Experimental Analysis and Optimization of Machining Parameters of AISI 4140 Steel

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Abstract- *Metal cutting is viewed as a process consisting of dependent and independent variables to produce a desirable output performance characteristics. The independent input variables are work piece material, geometry of the work piece, type of machining processes, tool material and cutting parameters. The dependent variables of the turning process are power, cutting force, tool wear, material removal rate, surface finish etc. The fundamental and most common operation in almost all mechanical engineering industry is "Turning". To survive in this combat competition the industries are required to be more cost conscious. Therefore, they are in need to use the resources very effectively, producing high quality end products with minimum possible or zero defects.*

Turning is one of the fundamental operations in mechanical industry. The process parameters involved with the turning process are generally spindle speed, feed rate, depth-of-cut, tool nose radius and tool rake angle. Cutting speed and feed rate affect surface roughness. Cutting tool inserts are helpful in obtaining better finishing cuts, which results in a very fine surface finish. Alternatively, when the inserts are used for roughing cuts, tool tends to fracture uncertainly. An experimental study found that Depth of-Cut (DOC) does not have an effect on surface microstructure, whereas, the feed, nose radius, work material, speed and tool point angle have a direct impact on surface roughness.

The surface quality plays an important role. The fatigue strength, corrosion resistance are improved by machined surface. Hence, surface roughness also affects the functional attributes of parts, such as contact causing surface friction, wearing, light reflection, heat transmission, ability of distributing and holding a lubricant, coating, or resistance fatigue. The surface roughness is mainly a result of various processes parameters.

Keywords- *Metal cutting, Depth of-Cut (DOC), machining processes, tool material and cutting parameters*

1. INTRODUCTION

Machining is the most wide spread metal machining process in mechanical manufacturing industry. The goal of changing the geometry of raw material in order to for mechanical parts can be met by putting material together.This inherently develops economic losses such as tool wear, damaged work piece etc. Therefore the predominant parameters that affect machinability properties are tool geometry and other machining parameters. The determination of process parameters to obtain an optimized objective function will bring down the economics of machining. In any manufacturing systems, the input to the system includes energy, capital investment, manpower, material etc.

The economics of machining involves minimum cost of production, minimum surface roughness, minimum cutting force, minimum tool wear, maximum metal removal rate, maximum production rate, minimum flank wear and maximum tool life. Turning process is the conventional process of metal cutting operation with the usage of single point cutting tool. Metal cutting is viewed as a process consisting of dependent and independent variables to produce a desirable output performance characteristics.

The independent input variables are workpiece material, geometry of the workpiece, type of machining processes, tool material, cutting parameters. The dependent variables of the turning process are power, cutting force, tool wear, material removal rate, surface finish etc. Work piece of different shapes, dimensions and different materials are worked in a metal working industry.

1.1. OBJECTIVE OF THE RESEARCH

Based on the literature review on metal cutting of AISI 4140 material, surface roughness, flank wear, etc., the following objectives are formulated for the present work;

1. To investigate the influence of cutting process parameters on AISI 4140 steel with carbide tool.
2. To study the effect of surface roughness and flank wear on turning of AISI 4140 work material with carbide tool.
3. To analyze the experimental data on surface roughness and flank wear using Taguchi technique, Response surface methodology.

1.2.MOTIVATION AND SCOPE OF THE PRESENT WORK

Most of the researchers considered several cutting tools for hard turning of AISI 4140 steel. The present work is focused on turning of AISI 4140 steel using carbide tool. Also the work is focused on the determination of optimum selection of cutting process parameters like cutting speed, feed and depth of cut for AISI 4140 work material.

1.3.CHALLENGES

AISI4140 steel are familiar in numerous applications due to their enhanced mechanical properties such as high strength, toughness and impact resistance. However these properties are influenced by the alloying element and heat treatment used. The major challenge in turning of AISI 4140 steel are expressed in high adhesion affinity and excessive hardening during high cutting speeds, high thermal loads. This leads to unfavorable chip breakage and increased burr formation and ultimately results not only in quality of the work piece but also the tool wear.

2. LITERATURE REVIEW

Machining parameter and tool geometry are the criterion for machinability. Machinability model represents the functional relationship between the input parameters and output responses such as cutting speed, feed, and depth of cut and cutting force, power consumption, tool wear, tool life respectively. Several literature reviews pertaining to machining, carbide cutting tool, AISI 4140 work material, Optimization techniques are discussed here.

