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Experimental analysis and effect of interface temperature and chip morphology on surface roughness & flank wear in hard turning of AISI 52100

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Abstract — *In this research work, hard turning of AISI 52100 (chrome steel) having hardness of 57 HRC is considered for analysis of machined surface roughness and tool flank wear using CBN cutting tool insert. This chrome steel bears having high hardness, wear resistance, surface finishing and dimensional precision; it is widely used to manufacture mechanical components, notably in balls and roller bearing. The temperature developed during machining is critical for analysis since it effects wear of the cutting tool and increases the surface roughness of the machined surface. The interface temperature, surface roughness, flank wear and chip morphology generated during machining will depend on the machining parameters chosen for this material. Experiments are designed based on Taguchi's Design of Experiment, for three input parameters each has three levels based on an L9 Orthogonal array. The output responses are analyzed based on Signal-to-Noise ratio and statistical tool like ANOVA and regression. The effect of interface temperature and chip morphology on surface roughness and flank wear is analyzed and the optimum cutting conditions are evaluated for minimizing surface roughness of work piece and tool flank wear to a considerable amount. The experimental results indicated that rise in interface temperature increases the surface roughness and tool flank wear. At optimum condition surface roughness value decreases when shape of chip changes from continuous to discontinues type. Results also shows when flank wear increases, shape of chip changes from continuous spring saw tooth wavy type to continuous spring one side flat one side saw tooth type chip.*

Keywords- *Hard turning; Interface temperature; chip morphology; surface roughness; flank wear*

I. INTRODUCTION

Hard turning really started to develop at the beginning of the nineties. The reason for this was the availability of new tool materials and the capability of designing a turning machine that was rigid, stable and accurate enough to successfully finish hard turn. Hard turning is machining process performed on hardened materials with the aim of replacing grinding operation. Hard turning, which is the dominant machining operation performed on hardened materials. Recently hard cutting operations using tools with geometrically defined cutting edges have become increasingly capable of replacing grinding operations providing good surface finish [1, 3]

INTERFACE TEMPERATURE

Temperature on the chip-tool interface is important parameters in the analysis and control of machining process. Due to the high shear and friction energies dissipated during a machining operation the temperature in the primary and secondary shear zones are usually very high, hence affect the shear deformation and tool wear. In a single point cutting, heat is generated at three different zones i.e. primary shear zone, chip tool interface and the tool work-piece interface as shown in Figure. 1. The primary shear zone temperature affects the mechanical properties of the work piece-chip material and temperatures at the tool-chip and tool-work piece interfaces influence tool wear at tool face and flank respectively. Total tool wear rate and crater wear on the rake face are strongly influenced by the temperature at chip-tool interface. Therefore, it is desirable to determine the temperatures of the tool and chip interface to analyze or control the process. There are number of methods for measuring the chip tool interface temperature: Tool work thermocouple, Radiation pyrometers, embedded thermocouples, Infrared thermometer, and indirect calorimetric technique. [6, 7]

