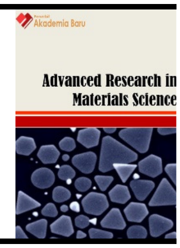
Penerbit Akademia Baru

Journal of Advanced Research in Materials Science

Journal homepage: www.akademiabaru.com/arms.html
ISSN: 2289-7992



Optimization of Surface Roughness on S50 Carbon Steel in CNC Milling Machine using Response Surface Methodology

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ARTICLE INFO

Article history:
Received 11 February 2018
Received in revised form 9 April 2018
Accepted 13 May 2018
Available online 2 September 2018

ABSTRACT

Machining process reflects how it can contribute to the quality of good surface roughness, Ra especially in CNC milling operations. The surface roughness of material reflects the quality of the surface obtained as good surface finish can improvise the mechanical properties and minimize tool wear. Parameters such as spindle speed, federate and depth was studied through response surface methodology using central composite design. S50 carbon steel material sizing 16 x 20 x 160 were machined in CNC JOHNFORD VMC -600 to obtain the surface roughness. The material S50 carbon steel is a highly used material in semiconductor industry were parts like a base plate and die mold is fabricated from it. The optimization process was done in Minitab version 16 using Design of Experiment. Two High-speed steel (HSS) 8mm end mill were used to run 20 experimental cuttings for roughing and finishing. The final optimal parameter values obtained from the optimization process were 1090 RPM, 95 mm/min and depth of 0.5153 mm.

Keywords:
Response surface methodology, central composite design, design of experiment, S50 carbon steel, surface roughness, optimization

1. Introduction

Milling is the process of removing unwanted stock (swarf) from the surface of the material using rotary cutters. The milling operation is done by utilizing these parameters federate, depth, spindle speed, and coolant. The surface roughness of material reflects the quality of the surface obtained. Response surface methodology is a collection of mathematical and statistical techniques that are used for modeling and analysis of problems [1].

The manufacturing industry especially high precision tool makers are looking for more effective methods to improvise on surface roughness. The industry is currently depending on operator/technician skill to come up with a good quality with the random utilization of parameters.

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The carbon steel material is challenging material as it consumes time to process. A proper method has to be developed based on Design of Experiment (DOE) to come with a common solution. As this would ensure carbon steel will have its own specific parameter values for surface quality which reduces time significantly milling on mild steel.

The manufacturing industry especially high precision tool makers such as semiconductor industry currently have no proper method to provide good surface quality of carbon steel materials. Depending on technician skills is time-consuming while the outcome on surface roughness varies, not up to the expectation. While there are many factors such as tool wear, vibrations which affects a good surface finish, a proper technique with identified parameters would cut down company's expenses on trial and error methods, reducing rejected work piece thus saving time.

2. Design of Experiment

Design of experiment (DOE) method is a systematic approach on how to investigate determine and improvise the factors that contribute to a process in terms of input and output. The DOE uses the statistical method to analyze the data and selection of parameters with the best output [2].

The basic DOE concepts used in this experiment are:

- Controllable factors: These input parameters such as federate, depth, spindle speed can be controlled /changed in an experiment.
- Uncontrollable input factors: Parameters that cannot be changed in a process. Working condition temperature.
- Responses / output measures: the outcome of a process such as surface roughness, exact dimensions, type of finishing.

A. Response surface methodology

Response surface methodology (RSM) is a mathematical and statistical method developed for modeling and analysis of optimization response influenced by variables. The objective of RSM is to optimize the output variables influenced by the input variables [3]. A series of tests called runs where changes made in input variables in order to identify the changes occur in the output response [4].

B. Central composite design

The central composite design (CCD) was created by Box and Wilson in the year 1951 and widely used design for second order design. The CCD design is primarily based on two-level factorial or factorial designs with 2k addition combinations of +1 and -1 levels of factor, where k is the number of independent variables pointing to star points between the axes and repeated points at the centroid [5].

