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Fuzzy Inference System for Prediction During Precision Turning Of Ti-6al-4v

M. Anthony Xavior[a] & R. Vinayagamoorthy[b]*

Professor [a], Research Scholar [b] School of Mechanical and Building Sciences

VIT University, Vellore – 14 Tamil Nadu, India Phone: 919994126328

Abstract

This research work focuses on precision turning of Ti6Al4V material to investigate the machinability of the material. Precision turning is a type of machining where, very low feed rate and depth of cut is being used to machine using a cutting insert with a lower nose radius. The cutting parameters considered for the experiments include the cutting speed, feed rate, depth of cut and nose radius. PVD coated carbide cutting inserts with different nose radius and constant rake and clearance angle are being considered for experimentation. The experimentation was designed based on Taguchi's L 27 orthogonal array. Three different levels of cutting parameters were being considered for the experimentation. The turning experiments were carried out on a conventional variable speed motor lathe under dry working conditions. Based upon the experimental values, Analysis of Variance (ANOVA) was conducted to understand the influence of various cutting parameters on cutting force, surface roughness and cutting tool temperatures during precision turning. There are a number of techniques available for predicting responses using input parameters and the present work uses Fuzzy Inference System (Mamdani Fuzzy logic) to predict the out put parameters.

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Keywords: Titanium alloys; Precision machining; Cutting tool temperature; Surface roughness; Cutting force; ANOVA; Fuzzy Inference System;

Introduction

Titanium and its alloys have played a significant role in the field of aerospace, energy, chemical and bio medics due to its high strength to weight ratio and exceptional mechanical and chemical properties. Machining of titanium alloys is a major concern because of its low thermal conductivity that prevents the dissipation of heat easily from the tool chip interface, which in turn heats up the tool due to increasing temperature resulting in lower tool life. Titanium forms alloys easily due to high chemical reactivity that causes weld and smear formation along with rapid cutting tool destruction. Titanium has comparatively low elasticity modulus than steel. Therefore the work piece has a tendency to move away from the cutting tool unless the proper backup is used. Also thin parts may deflect under tool pressures, causing chatter, tool wear and tolerance problems. [1] Selection of cutting conditions, tool material and its coating and cutting edge geometry is important not only to increase the productivity of machining operation but also to obtain a desirable surface integrity (i.e. residual stresses roughness, etc.) of the finished machined part. Hence, comprehensive reviews on the machinability of titanium alloys are provided [2 – 3] Roughness plays a primary role in the interaction of a material with its surroundings. Rough surfaces deteriorate quickly and have a greater coefficient of friction than smooth surfaces.

* Corresponding author. Tel.: +0-0416-22216; fax: +0-000-000-0000 .
E-mail address: manthonyxavior@vit.ac.in, vinayagamoorthy.r@vit.ac.in

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Roughness often predict the performance of a mechanical component, as defects in the surface may result in the formation of nucleation sites for cracks or corrosion [4-6]. Measurement of surface roughness of a finished component is critical in order to meet design standards for manufacturing processes.

Selection of machining condition/parameter is tedious and difficult and depends mainly on the experience and capabilities of the operators and also the machining parameters catalogue provided by the builder for the finished product. So, the optimization of operating parameters is of primary importance where the cost and quality of a machined product are concerned. In precision machining operation, the quality of surface finish is an important requirement of many bored work pieces and parameter in precision manufacturing engineering. It is characteristic that could influence the performance of precision mechanical parts and the production cost. Various failures, some time catastrophic, leading to high cost, have been attributed to the surface finish of the component in question. [7] For these reasons there have been research developments with the objective of optimizing the cutting condition to obtain a surface finish. During a precision turning operation, the cutting tool and the work piece subjected to a prescribed deformation as a result of the relative motion between the tool and work piece both in the cutting speed direction and feed direction. [8-10] As a response to the prescribed deformation, the tool is subjected to traction and thermal loads on those faces that have interfacial contact with the work piece or chip. The cost of machining a Ti6Al4V sample is very high and highly time consuming process. The machining of titanium alloys is a major production problem, and often the cutting speed is low. Titanium and titanium alloys have low thermal conductivity and high chemical reactivity with many cutting tool materials. Hence, on machining, the cutting tools wear very rapidly due to the high cutting temperature and strong adhesion at the tool chip interface and tool work piece material interface. Many researchers have studied the machinability of titanium alloys in the past [11].

