output parameters. Measured values are used to generate the fuzzy “IF- THEN” Rules. Defuzzyfication is required to convert the fuzzy quantity into the real value. Here centroid of area (COA) method of defuzzyfication is used, due to its wide acceptability.

Fuzzy modeling for surface roughness and flatness

Figure 5 and 6 show the triangular membership functions for speed, feed and depth of cut as input and surface roughness and flatness as output. A set of 8 rules have been constructed based on the actual measured results of flatness and surface roughness in face milling operation.

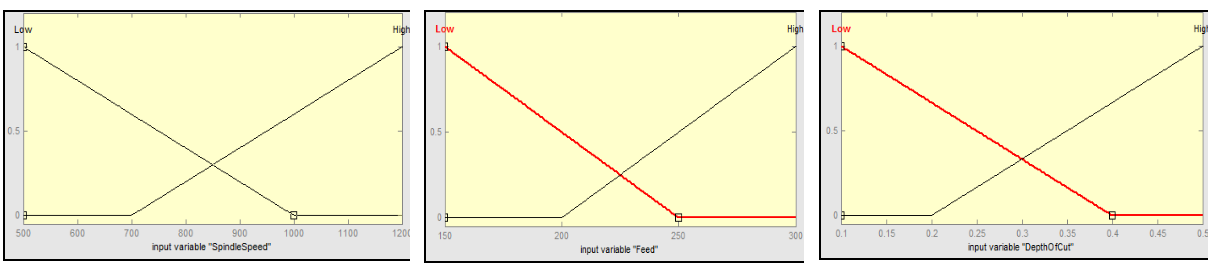


FIGURE 5 Membership function for spindle speed, feed and depth of cut

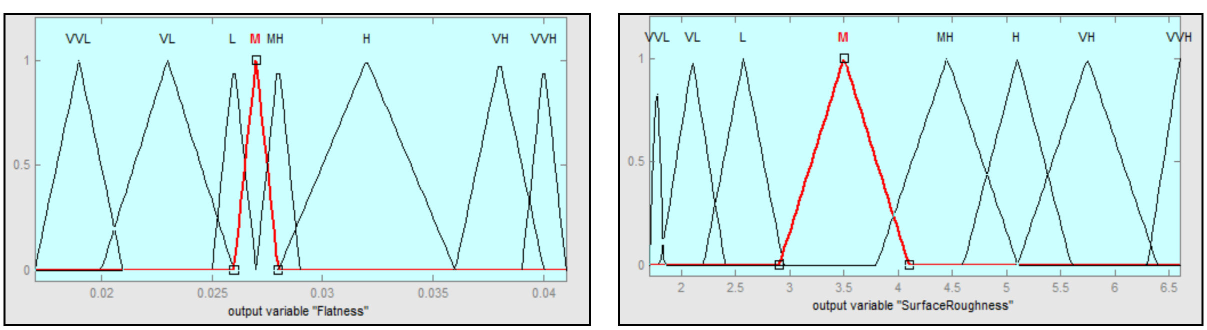


FIGURE 6 Membership Function for flatness and surface roughness

Defuzzyfication for flatness and Surface roughness is done using centroid of area (COA) method and various fuzzy surfaces are shown in Fig. 7. Four new experiments are conducted to check the accuracy of the developed model. The experimental and predicted values are close to each other, which justifies the use of developed model.

