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Parametric Investigation of a Form Tool Wear and Dimensional Inaccuracy in Turning Operation of AISI 1045

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ABSTRACT

In any manufacturing setup, turning operation is the most frequently used metal cutting process especially for axis symmetric circular parts. This paper reports the effects and optimization of two process parameters (feed rate & cutting speed) on two response factors (tool wear & dimensional inaccuracy) in turning operation of aplain carbon steel AISI 1045. Flat form tool of high speed steel (HSS) having various profiles has been used for turning operation. The experimentation is done under varying cutting conditions by changing the feed rate and cutting speed on a precision lathe machine using plain carbon steel of finished diameter 30mm as work piece material each time. Optimal settings of the process parameter are achieved using response surface methodology (RSM). Analysis of variance (ANOVA) is used to identify the significance of control factors. It is found that the most significant factor which affects the tool wear and dimensional inaccuracy is the feed rate.

1. Introduction

Though the technological advancements are continuously taking place, turning is still the most occupied and convincing metal shaping process used in manufacturing industry. The reason is high degree of variability of the process conditions in turning [1]. Rotational motion is the primary cutting motion in turning while the tool is fed parallel to rotational axis [2]. Cutting conditions like the cutting speed and the feed rate affect the two most important performance measures for the turning operation namely tool wear and dimensional inaccuracy. The cutting conditions must also be considered in relation to the tool life.

Surface roughness of the machined part is another wear criteria which is significantly important [3]. Tool wear is usually continuous process, like common pencil tip wear. The rate of tool wear depends on the materials of tool and work piece, tool shape, cutting fluids, process parameters (like cutting speed, feed and depth of cut) and tool machine distinctiveness [4].

Various approaches have been adopted by researchers for the improvement in the performance features of turning operation by applying different cutting conditions and by using different cutting fluids [5-10]. Erry Yulian et al. [5] studies the effect of varying rake angles and different cutting speed on surface roughness and tool wear in machining of cermet (CT5015). Rake angles 0, -3. -6, -9 and -12 respectively and cutting speed 1000 m/minute and feed rate 800 mm/minute have been applied. The study was resulted in a statement that higher negative rake angles cause higher tool wear thereby shorter tool life and poor surface finish. N. R. Dhar et al. [6] investigated the performance of cryogenic cooling produced by a jet of liquid nitrogen on the temperature of cutting zone, surface finish, tool wear and dimensional inaccuracy in the turning of AISI-4037 steel at a combination of cutting speed and feed meeting the industrial requirements using coated carbide insert. They concluded that cryogenic cooling has a substantial benefit on tool life, surface finish and dimensional deviation.

Tzeng Yih-fong [7] applied Taguchi dynamic approach coupled with a proposed ideal function model to develop a set of optimal turning parameters for producing high dimensional precision and accuracy in the computerized numerical control turning process and concluded that the dimensional inaccuracy of the work piece is mostly affected by the parameters attached to the cutting tool and feed. M. Anthony Xavior et al. [8] determined the effect on tool wear and surface roughness

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by the cutting fluids in the turning operation of AISI 304 with carbide tool. They concluded that in general, coconut oil performed better than emulsion and neat cutting oil to reduce the tool wear and to improve the surface finish.

Yong Huang et al. [9] studied the effect of cutting conditions on tool performance in CBN hard turning 52100 bearing steel. Based on flank wear criterion, the tool performance was evaluated as a function of cutting conditions. In this work, the impact of various cutting conditions on tool life was statistically evaluated. The cutting speed had much higher effect on tool life than feed rate and depth of cut and achieved a good agreement between prediction equations and experimental data.

K. Katuku et al. [10] investigated tool wear, chip formation and cutting forces while turning ASTM austempered grade 2 ductile iron in dry conditions. PcBN cutting tips were used for finishing purposes. The machining conditions were 0.2mm depth cut, 0.05mm/rev feed and 50 to 800m/min cutting speed range. As a result, the primary phenomenon i.e. localized shear in the primary and secondary shear zones of the chips formed which controls the rate of wear and both static and dynamic cutting forces appeared when the cutting speed is more than 150m/min. An acceptable range cutting velocity was determined to be between 150 and 500m/min.

Response surface methodology (RSM) is a powerful statistical tool most commonly used not only to design, develop and model new industrial as well domestic parts but also for significant improvement and optimization of the existing setup and system [11]. RSM is used to optimize the already in operation systems [11-14] as well for the optimization of simulated and modelled processes [15-18] in machining operations.