The tool life was influenced significantly by the temperature generated and the forces exerted at or near the cutting edge of the tools. Therefore, changes in cutting speeds and feed rates will directly influence the cutting forces and temperature generated, especially during dry cutting, and hence the tool life. [12] For a 4 factor 3 level experiment more than 80 experiment have to be carried out leading to a very huge expenditure and waste of time. Taguchi [13] designed certain standard orthogonal arrays by which the instantaneous and independent evaluation of two or more parameters for their ability to affect the variability of a particular product or process distinctiveness can be done in a minimum number of tests.

Experimental procedure:

The target material used for the experimentation is Ti-6Al-4V. Gedee Weiler MLZ 250V variable speed adjusting capstan lathe is used for the experiment. And the experimental setup is shown in Fig 1. PVD coated carbide tool with 98 HRC hardness, nose radius of 0.1 0.2 and 0.4 were used for the turning operation. Surface roughness were measured using mitutotyo surftest SJ-301 portable surface roughness tester with a sampling length of 4 mm. [14-15] the cutting temperature was measured using a thermocouple. The cutting parameters were so selected after comparison with different literature surveyed. The design of experiments and analysis of variance was done using Minitab 15 software.

Fig 1 Experimental setup

Design of Experiments and Observations

Design of Experiments is a highly efficient and effective method of optimizing process parameters, where multiple parameters are involved. The design of experiments using the Taguchi approach was adopted to reduce the number of trials. The time and cost for doing an experiment is very high, therefore it is necessary to select an orthogonal array with minimum number of trials. In this research work L27 orthogonal array is chosen which a multilevel experiment is where feed rate, depth of cut, cutting speed and nose radius are the four factors considered in the experiment. Table 1 shows the machining parameters and their levels considered for experimentation.

Cutting parameter	Level 1	Level 2	Level 3
Feed (mm/rev)	0.02	0.04	0.06
Depth of cut (mm)	0.05	0.10	0.15
Cutting speed (m/min)	30	60	90
Nose radius (mm)	0.1	0.2	0.4

Table 1 Machining parameters and their level

The proposed work is to perform machining under the selected levels of conditions and parameters and to estimate the, cutting force, cutting temperature and surface roughness generated as the result of the machining process. Table 2 shows the machining parameters and observation for each trail of experiments.

Results and Discussion

From the series of machining experiments conducted with PVD coated carbide tools to study the individual effects of various parameters on the surface roughness, cutting force and cutting temperature, several important relationships were established. Fig 2, 3 and 4 shows the residual plots for cutting temperature, surface roughness and cutting force respectively.

ANOVA for Cutting Tool Temperature

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Feed	1	800.00	800.00	800.00	58.74	0.000
Depth of cut	1	1701.39	1701.39	1701.39	27.97	0.000
Cutting speed	1	184.22	184.22	184.22	13.79	0.002
nose radius	1	3.43	3.43	3.43	0.25	0.621
Error	22	299.63	299.63	13.62		
Total	26	2978.67				

S = 3.69045 R-Sq = 89.94% R-Sq (adj) = 88.11%

ANOVA for surface roughness

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Feed	1	0.60134	0.60134	0.60134	88.88	0.000
Depth of cut	1	0.00980	0.00980	0.00980	1.45	0.242
Cutting speed	1	0.00436	0.00436	0.00436	0.64	0.431
Nose radius	1	0.30156	0.30156	0.30156	44.57	0.000
Error	22	0.14884	0.14884	0.00677		
Total	26	1.06590				

S = 0.0822527 R-Sq = 86.04% R-Sq(adj) = 83.50%

S. No.	Feed (mm/rev)	Depth Of Cut (mm)	Cutting Speed (mm/min)	Nose Radius (mm)	Cutting Force(N)	Max. Tool Wear (mm)	Surface roughness	Cutting tool temp
1	0.02	0.05	30	0.1	25	25	0.45	47
2	0.02	0.05	60	0.2	34	34	0.42	49
3	0.02	0.05	90	0.4	24	24	0.47	54
4	0.02	0.10	30	0.2	36	36	0.47	59
5	0.02	0.10	60	0.4	38	38	0.42	64
6	0.02	0.10	90	0.1	26	26	0.65	59
7	0.02	0.15	30	0.4	33	33	0.58	63
8	0.02	0.15	60	0.1	32	32	0.64	64
9	0.02	0.15	90	0.2	37	37	0.43	49
10	0.04	0.05	30	0.1	32	32	0.76	51
11	0.04	0.05	60	0.2	38	38	0.67	53
12	0.04	0.05	90	0.4	27	27	0.6	52
13	0.04	0.10	30	0.2	26	26	0.69	62
14	0.04	0.10	60	0.4	22	22	0.61	59
15	0.04	0.10	90	0.1	33	33	0.79	69
16	0.04	0.15	30	0.4	24	24	0.57	76
17	0.04	0.15	60	0.1	38	38	0.81	72
18	0.04	0.15	90	0.2	27	27	0.71	52
19	0.06	0.05	30	0.1	30	30	0.97	57
20	0.06	0.05	60	0.2	25	25	0.82	63
21	0.06	0.05	90	0.4	27	27	0.68	68
22	0.06	0.10	30	0.2	30	30	0.87	69
23	0.06	0.10	60	0.4	21	21	0.57	77
24	0.06	0.10	90	0.1	34	34	1.12	76
25	0.06	0.15	30	0.4	27	27	0.69	83
26	0.06	0.15	60	0.1	35	35	1.19	82
27	0.06	0.15	90	0.2	33	33	0.89	48