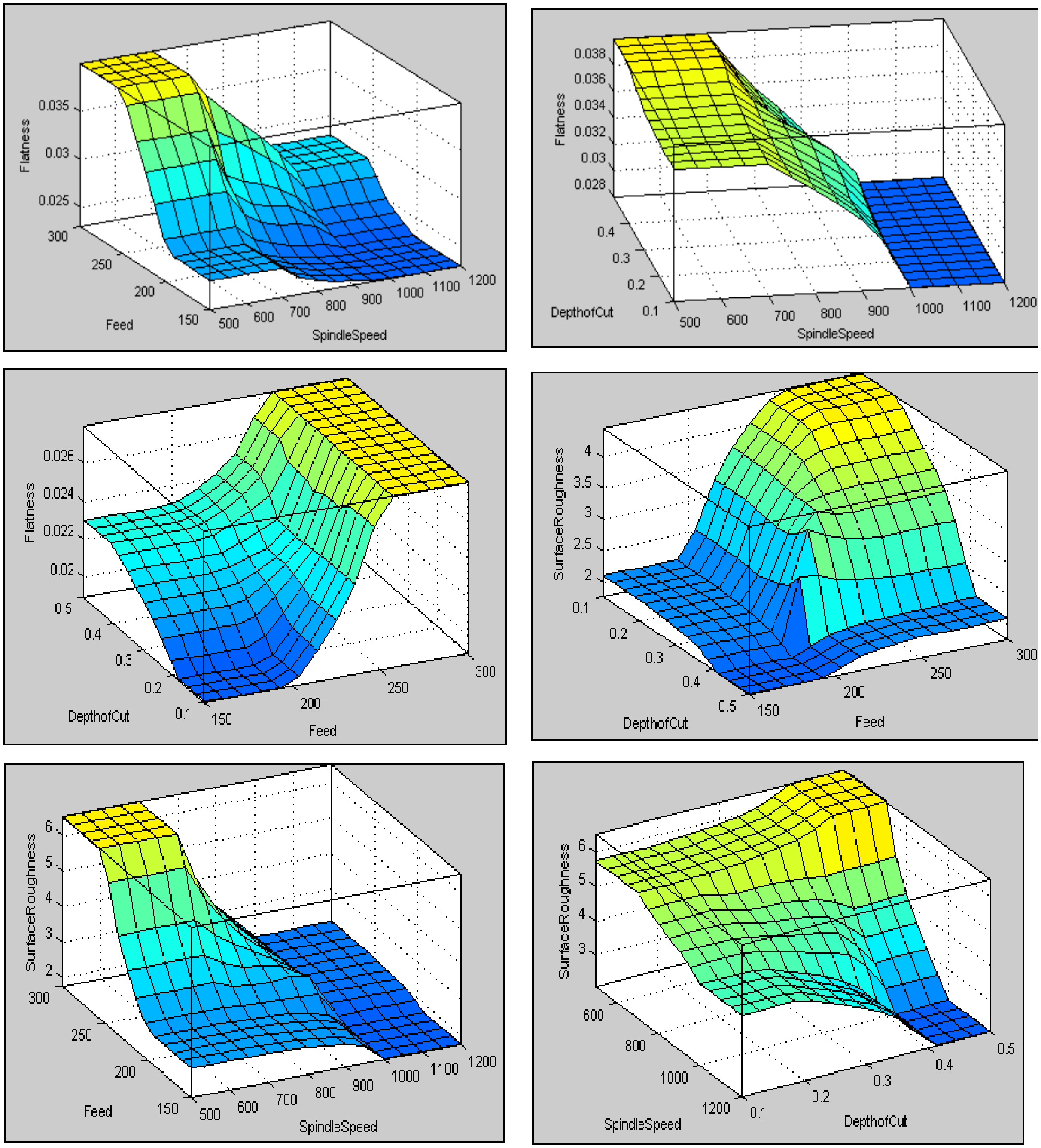


FIGURE 7 Fuzzy surfaces for flatness and surface roughness

Fuzzy modeling for cylindricity and perpendicularity: By using the same method fuzzy modeling is done for cylindricity and perpendicularity. Fig. 8 shows the fuzzy surfaces after defuzzyfication for cylindricity and perpendicularity. To validate the model fuzzy predicted values are compared with the experimental one for each run. Table 9 shows the comparison of values along with the errors.

