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A study on machining capability of a 2-DoF PKM-based milling machine

Sanjay Darvekar[a], A. B. Koteswara Rao[a], K. Ramji[b]*

[a]Gayatri Vidya Parishad College of Engineering, Visakhapatnam-530048, INDIA
[b]Andhra University, Visakhapatnam-530018, INDIA

Abstract

In the recent past, Parallel Kinematic Machines (PKM) with fixed-length legs have been claimed for their potential use as machine tools due to smaller moving masses leading to the high dynamic characteristics and accuracy. In this paper, the machining capability of a 2-Degrees-of-Freedom (DoF) PKM-based milling machine is explored. Stiffness of the PKM was estimated using finite element analysis approach. Extensive experimentation was carried out by varying machining conditions, i.e., cutting speed, feed rate and depth of cut to study the variation in performance measures, namely, surface roughness and material removal rate. Regression models were developed to predict the surface roughness. An attempt was made to find the optimum machining conditions for PKM using Genetic Algorithm. The experimental results confirm the capability of fixed-length leg PKM-based machine tool to perform machining operations upon metals like hard Aluminium alloys.

Keywords: *PKM, milling, surface roughness, regression models, Genetic Algorithm*

1. Introduction

In order to meet the requirement of high accuracy and stiffness, conventional machine tools are designed with massive structures. This imposes serious limitation on its flexibility and dynamic characteristics. To overcome these limitations, Parallel Kinematic Machines (PKMs) have been introduced in the recent past. PKMs have, in

* Corresponding author. Tel.: +91-903-220-7683; fax: +91-891-273-9605.
E-mail address: sanjay_darvekar@gvpce.ac.in

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general, smaller moving masses, high rigidity and high stiffness to weight ratio [1-2]. Although the PKMs provide smaller workspace volume compared to conventional machine tools, they gives excellent accuracy and high speed machining ability [3-4]. PKMs with fixed-length legs and lesser Degrees-of-Freedom (DoF) are considered more suitable for machine tool applications as they offers more stiffness and workspace in comparison to PKMs with telescopic legs [5]. For example, a 3-PRRR parallel manipulator that employs only revolute and prismatic joints to achieve pure translation motion of the moving platform [6]. On similar lines, another 3-DoF translational parallel manipulator, Orthoglide, was proposed in [7] for the use as a machine tool. Existing planar 2-DoF parallel manipulators are also being explored for machine tool applications [8-9]. Hybrid five axis milling machines based on PKM and Serial Kinematic Machine (SKM) structures have also been considered for machining application [10-11]. However, limited research is found on experimental study of the performance of PKM for metal cutting operations. The authors have developed an optimized prototype of a 2-DoF PKM, to explore its capability for milling applications.

The effect of cutting parameters upon surface roughness and material removal rate in end-milling process on conventional machine tools are available in [12-14] and many others. It is a known fact that stiffness and dynamic characteristics of PKM are different from those of conventional machine tools based on serial kinematics [3, 15]. Therefore, the machining parameters like cutting speed, feed rate, depth of cut recommended for conventional milling machine may not hold good for the PKM-based machine tools. Hence, to assess the suitability of PKM for industrial application, a study on its performance for various cutting parameters and optimization is very much required. To investigate the performance of PKM, for end-milling application, exhaustive experimentation was carried out. The effect of speed, feed and depth of cut on surface roughness and Metal Removal Rate (MRR) were studied and analyzed. Optimum speed, feed and depth of cut were obtained using Genetic Algorithm (GA).