Table 2 Experimental observations

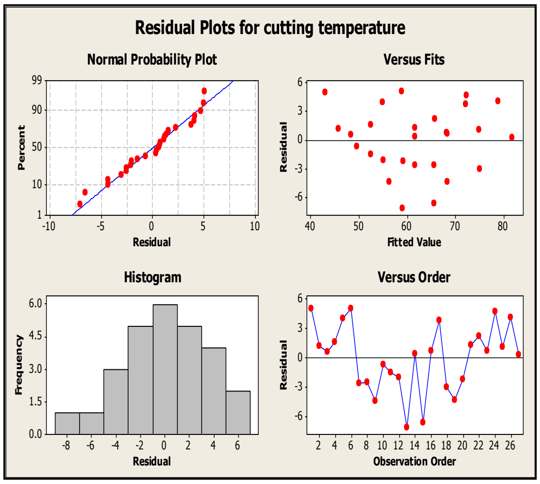


Fig 2 shows the residual plots for Cutting temperature

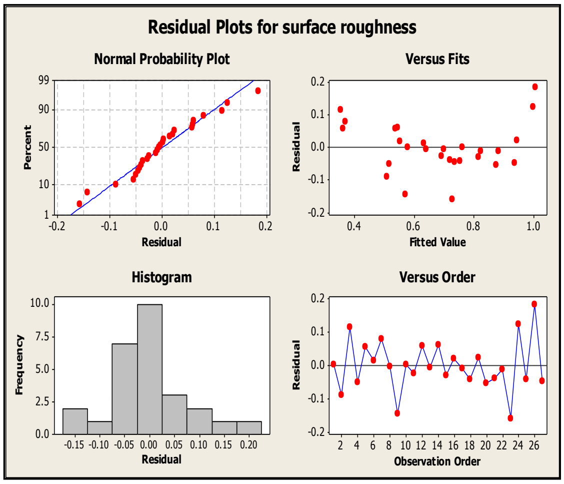


Fig 3 shows the residual plots for Surface roughness

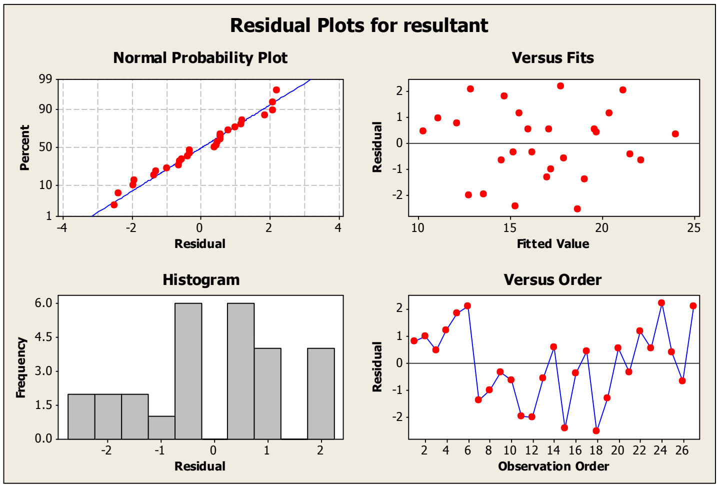


Fig 4 shows the residual plots for Cutting force

ANOVA for Cutting Force

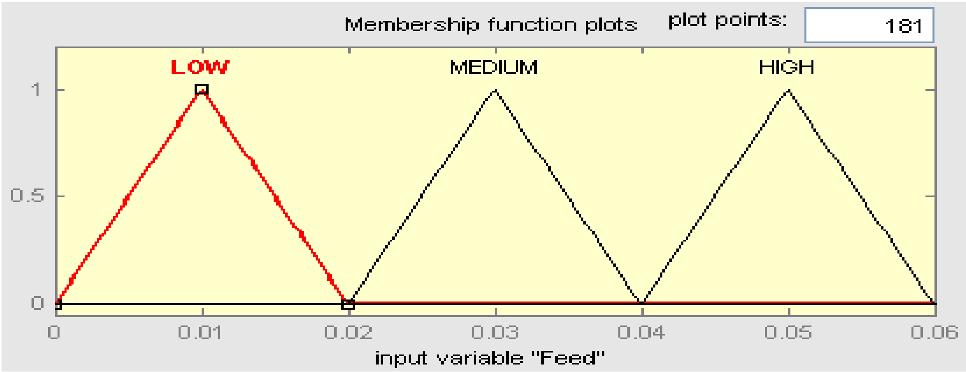
Analysis of Variance for resultant, using Adjusted SS for Tests

Source	**DF**	**Seq**	**SS**	**Adj SS**	**Adj MS**	**F**	**P**
Feed	1	108.108	108.108	108.108	48.90	56.8	0.000
Depth of cut	1	183.659	183.659	183.659	82.72	31.2	0.000
Cutting speed	1	27.502	27.502	27.502	11.89	12.8	0.002
Nose radius	1	1.789	1.789	1.789	0.83	0.27	0.378
Error	22	49.636	49.636	2.221			
Total	26	366.704					