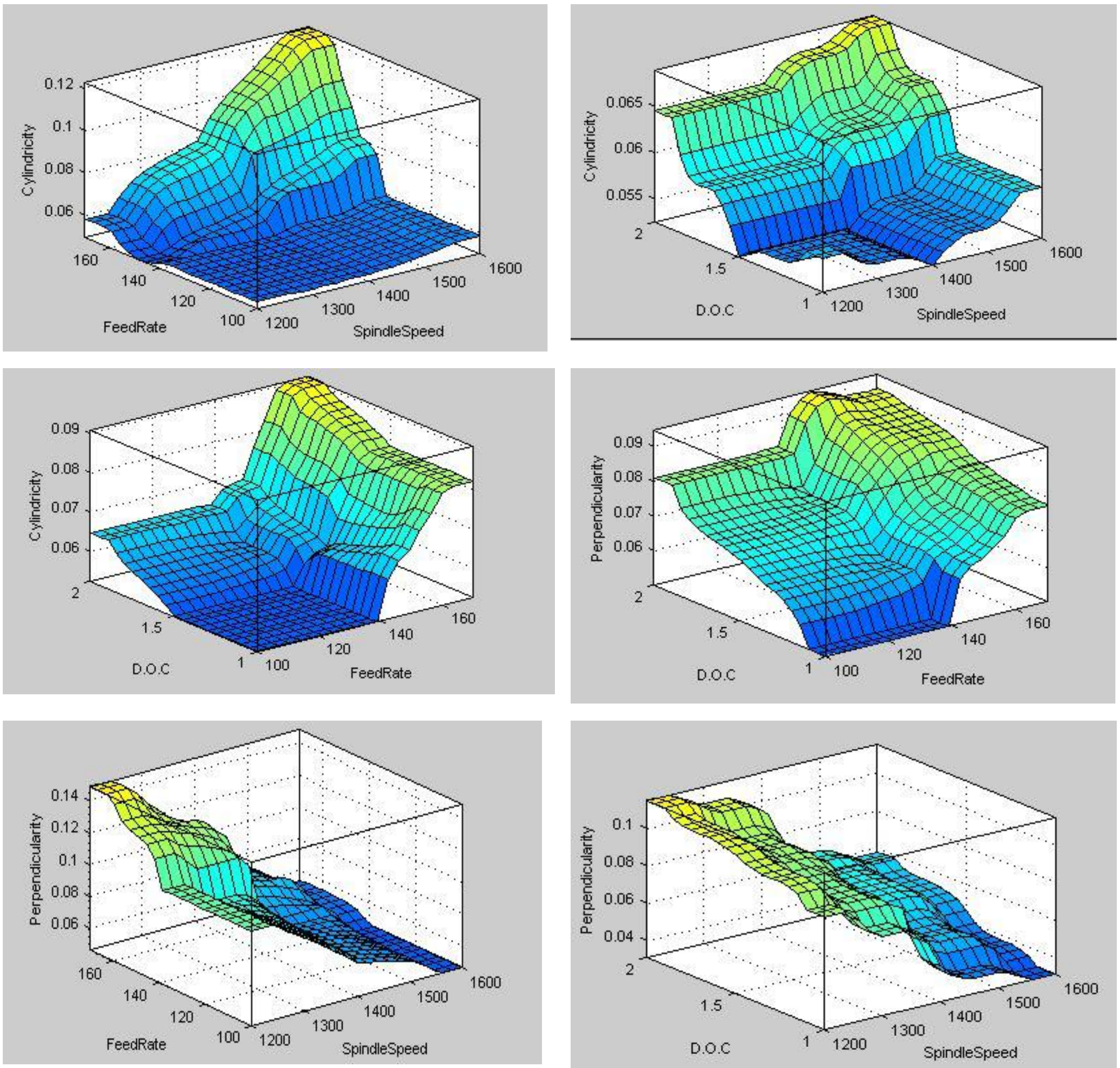


FIGURE 8 Fuzzy surfaces for cylindricity and perpendicularity

TABLE 9: Comparison of experimental and fuzzy predicted values of cylindricity and perpendicularity along with the % error