This investigation is an effort to enhance the basic performance characteristics (i.e. tool wear and dimensional accuracy) for AISI 1045 as work piece material and high speed steel (HSS) as tool material. AISI 1045 is important steel commonly used in gears, shafts, axles, bolts, studs, machine parts and other structural purposes and HSS being used most commonly as tool materials for turning operations [19, 20]. Four different profiles including internal arc, external arc, triangular section and notch has not been investigated in the literature using AISI 1045 as work piece material and using RSM at the same time. RSM has been applied for the parametric optimization of the machining process in terms of tool wear and dimensional inaccuracy of the work piece and finally mathematical relations are developed for the prediction of the performance indicators of the form turning operation of AISI 1045.

Work piece of finished diameter 30 mm is used during experimentation and its length is 310mm. Hardness of work piece measured is 15.6 HRC.

2. Materials and Methods

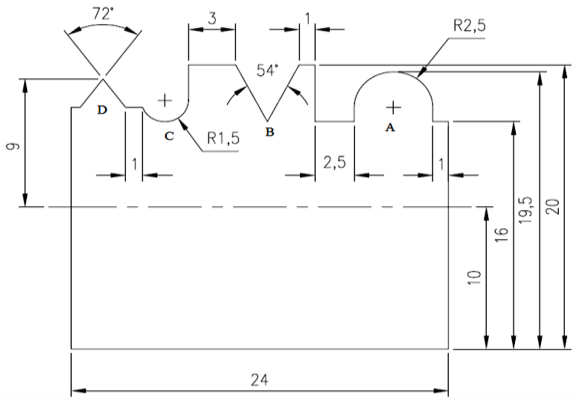
2.1 Form Tool Geometry

The composition of high speed steel (HSS) grade M2 used herein is shown in Table 1.

Table 1. Composition of high speed steel (HSS) [20]

Constituent	C	Cr	Mo	W	V
Composition (%)	0.90	4.10	5.00	6.40	1.90

Hardness of form tool was measured as 63.7 HRC. The geometry or profiles of the form tool used during experimentation is shown in Fig. 1. The profile of the form tool includes external and internal arcs with radii 2.5mm and 1.5 mm respectively and a triangular section with internal angle as 54^o and a notch of angle 72^o. These profiles are marked as A, B, C and D in Fig.1.



A. Interior arc with 2.5mm radius B. Triangle with included angle of 54°
C. External arc of radius 1.5 mm C. Notch with angle 72°.

Fig. 1: Details of form tool profiles (all dimensions in mm).

2.2 Work-piece Material Specifications

The composition of plain carbon steel 1045 used here as work-piece is shown in Table 2.

Table 2: Composition of AISI 1045 [19]

Constituent	C	Mn	P	S	Si
Composition (%)	0.40	0.75	0.020	0.030	0.25

2.3 Experiment Conditions

Form tool of high speed steel with a width of cut of 24 mm is used as a working tool whereas AISI 1045 of finished diameter 30mm and length of 310mm is used as work piece. Simple turning operation is done on precision Lathe by using a HSS form tool. The cutting speed can be converted from m/min to rpm using the Eq.1 [11].

$$N = \frac{1000 \times V_c}{\pi \times D} \tag{1}$$

Where N is the spindle speed in rpm, V_c is the cutting speed in m/min and D is the diameter of the workpiece in mm.

Table 3: RSM design matrix

Level	Process parameters	
	Vc (m/min)	f (mm/rev)
1	33	0.036
2	36	0.046
3	33	0.036
4	36	0.029
5	30	0.046
6	28	0.036
7	33	0.036
8	30	0.029
9	33	0.023
10	33	0.058
11	33	0.036
12	38	0.036
13	33	0.036

Table 3 shows the RSM design matrix of all the possible combinations of process variable levels.

2.4 *Response Measurements*

Tool profiles are measured using the manual CMM (Co-ordinate Measuring Machine) before and after the machining and the image of the worn tool is captured using QC5000 software. Before and after machining, the tool profiles are measured and their difference is calculated as tool wear. For profiles of radii 1.5mm and 2.5mm, tool wear is the difference between the two radii before and after machining.