Choudhary& El-baradie (1997) developed surface roughness modelfor turning steel using response surface methodology. The cutting speed, feed and depth of cut are selected as the process parameters against the response surface roughness. The turning process is carried in dry conditions using uncoated carbide inserts. Noordin *et al.* (2004) investigated the performance of coated carbide tools when turning AISI 1045 steel using Response surface methodology. The experimental plan is based on face centred, Central Composite Design (CCD). It is concluded that feed is the most significant factor that influences the surface roughness.

Aggarwal *et al.* (2008) used response surface methodology and Taguchi technique in optimizing the power consumption for CNC turned parts of AISI P-20 tool steel. Experimental investigations are carried out to optimize power consumption in the turning process in cryogenic conditions. The process parameters considered in this work are nose radius, cutting environment, depth of cut etc. The results obtained from Taguchi technique and Response surface methodology are near similar and proved to be the mostefficient method in the analysis of optimization.

Liao &Shiue (1996) examined the turning of Inconel 718 by using carbide device and concluded that at high cutting velocity, the particles will diffuse into the fastener by grain diffusion process. Dudzinski *et al.* (2004) concentrated on the advances of machining of Inconel718. It is observed that the expenses of coolant are critical and it is our times the cost of consumable tooling utilized as a part of the cutting activities. To lessen the expenses of coolant and to make the procedures ecologically favourable, the manufacturing engineers advance toward dry cutting conditions.

Sahoo *et al.* (2012) investigated several aspects related to machining of AISI steel. Regression models are developed and it is observed that the coated inserts performed better when compared to the uncoated inserts. Singh &Rao (2007) investigated the effects of cutting conditions and tool geometry on the surface roughness in turning of AISI steel using ceramicinserts as the cutting tool. It is observed that feed is the dominating parameter in determining the optimum surface roughness followed by nose radius and cutting speed. Mathematical modelling for the surface roughness is developed using Response surface methodology. Das *et al.* (2015) investigated machinability of hardened steel using Response surface methodology.

3. EXPERIMENTAL METHODOLOGY

3.1. INTRODUCTION

Machinability, tensile strength and ductility properties of the work piece AISI 4140 is improved due to the addition of carbon content. These improved properties bring a wide range of applications of the work piece AISI 4140 in automobiles, spindles, gears, shafts, crane machinery, marine industry, cutting machineries etc. The corrosion resistance of the work material is improved by increasing the percentage of chromium composition and addition of chromium indirectly increases the resistance to the oxidation. The case hardening process such as nitriding and case hardening increases thesurface roughness of the work material to a greater extent.

3.2. WORK MATERIAL

Based on the economic considerations, the choice made for machining AISI 4140 steel is a coated carbide tool. AISI 4140alloysteeliscomposition of chromium, molybdenum, manganese containing low alloy steel with high fatigue strength, abrasion, impact, resistance, toughness and torsional strength. Experiments are conducted with AISI 4140 steel, which is normallyavailable from stocks in bar. The aim of the present research work is to optimize process parameters for the minimization of the surface roughness and flank wear using carbide tool under dry cutting conditions. The AISI 4140 work material of 50mm diameter initially is shown in the Figure 3.1.

The Figure 3.2 shows the detailed drawing of the dimensions of the workpiece to be produced during the process of machining. The workpiece selected for this research work is AISI 4140 steel and the composition of the work piece is given in Table 3.1.

Table 3.1 Chemical composition of AISI4140

Element	Composition, %
C	0.38
Si	0.15
Mn	0.6
S	0.040
P	0.035
Cr	0.7
Ni	1.65
Mo	0.2

Figure 3.1Work Material

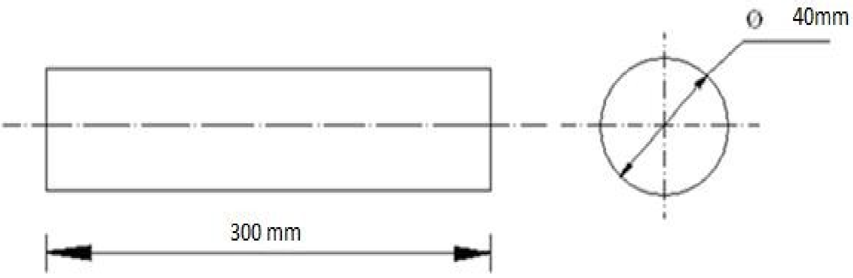

Figure 3.2Dimensions of the work piece

3.3. TOOL MATERIAL

The coated carbide tool gives better performance with respect to different cutting speeds and feeds. But from experimental point of view carbide tool fails due to thermal softening and subsequent plastic deformationof the cutting edge. The performance of the coated carbide tool in the machining process of AISI 4140 is discussed in this thesis. The cutting tool used for the purpose of machining AISI 4140 steel is shown in the Figure 3.3.