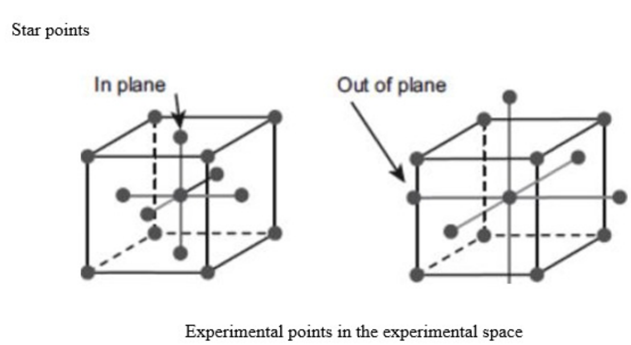

Fig. 1. Central Composite Design [5]

Star points also known as axial points fixed axially at a distance termed a from the centre to generate quadratic term. The value alpha a is important as it could determine axial points positions in experimental design value, the design can be termed spherical, orthogonal, rotatable, or face-centered depending on alpha value.

The star points represent low and high for each factor in the design replicate terms which represented by centre points provide a good and independent estimate of the experimental error. This will provide robustness to the experiment or more accuracy in obtaining values [6].

2.1 The Experiment Variables

A number of experiments designed by CCD will be

$$N = k^2 + 2k + n \quad (1)$$

where
N = is the total number of experiments,
K = is the number of factors studied, and
N = is the number of replicates.

The CCD is a better choice compared to full factorial three - level design since it demands a smaller number of experiments to produce providing results. When the experimental space is square or cubical this type of design is advantageous when the factors are varied independently of one another. This will be the sole reason for the experiment to be conducted in central composite design [7].

2.1.1 Surface roughness

Surface roughness plays an influential role in quality and productivity in the manufacturing industry. Surface roughness is an important criterion of a quality product when as it plays an influential role on mechanical properties such as fatigue, corrosion, wear, creep life and etc. to machine tools and machine components. Below is the figure of cutting phenomena that affects the surface roughness [8].

Fig. 2. Surface roughness Fishbone diagram parameters [8]

2.1.1.1 Surface roughness tester

The Perthometer M1 series is the ideal measuring instrument for surface roughness parameters such as Ra, Rz, Rmax, and RPc as per DIN EN ISO/AMSE/prEN 10049. This measuring device fulfills the international standard for precise, swift and on-site roughness measurement. The most significant performance of this device is that measurements can be performed in a different position such as vertical, horizontal with minimal time setting. This device comes with the ISO 3247 standard for surface roughness.

Fig. 2. Perthometer Ml device with stylus

2.2 Machining Hardware and Material Selection

The CNC JOHNFORD VMC -600 machine was selected as it offers the challenges set by the current manufacturing company to be studied and hence to obtain the best machining parameters which desired for machining S50 carbon steels materials.

The HSS high-speed steel is chosen as it has high toughness and affordable while displays high cutting speed characteristics. Another important consideration taken into account is the number of flutes as each number has its own function. The common number of flutes used in the industry is the 2 flutes and 4 flutes. Conventional milling application generally goes for 2 flute end mill since it designed for maximum space chip ejection and for drilling. The 4 flute end mill designed to be more rigid, reducing chip load and contributes good surface finish in high cutting speed. The 4 flute end mill is suitable for CNC milling machining. Figure 4 shows the nomenclature of a typical 4 flute end mill.

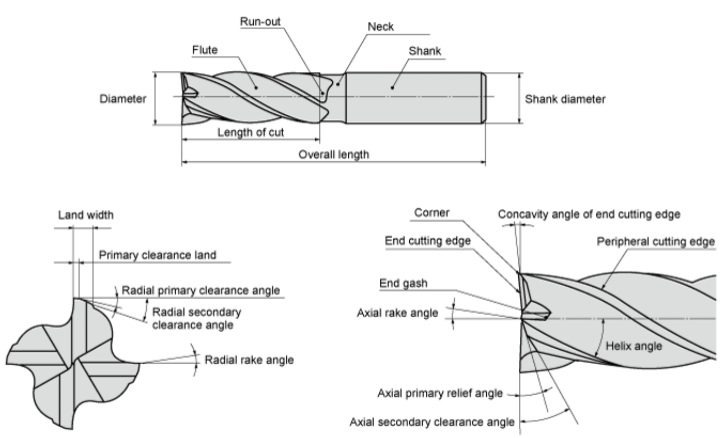

Fig. 4. End mill nomenclature [9]

S50 Carbon Steel - It's highly used in the manufacturing sector as the material offer good strength, ductility and good toughness. This particular material Carbon steel is considered to be the best steel for semiconductor parts as the material has good strength and wear resistance. The material machining characteristics can be improved if higher mechanical properties are added.