2. Description of a 2-DoF PKM

A typical planar 2-DoF PKM is shown in Fig 1. It consists of two vertical rails with ball screws along which the two sliders move. The tool platform is connected to the sliders by two identical legs. Since each leg consists of a four bar mechanism, the orientation of the tool platform remains constant and imparts the required stiffness and rigidity to the PKM. The legs are connected by the means of revolute joints. Actuation of the sliders provides the desired position to the tool platform. The legs are fixed-length and can be made light and stiff. Thus, the mechanism is expected to offer better stiffness characteristics when compared to those with telescopic legs, and

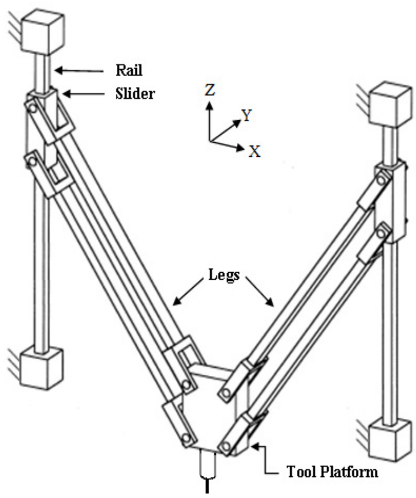


Fig. 1. A 2-DoF PKM

Fig. 2. Prototype of PKM developed at GVPCOE

hence can be used in machine tools [16]. Moreover, these PKMs offer larger workspace since all the joints are of a single DoF type.

3. Development of PKM prototype

Leg length and distance between rails are the critical parameters that determine the performance characteristics of PKM viz. stiffness, dexterity and workspace. Thus, special attention was given to optimize the dimensions of PKM to maximize the stiffness, dexterity and workspace, as presented in [9]. Optimized dimensions of PKM include leg length L = 660 mm and half of the distance between two rails R = 400 mm. The values of other parameters considered while optimization are: stroke length S = 380 mm, radius of tool platform r = 40 mm and cross section of each leg: 40 x 60 mm. Based on the machine tool specification given in Table 1 and optimized dimensions a prototype of 2-DoF PKM was designed. Finite Eelement Analysis (FEA) and other design steps are not presented in this paper considering the limitation of the scope and space. However, stiffness needs to be mentioned to know the machining capability of the PKM. The PKM structure is stiffer along Z-axis (133.9 $N/\mu m$). Stiffness along X-axis (28.2 $N/\mu m$) and Y-axis (24.5 $N/\mu m$) are relatively low. Stiffness of the tripod based PKM machine is in the range of 35-140 $N/\mu m$, [17] which almost matches with the stiffness of the 2-DoF PKM. A specially designed PC based controller was used to precisely control the slider positions. Software programs were developed using inverse kinematic equations presented in [9] to obtain tool path for machining. The same terminology of 'G' and 'M' code used in conventional NC programming was used here to embed the tool path equations, so that no special training is required for PKM programming. The design values of machining accuracy and repeatability of the prototype are 25μm and 10μm respectively. A photograph of developed prototype is shown in Fig 2. The prototype consists of two sliders or carriages on the two vertical lead screws driven independently by two A/C servomotors (750 W), and the spindle is driven (rated speed 3000 RPM) by another A/C servomotor (750 W).

4. Design of Experiment

4.1. Experimental Setup

In order to explore the machining performance of PKM, an experiment was designed to perform pocket milling operations at various spindle speed, feed rate and depth of cut. Five levels of speed and feed were chosen respectively while four levels of depth of cut were considered for the experimental investigations, as listed in Table 2. The selection of levels within the ranges was performed using statistical experimental design technique, the five-level full factorial design. Considering the small diameter and limitation to withstand cutting forces of the tool, 5th level of depth of cut was eliminated. A total of 100 experiments were conducted employing 4 fluted HSS end-milling tool of 6 mm diameter and 40 mm overhang. The workpiece material used is Aluminum Al5083 (4.6% Mg, 0.6% Mn, 0.1% Cr, Yield Strength 219 MPa). Its mechanical properties are given in [18]. The workpiece is a plate of 160 × 80 × 6 mm.