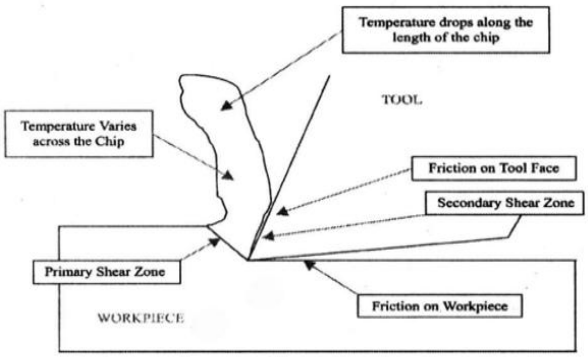

Fig.1 Heat generated during turning

CHIP MORPHOLOGY

Two parameters influencing the chip morphology and segmentation in hard turning are the Feed rate and the microstructure of material. The lowest feed rate facilitates the formation of uniform chips (continuous chip). Higher feed rates results in segmentation of the chips (Discontinuous chip). Chip serration causes the formation of microwaves on the machined surface, and this increases surface roughness. At different serration stages the influences of chip serration on wave amplitude are different, resulting in different surface roughness at different cutting speeds. The maximum value of machined surface roughness appears at about the middle rather than beginning or ending of serration range. The minimum surface roughness is at chip serration stage corresponding to separated segments. This hints the machining with higher cutting speed at separated segments chip is feasible under the permission of tool wear. Chip segmentation degree has no effects on the chip serration caused surface roughness. The principal factor influencing the machined surface roughness is the thickness of sawed segment of saw-tooth chip. The width of the sawed segment has weak effect on the machined surface roughness.[8]

II. LITERARTURE REVIEW

Sudhansu Ranjan Das et.al [1] have investigated the effect of cutting parameters on the performance characteristics in finish hard turning of AISI 52100 bearing steel with CBN tool. The combined effects of the process parameters on two performance characteristics are investigated employing Taguchi's L9 orthogonal array and analysis of variance (ANOVA). The results show that feed rate and cutting speed strongly influence surface roughness. However, the depth of cut is the principal factor affecting cutting force, followed by feed.

k. Subramanyam et.al [2] have described about a comparison of surface roughness and tool tip temperature between ceramics and cubic boron nitride (CBN) cutting tools when machining AISI 52100 hardened steel using the Taguchi method. An orthogonal design, signal-to-noise ratio (S/N) and analysis of variance (ANOVA) were employed to determine the effective cutting parameters on the surface roughness. The results indicated that in case of surface roughness the feed rate (f) was found to be a dominant factor, followed by the cutting speed (V), lastly the tool hardness (TH) and in case of tool tip temperature speed was found to be dominant factor, followed by the tool hardness (TH), lastly the feed rate (f).comparison of surface roughness and tool tip temperature between ceramics and cubic boron nitride (CBN) cutting tools

N. Senthil Kumar et.al [3] have investigated the inter-relationship between workpiece tool interface temperature and wear at the flank face of the cutting tool during machining hardened alloy steels using carbide-cutting tools. The temperature developed during machining is critical for analysis since it effects wear of the cutting tool and increases the surface roughness of the machined surface and result shows that minimum flank wear is obtained for higher depth of cut, moderate feed rate. With the increase in cutting speed, the flank wear of the tool also increases. Lesser temperature is sensed at the rake face of the insert when the depth of cut and feed rate are lower, with moderate cutting speed. Cutting zone temperature increases with the increase in relief angle of tool and included angle of cutting insert due to lesser contact area

S.Ben Salem et.al [4] has investigated the chip formation to obtain the optimal cutting conditions and to observe the different chip formation mechanisms. Analysis of machining of a hardened alloy, cold work steel: AISI D2 showed that there are relationships between the chip geometry, cutting conditions and the different micrographs under different metallurgical states. The results shows the microstructure reveal that the process of the chip formation gives a continuous form (shearing) in case of annealing and it occurs by crack propagation in case of quenched structure. Thus, the type and the shape of chip depend directly on the physical and mechanical properties of machined material. At high cutting speeds, a considerable amount of fresh martensite are found within the microstructure of the chip that results in lower micro hardness values. As the cutting speed increases, the chips become relatively ductile. Thus, more the cutting speed increases more the chips are segmented microscopically. However, in a macroscopic state, the chips are increasingly in continuous form; this is probably, due to their ductility, and less effect of edge is observed. The method ANOVA permitted us to conclude that the cutting speed and the feed influence significantly the cutting force, whereas, their interactions do not influence this, The chip segmentation mechanism needs clear identification since the effect of cutting conditions on machining process information depends on the chip segmentation mechanism. The shear band spacing model should be improved such as considering the work hardening effect to increase its predictive qualifications.

