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Process Parameter Optimization for Turning Operation of Titanium Alloy (Ti6Al4V) Using Fuzzy Logic Methodology

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Abstract

Titanium alloys are known as difficult-to-machine materials mainly due to low thermal conductivity leading to "high reactivity with cutting tools" causing poor tool life. This paper aims to optimize process parameters for machining Ti6Al4V in order to increase tool life and to obtain good surface finish. Experiments were conducted based on central composite design and a quadratic regression model has been developed. The relationship between input parameters (speed, feed rate, depth of cut) and output parameters (tool life and surface roughness) were studied. Experiments were carried out using conventional lathe machine TurnMaster40. The process parameters were optimized for better tool life and surface finish using Fuzzy Logic methodology.

Keywords: comprehensive output measures (COM), fuzzy logic approach, surface roughness, tool life

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INTRODUCTION

Machining is a term that covers a large collection of manufacturing processes designed to eliminate unwanted material, usually in the form of chips, from a work piece. Turning is a machining process for generating external surfaces of revolution by the action of a cutting tool on a rotating work piece, usually in a lathe. Central composite design has been concerned with the optimization of a single performance characteristic. The definition of performance characteristics such as lower-the-better, higher-the-better and nominal-the-better contains a degree of uncertainty and vagueness.

The importance of each performance characteristic may vary. The application of the central composite design in a process with multiple performance characteristics cannot be straightforward. Fuzzy logics can deal with uncertain and vagueness. In this study, a fuzzy reasoning of multiple performance characteristics has been developed based on fuzzy logic which transforms optimization of multiple performance characteristic into optimization of a single Comprehensive Output Measure (COM).

Problems in Machining of Titanium Alloys

The following properties of titanium alloys are the main reasons to face the problems in machining:

- High thermal stress at the cutting edge due to the low heat dissipation by the chips and the work piece. By the combination of low thermal conductivity and high thermal capacity 30% more heat must be absorbed by the cutting edge compared to the machining of steel. When machining titanium, the cutting temperatures are approximately twice as high. Diffusion and adhesion processes are thus enhanced, high temperature gradients occur whereby thermal stress emerges.

- High pressure loads on the cutting edge due to the low plasticity of titanium alloys and further increased at elevated cutting speeds due to the decreasing shearing angle.
- Highest pulsating loads due to the formulation of segmented chips, which is rooted in the hot strength behavior of the material.
- Tool failure by chippings due to high cutting forces and self-induced chatter.
- Vibration affinity of unstable work pieces due to the low Young's modulus.
- Danger of wear by diffusion due to high reactivity of titanium, involving the weakening of the cutting material.
- Strong affinity to adhesion due to the heat accumulation in the cutting zone, involving tool failure.

Methodology

- Step 1: Tool selection.
- Step 2: Selection of process parameters.
- Step 3: Design of Experiments (DOE).
- Step 4: Conducting the experiments as per DOE.
- Step 5: Measurement of tool life and surface roughness.
- Step 6: Optimizing process parameters using fuzzy logic methodology.
- Step 7: Result.

Selection of Cutting Tool

Due to the thermal properties of steel cutting grades of cemented carbides, that cutting tool is not suitable for machining of titanium alloy. Even though ceramics have improved in quality and focused increased application in the machining of difficult-to-cut materials, especially high temperature alloys, they have not replaced cemented carbides and high speed steels due to their poor thermal conductivity and their relatively low fracture toughness and their reactivity with titanium. Tungsten carbide (WC/Co) cutting tools have proven their superiority in almost all machining processes of titanium alloys. For our study, K313 (WC/Co) tool is used.

Selection of Process Parameters

To select the process parameters affecting the selected machining quality characteristic of turned parts, the causes and effects for turning operation of titanium alloy should be identified. A cause and effect diagram was constructed and shown in Figure 1. The identified process parameters were the cutting tool parameters – tool geometry, tool material, the cutting parameters – spindle speed, feed rate, depth of cut, work piece related parameters – hot-worked, difficult-to-machine. The following process parameters were thus picked up for the present work: Cutting speed, feed rate, and depth of cut (Tables 1, 2).