3. Methodology

3.1 Parameter Settings

Minitab V 16 has been used to design analyze and optimise the response surface methodology. The low surface roughness of aluminum and mild steel were studied. The parameters such as cutting speed, feed rate and depth of cut are the input parameters while Ra is the desired output. Single point high-speed steel is used as the cutting tool for machining. By evaluating 3 different levels of control factors the optimum levels were obtained. The parameters that have been used to create the central composite design is shown in Table 1. The average value (0) has not been shown in below as the value is created automatically in Minitab. Table 2 shows the Run Order generated by Minitab which later on to be used to run the experiments. The values for the parameters were used Application of DOE for Identifying Optimum Surface Roughness in CNC end Milling Process by [10].

Table 1
Parameter settings

Parameters	**Levels**	
	Low (-1)	**High (1)**
Cutting speed (rpm)	1000	1400
Feed rate (mm/m)	80	100
Depth mm	0.5	1

Table 2
Central Composite Design

StdOrder	**RunOrder**	**PtType**	**Blocks**	**S.speed**	**Feed rate**	**Depth**
3	1	1	1	1081.08	95.946	0.60135
17	2	0	1	1200.00	90.000	0.75000
9	3	-1	1	1000.00	90.000	0.75000
8	4	1	1	1318.92	95.946	0.89865
10	5	-1	1	1400.00	90.000	0.75000
19	6	0	1	1200.00	90.000	0.75000
6	7	1	1	1318.92	84.054	0.89865
18	8	0	1	1200.00	90.000	0.75000
7	9	1	1	1081.08	95.946	0.89865
15	10	0	1	1200.00	90.000	0.75000
2	11	1	1	1318.92	84.054	0.60135
5	12	1	1	1081.08	84.054	0.89865
11	13	-1	1	1200.00	80.000	0.75000
1	14	1	1	1081.08	84.054	0.60135
20	15	0	1	1200.00	90.000	0.75000
16	16	0	1	1200.00	90.000	0.75000
14	17	-1	1	1200.00	90.000	1.00000
12	18	-1	1	1200.00	100.000	0.75000
13	19	-1	1	1200.00	90.000	0.50000
4	20	1	1	1318.92	95.946	0.60135

3.2 Machining

The material is prepared through the squaring process first before being sent to CNC milling department. This is a compulsory process to make sure all surface of the material is free from any defects such as burr and uneven surfaces, this will also be the standard base for each specimen. While roughing the material burr is removed using the deburring tool. The material surface is then ground to get even surfaces as shown in Figure 5. This work is crucial to ensure that the surface roughness is not compromised when machining is done in CNC milling machine.

Fig. 5. Actual Specimen after Grinding Process

Later on, the CNC machining process is done according to the machining parameters such as RunOrder, Speed, Feed Rate and Depth generated in Table 2 which was discussed earlier.

3.3 Measurements

The Perthometer is used to get the Ra values from the milled block by placing the stylus on the milled slots as shown in Figure 6 the same is process is repeated for workpiece 2 and 3or PPT. All Ra value results are tabulated in Table 3.