K.Senthil Kumar et.al[5] have performed some experiments to investigate the influence of turning parameters on the flank wear and chip morphology during a turning of Super duplex stainless steel SAF 2507 with uncoated carbide tool. Liquid CO2 which acts as a coolant, forms a gas cooled environment. The gas cooled machining in turn was compared with the dry and wet machining. Totally 18 experiments were conducted in order to measure the flank wear (Vb) with a tool makers microscope. The experiments were performed with the same cutting conditions and tool characteristics on the three methods of cooling. During the experimental procedure the removed chips were collected and evaluated together with the various cutting conditions. Using MINITAB 15 software, the optimized values of machining parameters were predicted using response surface methodology. Confirmation tests were carried out to compare the results of predicted values with the experimental value. The flank wear and the chips produced at the optimized values are analysed by scanning electron microscope from the experimental results, it was found that flank wear gets reduced in case of gas cooled machining. The cutting zone temperature and force acted during turning operation were also considerably reduced in case of gas cooled machining. Gas cooled machining (using liquid CO2 as coolant) was found to be an excellent alternative to conventional dry machining and wet machining.

III. EXPERIMENTAL SETUP

The experiment was conducted on high precision lathe machine modal NH-22 of HMT make for hard turning operation of Bearing Steel AISI 52100 of 90 mm round bar of 380 mm length using a CBN inserted type cutting tool.

Bearing steel (AISI 52100) is high carbon chromium steel, with small quantities of silicon and manganese. Bearing Steel is exceptionally hard and wear resistant, and is an excellent choice for applications where high operating temperatures is needed. The chemical compositions of bearing steel (AISI 52100) are given in Table-1 CBN insert of sandwik make ISO designation CNGA 120408S01030A, diamond shape, included angle 80^0, nose radius 0.8 mm, clearance angle 0^0, orthogonal rake angle -6^0 , inclination angle -6^0 , and tool holder of ISO designation DCLNR2525M-12, right hand type , tool cutting edge angle 95^0 , tool lead angle -5^0 was used as a cutting tool during the experiment.

Interface temperature (T) ^{0}c was measured with Infrared thermometer IR-865U. Surface roughness (Ra) was measured with Surface roughness tester SJ210. And Tool flank wear was measured (F) with tool maker microscope. The experimental set up is shown in **figure 2.**

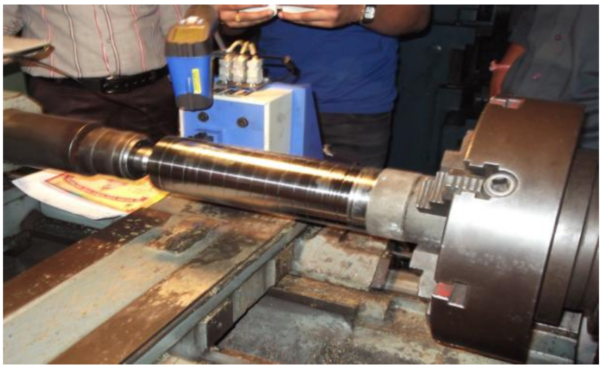

Fig. 2 Experimental set up

The working ranges of the parameters for subsequent design of experiment, based on Taguchi's L9 (33) orthogonal array (OA) design have been selected. In the present experimental study, cutting speed (v), feed (f) and depth of cut (d) have been considered as cutting parameters. The identified parameters and their associated levels are given in Table-2. According to Taguchi quality design concept, for three levels and three parameters, nine experiments are to be performed and hence L9 orthogonal array was selected as shown in Table-3.

Table -1 Chemical composition of the AISI 52100 steel (%)

C	Si	Mn	P	S	Cr
1.010	0.260	0.430	0.027	0.022	1.490

Table-2 Cutting Parameter and their level

Parameter	Symbol	Units	Level		
			1	2	3
Cutting Speed	V	m/min	82	119	156
Feed	F	mm/rev	0.05	0.06	0.07
Depth of cut	D	mm	0.2	0.3	0.4