Table 1. Machine tool specifications required for design of PKM

Sr. No	Parameters	Description
1	Maximum Drill Tool and End-mill diameter	12 mm
2	Maximum Spindle Speed	3000 RPM
3	Tool material	HSS
4	Workpiece material	Structural Steel [BHN 130, Yield Stress 250 MPa]

Table 2. Levels of cutting parameters

Parameters	Levels 1	2	3	4	5
Spindle speed 'V' (RPM)	1400	1800	2200	2600	3000
Feed rate 'f' (mm/min)	40	80	120	160	200
Axial depth of cut 'a_p' (mm)	0.1	0.3	0.5	0.7	--

4.2. Measurement Procedure

Surface roughness (R_a) of the machined surface and *MRR* are considered to evaluate the performance of PKM. R_a, is a well-known, widely used parameter for industrial quality control and offers a simple test for comparing surface quality of machined surfaces. Machined surfaces are measured by using a stylus type surface roughness tester, (Mitutoyo, SJ 201). Cut-off length during measurement is set to be 2.5 mm to enable scanning of the whole surface. Surface roughness was measured along the direction of feed, with nine measurements on each machined surface and average was taken. Measurement setup is shown in Fig 3(a). Figure 3(b) shows the nine different measurement points on each machined pocket. Appropriate precautions were taken to eliminate bending of the workpiece plate due to clamping force by bolting the plate to a fixture. Cutting tool was cleaned and examined after each cutting process. Surface roughness values obtained for various machining conditions are presented in Appendix A.1.

(a) 

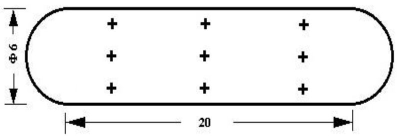
(b) 

Fig. 3. (a) Surface roughness measurement (b) Points for roughness measurement on the machined surface

5. Regression Modeling

To study the influence of speed, feed and depth of cut on surface roughness two mathematical models, the exponential model and quadratic model, were selected [13]. They are the two most widely used models in obtaining the relationship between machining parameters. The exponential model can be expressed as:

$$R_a = aV^b f^c a_p^d \tag{1}$$

where, V is the spindle speed in RPM, f is the feed rate in mm/min, a_p is the axial depth of cut in mm and $a-d$ are constants.

The quadratic model can be expressed as:

$$R_a = c_1 + c_2V + c_3f + c_4a_p + c_5Vf + c_6Va_p + c_7fa_p + c_8V^2 + c_9f^2 + c_{10}a_p^2 \tag{2}$$

where $c_i \, for \, i = 1 to 10$ are constants.

Based on the 75 data sets presented in Appendix A.1, the regression fit process was carried out with the aid of DataFit 9.0 [19]. The regression models were obtained as:

$$R_a = 4.227 V^{-0.4051} f^{0.2706} a_p^{0.1406} \tag{3}$$

$$R_a = 0.7194 - 2.86\times10^{-4} V - 0.0012 f + 0.2605 a_p - 5.27\times10^{-7} Vf - 7.769\times10^{-5} V a_p + 0.00109 f a_p + 6.187\times10^{-8} V^2 + 4.229\times10^{-6} f^2 + 0.04319 a_p^2 \tag{4}$$

Coefficient of regression, R^2 values for quadratic and exponential models were obtained as 0.969 and 0.904, respectively. Thus, having a better fit precision, a quadratic model was selected for the optimization of cutting parameters in this study.

6. Surface roughness optimization by GA

6.1. Optimization problem formulation

It is important to select the appropriate machining parameters to improve the product quality such as surface roughness, machining time, material removal rate, etc. GA was employed to obtain the optimal values of machining parameters such as speed, feed rate and depth of cut. The quadratic model developed for data fit in the earlier section was used as an objective function for optimization.

The objective function can be defined as

Find:

$$V, f, a_p$$

To minimize

$$f(x) = g(R_a) \tag{5}$$

Subject to constraints:

$$MRR \geq MRR_{limit}$$

$$R_a \leq R_{a,limit}$$

within parameter ranges:

$$1400 \leq V \leq 3000$$

$$0 \leq f \leq 200$$

$$0.1 \leq a_p \leq 0.7$$

where $g(R_a)$ indicate an objective function based on Equation (4). $R_{a,limit}$ and MRR_{limit} indicate the upper and lower limits that need to be satisfied for surface roughness and material removal rate, respectively. For the calculation of *MRR* the following analytical equation is used:

$$MRR = D f a_p \tag{6}$$

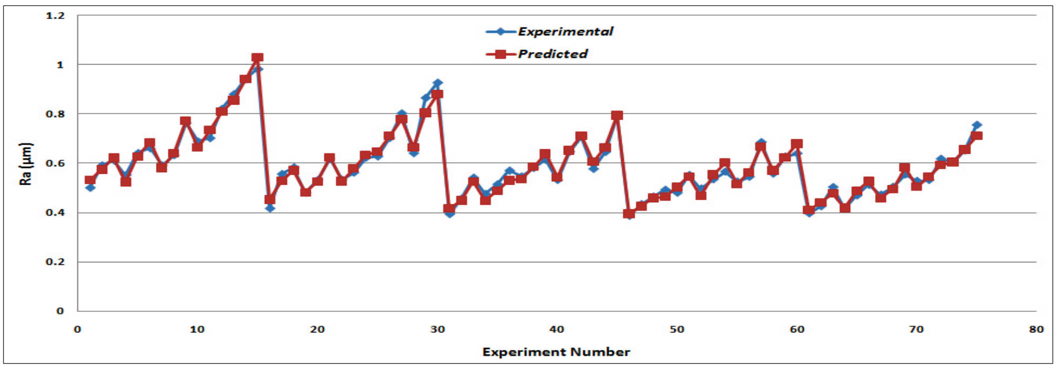
where D is the diameter of the tool in mm.

6.2. Optimization problem solution

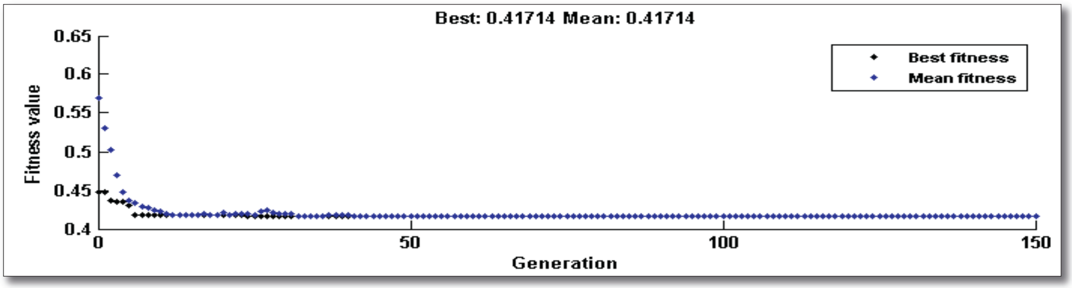
GA, is a global optimization method, developed to solve the optimization problem expressed by Equation (5). GA is based on natural selection that drives the biological evolution process: Darwin's theory of survival of the fittest. The solution of an optimization problem with GAs begins with a set of potential solutions known as chromosomes. The entire set of these chromosomes comprises a population that is randomly generated or selected. The chromosomes evolve during several iterations or generations. New generations known as the offspring are generated utilizing the crossover and mutation technique. Crossover is the process of splitting two chromosomes and then combining one-half of each chromosome with the other pair. Mutation involves flipping a single bit of a chromosome. The chromosomes are then evaluated using a certain fitness criteria and the best ones are kept while the others are discarded. Over successive generations, the population evolves until one chromosome with the best fitness value is obtained and is taken as the best solution of the problem. The critical parameters in GA are the size of the population, mutation rate, number of iterations (generations), etc. In this study, population size of 20, crossover rate of 0.8, mutation rate 0.1, and the number of generations of 150 were used, as it's a typically recommended good practice. The GA optimization was implemented in MATLAB 8.0.