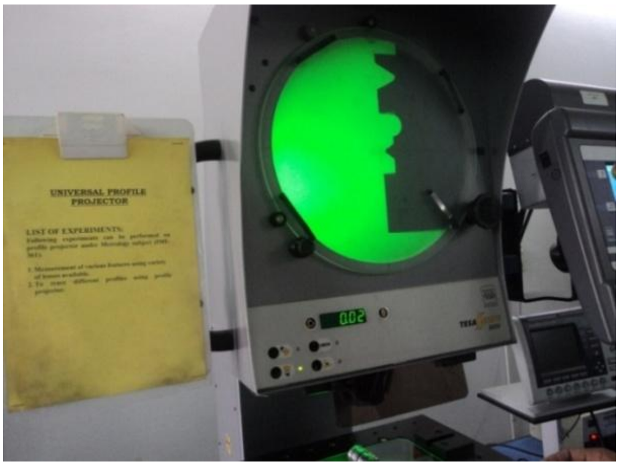


Fig. 2: Measurement of work-piece profile after the turning operation using Universal Profile Projector

For angular profiles, tool wear is the angular difference between profiles before and before after experimentation. Machined work piece profiles are measured using universal profile projector the demonstration as shown in Fig. 2.

Similarly dimensional inaccuracy is the difference between measurements of the tool profiles before machining and measurements of work piece profiles after machining. Each time the machining is done, a new form tool is used for experimentation purposes.

3. Results, Analysis and Discussion

The measurements of tool wear and dimensional inaccuracy for the design matrix are tabulated in Table 4 and 5. RSM and analysis of variance (ANOVA) are used for the statistical analysis of the performance measures.

Table 4: Radial and angular measurement of wear of form fool profile

Exp. No	Vc (m/min)	f (mm/rev)	Radial (mm)		Angular (degree)	
			at arc of r2.5	at arc of r1.5	at angle 54^o	at angle 72^o
1	33	0.036	0.0445	0.0805	1.5509	1.5484
2	36	0.046	0.0995	0.5415	2.5314	2.1642
3	33	0.036	0.0444	0.0804	1.5487	1.5256
4	36	0.029	0.0155	0.0615	0.9233	0.9734
5	30	0.046	0.0568	0.5065	2.5181	2.0909
6	28	0.036	0.0585	0.0800	1.2042	1.2345
7	33	0.036	0.0443	0.0801	1.5442	1.5689
8	30	0.029	0.0305	0.0645	0.8847	0.9005
9	33	0.023	0.0595	0.0185	0.5142	0.1103
10	33	0.058	0.1545	1.3649	3.1858	2.9512
11	33	0.036	0.0441	0.0803	1.5391	1.5648
12	38	0.036	0.0599	0.0875	1.6177	1.7012
13	33	0.036	0.0446	0.0804	1.5351	1.5339

Table 5: Radial and angular measurement of dimensional inaccuracy on work piece profile

Exp. No	Vc (m/min)	f (mm/rev)	Radial (mm)		Angular (degree)	
			at arc of r2.5	at arc of r1.5	at angle 54	at angle 72
1	33	0.036	0.1225	0.2745	1.5056	1.6042
2	36	0.046	0.9925	0.9415	2.5744	3.0158
3	33	0.036	0.1245	0.2705	1.5156	1.6142
4	36	0.029	0.0935	0.0825	1.0244	0.9958
5	30	0.046	0.8605	0.9515	2.5056	2.9358
6	28	0.036	0.1265	0.2145	1.3756	1.5758
7	33	0.036	0.1205	0.2715	1.5156	1.5942
8	30	0.029	0.0895	0.0885	0.9744	0.9342
9	33	0.023	0.0105	0.0189	0.3356	0.2442
10	33	0.058	1.5001	1.9531	3.5211	4.6112
11	33	0.036	0.1201	0.2735	1.5153	1.5891
12	38	0.036	0.1991	0.0921	1.5998	1.8291
13	33	0.036	0.1257	0.2756	1.5101	1.5991

3.1 Analysis of Variance (ANOVA)

ANOVA with 95% confidence level is performed and results for tool wear and dimensional inaccuracy are tabulated in Tables 6 and Table 7 respectively for the first profile of the form tool. According to ANOVA for tool wear at arc of radius 2.5mm, the significant parameter is the feed rate having percentage contribution 89.5% whereas the cutting speed is the least significant parameter.