Table-3 Orthogonal array L9 of Taguchi method using minitab-16 software

Sr. No	Cutting parameter			T (^{0}C)	Ra (µm)
	V m/min	F mm/rev	D mm		
1.	82	0.05	0.2	73.4	2.343
2.	82	0.06	0.3	60.1	0.762
3.	82	0.07	0.4	59.7	0.435
4.	119	0.05	0.3	79.3	4.924
5.	119	0.06	0.4	72.5	0.512
6.	119	0.07	0.2	69.2	0.430
7.	156	0.05	0.2	65.7	0.503
8.	156	0.06	0.4	53.7	1.121
9.	156	0.07	0.3	74.9	0.498

Flank wear of CBN insert was measured at cutting speed 156 m/min, Feed rate 0.05 mm/rev and depth of cut 0.2 mm as minimum surface roughness 0.408 µm achieved at this cutting parameter during experiment and flank wear measured at every 65 mm cutting length by using tool maker's microscope and readings are mention in Table - 4.

Table - 4: Tool flank wear of CBN cutting tool insert

Sr. No.	Cutting Length(mm)	Interface Temperature (^{0}c)	Flank wear(mm)	Surface Roughness(µm)
1	65	76.5	0.082	0.749
2	130	78.6	0.123	1.420
3	195	80.7	0.167	1.453
4	260	82.5	0.218	0.419
5	325	85.4	0.262	0.588
6	390	88.3	0.299	0.491
7	455	92.4	0.345	0.446
8	520	97.3	0.380	0.530

IV. RESULT & DISCUSSION

ANALYSIS OF SURFACE ROUGHNESS USING TAGUCHI, REGRESSION AND ANOVA

Taguchi method - The most essential criterion in the Taguchi method for analyzing experimental data is signal/noise ratio. In this study, the S/N ratio smaller is better is selected to obtain optimum cutting conditions, according to the Taguchi method. Thus, the optimum cutting condition was found as 7.987 S/N ratios for Ra in L9 orthogonal array in Table 5. The optimum cutting conditions, which were the cutting speed of 156 m/min, the feed rate of 0.05 mm/rev and the depth of cut of 0.2 mm were obtained for the best Ra. Fig 3 shows main effect plot for Ra. It shows that cutting speed increase surface roughness decreases and as depth of cut and feed rate decreases surface roughness decreases.

Table - 5: Taguchi method analysis of S/N ratio using minitab-16 software

Sr. No.	Cutting speed (m/min)	Depth of cut (mm)	Feed rate (mm/rev)	Surface roughness (µm)	Signal to noise Ratio
1	82	0.05	0.2	0.915	0.772
2	82	0.06	0.3	1.760	-4.910
3	82	0.07	0.4	2.620	-8.366
4	119	0.05	0.3	0.920	0.724
5	119	0.06	0.4	1.795	-5.081
6	119	0.07	0.2	1.385	-2.829
7	156	0.05	0.2	0.408	7.787
8	156	0.06	0.4	1.572	-3.929
9	156	0.07	0.3	1.683	-4.522

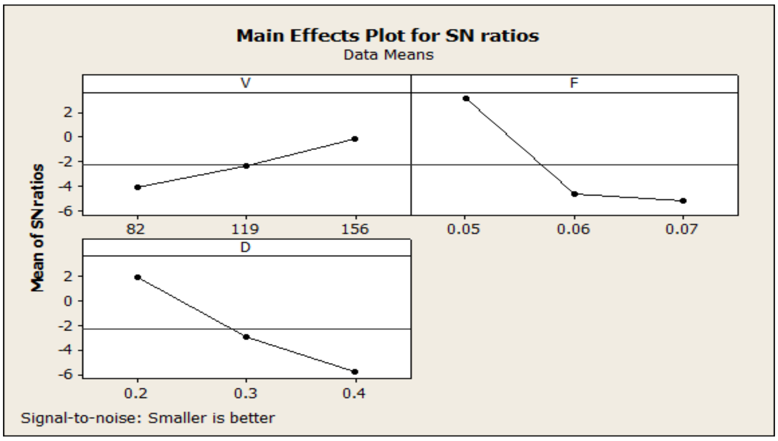

Fig. 3 Main effect plot of S/N ration for surface roughness

Regression for Surface Roughness: Analysis of the influence of each control factor (V, F, D, and T) on the surface roughness has been performed with a so called regression analysis response table. Response table of regression analysis for surface roughness are shown in table 6.