Figure 3.3Tool Material

3.4. EQUIPMENTS USED

The experiment was conducted on a CNC Lathe as shown in the Figure.2.4 using AISI 4140 alloy steel and coated carbide tool. Surface roughness tester was used to measure the surface roughness and High resolution Scanning Electron Microscope are used for measuring the Flank wear. This work material is machined using carbide tool with cutting speed, feed and depth of cut taken as the process parameters. The responses considered against these process parameters are surface roughness and flank wear. Designs of experiments are used to conduct the experiments for minimization of surface roughness and flank wear. The specifications of the CNC lathe used for the process of turning are given in Table 3.2.

Table 3.2 Specification of the Turning machine

Item description	Technical Details	Specifications
Capacity	Height of the Centre Swing over cross slide Swing over bed Distance between centers	185 mm 200 mm 350 mm 1000 mm
Speed	Number of speed Speed range	8 100 – 1800 rpm
Main spindle	Spindle bore Taper bore in sleeve	25mm MT-3
Bed	Bed width	250 mm
Feeds	Number of longitudinal feed Number of transverse feeds	24 24

Electrical connection	Motor Power source	3 HP 3 Phase AC Supply
Weight and Space	Weight Space	700 Kg 1950 x 900 mm

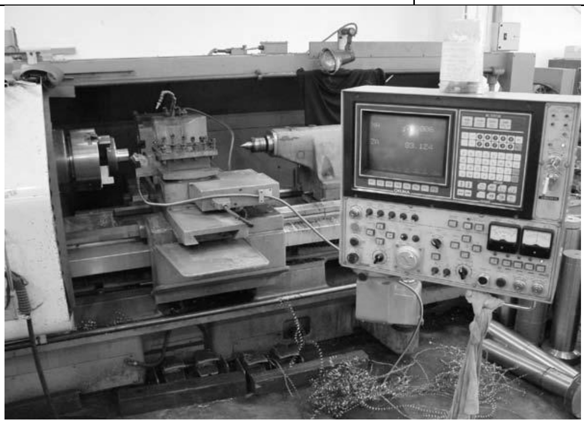

Figure 3.4 CNC Lathe

The typical methodology and equipment setup for the experimentalwork conducted is presented in Figure 3.5.

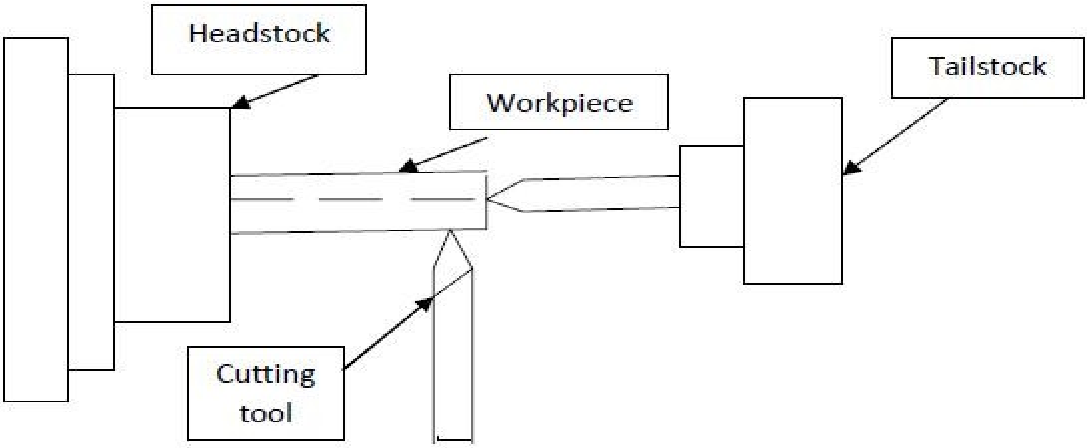

Figure 3.5 Experimental setup

3.5. MACHINING PARAMETERS AND THEIR LEVELS

The functional ability of machined component solely depends upon surface property such as surface roughness as it is a dependent variable.Component functionality in machining process can be improved and optimized by an increased knowledge of the surface generation mechanism. The effect of process parameters on several responses in turning process had been investigated by numerous investigators.