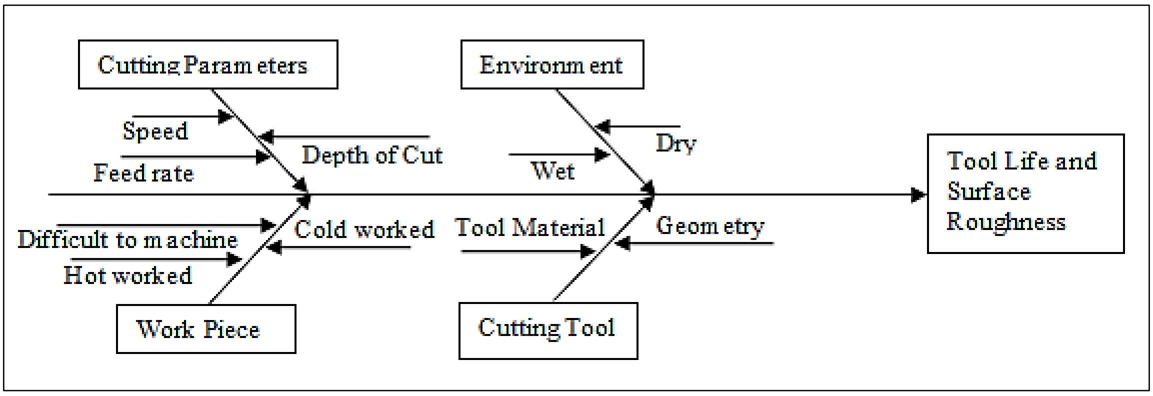

Fig. 1. *Construction of Cause and Effect Diagram.*

Table 1. *Parameters – Input and Output.*

S no.	Input parameters	Output parameters
1	Speed (rpm)	Tool life (min)
2	Feed rate (mm/rev)	
3	Depth of cut (mm)	Surface roughness (R_a)

The appropriate *working range* for each potential factor considered is selected. Using MINITAB software the conditions are applied and the order of the experiments is taken. The experimental results obtained by conducting the DOE are given in Table 3 as follows.

Table 2. *Working Range.*

Parameters	Range		
	Low	Intermediate	High
Speed (rpm)	280	400	630
Feed rate (mm/rev)	0.2	0.25	0.315
Depth of cut (mm)	0.1	0.15	0.2

Table 3. *Experimental Results.*

Run order	Speed (rpm)	Depth of cut (mm)	Feed rate (mm/rev)	Tool life (min)	Ra (μm)
1	400	0.15	0.25	5.344	1.75
2	400	0.15	0.25	4.676	1.734
3	280	0.15	0.25	13.8452	2.114
4	280	0.2	0.2	16.486	1.973
5	280	0.1	0.2	21.723	1.421
6	400	0.15	0.2	12.923	1.672
7	400	0.15	0.25	6.681	1.802
8	400	0.15	0.315	6.074	1.923
9	630	0.1	0.2	5.728	1.034
10	400	0.1	0.25	6.325	1.327
11	630	0.1	0.315	1.728	1.473
12	630	0.2	0.315	1.106	1.621
13	400	0.2	0.25	2.698	1.973
14	280	0.2	0.315	2.898	2.398
15	400	0.15	0.25	5.231	1.832
16	400	0.15	0.25	7.348	1.744
17	280	0.1	0.315	8.704	1.836
18	400	0.15	0.25	6.252	1.742
19	630	0.2	0.2	2.306	1.638
20	630	0.15	0.25	4.258	1.902

Using MINITAB software analysis of variance for tool life and surface roughness has been carried out. As a result of analysis of variance for tool we have got R-squared= 96.98%. It is a measure for Goodness-of-fit.

In general higher the value of R-squared, better the model fits the data. Similarly we have got R-squared for surface roughness as 89.90%. Finally the regression equation for tool life and surface roughness has been derived.

$$\text{Tool Life}=136.278-0.21918s+227.792d-639.325f+0.000122458s^2-1107.93d^2+863.297f^2+0.0972917sd+0.255540sf+93.5971df$$

$$R_a=-1.01447-0.00831291s+29.8640d-115.1870f+7.83271E\text{-}0.6s^2-82.8d^2-24.3799f^2$$

Surface Plot for Tool Life

Surface plots are created by taking two input parameters in each axis and the output parameter on the other axis.