The Regression equation is Ra = 10.2472 - 0.0225599 V - 21.4614 F + 5.21042 D - 0.10139 T

Table-6: Regression of surface roughness of workpiece material

. Coefficients				
Term	**Coef**	**SE coef**	**T**	**P**
Constant	10.2472	1.40359	7.3007	0.002
V	-0.0226	0.00183	-12.3338	0.000
F	-21.4614	7.87273	-2.7260	0.053
D	5.2104	0.17422	29.9079	0.000
T	-0.1014	0.01208	-8.3914	0.001

Table -7 Analysis of Variance using regression for Ra

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	4	3.30831	3.30831	0.82708	1654.69	0.00000
V	1	0.44390	0.07604	0.07604	152.12	0.00025
F	1	1.97800	0.00371	0.00371	7.43	0.05265
D	1	0.85120	0.44710	0.44710	894.48	0.00001
T	1	0.03520	0.03520	0.035196	70.41	0.00110
Error	4	0.00200	0.00200	0.00050		
Total	8	3.31030				

Summary of Model : S = 0.0223571 R-Sq = 99.94% R-Sq(adj) = 99.88% PRESS = 0.0107170 R-Sq(pred) = 99.68%

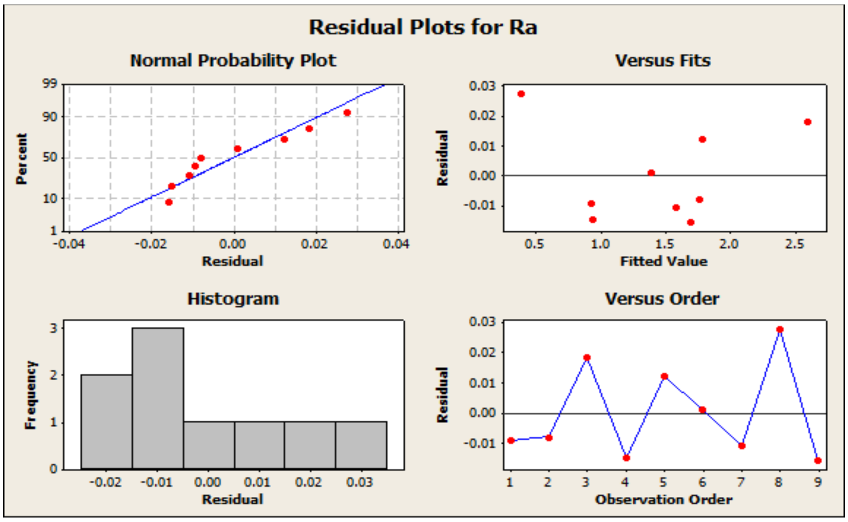

Fig. 4 Residual plot for surface roughness

The results of surface roughness from the regression analysis are shown in the Tables 6 & 7 respectively. The P values in the respective Analysis of Variance for Ra, using Adjusted SS for Tests tables which are less than 0.05 indicate that it is statistically significant on the performance and F value indicate that surface roughness mostly influence by depth of cut, then cutting speed , interface temperature and lastly by feed rate when interface temperature considered. Fig 4 shows residual plot for surface roughness.

ANOVA : As experiment was developed for assessment of surface roughness which was influenced by cutting speed, feed rate, and depth of cut. The Table 8 illustrates the responses of surface roughness. Analyses were done with ANOVA results for the identifying factors which are affecting the performances.