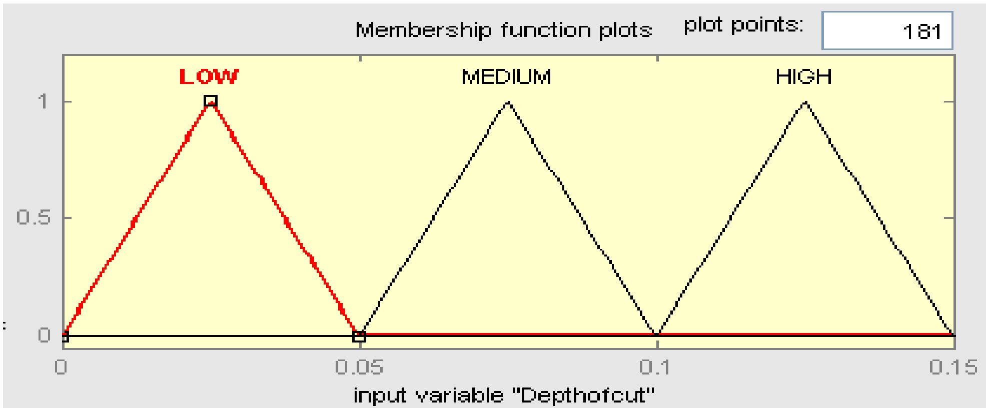
S = 1.48685 R-Sq = 86.70% R-Sq (adj) = 84.28%

The results: using the Fuzzy logic Tool box in MATLAB 2012

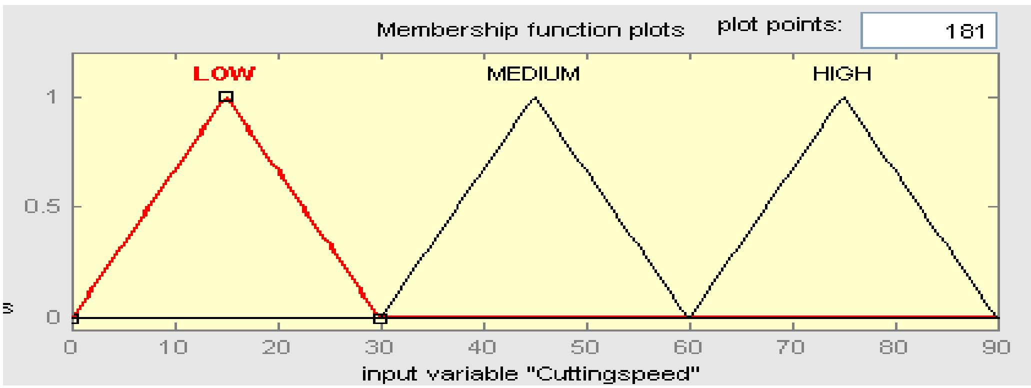
With the help of Design of experimental technique, the rule box is generated in a fuzzy logic toolbox in MATLAB 2012. There were 3 inputs (Low, Medium and High) and 3 outputs (Low, Medium and High) and each input has three membership functions and each output has three membership functions. Ranges of input function are set according to the value given. To use of normalized data in above range of output functions was divided and thereby membership functions were plotted. Fig 5 shows in the membership functions with range was determined as shown Membership function input variable