Table 6: ANOVA for tool wear at arc of radius 2.5 mm

Factors	Sum of squares	P-value	F-ratio	Percentage contribution
Cutting speed	0.0001	0.098	3.65	0.95
Feed rate	0.0094	0.000	52.51	89.5
Cutting speed*feed rate	0.0009	0.057	5.18	8.6
Error	0.0001	-	-	0.95
Total	0.0105	-	-	100.00

Table 7. ANOVA for dimensional inaccuracy at arcof radius 2.5 mm

Control factors	Sum of squares	P-value	F-ratio	Percentage contribution
Cutting speed	0.0069	0.52	0.46	0.32
Feed rate	2.1674	0.000	87.74	99.4
Cutting speed*feed rate	0.0043	0.686	0.18	0.2
Error	0.0017	-	-	0.08
Total	2.1803	-	-	100.00

ANOVA for dimensional inaccuracy at arc of radius 2.5mm reveals that the significant parameter is the feed rate having percentage contribution 99.4% whereas the least significant parameter is the cutting speed. The P values for tool wear and dimensional inaccuracy for each profile is quite low than 0.05(α-value) proves that models are statistically significant.

4. Mathematical Relations for Tool Wear and Dimensional Inaccuracy

Tool wear and dimensional inaccuracy are expressed mathematically in terms of control factors. Both the performance measures are quantified using response surface regression model. Mathematical relationship for the prediction of tool wear and dimensional inaccuracy for each profile of the form tool in terms of feed rate (f) and cutting speed (Vc) is developed using constants and coefficients obtained by response surface regression method. The relations for tool wear and dimensional inaccuracy are given in Eq. (2) through Eq. (9).

A- Interior arc with 2.5mm radius

$$\text{Tool wear} = 0.059 + 0.017\,Vc + 0.055f + 0.004\,Vc^2 + 0.41f^2 + 0.05\,Vc.f \quad (2)$$

$$\text{Dimensional inaccuracy} = 0.36+0.0696Vc + 0.84f + 0.091Vc^2 + 0.425f^2 + 0.1121Vc.f \quad (3)$$

B- Triangle with included angle of 54°

$$\text{Tool wear} = 1.9+0.116Vc+1.45f-0.05Vc^2-0.049f^2-0.0597Vc.f \quad (4)$$

$$\text{Dimensional inaccuracy} =1.972+0.086Vc+1.592f - 0.0182Vc^2-0.009f^2+0.00285Vc.f \quad (5)$$

C- External arc of radius 1.5mm

$$\text{Tool wear} = 0.23 + 0.015Vc + 0.66f+0.02Vc^2 + 0.48f^2 + 0.034Vc.f \quad (6)$$

$$Dimensional\ inaccuracy = 0.53 - 0.0366Vc + 0.998f - 0.101Vc^2 + 0.478f^2 + 0.008Vc.f \quad (7)$$

D- Notch with angle 72°

$$Tool\ wear = 1.89 + 0.153Vc + 1.315f - 0.073Vc^2 - 0.33f^2 - 0.035Vc.f \quad (8)$$

$$\text{Dimensional inaccuracy} = 2.11 + 0.099Vc + 2.19f + 0.187Vc^2 + 0.3498f^2 + 0.00147Vc.f \quad (9)$$

Figure 3 is the graph showing the variation in tool wear and dimensional inaccuracy at profile A (interior arc with 2.5mm radius). The variation in dimensional inaccuracy is not more than 0.2mm in all runs except experiments 2, 5 and 10 while the variation in tool wear is not more than 0.18mm throughout the experimental range. The values of dimensional inaccuracy for experiments 5 and 10 are unexpectedly high and the reason behind this believed to be higher values of feed rate. With the increased feed rate and consequently increased material removal rate causes increased heat generation and adverse effect on chip formation. The chipping phenomenon adversely affects the dimensional accuracy of the part. Due to localized case hardening phenomenon by the friction may also be one of the causes of low rate of tool wear. Almost similar sort of effects can be seen in the Figs. 4 -6 for observation numbers 2, 5 and 10 at arc with 1.5mm radius and at angle of 72° respectively.