Table-8: ANOVA of surface roughness of workpiece material

Source	DF	Seq SS	Adj SS	Adj MS	F	P	C
V	2	0.47582	0.47582	0.23791	100.49	0.010	14.36%
F	2	2.27780	1.03772	0.51886	219.16	0.005	68.80%
D	2	0.55195	0.55195	0.27597	116.57	0.009	16.68%
Error	2	0.00474	0.00474	0.00237			0.16%
Total	8	3.31030					

The results of surface roughness from the ANOVA are shown in the Tables 6. The P values in the respective ANOVA tables which are less than 0.05 indicate that it is statistically significant on the performance. The last column of each ANOVA tables indicates the percentage contribution of each source to the total variance indicating the magnitude of influence.

From the table 6 it is clear that surface roughness mostly affected by feed rate up to 68.80% , by depth of cut up to 16.38% and lastly by cutting speed up to 14.36 %.

Flank wear

Analysis of Flank wear

Regression for Flank wear

Analysis of the influence of control factor cutting length and interface temperature on the flank wear has been performed with a so called regression analysis response table. Response table of regression analysis for flank wear are shown in table 9 & 10.

Table 9: Regression of flank wear on the cutting length for CBN TOOL

The regression equation is FW = 0.226 + 0.000779 L -0.00258 T

Coefficients

Term	Coef	SE coef	T	P
Constant	0.22629	0.06652	3.40	0.019
L	0.00078	0.00004	18.96	0.000
T	-0.00258	0.00092	-2.81	0.038

Table 10 : Analysis of Variance using regression for flank wear wear on the cutting length for CBN TOOL.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	2	0.07871	0.07871	0.03936	4246.08	0.00000
L	1	0.07864	0.00333	0.00333	359.63	0.00000
T	1	0.00007	0.00007	0.00007	7.87	0.03774
Error	5	0.00005	0.00005	0.00000		
Total	7	0.07876				

Summary of Model

S = 0.00304447 R-Sq = 99.94% R-Sq(adj) = 99.92% PRESS = 0.000114368 R-Sq(pred) = 99.85%

The results of flank wear from the regression analysis are shown in the Tables 9 & 10 respectively. The P values in the respective Analysis of Variance for FW using Adjusted SS for Tests tables which are less than 0.05 indicate that it is statistically significant on the performance and F value indicate that flank wear mostly influence by cutting length, then interface temperature. Fig 5 shows effect of cutting length and interface temperature on flank wear and fig 6 shows residual plot for flank wear. As shown in fig 5 as cutting length and interface temperature increase flank wear increases.