Treatment combinations			Cylindricity			Perpendicularity		
A	B	C	Experimental (Avg. of 2 replicates)	Fuzzy	% Error	Experimental (Avg. of 2 replicates)	Fuzzy	% Error
1	1	1	0.056	0.056	0.00	0.091	0.091	0.55
1	1	2	0.053	0.053	0.00	0.101	0.105	4.48
1	1	3	0.064	0.065	1.89	0.115	0.115	0.44
1	2	1	0.058	0.058	0.87	0.109	0.105	3.67
1	2	2	0.049	0.049	0.20	0.132	0.132	0.38
1	2	3	0.061	0.061	0.00	0.139	0.140	0.72
1	3	1	0.062	0.061	0.81	0.139	0.140	0.72
1	3	2	0.057	0.058	2.65	0.149	0.149	0.34
1	3	3	0.066	0.065	1.22	0.152	0.154	1.32
2	1	1	0.053	0.053	0.94	0.050	0.050	1.01
2	1	2	0.052	0.053	1.94	0.066	0.068	3.36
2	1	3	0.064	0.065	1.09	0.080	0.081	2.01
2	2	1	0.069	0.069	0.73	0.068	0.068	0.30
2	2	2	0.060	0.061	1.67	0.082	0.081	0.49
2	2	3	0.069	0.069	0.73	0.095	0.095	0.32
2	3	1	0.083	0.082	0.61	0.078	0.078	0.65
2	3	2	0.081	0.082	1.86	0.085	0.085	0.00
2	3	3	0.091	0.091	0.55	0.092	0.091	1.09
3	1	1	0.058	0.058	0.00	0.030	0.030	0.33
3	1	2	0.058	0.058	0.87	0.046	0.046	1.10
3	1	3	0.069	0.069	0.00	0.058	0.058	0.00
3	2	1	0.083	0.082	1.20	0.042	0.042	1.20
3	2	2	0.079	0.082	3.80	0.053	0.054	1.89
3	2	3	0.095	0.095	0.53	0.061	0.061	0.00
3	3	1	0.123	0.123	0.00	0.045	0.046	2.22
3	3	2	0.122	0.123	0.82	0.055	0.054	1.82
3	3	3	0.133	0.134	0.75	0.061	0.061	0.00
Average Error in Prediction					**0.89**			**1.15**

7. Achievement with respect to objective

The developed predictive models of flatness and surface roughness during face milling will be helpful to the practicing engineers. Same way the predictive models of cylindricity and perpendicularity may be helpful. These models will help designers in selecting appropriate geometric tolerances on the machined component. Same approach can be extended for other materials and components.

8. Conclusions

- From the fuzzy surfaces it seems that to achieve good surface roughness high spindle speed, high depth of cut and lower feed rate is desirable. While for reducing the flatness error high spindle speed, lower depth of cut and lower feed rate is desirable. To validate the models developed by fuzzy logic and regression four more experiments are performed. The error in predicting surface roughness by fuzzy logic is 8.56% and by regression 10.98%. The error in predicting flatness by fuzzy logic is 3.12% and by regression 7.06%. The presence of curvature in the analysis of flatness and surface roughness, leads to second order regression models, hence rotatable central composite design is used.
- The GRA shows 2nd run order as optimize one, with speed 1200 rpm, feed 150 mm/min and depth of cut 0.1 mm. So, this set of combination optimizes flatness and surface roughness, which are 0.019 mm and 2.1035 µm respectively.
- Spindle speed, feed, depth of cut and interaction between spindle speed and feed are significant parameters ($p < 0.05$) for cylindricity and perpendicularity.
- Minimal cylindricity on WCB material can be achieved by lower spindle speed, lower feed and moderate depth of cut. While minimal perpendicularity can be achieved by higher spindle speed, lower feed and lower depth of cut.
- The predicted and experimental results are fairly close to each other. The average prediction errors for cylindricity and perpendicularity are 2.34% and 2.39% respectively. This justifies the use of model for further prediction with more than 95% confidence level.
- The average prediction errors for cylindricity and perpendicularity using fuzzy modelling are 0.89% and 1.15% respectively.
- The largest value of GRA is achieved at the 19th run order with spindle speed of 1600 rpm, feed rate of 100 mm/min and depth of cut of 1 mm. Thus machining at this combination optimizes cylindricity and perpendicularity.

Future Scope:

The pareto optimality or genetic algorithm can be used to further optimize the process parameters. The same approach can be used for other materials also. Artificial neural network (ANN) can also be used for modelling.