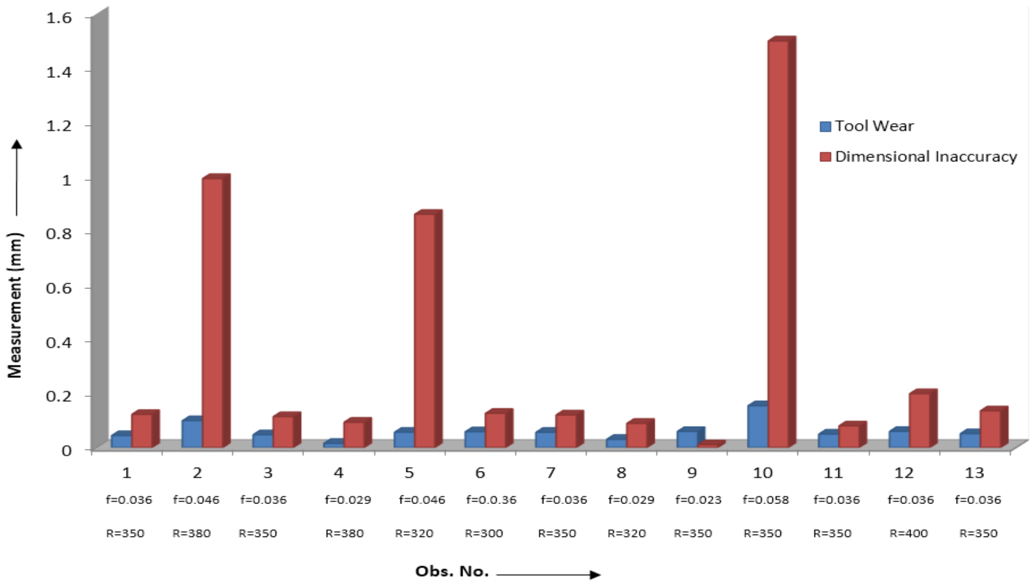


Fig. 3: Radial tool wear and dimensional inaccuracy for form tool-internal arc of 2.5mm radius

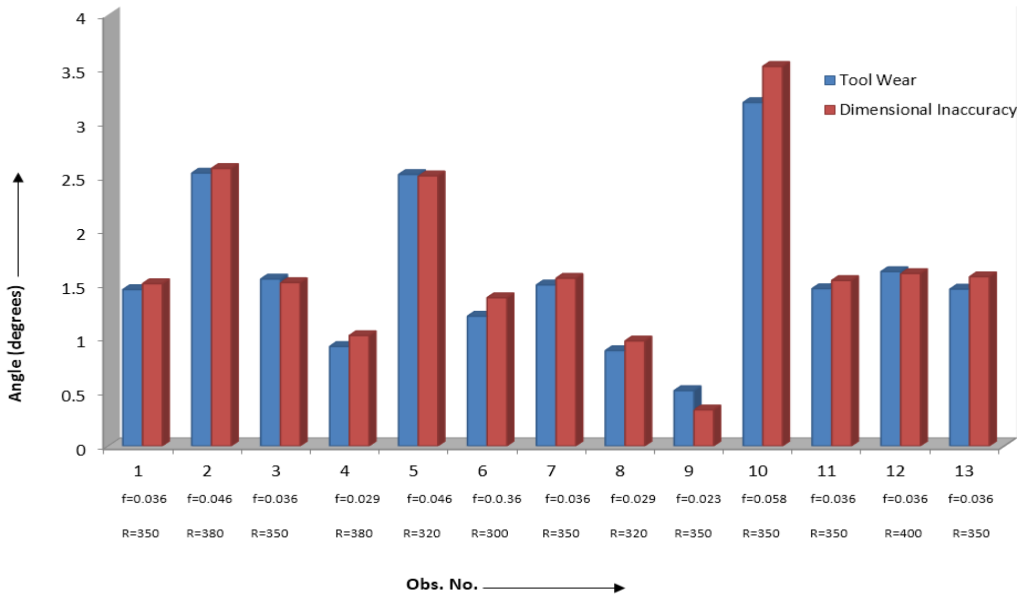


Fig. 4: Angular variation of tool wear and dimensional inaccuracy for form tool- angle of 54°