7. Results and Discussion

Exponential and Quadratic models were explored for prediction of Surface Roughness for different machining parameters. Maximum percentage error in experimental values and modeled values with Quadratic fit and Exponential fit were obtained as 8.9% and 12.07%, respectively. Similarly, coefficient of regression R^2 values in quadratic and exponential model were found to be 0.96 and 0.9, respectively. Validation of the quadratic model was performed with 25 experimental data sets, as presented in Appendix A.2. The validation data set was selected sequentially according to the level of depth of cut. The maximum error between the experimental and predicted values of R_a (Fig 4 (a)) was found to be less that 10% and hence the model can be considered suitable for the prediction of R_a . Optimal machining parameters for best surface roughness in finish cut (without constraints), and for best surface roughness in rough cut with the constraints of $R_a \leq 1$ µm, and 600 < MRR < 840, were obtained by using GA. For the best surface roughness during finish cut, cutting parameters were obtained using GA as V = 2387 RPM, f = 40 mm/min, a_p = 0.1 mm, as shown in Table 3. Figure 4(b) shows the variation of fitness value (R_a) with a number of generations. For the first 30 generations the variation of R_a is more and then it converges to the optimum value of 0.417 µm. Table 4 shows a set of optimal cutting parameters for best R_a with *MRR* as a constraint function.



(a)



(b)

Fig. 4. (a) Deviation between experimental and regression values of roughness (b) Variation of fitness value (R_a) with generations.

Table 3. Optimization result without constraints

Optimum cutting parameters			R_a (µm)		
V (RPM)	f (mm/min)	a_p (mm)	GA	Experiment	% Error
2387	40	0.1	0.41	0.39	4.87

Table 4. Optimization machining conditions with constraints on $R_a \leq 1$ and MRR

Sr. No	MRR_{limit} mm^3/min	Optimum cutting parameters			R_a (µm)			MRR mm^3/min
		V RPM	f mm/min	a_p mm	GA	Experimental	% Error	
1	600	2589	145	0.68	0.62	0.64	3.28	591.6
2	640	2976	173	0.61	0.61	0.65	6.15	633.2
3	740	2817	191	0.64	0.66	0.72	8.33	733.4
4	800	2906	190	0.7	0.66	0.73	9.58	798
5	840	2610	200	0.7	0.72	0.77	6.49	840

Validation of GA results was performed with a few experiments as shown in Table 4. It may be noted that the GA results are in good agreement with the experimental results and all the values of R_a are within error limits of 10%. The effect of feed rate and depth of cut on the surface roughness can be observed in Fig 5(a). Similarly, Fig 5(b) shows the effect of spindle speed and feed rate on the surface roughness. Figure 5(c) depicts the effect of spindle speed and depth of cut upon surface roughness. With the constraints of roughness and material removal rate, it can be seen from Table 4 that it is not possible to reduce the R_a value without sacrificing MRR.

8. Conclusions

In this paper the design and development of a 2-DoF PKM for machine tool application was discussed in brief. Influence of machining parameters, viz., spindle speed, feed rate and depth of cut upon the performance of PKM was studied. Regression models suitable to predict surface roughness for different cutting parameters were developed and validated. GA optimization was carried out to obtain the range of optimal cutting parameters for specific surface roughness and MRR limits. Experimental observations revealed that the feed has maximum impact upon the surface roughness of the machined surface followed by the depth of cut. Cutting speed also cannot be neglected to improve the surface roughness, although it has less influence. Optimal machining conditions obtained in this paper could be applicable to other fixed-length leg PKM machine tools.