Three levels are selected for the given three factors and correspondingly L_{27} Orthogonal array is selected for conducting the experiments through implementing the Design of Experiments.

Design of experiments is a systematic approach used by several researchers in the prediction of optimum surface roughness in turning operation. Response surface methodology and Taguchi techniques are familiarly used methodologies in Design of experiments to predict the optimization of surface roughness and flank wear in turning operations.

The machining parameters levels and the experimental conditions for analysis of turning of AISI 4140 steel are presented in Table.3.3 and Table.3.4 respectively.

Table 3.3 Level of Parameters

Process Parameters	Level 1	Level 2	Level 3
Cutting speed (m/min)	135	185	240
Feed, mm/rev	0.04	0.05	0.06
Depth of cut, mm	1	1.25	1.5

Table 3.4 Machining conditions

Experiment Run	Cutting Speed, m/min	Feed Rate, mm / rev	Depth of Cut, mm
1	1	1	1
2	1	1	1
3	1	1	1
4	1	2	2
5	1	2	2
6	1	2	2
7	1	3	3
8	1	3	3
9	1	3	3
10	2	1	2
11	2	1	2
12	2	1	2
13	2	2	3
14	2	2	3
15	2	2	3
16	2	3	1
17	2	3	1
18	2	3	1
19	3	1	3
20	3	1	3
21	3	1	3
22	3	2	1
23	3	2	1
24	3	2	1
25	3	3	2
26	3	3	2
27	3	3	2

The experiments are conducted and the surface roughness and flankwear are measured at the end of each experiment. The values are recorded andpresented as shown in the Table 3.5.

Table 3.5 Experimental data

Expt Run	Cutting Speed, m/min	Feed rate, mm / rev	Depth of Cut, mm	Surface Roughness,μm	Flank wear, mm
1	135	0.04	1.00	5.3	0.7
2	135	0.04	1.25	4.6	0.8

3	135	0.04	1.50	4.3	0.7
4	135	0.05	1.00	4.9	0.6
5	135	0.05	1.25	5.5	0.4
6	135	0.05	1.50	5.1	0.7
7	135	0.06	1.00	5.2	0.7
8	135	0.06	1.25	4.8	0.6
9	135	0.06	1.50	3.9	0.6
10	185	0.04	1.00	3.6	0.6
11	185	0.04	1.25	4.7	0.5
12	185	0.04	1.50	4.5	1.0
13	185	0.05	1.00	4.3	0.7
14	185	0.05	1.25	5.7	0.5
15	185	0.05	1.50	6.5	0.8
16	185	0.06	1.00	3.6	0.5
17	185	0.06	1.25	5.1	0.6
18	185	0.06	1.50	3.7	0.6
19	240	0.04	1.00	2.0	0.7
20	240	0.04	1.25	4.5	0.6
21	240	0.04	1.50	4.0	1.0
22	240	0.05	1.00	2.2	0.6
23	240	0.05	1.25	3.9	0.7
24	240	0.05	1.50	4.2	0.8
25	240	0.06	1.00	2.2	0.7
26	240	0.06	1.25	3.1	0.7
27	240	0.06	1.50	3.7	0.7

4. OPTIMIZATION OF MACHINING PARAMETERS

The evolutionary algorithms and swarm intelligence based algorithms are the major important groups in population based algorithm, Rao(2016). Genetic Algorithm, Evolution strategy, differential evolution are some of the popular evolutionary based algorithm used by most of the researchers in the previous years. Particle swarm optimization, Ant colony algorithm, Fire fly algorithm etc., are some of the popular algorithms based of swarm intelligence based techniques used by the researchers in the previous years. The various approaches for the optimization algorithms are shown in Figure 4.1.

All these evolutionary based and logical search based algorithms involve with the common controlling parameters. The common controlling parameters include population size, total number of iterations or generations, etc. The some algorithm-specific control parameters are available with certain algorithms apart from the common controlling parameters. The Table.4.1 gives the algorithm of specific controlling parameters for several algorithms used by the several researchers.