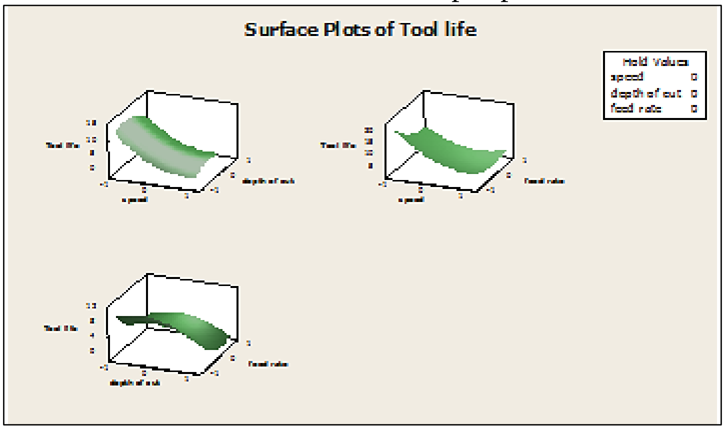

Fig. 2. *Surface Plots of Tool Life*.

From Figure 2 it is inferred that

- When speed value is minimum and depth of cut has intermediate value, the tool life is maximum.
- When speed is minimum and feed rate has low value, the tool life is maximum.
- When depth of cut is minimum and feed rate has minimum value, the tool life is maximum**.**

Surface Plot for Roughness

From Figure 3 it is inferred that

- When speed is maximum and depth is cut is minimum, the roughness value is low.
- When speed is maximum and feed rate is minimum, roughness value becomes low.
- When depth of cut is minimum and feed rate is minimum, roughness value becomes minimum.

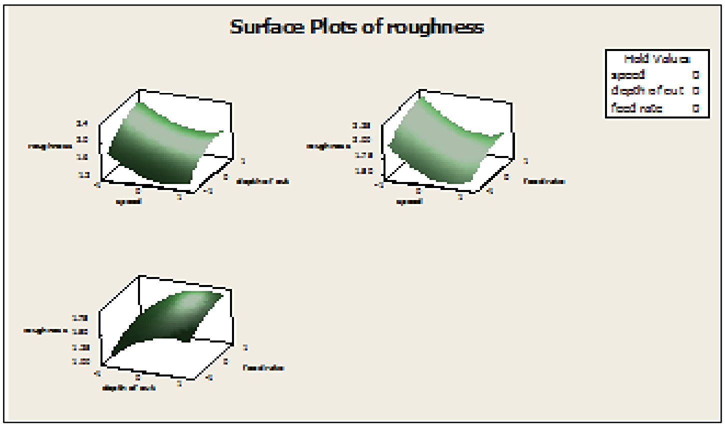

Fig. 3. *Surface Plots of Roughness*.

Fuzzy Logic Implementation and Results for Multiple Responses in Turning Process

A fuzzy logic unit (FLU) contains a fuzzifier, membership functions, a fuzzy rule base, an inference system, and a defuzzifier. In the first place, the fuzzifier utilizes membership functions to fuzzify the S/N ratios. Next, the inference system performs a fuzzy reasoning on fuzzy guidelines to produce a fuzzy value. At long last, the defuzzifier converts the fuzzy value into a COM. In the present work, fuzzy reasoning depends on the two-input–

one-output fuzzy logic unit. In view of the present work, Table 4 gives the Fuzzy Base Rule. In this work, three fuzzy subsets are assigned in the two inputs as shown in Figures 4 5 and five subsets are assigned in the output as shown in Figure 6 (Table 5).

Table 4. *Fuzzy Rule Base.*

COMPREHENSIVE OUTPUT MEASURE		Surface Finish ($1/R_a$)		
		Small	Middle	Large
Tool Life	Small	Very Small	Small	Middle
	Middle	Small	Middle	Large
	Large	Middle	Large	Very Large