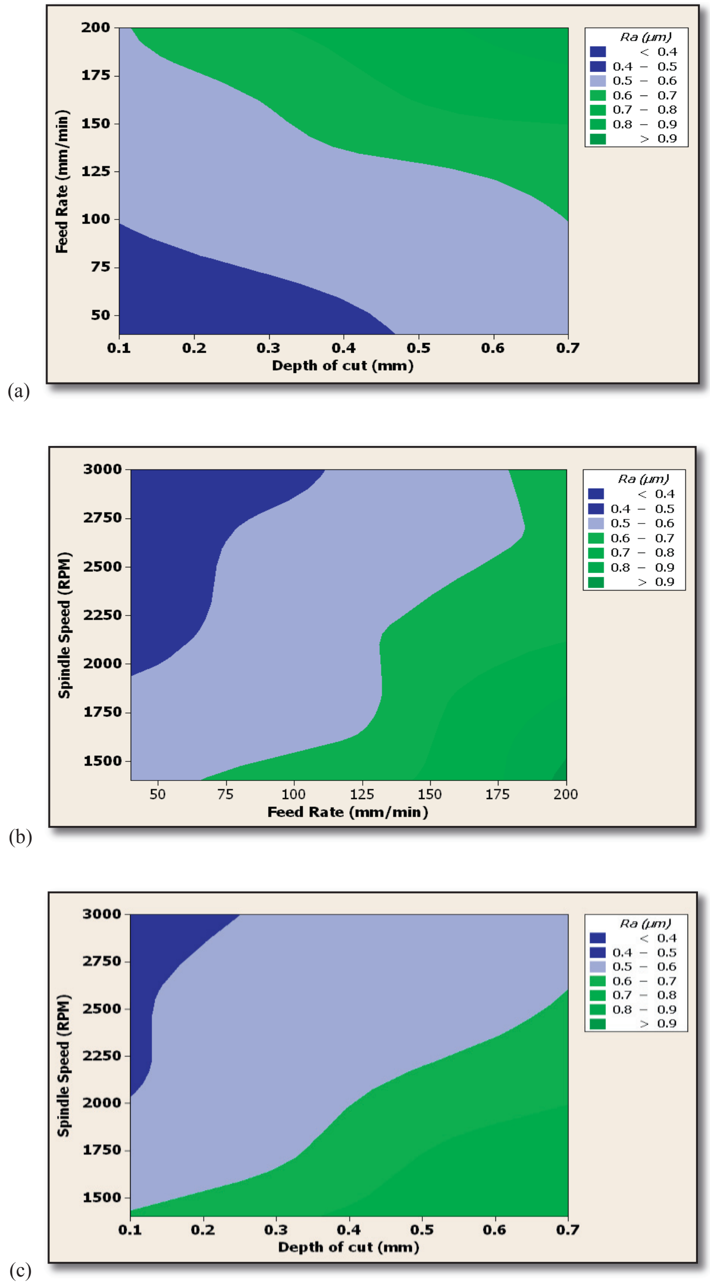


Fig. 5. (a) Variation of Surface Roughness with Feed Rate and Depth of Cut (b) Variation of Surface Roughness with Spindle Speed and Feed Rate (c) Variation of Surface Roughness with Spindle Speed and Depth of Cut

From the experimental results and the stiffness values obtained by FEA it can be concluded that a 2-DoF PKM machine tool can successfully perform the machining operation upon metals like high strength Aluminium alloy. Surface roughness obtained by the machine tool highly depend upon stiffness and vibration characteristics of the mechanism. As the obtained results i.e. surface roughness are well within the permissible range of 0.4 – 1.8 μm [20], it indicates the safe stiffness and vibration characteristics of the PKM. The obtained results are helpful to assess the suitability of PKM-based machine tools for machining applications. The proposed mechanism with additional table movement in Y-direction may be used as a 3-axis milling machine to perform similar machining operations like a conventional 3-axis milling machine.

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Appendix A.