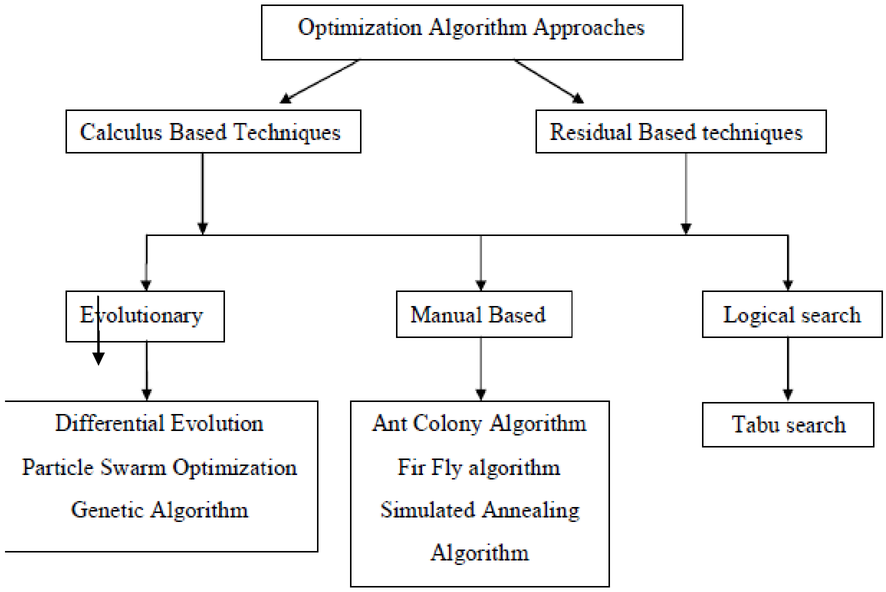

Figure 4.1Optimization Algorithm Approaches

5. RESULTS AND DISCUSSION

5.1. INTRODUCTION

The results obtained through various optimization techniques for analyzing the optimization of cutting process parameters in turning AISI 4140 steel is discussed in this chapter. The effect of machining parameters such as cutting speed, feed rate and cutting speed on surface roughness and flank wear are investigated in this research work. Taguchi Grey Relational Analysis, Taguchi Technique, Response surface methodology and Jaya Algorithm are used as the optimization tools for the analysis and investigationof the cutting process parameters of AISI 4140 steel.

5.2. OPTIMIZATION USING TAGUCHI GREY RELATIONALANALYSIS

Surface roughness is determined using three process parameters cutting speed, feed rate and depth of cut. The Taguchi grey relation analysis correlates the experimental data and the desired data and calculates the grey relational coefficient. The design of experiments are used to conduct the experiments containing three factors at three levels. L_9 Orthogonal array is used and nine experiments are conducted. The several values of surfaceroughness recorded for each experiment and is shown in Table 5.1.

Table 5.1 Experimental data for Surface Roughness and Flank wear

Expt Run	Cutting Speed, m/min	Feed, mm/rev	Depth ofcut, mm	Surface Roughness,μm	Flank wear, mm
1	135	0.04	1.00	5.3	0.7
2	135	0.05	1.25	5.5	0.4
3	135	0.06	1.50	3.9	0.6
4	185	0.04	1.25	4.7	0.5
5	185	0.05	1.50	6.5	0.8
6	185	0.06	1.00	3.6	0.5
7	240	0.04	1.50	4.0	1.0
8	240	0.05	1.00	2.5	0.6
9	240	0.06	1.25	1.8	0.9

Table 5.2 presents values obtained through Taguchi Grey Relational Analysis (TGRA).

Table 5.2 Calculated Signal to Noise ratio and normalized values

Expt runs	Signal to noise ratio		Normalized values	
	R_a, μm	VB, mm	R_a, μm	VB, mm
1	-14.6382	4.45146	0.85209	0.14167
2	-14.9451	4.45146	0.87975	0.14167
3	-11.8213	4.27918	0.59825	0.17200
4	-13.5137	4.70154	0.75076	0.09764
5	-16.2796	1.38102	1.00000	0.68225
6	-11.3028	4.62724	0.55153	0.11073
7	-12.1983	-0.42379	0.63222	1.00000
8	-6.8721	5.25615	0.15227	0.00000
9	-5.1823	0.62101	0.00000	0.81606

The surface roughness reduced continuously with increase in feed afterward. But it was also observed that the surface roughness increased with increase in depth of cut. The confirmation tests are shown in Table.5.3 for these predicted values against the experimental results. Using Taguchi

Grey Relational Analysis, the optimal parameters combinations are found to be cutting speed 185m/min; feed 0.04mm/rev and depth of cut 1.50 mm.