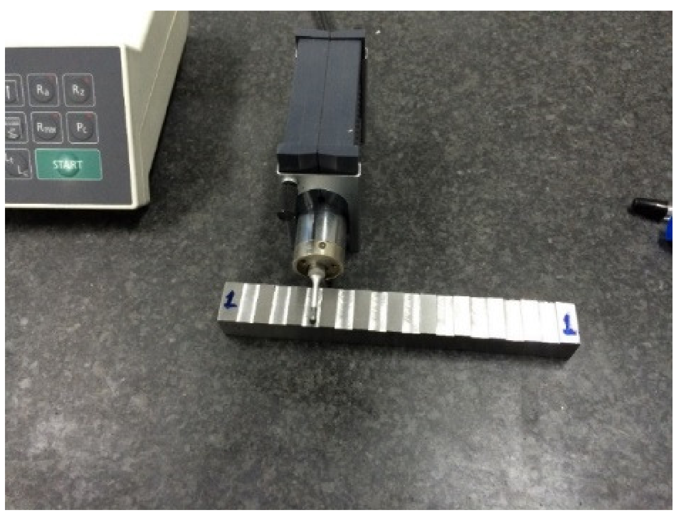

Fig. 6. Data sampling using Perthometer from machined specimen

Table 3
Ra Values Results according to RunOrder

StdOrder	RunOrder	PtType	Blocks	S.speed	Feed rate	Depth	Ra, µm
3	1	1	1	1081.08	95.946	0.60135	0.9550
17	2	0	1	1200.00	90.000	0.75000	1.2060
9	3	-1	1	1000.00	90.000	0.75000	1.1550
8	4	1	1	1318.92	95.946	0.89865	1.6820
10	5	-1	1	1400.00	90.000	0.75000	1.3140
19	6	0	1	1200.00	90.000	0.75000	1.3300
6	7	1	1	1318.92	84.054	0.89865	1.7455
18	8	0	1	1200.00	90.000	0.75000	1.7890
7	9	1	1	1081.08	95.946	0.89865	2.2380
15	10	0	1	1200.00	90.000	0.75000	1.5500
2	11	1	1	1318.92	84.054	0.60135	1.9770
5	12	1	1	1081.08	84.054	0.89865	1.7410
11	13	-1	1	1200.00	80.000	0.75000	2.2060
1	14	1	1	1081.08	84.054	0.60135	1.9425
20	15	0	1	1200.00	90.000	0.75000	1.9745
16	16	0	1	1200.00	90.000	0.75000	1.6770
14	17	-1	1	1200.00	90.000	1.00000	1.7345
12	18	-1	1	1200.00	100.000	0.75000	1.9595
13	19	-1	1	1200.00	90.000	0.50000	1.3940
4	20	1	1	1318.92	95.946	0.60135	1.9775

3.4 Analysis

Results obtained in Table 3 are later fed to the Minitab generated CCD design. Figure 7 shows the low settings is selected as the objective of the optimization is to get the minimal surface roughness, Ra.

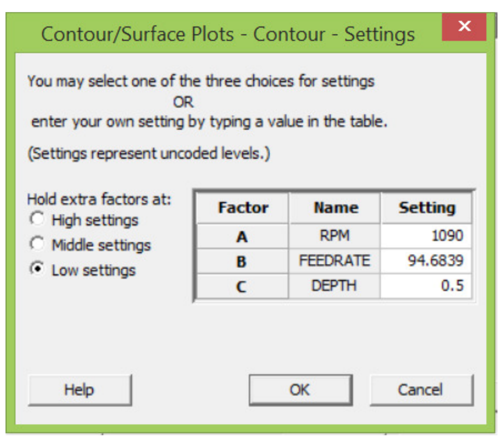

Fig. 7. Minitab's Contour Settings

4. Results and Discussion

The obtained data was interpreted and optimization was done. The best surface roughness Ra values that have been obtained was in the Run Order 1, which is 0.955 µm. the optimization region lies around Run Order1 surface roughness region.

Figure 8 shows the Residual plots for Ra which includes normal probability plot, histogram, versus fits and versus order been generated. The normal probability plot indicates the obtained data is reliable as the data point falls closely to the fitted distribution line (middle blue line).

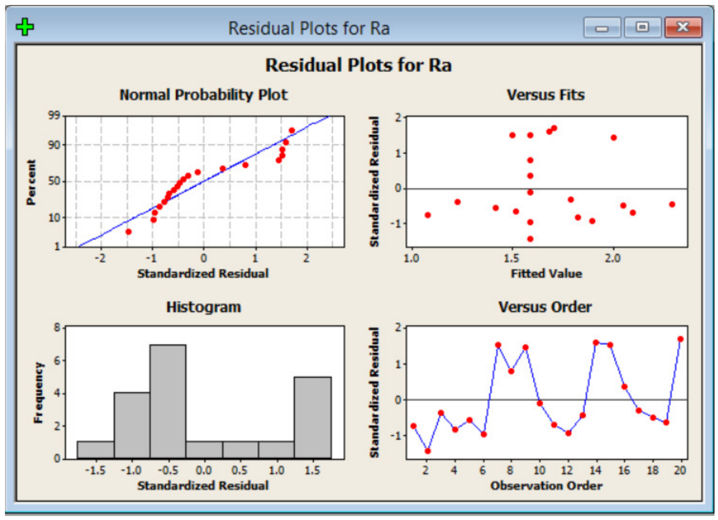

Fig. 8. Residual Plots for Ra

4.1 RSM Analysis

Figure 9 shows the graph contour plot of Ra vs. Feedrate. The black arrow indicates the lowest value of Ra can be identified in that region (white colour) < 0.5µm, the optimization process is based on this region since the target is smooth surface while the white arrow shows the largest value of Ra > 2.5µm that can be obtained in that region (dark green) which is not desirable since the Ra values gives rough finishing surface.