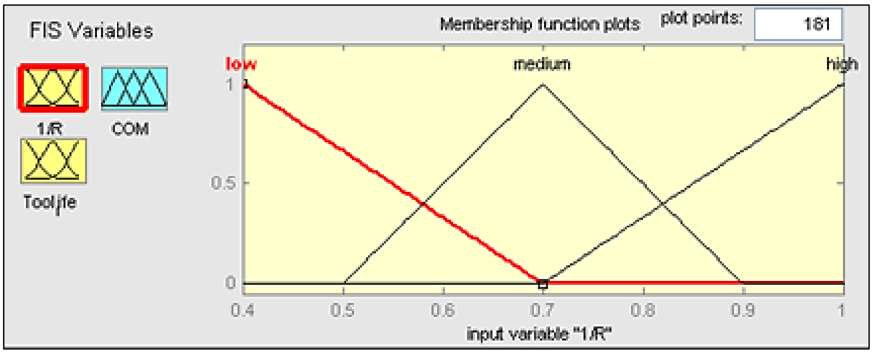

Fig. 4. *Input Variable of Plot.*

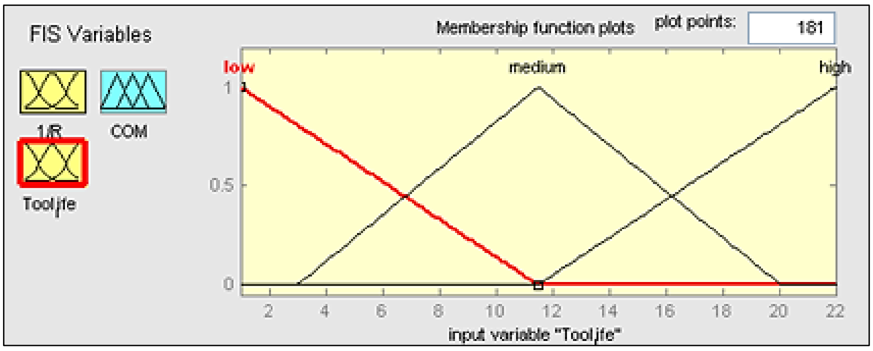

Fig. 5. *Input Variable of Plot.*

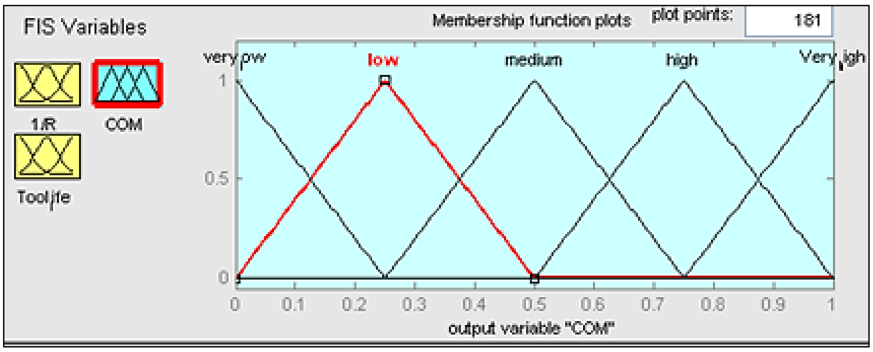

Fig. 6. *Output Variable of Plot.*

Table 5. *Results for Comprehensive Output Measures (COM).*

Run order	COM	Run order	COM
1	0.322	11	0.249
2	0.302	12	0.238
3	0.317	13	0.108
4	0.396	14	0.0827
5	0.75	15	0.298
6	0.447	16	0.341
7	0.314	17	0.316
8	0.254	18	0.341
9	0.596	19	0.236
10	0.429	20	0.242

Since the experimental design is orthogonal, it is possible to separate out the effect of each machining parameter at different levels. The mean of the Comprehensive Output Measure for speed, feed rate and depth of cut at levels 1, 2 and 3 are calculated and shown in Table 5.

The mean of the Comprehensive Output Measure for each level of the machining parameters is summarized and called the comprehensive output measure as shown in Table 6.

Table 6. *Mean of the Comprehensive Output Measure for Speed, Feed Rate and Depth of Cut.*

	Level 1	Level 2	Level 3
Speed (rpm)	**0.37234**	0.3156	0.3122
Feed rate (mm/rev)	**0.485**	0.3014	0.22794
Depth of cut (mm)	**0.468**	0.3178	0.21214

CONCLUSION

As a result of using fuzzy logic, the life of the *tool* can be increased and *surface finish* of titanium alloy can be improved. Based on the experimental results the conclusion can be drawn as follows.

- The most important factors affecting the turning process have been identified as Speed, Feed Rate and Depth of cut.
- From Table 7, the level 1 value is the optimized result.

Table 7. *The Optimized Value for Machining of Titanium Alloy Has Been Highlighted.*

Parameters	Range		
	Low	Intermediate	High
Speed (rpm)	**280**	400	630
Feed rate (mm/rev)	**0.2**	0.25	0.315
Depth of Cut (mm)	**0.1**	0.15	0.2

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