9. Copies of papers published and a list of publications arising from the thesis

1. Saurin Sheth and P M George, *Experimental Investigation and Fuzzy Modeling of Flatness and Surface Roughness for WCB Material Using Face Milling Operation*, 28th International conference on CAD/CAM, Robotics and Factories of Future, ***Lecture Notes in Mechanical Engineering, Springer India***, 2016, pp- 769-777. DOI: 10.1007/978-81-322-2740-3_74. (Scopus Indexed)
2. Saurin Sheth and P M George, *Experimental Investigation, Prediction and Optimization of Cylindricity and Perpendicularity during drilling of WCB Material using Grey Relational Analysis*, **Precision Engineering**, **Elsevier,** 45, 2016, pp 33-43. DOI: 10.1016/j.precisioneng.2016.01.002. (Scopus indexed & Thomson Router I.F.= 1.914)
3. Saurin Sheth and P M George, *Experimental Investigation and Prediction of Flatness and Surface Roughness during Face Milling Operation of WCB*, ***Procedia Technology***, ***Elsevier***, 23, 2016, pp 344-351. DOI: 10.1016/j.protcy.2016.03.036. (Scopus Indexed)
4. Saurin Sheth and P M George , *Experimental Investigation and Optimization of Flatness and Surface Roughness using Grey Relational Analysis for WCB Material during Face Milling Operation*, ***Advances in Intelligent Systems Research, Atlantis Press, Springer***, 137, 2017, pp 65-70. (Scopus Indexed)
5. Saurin Sheth and P M George, *A fuzzy logic based modeling of cylindricity and perpendicularity during drilling of WCB material.* (In Process)

10. Patents/ Copyright

Not applied

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12. Partial List of References

1. Gene R. Cogorno "*Geometric* Dimensioning and Tolerancing for Mechanical Design" McGraw-Hill, New York, 22-Apr-2011
2. David A. Madsen "Geometric Dimensioning and Tolerancing: Based on ASME Y14.5-2009" Feb 15, 2010
3. Paul J. Drake, Jr. "Dimensioning and Tolerancing Handbook" McGraw-Hill, New York
4. James D meadows, "Geometric Dimensioning and Tolerancing" marcel Dekker, Inc.
5. Jiju Antony, "Design of Experiments for Engineers and Scientists", Elsevier Science and Technology Books, 2003
6. Montgomery, D.C., "Design and Analysis of Experiments", 5th Edition, John Wiley & Sons, 2005
7. P M Tadvi, P M George and R G Jivani, "Investigation of Effect of Cutting Parameters on Geometric Tolerances in CNC Turning – A Review ", at "National Conference on Recent Trends and Technology", organized by B.V.M. Engineering College, V. V. Nagar, Gujarat during 13-14 May, 2011. ISBN NO: 978-81-921558-4-7.
8. N A Vora, P. M. George and S P Joshi, "Effect of Machining Parameters on Geometric Form Control and Orientation Control – A Review " at "National Conference on Recent Trends and Technology", organized by B.V.M. Engineering College, V. V. Nagar, Gujarat during 13-14 May, 2011. ISBN NO: 978-81-921558-4-7.
9. Tugrul O¨ zel, Yigit Karpat, "Predictive modeling of surface roughness and tool wear in hard turning using regression and neural networks " International Journal of Machine Tools & Manufacture , vol. 45 (2005) 467–479.
10. Tony L. Schmitz, John C. Ziegert, J. Suzanne Canning, Raul Zapata, "Case Study: A comparison of error sources in high-speed milling", Precision Engineering 32 (2008), pp. 126-133.
11. Hocken, R. J., and Pereira, P. H. (Editors). Coordinate Measuring Machines and Systems. 2nd Edition. CRC Press. 2012, ISBN-13: 978-1574446524.

12. P. M. George, B. K. Raghunath, L. M. Manocha, A. M. Warrior, " EDM machining of carbon–carbon composite—a Taguchi Approach", Journal of Material Processing Technology, vol.145, 2004 , pp. 66-71(6).
13. Vishal Francis, Ashutosh, Dubey, “Application of Taguchi and response surface methodologies for surface roughness in face milling operation,” International Journal of Mechanical and Production Engineering Research and Development, ISSN 2249-6890, Vol. 3, Issue 2, pp. 213-220, Jun 2013.
14. D. Bajic, B. Lela, D. Zivkovic, “Modeling of machined surface roughness and optimization of cutting parameters in face milling,” Metalurgija 47 (2008) 4, pp. 331-334.
15. Woo kang kim, Hong T. K. Geun. M. R., Geon H.K. 2013. Study on High-speed cutting characteristics using design of experiments. International journal of precision engineering and manufacturing. 14 (10), 1869-1872.
16. P. Krajnik, J. Kopac, A. Sluga, “Design of grinding factors based on response surface methodology,” Journal of Materials Processing Technology 162–163, pp. 629-636, 2005.
17. B.M. Umesh Gowda, H.V. Ravindra, S. Prathik Jain, Mohinder N Rah, G.V. Naveen Prakesh, G. Ugrasen, “Comparative study of surface roughness and cylindricity of aluminium silicon nitride material using MRA GMDH & Pattern recognition technique in drilling”, Procedia Materials Science, 2014, 6, 1770-1779.
18. Jayalakshmi; George, P.M.; Joshi, S.P., “Modeling of GD&T Requirements of Crankshaft Flange Using DOE. Proceedings of the 5th International & 26th All India Manufacturing Technology, Design and Research Conference (AIMTDR 2014), IIT Guwahati, Assam, India, 2014, 310:1-6.
19. Adamczak, Stanislaw.; Janecki, Dariusz.; Makiela, Wlodzimierz.; Stepien Krzysztof. Quantitative comparision of cylindricity profiles measured with different methods using Legendre-Fourier coefficients. Metrology and measurement systems. 2010. XVII (3), 397-404.
20. Miroslav Dovica, Alexander vegh, “Comparison of the cylindricity deviation using different evaluation methods”, American Journal of Mechanical Engineering, 2013, vol. 1, no. 7, 339-342.