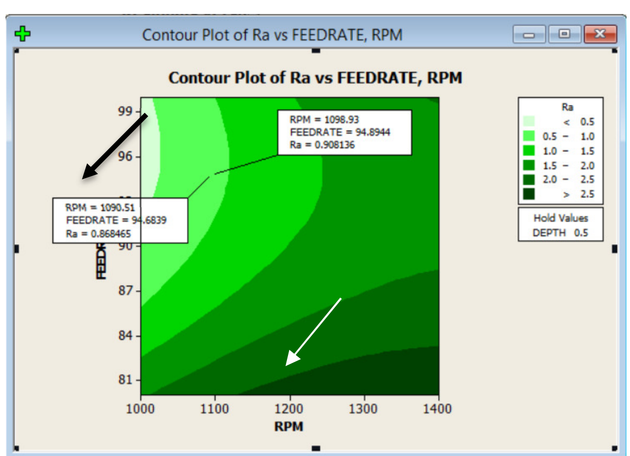

Fig. 9. Contour Plot of Ra vs. Feedrate, Rpm

It is clearly shown in Figure 10 that the cutting speed value is < 1100 while the feedrate value is around 94 to 95 mm/min. the hold value is the depth which is 0.5 mm. The past research in the literature proved that the cutting speed affects the most following feedrate.

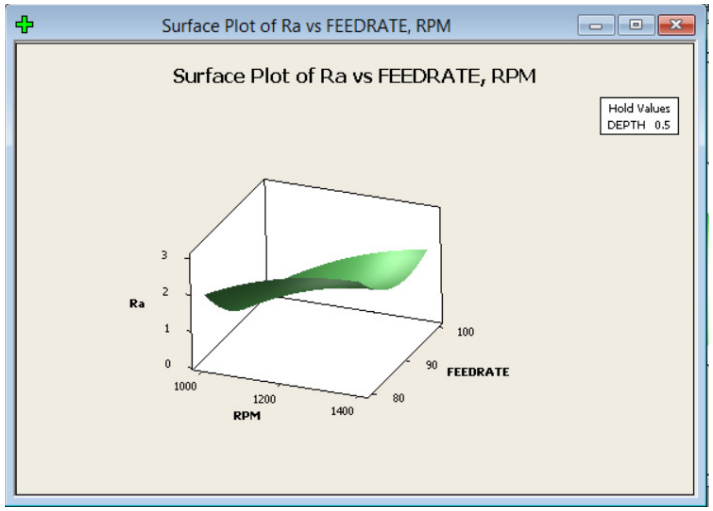

Fig. 10. Surface Plot of Ra vs. Feedrate, Rpm

Figure 11 and Figure 12 shows the feederate value = 94.68 is the hold values which indicates the spindle speed and depth value region may be obtained around that region. The federate is taken from Figure 10 to see the significant effect of interactions. Figure 12 also indicates the spindle speed value should be less than < 1100 and federate value around 95 mm/min.