Table 5.3 Validation Test

Sl. No	Responses	Optimal parameters combinations (*v*=185m/min; *f*=0.04mm/rev; *d*=1.50mm)	
		Predicted	Experimental
1	Ra, µm	6.09	5.98
2	V_b, mm	0.84	0.91

The optimized process parameter range for surface roughness and flank wear are; Surface Roughness, Cutting speed = 135m/min, feed = 0.04mm/rev, depth of cut = 1.5mm and for flank wear, Cutting speed = 240m/min, feed = 0.04mm/rev and depth of cut = 1.5mm. The main effects plot for S/N ratios for surface roughness and Flank wear are shown in Figure 5.1.

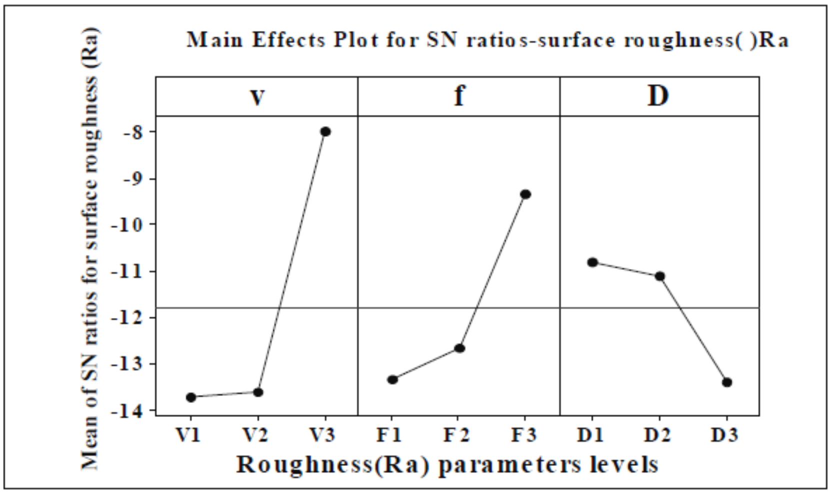

Figure 5.1 Main effects plot for S/N ratio for surface roughness

The ANOVA table for surface roughness is given in Table 5.4. It is observed that the R^2 value is 92.04 and hence confirms the consistency of the mathematical equation. From ANOVA table, it is noted that the highest contributing factor is the cutting speed with 54.2% of contribution. Figure 5.2 (a) presents the contour plots which show the effect of cutting speed and feed rate withsurface roughness. It is observed that, the increase in cutting speed has a very little effect on surface roughness, whereas with the increase in the feed rate, surface roughness increases significantly. Figure 5.2 (b) presents the contour plots which shows the effect of cutting speed and depth of cut with surface roughness. It is observed that the surface roughness shows very little modifications with increase in cutting speed and depth of cut.

Table 5.4ANOVA table for Surface Roughness

Source	DF	Seq. Sumof Squares	Adj. Sum of Squares	Adj. Mean Square	F	P	% Contribution
V	2	10.1267	10.1267	5.0633	6.81	0.128	54.2115
F	2	5.1267	5.1267	2.5633	3.45	0.225	27.4449
D	2	1.9400	1.9400	0.9700	1.30	0.434	10.3854
Error	2	1.4867	1.4867	0.7433			7.9589
Total	8	18.6800					100