(a)

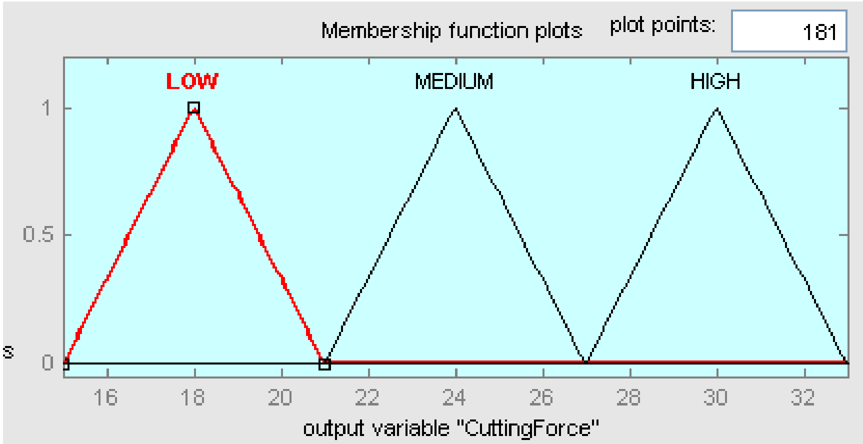


(b)

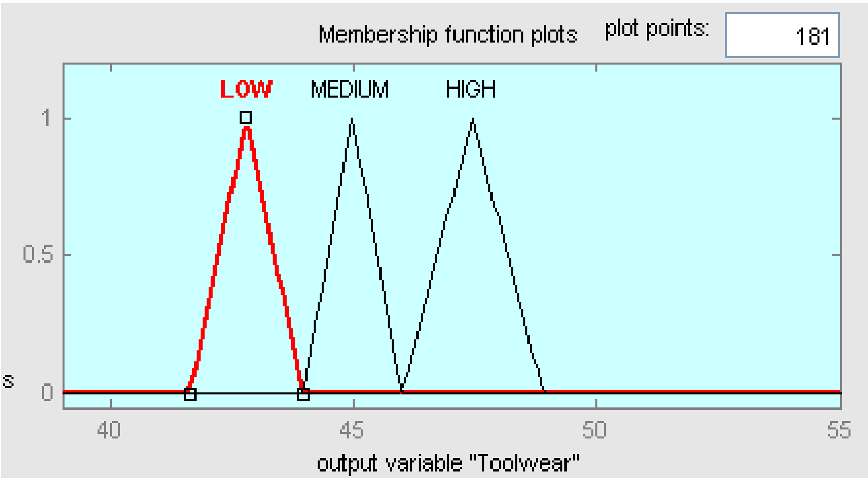


(c)

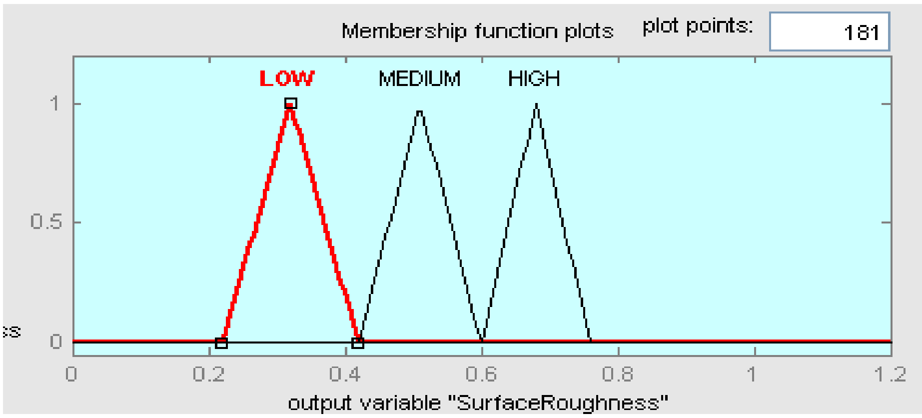
Fig 5(a,b,c) Membership function input variable Cutting speed, Cutting force and Tool wear (Low, Medium and High)



(a)



(b)



(c)

Fig 6.(a,b,c) Membership function for output variable Surface Roughness, Tool wear and Cutting force (Low, Medium and High)

Now with the help of data given of Inputs in Table 2 and normalized data of outputs in Table 3 the influence of each input was studied on responses using membership function plots above. Thus the rule box was formed accordingly Membership functions out variable fig 6 shows as Membership function for output variable Surface Roughness, Tool wear and Cutting force (Low, Medium and High).