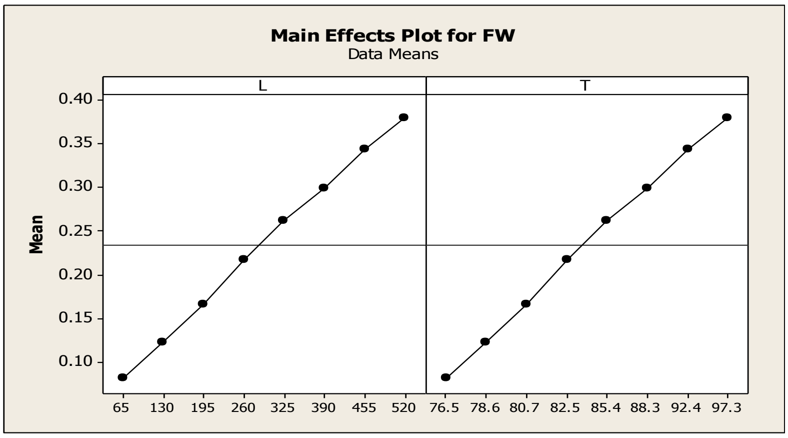

Fig. 5: Main effect plot for Flank wear

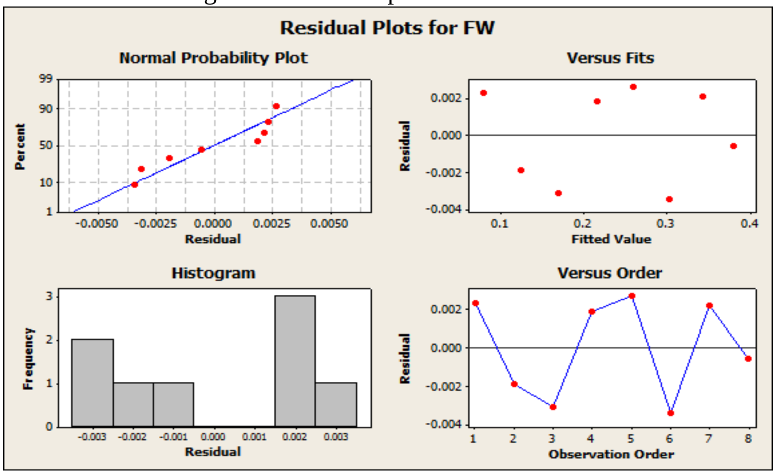

Fig. 6: Residual plot for Flank wear

Chip morphology - As per Table-3 various types of chip are forms at varying cutting speed, feed and depth of cut is shown in fig. 7 and type of chip form during measurement of flank wear at standard cutting parameter (Cutting speed – 156 m/min, F – 0.05mm/rev, D – 0.2 mm) that we have set for minimum surface roughness is shown in fig. 8

Fig.7 Chip morphology at various cutting speed, feed rate and depth of cut

It has been observed on basis of chip formation in fig.7 during hard turning at optimum condition, surface roughness value is decreasing when shape of chip changes from continuous type to discontinues loose chip.