A.1. Experimental results – Cutting Parameters, Surface Roughness and MRR

Sr. No	Cutting Parameters V RPM	f mm/min	a_p mm	R_a µm	MRR mm^3/min	Sr. No	Cutting Parameters V RPM	f mm/min	a_p mm	R_a µm	MRR mm^3/min
1	1400	40	0.3	0.50	72	39	2200	120	0.7	0.61	504
2	1400	40	0.5	0.59	120	40	2200	160	0.1	0.53	96
3	1400	40	0.7	0.61	168	41	2200	160	0.5	0.64	480
4	1400	80	0.1	0.55	48	42	2200	160	0.7	0.70	672
5	1400	80	0.5	0.64	240	43	2200	200	0.1	0.57	120
6	1400	80	0.7	0.66	336	44	2200	200	0.3	0.64	360
7	1400	120	0.1	0.59	72	45	2200	200	0.7	0.79	840
8	1400	120	0.3	0.63	216	46	2600	40	0.1	0.38	24
9	1400	120	0.7	0.76	504	47	2600	40	0.3	0.43	72
10	1400	160	0.1	0.68	96	48	2600	40	0.5	0.46	120
11	1400	160	0.3	0.70	288	49	2600	80	0.3	0.49	144
12	1400	160	0.5	0.82	480	50	2600	80	0.5	0.48	240
13	1400	200	0.3	0.88	360	51	2600	80	0.7	0.55	336
14	1400	200	0.5	0.94	600	52	2600	120	0.1	0.49	72
15	1400	200	0.7	0.98	840	53	2600	120	0.5	0.53	360
16	1800	40	0.1	0.41	24	54	2600	120	0.7	0.56	504
17	1800	40	0.5	0.55	120	55	2600	160	0.1	0.52	96
18	1800	40	0.7	0.58	168	56	2600	160	0.3	0.54	288
19	1800	80	0.1	0.48	48	57	2600	160	0.7	0.68	672
20	1800	80	0.3	0.53	144	58	2600	200	0.1	0.55	120
21	1800	80	0.7	0.61	336	59	2600	200	0.3	0.62	360
22	1800	120	0.1	0.53	72	60	2600	200	0.5	0.64	600
23	1800	120	0.3	0.56	216	61	3000	40	0.3	0.39	72
24	1800	120	0.5	0.62	360	62	3000	40	0.5	0.42	120
25	1800	160	0.3	0.62	288	63	3000	40	0.7	0.50	168
26	1800	160	0.5	0.70	480	64	3000	80	0.1	0.41	48
27	1800	160	0.7	0.80	672	65	3000	80	0.5	0.46	240
28	1800	200	0.1	0.64	120	66	3000	80	0.7	0.51	336
29	1800	200	0.5	0.86	600	67	3000	120	0.1	0.47	72
30	1800	200	0.7	0.92	840	68	3000	120	0.3	0.50	216
31	2200	40	0.1	0.39	24	69	3000	120	0.7	0.55	504
32	2200	40	0.3	0.45	72	70	3000	160	0.1	0.52	96
33	2200	40	0.7	0.54	168	71	3000	160	0.3	0.53	288
34	2200	80	0.1	0.47	48	72	3000	160	0.5	0.61	480
35	2200	80	0.3	0.51	144	73	3000	200	0.3	0.60	360
36	2200	80	0.5	0.57	240	74	3000	200	0.5	0.65	600
37	2200	120	0.3	0.54	216	75	3000	200	0.7	0.75	840
38	2200	120	0.5	0.58	360						

A.2. Experimental results to validate surface roughness obtained by quadratic fit model (QM)

Sr. No	Cutting parameters V RPM	f mm/min	a_p mm	R_a (µm) QM	Experim-ental	% Error	Sr. No	Cutting parameters V RPM	f mm/min	a_p mm	R_a (µm) QM	Experim-ental	% Error
1	1400	40	0.1	0.487	0.477	2.09	14	2200	160	0.3	0.60	0.587	2.35
2	1400	80	0.3	0.584	0.606	3.63	15	2200	200	0.5	0.746	0.723	3.27
3	1400	120	0.5	0.714	0.716	0.14	16	2600	40	0.7	0.495	0.522	5.07
4	1400	160	0.7	0.873	0.857	1.87	17	2600	80	0.1	0.421	0.441	4.49
5	1400	200	0.1	0.751	0.751	0.00	18	2600	120	0.3	0.504	0.526	4.17
6	1800	40	0.3	0.48	0.48	0.00	19	2600	160	0.5	0.612	0.636	3.77
7	1800	80	0.5	0.571	0.583	2.05	20	2600	200	0.7	0.758	0.744	1.95
8	1800	120	0.7	0.70	0.672	4.22	21	3000	40	0.1	0.404	0.373	8.45
9	1800	160	0.1	0.594	0.555	7.18	22	3000	80	0.3	0.453	0.432	5.09
10	1800	200	0.3	0.744	0.785	5.16	23	3000	120	0.5	0.533	0.521	2.31
11	2200	40	0.5	0.477	0.515	6.17	24	3000	160	0.7	0.641	0.691	7.12
12	2200	80	0.7	0.569	0.584	1.61	25	3000	200	0.1	0.547	0.535	2.24
13	2200	120	0.1	0.487	0.511	4.69							

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