Rule Box:

1. If a feed is Low and DOC are low and CS is low, then cutting force is low and tool wear low surface roughness is low.
2. If a feed is Low and DOC are low and CS is the medium, then cutting force is low and tool wear low surface roughness is low.
3. If a feed is Low and DOC are low and CS is high, then cutting force is low and tool wear low surface roughness is low.
4. If a feed is Low and DOC is medium and CS is low, then cutting force is low and tool wear low surface roughness is low.
5. If a feed is Low and DOC is medium and CS is the medium, then cutting force is low and tool wear low surface roughness is low.
6. If a feed is Low and DOC is medium and CS is high, then cutting force is low and tool wear low surface roughness is low.
7. If a feed is Low and DOC are high and CS is low, then cutting force is low and tool wear low surface roughness is low.
8. If a feed is Low and DOC are high and CS is the medium, then cutting force is low and tool wear low surface roughness is low.
9. If a feed is Low and DOC is high and CS is high, then cutting force is low and tool wear low surface roughness is low.
10. If a feed is medium and DOC is low and CS is low, then cutting force is medium and tool wear medium surface roughness is medium.
11. If a feed is medium and DOC is low and CS is the medium, then cutting force is medium and tool wear medium surface roughness is medium.
12. If a feed is medium and DOC is low and CS is high, then cutting force is medium and tool wear medium surface roughness is medium.
13. If a feed is medium and DOC is medium and CS is low, then cutting force is medium and tool wear medium surface roughness is medium.
14. If a feed is medium and DOC is medium and CS is the medium, then cutting force is medium and tool wear medium surface roughness is medium.
15. If a feed is medium and DOC is medium and CS is high, then cutting force is medium and tool wear medium surface roughness is medium.
16. If a feed is medium and DOC is high and CS is low, then cutting force is medium and tool wear medium surface roughness is medium.
17. If a feed is medium and DOC is high and CS is the medium, then cutting force is medium and tool wear medium surface roughness is medium.
18. If a feed is medium and DOC is high and CS is high, then cutting force is medium and tool wear medium surface roughness is medium.
19. If the feed is high and DOC is low and CS is low, then cutting force is high and tool wear high surface roughness are high.
20. If the feed is high and DOC is low and CS is the medium, then cutting force is high and tool wear high surface roughness are high.
21. If the feed is high and DOC is low and CS is high, then cutting force is high and tool wear high surface roughness are high.
22. If feed is high and DOC is medium and CS is low, then cutting force is high and tool wear high surface roughness is high.
23. If feed is high and DOC is medium and CS is medium, then cutting force is high and tool wear high surface roughness is high.
24. If feed is high and DOC is medium and CS is high, then cutting force is high and tool wear high surface roughness is high.
25. If feed is high and DOC is high and CS is low, then cutting force is high and tool wear high surface roughness is high.

26. If feed is high and DOC is high and CS is medium, then cutting force is high and tool wear high surface roughness is high.
27. If feed is high and DOC is high and CS is high, then cutting force is high and tool wear high surface roughness is high.