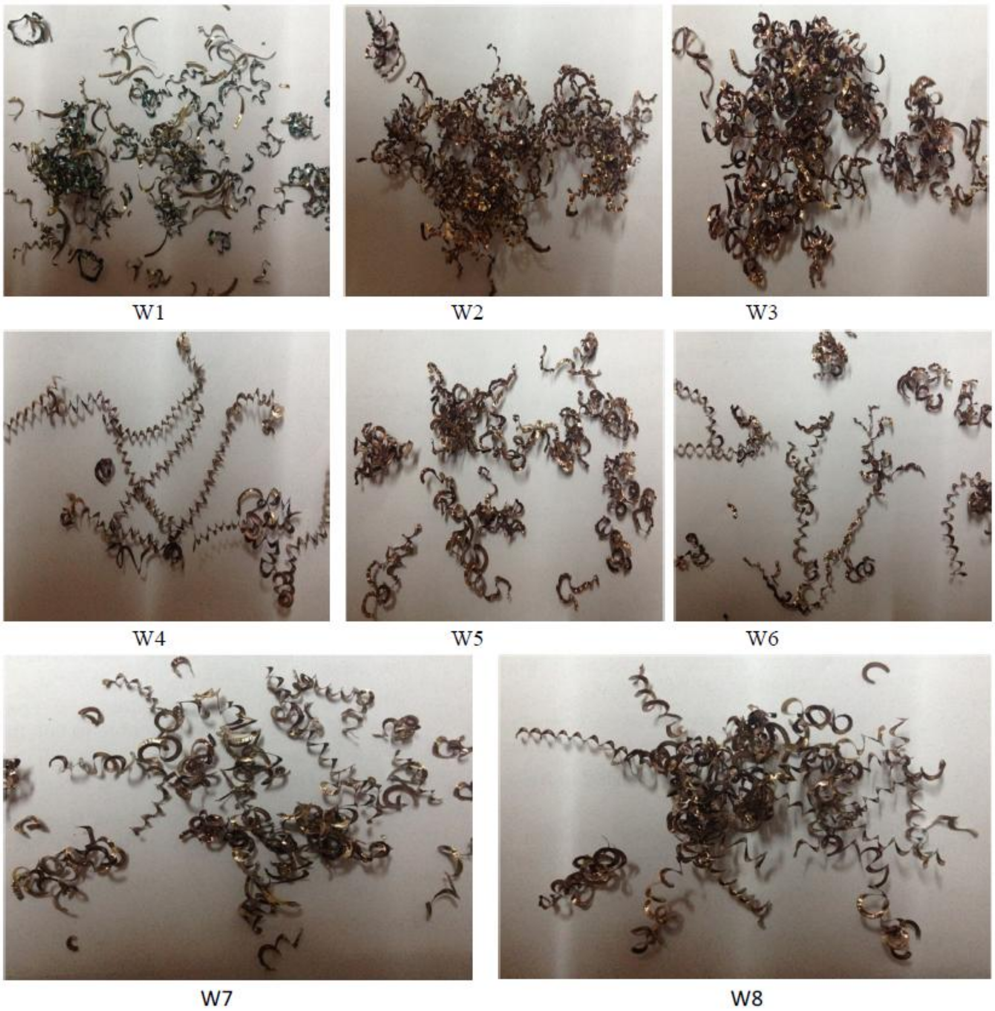

Fig. 8 - Chip morphology at 156 m/min cutting speed, 0.05 mm/rev and 0.2 mm depth of cut and varying cutting length

As per observation from fig. 8 when flank wear increases, shape of chip changes from continuous spring saw tooth wavy type to continuous spring one side flat one side saw tooth type chip.

Validation of regression model for work piece surface roughness

Here we use two unknown value of cutting speed , feed, depth of cut, interface temperature and compare to its by practical value and check the result obtain by practical value and predicted value is nearest.

The regression equation is

$$\mathbf{Ra = 10.2472 - 0.0225599\,V - 21.4614\,F + 5.21042\,D - 0.10139\,T}$$

Predicated value using regression equation:

1) Cutting speed =250 m/min
Feed = 0.05 mm
Depth of cut = 0.4 mm
Interface Temperature = 50.1 ^{o}C
Surface roughness = 10.2472-0.0225599*250-21.4614*0.05+5.21042*0.4- 0.10139*50.1
= 0.499mm

2) Cutting speed = 202 m/min
Feed = 0.06 mm
Depth of cut = 0.2 mm
Interface Temperature = 49.9 ^{o}C
Surface roughness =10.2472-0.0225599*202-21.4614*0.06+5.21042*0.2- 0.10139*49.9
= 0.385mm

Table-11 comparison of predicated and actual practical value for surface roughness

Sr no	Predicted value using regression equation for surface roughness in µm	Practical value for surface roughness in µm	Percentage variation
1	0.499	0.514	2.92 %
2	0.385	0.422	8.77 %

In here we see that predicated value and practical value are nearest means model is valid for above value.

Validation of regression model for tool flank wear

Here we use two unknown value of cutting length and compare to its by practical value and check the result obtain by practical value and predicted value is nearest.

The regression equation is Flank wear in mm = 0.226 + 0.000779 L -0.00258 T

Predicated value using regression equation:

1) Cutting length = 150 mm

Interface Temperature = 79.3 °C

Flank wear in mm = 0.226+0.000779*150-0.00258*79.3

= 0.138 mm

2) Cutting length= 280 mm

Interface Temperature = 83.0 °C

Flank wear in mm = 0.226 + 0.000779*280-0.00258*83.0

= 0.230mm

Table-12 Comparison of predicated and actual practical value for Tool Wear

Sr No	Cutting length	Predicted value using regression equation in mm for flank wear	Practical value in mm for flank wear	Percentage variation
1	150	0.138	0.140	1.42 %
2	280	0.230	0.235	2.17 %

In here we see that predicated value and practical value are nearest means model is valid for above value.

V. CONCLUSION

Machining experiment shows that surface roughness is mostly influenced by feed rate, depth of cut, and lastly by cutting speed. By increasing interface temperature and cutting length, tool flank wear and surface roughness are increased. Optimum cutting condition for minimum surface roughness is achieved at cutting speed 156 m/min, feed rate 0.05 mm/rev, depth of cut 0.2mm and interface temperature 62.3^{0}c. On basis of chip formation during hard turning at optimum cutting condition, surface roughness value decreases when shape of chip changes from continuous to discontinuous type. Similarly when flank wear increases, shape of chip changes from continuous spring saw tooth wavy type to continuous spring type one side flat one side saw tooth.

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