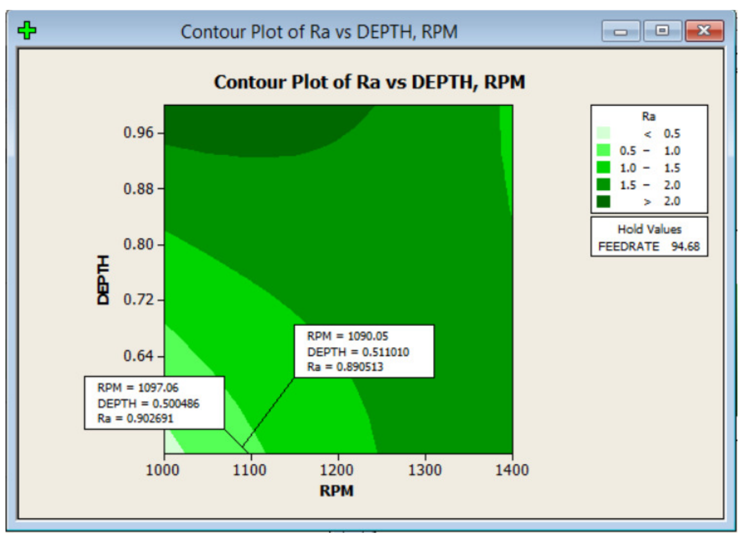

Fig. 11. Contour plot of Ra vs. Depth, Rpm

Figure 13 and Figure 14 shows the federate around value = 94.68 and the hold values are the RPM = 1090 which indicates the federate and depth value region may be obtained around that region. Figure 13 also emphasize that the depth doesn't affect the surface roughness unlike the spindle speed and federate. The RPM is taken from Figure 14 to see the significant effect of interactions. Figure 14 also indicates the spindle speed value should be less than <1100 and federate value around 95 mm/min.

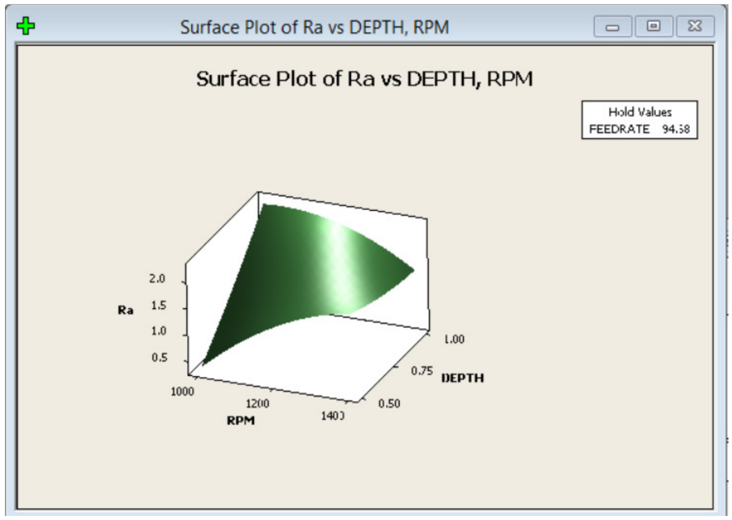

Fig. 12. Surface plot of Ra vs. Depth, Rpm

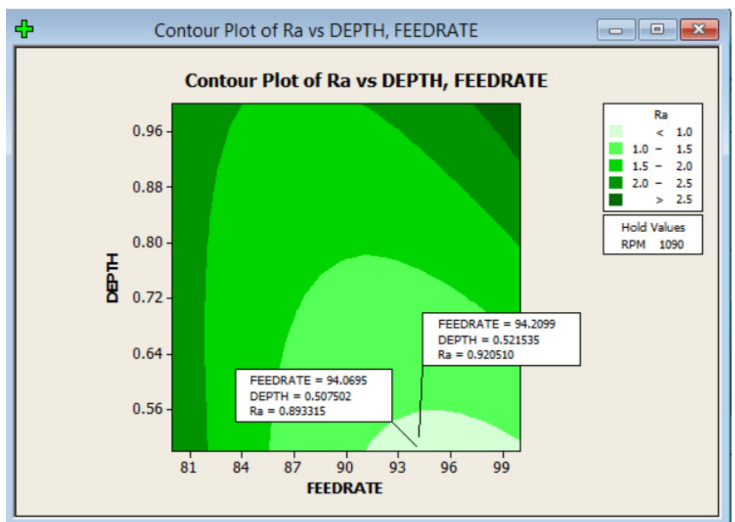

Fig. 13. Contour plot of Ra vs. Depth, Rpm

4.2 Optimization

Figure 15 shows the optimization plot where the final optimum values for parameters spindle speed is 1090 RPM, federate 94.68 mm/min and depth 0.5131 have been obtained. The composite desirability obtained is 1, which indicates the settings appear to have achieved favorable results for all responses as a whole. Composite desirability evaluates how the settings optimize a set of responses overall. Desirability ranges from value zero to one. One represents the ideal case; zero indicates that one or more responses are outside their acceptable limits.