S = 0.862168 R-Sq = 92.04% R-Sq(adj) = 68.17%

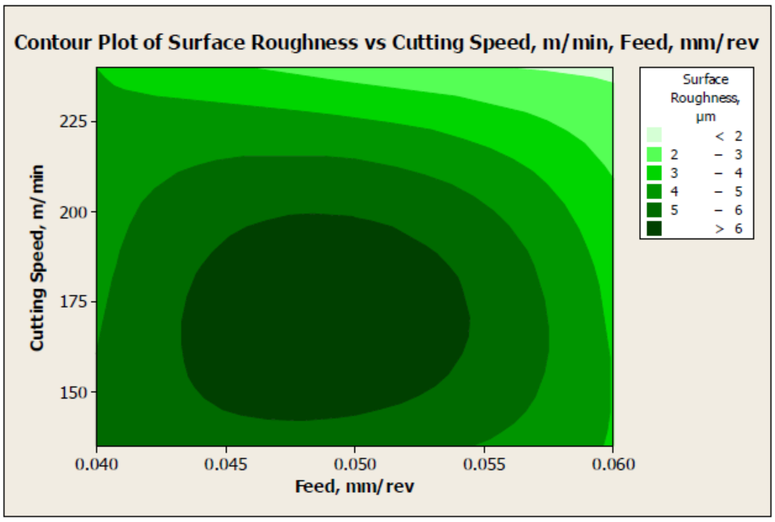

Figure 5.2 (a) Contour Plot of Surface roughness Vs Cutting speed andFeed

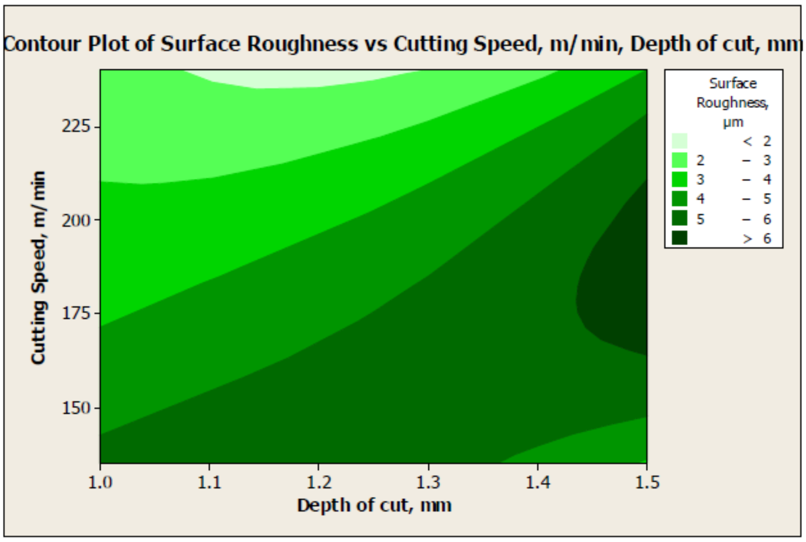

Figure 5.2 (b) Contour Plot of Surface roughness Vs Cutting speed anddepth of cut

6. CONCLUDING REMARKS AND SCOPE FORFUTURE WORK

6.1. INTRODUCTION

- In this work, the process parameters employed are cutting speed, feed and depth of cut. Surface Roughness was measured as the response. Surface roughness is measured using Mitutoyo Surface roughness tester. The Taguchi grey relation analysis is used to investigate the results for minimization of surface roughness and flank wear and found to be satisfactory. The optimum values for the surface roughness are determined using the surface plots and contours plots and the optimum values for surface roughness.

- Using Taguchi Grey Relational Analysis, the optimal parameters combinations are found to be cutting speed 185m/min; feed 0.04mm/rev and depth of cut 1.50 mm. Optimization of the cutting process parameter in turning of AISI 4140 steel using Response surface methodology and Taguchi technique are also carried out. The turning process is carried out in dryconditions to favor the environmental conditions by not polluting the environment by the usage of lubricants and cooling agents, which include the chemical agents. The surface roughness and flank wear are considered as the responses.

- The mathematical regression equations are also obtained for the response variables. The results of Jaya algorithm are compared with Genetic Algorithm and it is found that the results obtained through Jaya algorithm are closer and highly accepted. Confirmation tests are also conducted and the results are found to be efficient.

6.2. SCOPE FOR FUTURE WORK

The present research work involves with the determination of the optimum cutting process parameters for machining AISI 4140 steel. The cutting process parameters considered in this research work are cutting speed, feed and depth of cut. However the present research may be extended further considering the other process parameters such as varying the tool geometries, nose radius etc. The responses considered in this work are minimization of surface roughness and minimization of flanks wear.

However, the present work may be extended with the determination of the optimum cutting conditions for minimization of power consumption, cutting temperature, cutting forces, maximization of the tool life, material removal rate etc.

Also the present work is involved with the dry machining. The future researchers may extend the present research work taking into considerations rations of the wet machining and cryogenic machining. While considering the wet or cryogenic machining conditions, the environmental conditions are to be maintained for safer operations.

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