21. Emel Kuram, Babur Ozcelik, “Fuzzy logic and Regression modeling of Cutting parameters in Drilling operation using vegetable based cutting fluid” International Journal of Engineering & Material Science, Vol. 20, pp. 51-58, Feb. 2013.
22. P. Kovak, D. Rodic, V. pucovsky, B. Savkovic, M. Gostimirovic, “ Application of fuzzy logic and regression analysis for modeling surface roughess in face milling”, Journal of intelligent manufacturing, vol. 24 , pp. 755-762, 2013.
23. Emel Kuram, Babur ozcelik, “Micro-milling performance of AISI 3014 stainless steel using Taguchi method and fuzzy logic modeling”, intelligent manufacturing, pp. 1-14, 2014.
24. Cukor G., Jurkovic z., sekulic M., “Rotatable Central Composite design of experiments versus Taguchi Method in the optimization of turning”, Metalurgija, vol. 50, 1, pp. 17-20, 2011.
25. S. Bharathi Raja, N. Baskar, “Application of particle swarm optimization technique for achieving desired milled surface roughness in minimum machining time”, Expert systems with applications, vol. 39, pp. 5982-5989, 2012.
26. A.H.A. Shah, A.I. Azmi, A.N.M. Khalil, “Grey relational analyses for multi-objective optimization of turning S45C carbon steel”, IOP conf. Series: Materials science and engineering, vol. 114, pp. 1-11, 2016.
27. A. Markopoulos, W. Habrat, N. Galanis, N. Karkalos, “ Modelling and Optimizaiton of Machining with the use of statistical methods and soft computing”, Design of experiments in production engineering, management and Industrial engineering, Springer international publishing, Switzerland, 2016. Pp. 39-88.
28. Senthilkumar, N.; Tamizharasan, T.; Anandakrishnan, V. Experimental investigation and performance analysis of cemented carbide inserts of different geometries using Taguchi based grey relational analysis. Measurement. 2014, 58, 520-536.
29. Moroni, Giovanni; Petro, Stefano. Inspection strategies and multiple geometric tolerances. Procedia CIRP. 2013, 10, 54-60.
30. S.P. Frechette, A.T. Jones, B. R. Fischer, “Strategy for testing conformance to geometric dimensioning & tolerancing standards”, Procedia CIRP, 10, pp. 210-213, 2013.