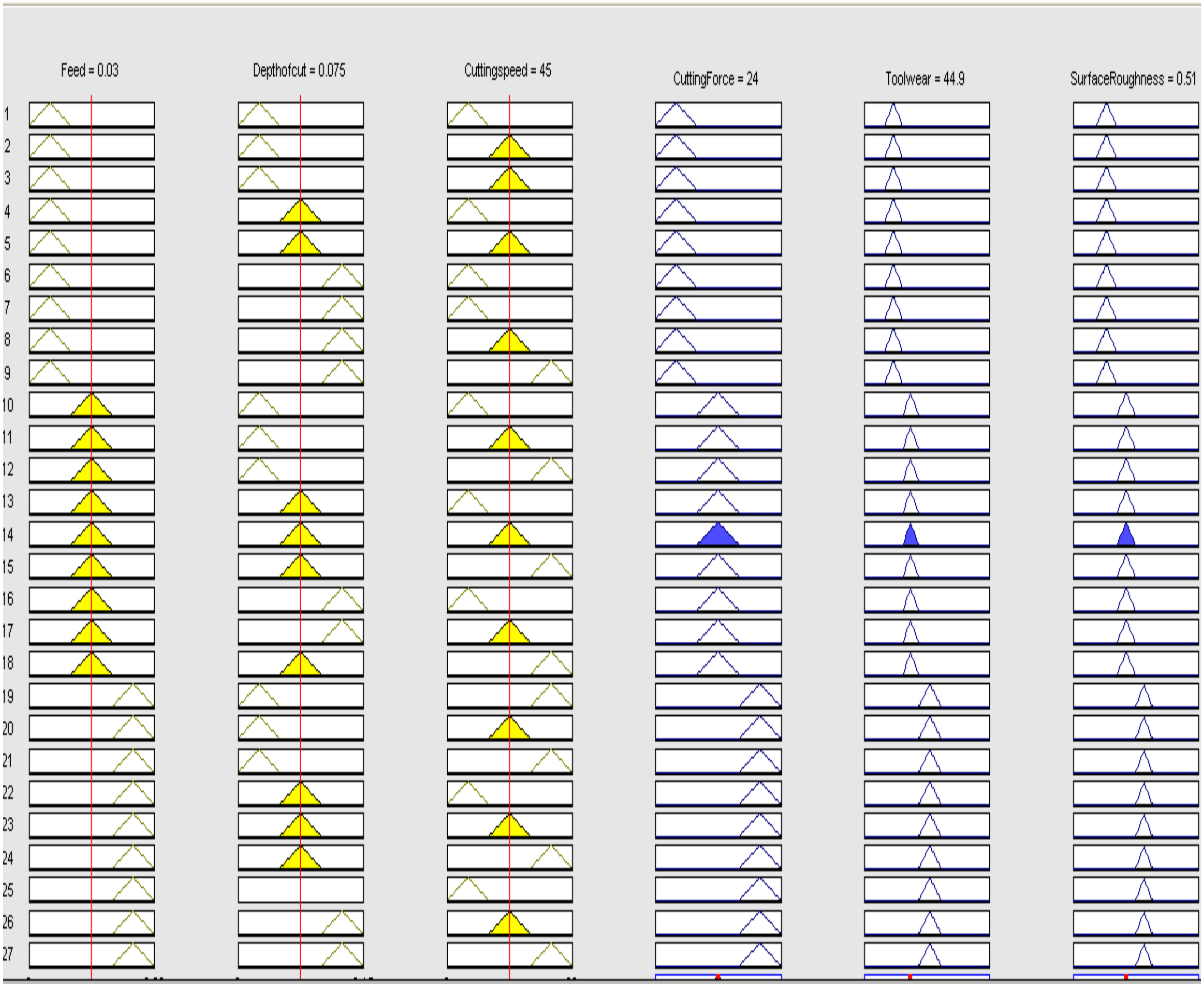


Fig: 7 Rules Shown in MATLAB 2012 Fuzzy tool box for this Experiment

Defuzzification means the fuzzy to crisp conversions. Fig: 6 shows the Membership function for output variable Surface roughness cutting forec the fuzzy results generated cannot be used as such to the applications, hence it is necessary to convert the fuzzy quantities into crisp quantities for further processing. This can be achieved by using defuzzification process. The defuzzification has the capability to reduce a fuzz to a crisp single-valued quantity or as a set, or converting to the form in which fuzzy quantity is present [14]. Defuzzification can also be called as "rounding off" method. Fig: 7 Rules Shown in MATLAB 2012 Fuzzy tool box for this. Fig: 8 shows the Experiment Defuzzification reduces the collection of membership function values into a single sealer quantity.