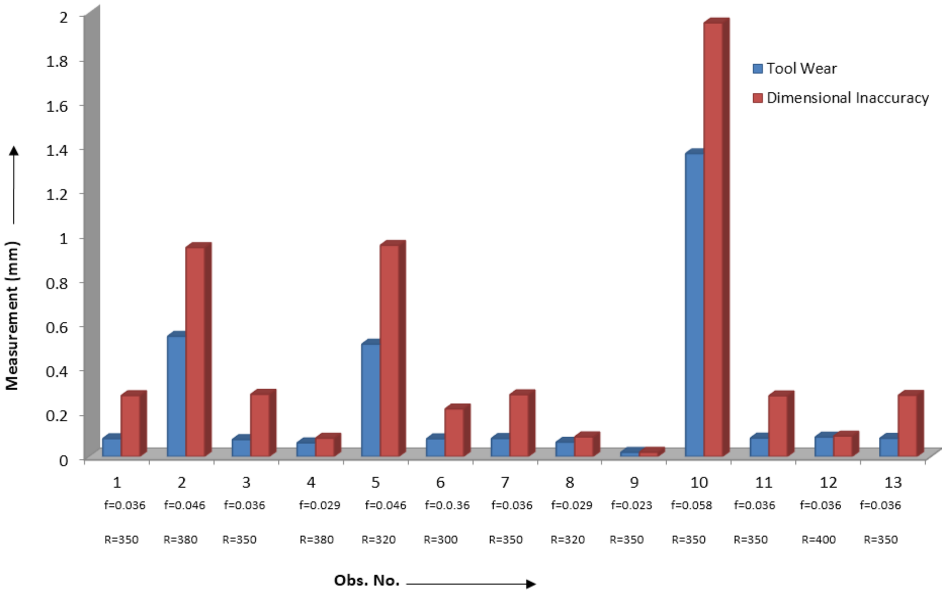


Fig. 5: Radial tool wear and dimensional inaccuracy for workpiece-arc with 1.5mm radius.

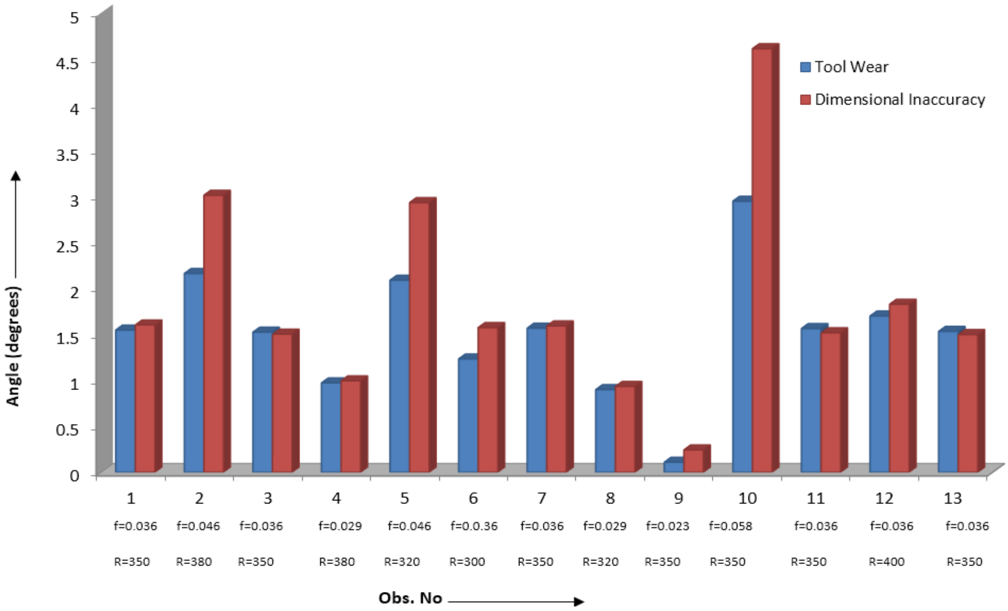


Fig. 6: Angular tool wear and dimensional inaccuracy for workpiece-Angle of 72^o

5. Conclusion

The influenced optimization of two parameters i.e. cutting speed and feed rate tool wear and dimensional accuracy are investigated using Response surface methodology as a design of experiment technique in this study. Comprehensive statistical analyses (ANOVA) is done for the identification of the significance of process parameters on selected response variables. It is found that at constant cutting speed, the tool wear increases as the feed rate increases for a given cutting speed. The impact of form tool wear on dimensional accuracy and surface finish changes considerably depending upon each profile of the tool and it is highest for the notch of included angle 54^o and lowest for the external curve of radius 2.5mm of the profile of the form tool. Tool life and dimensional accuracy can be improved by using lower feed rates. Finally mathematical relations for the prediction of tool wear and dimensional inaccuracy against each profile of the form tool are developed using regression analysis. Analysis of heat affected zones at various places of tool profile, metallographic and microscopic analysis are the possible future work dimensions in the same stream.

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