31. M. Hadzistevic, B. Strbac, V. Spasic Jokic, M. Delic, M. Sekulic, J. Hodolic, "Factors of estimating flatness error as a surface requirement of exploitation", Metalurgija, 2015, 54, 1, 239-242.
32. Elmesbahi. A, Rechia. A and Jaider. O, 2014. Optimized – automated choice of cutting tool machining manufacturing features in milling process. 11th World congress on computational mechanics (WCCM XI), Spain
33. C. Cui, T. Li, L.A. Blunt, X. Jiang, H. Huang, R. Ye, W. Fan, "The assessment of straightness and flatness errors using particle swarm optimization", Procedia CIRP, 10, 2013, 271-275.
34. R. Raghunandan, P. Venkateswara Rao, "Selection of an optimum sample size for flatness error estimation while using coordinate measuring machine", International Journal of machine tools & Manufacture, 47, 2007, 477-482.
35. P. Pedone, D. Romano, "Designing small samples for form error estimation with coordinate measuring machines", Precision Engineering, 35, 2011, 262-270.
36. S. P. Frechette, A.T. Jones, B.R. Fischer, "A strategy for testing product conformance to geometric dimensioning & tolerancing standards: Technical notes", procedia engineering, 2011.
37. Meng Wang, Lifeng Xi, Shichang Du, "3D surface form error evaluation using high definition metrology", Precision Engineering, 38, 2014, 230-236.
38. Balkrishna Rao, Chinmaya R. Dandekar, Yung C. Shin, "An experimental and numerical study on the face milling of Ti-6Al-4V Alloy: Tool performance and surface integrity", Journal of material processing technology, 211, 2011, 294-304.
39. Eysion A. Liu, Qian Zou, "Machined Surface Error Analysis- A face milling approach", Journal of advanced manufacturing systems, vol. 10, no. 2, 2011, 293-307.
40. Patricia Munoz- Escalona, Paul G. Maropoulos, "A geometrical model for surface roughness prediction when face milling Al 7075- T7351 with square insert tools", Journal of manufacturing systems, 2014.
41. B. Denkena, E. Hasselberg, "Influence of the cutting tool compliance on the work piece surface shape in face milling of work piece compounds", Procedia CIRP, 31. 2015, 7-12.

42. Binaca Maria Colosimo, Ester Gutierrez Moya, Giovanni Moroni, Stefano Petro, " Statistical Sampling strategies for Geometric Tolerance Inspection by CMM", Economic Quality Control, 23 (1), 2008, 109-121.
43. D. Yu. Pimenov, "Experimental Research of Face Mill Wear Effect to Flat Surface Roughness", Journal of Friction and Wear, 2014, 35 (3), 250-254.
44. C. Vila, H.R. Siller, C.A. Rodriguez, G.M. Bruscas, J. Serrano, "Economical and technological study of surface grinding versus face milling in hardened AISI D3 steel machining operations", International Journal of Production Economics, 2012, 138, 273-283.
45. Emel Kuram, Babur Ozcelik, "Multi-objective optimization using Taguchi based grey relational analysis for micro-milling of Al 7075 material with ball nose end mill", Measurement, 2013, 46, 1849-1864.
46. E. Kuram, B. Ozcelik, E. Demirbas, E. Sik , I.N. Tansel, "Evaluation of New Vegetable- Based Cutting Fluids on thrust force and surface roughness in drilling of AISI 304 using Taghuchi Method ", Materials and Manufacturing Processes, 2011, 26, 1136-1146.
47. Wei-Piao Wu, "Investigation of the effects of face-milling parameters of ultra-large-scale plane on milling quality", International journal of advanced manufacturing technology, 2008, 37, 241-249.
48. H. Schwenke, W. Knapp, H. Haitjema, A. Weckenmann, R. Schmitt, F. Delbressine, "Geometric error measurement and compensation of machines-An update", CIRP Annals- Manufacturing Technology, 2008, 57, 660-675.
49. Csaba Felho, Bernhard Karpuschewski, Janos Kundrak, "Surface roughness modeling in face milling", Procedia CIRP, 2015, 31, 136-141.
50. Mohammadjafar Hadad, Mohammadjavad Ramezni, "Modeling and analysis of a novel approach in machining and structuring of flat surfaces using face milling process", International Journal of Machine Tools & Manufacture, 2016, 105, 32-44.
51. Qiang Chen, Xueheng Tao, Jinshi Lu, Xuejun Wang, "Cylindricity Error Measuring and evaluating for engine cylinder bore in manufacturing procedure", Advances in Materials Science and Engineering, 2016, http://dx.doi.org/10.1155/2016/4212905.

52. Wen, Xiu-Lan.; Huang, Jia-Cai.; Sheng, Dang-Hong.; Wang, Feng-Lin, "Conicity and cylindricity error evaluation using particle swarm optimization", Precision Engineering, 2010, 34, 338-344.
53. Dawit H. Endrias, His-Yung Feng, Ji Ma, Lihui Wang, M. Abu Taher, "A combinatorial optimization approach for evaluating minimum-zone spatial straightness errors", Measurement, 2012, 45, 1170-1179.