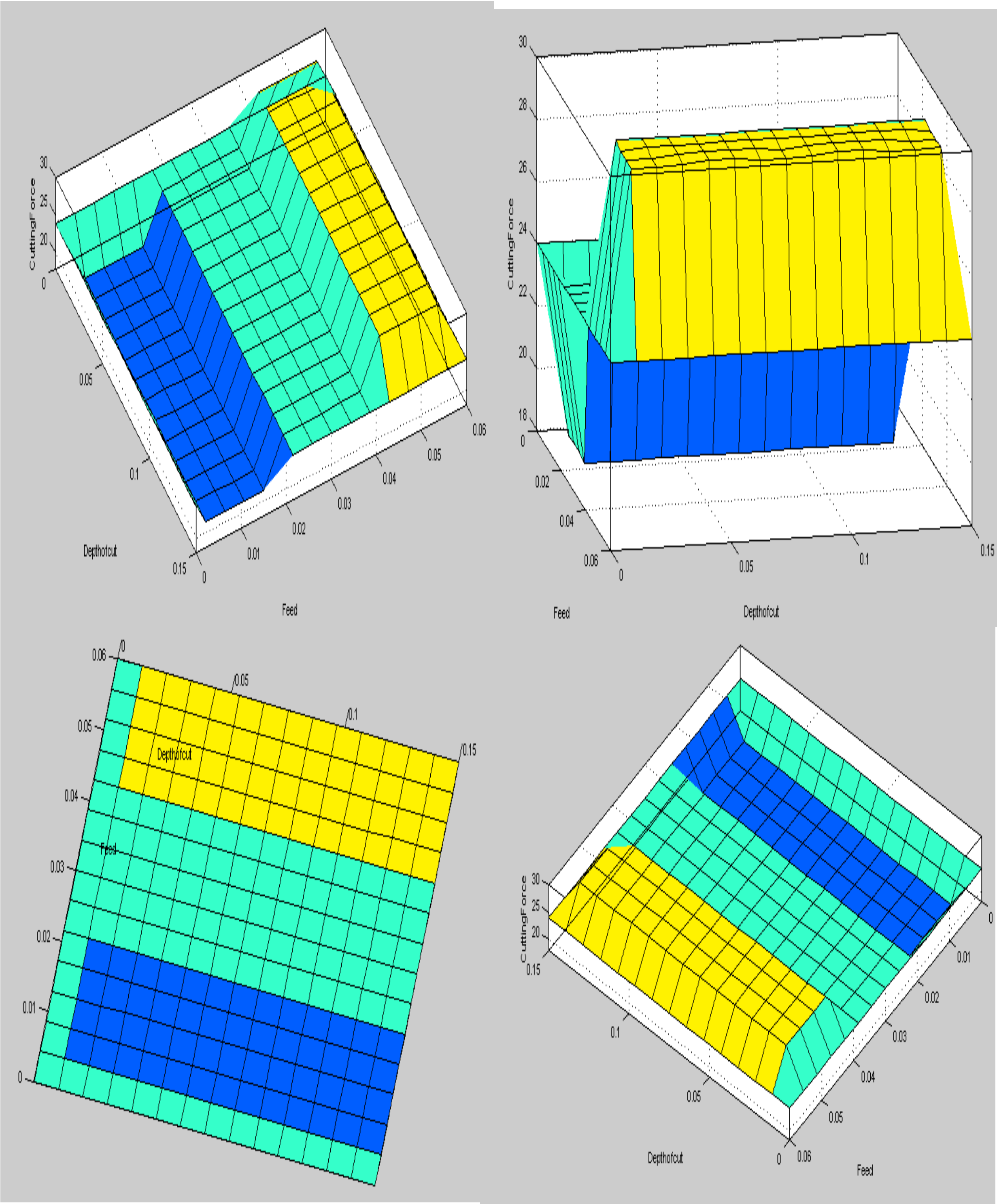


Fig 8. Membership functions for input and output variables

Percentage influence of each cutting parameter on output parameter

Cutting Parameters	Cutting Temperature	Surface Roughness	Cutting Force	Cutting(FIS) Temperature	Surface(FIS) Roughness	Cutting Force(FIS)
Feed	19.82%	52.32%	29.55 %	25%	49.37%	29.98%
Depth of cut	36.54%	24.36%	49.39 %	39%	26.43%	48.34%
Cutting speed	25.51%	8.6%	7.2%	23%	7.9%	6.9%
Nose radius	0.56%	0.25%	0.49%	0.46%	0.28%	0.56%
Error	15.57%	14.47%	13.2%	10.98%	16.02%	14.22%
Total	100%	100%	100%	100%	100%	100%

Table 3 Percentage influence of cutting parameter

Table 3 shows the Percentage influence of all cutting parameters on each of the output parameters. It was found that the depth of cut has more influence on cutting force and cutting temperature.

CONCLUSIONS

Precision turning experiments were conducted on Ti-6AL-4V material to investigate its machinability in terms of cutting force, cutting zone temperature and surface roughness.. The graphs between experimental and predicted results were plotted for % Tool wear, Cutting force and Surface roughness. Correlation coefficients were determined between experimental results and predicted results that show the strong linear relationship between them. The low percentage error shows that the results predicted by Mamdani fuzzy logic were highly accurate and precise. The percentage influences of all cutting parameters in the output parameter were determined and the results found were in line with published research. The residual plots show a good understanding of the relationship between various cutting and output parameters. Future work can be focused on the dimensional accuracy observed in the work specimen as the result of precision machining. Study on observed results shows that there are a large number of conflicting factors independently or interaction with others may influence the dimensional accuracy.

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