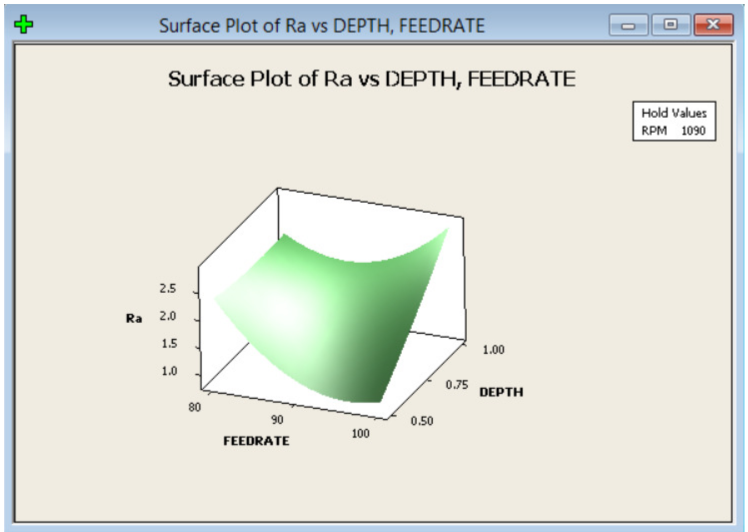

Fig. 14. Surface plot of Ra vs. Depth, Rpm

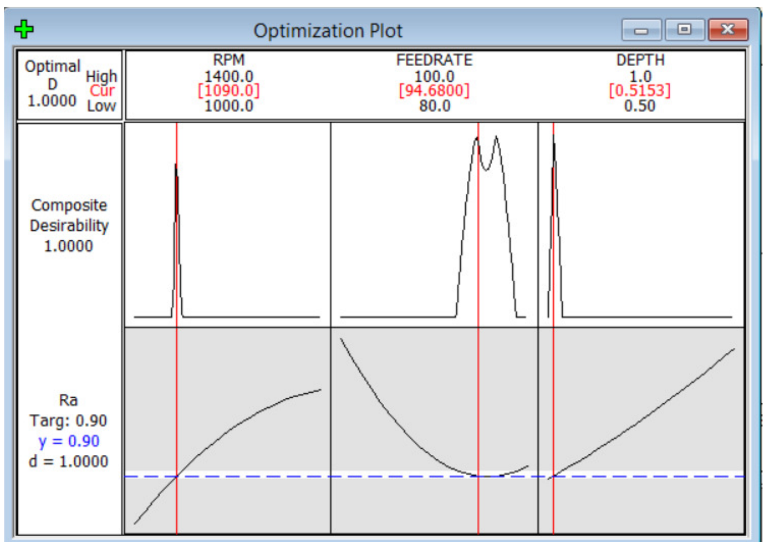

Fig. 15. Optimization Plot

4.3 Verification

The value obtained in final optimization plot Figure 15 is used in machining for result verification. The value was taken using the Perthometer surface roughness tester and tabulated as below in Table 4. The average value of result verification is 1.3210µm shown in Table 5.

Table 4
Verification Results

Machined slot	Slot 1	Slot 2	Slot 3	average
Ra,µm	1.505	1.949	1.7025	1.71

Table 5
Verification Results

Response	Parameters			Ra (µm)
	Spindle Speed (Rpm)	Feedrate (mm/min)	Depth (mm)	
Run order 1	1081.08	95.946	0.60135	0.955
Optimal result	1090	94.68	0.5153	1.71

The optimal result obtained is 1.71µm which is higher than 0.955µm, as the intended Ra value should have the range between 0.8595µm to 1.0505µm as per the requirement. There are few factors which contribute to the significant difference of the higher Ra value as the machining for the 20 experimental runs were done in Precision Tool Tech company, while the result verification machining was done in UNISEL's CNC lab. This is due to unavailability of the *CNC JOHNFORD VMC - 600* machine during the verification process. A similar CNC machine was chosen to complete the study. At the same time, there is a shortage of end mill has prompted us to use the same end mill for roughing and finishing. The longer the duration of machining the end mill subjected to wear which translate to a rougher finishing. The use of different CNC machine has given us higher Ra values as the settings for the CNC machines are different. Another contributing factor is the Perthometer. The Ra value which obtained initially were higher compared to the current Ra readings as the Perthometer were calibrated for EDM Ra readings. Human/operator also might have contributed to the result verification reading as right after each milling process the machined slot needs burr removal using fine sandpaper. Improper removal of burr must have added to the error taking Ra reading using Perthometer.

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