Investigation on the Influence of Cutting Parameters on Machining Performance during Turning of Difficult-to-Machine Steels

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Abstract
The influence of cutting parameters viz. cutting speed, feed rate and depth of cut, tool geometry viz. rake angle, clearance angle and nose radius on turning of AISI 304 stainless steel, AISI 52100 bearing steel and AISI D2 tool steel with advanced cutting tools like multicoated carbide, cermet and alumina inserts are investigated experimentally. The machining performance (i.e. output parameters) considered in this article are surface roughness, flank wear and tool-shim interface temperature. Experiments are conducted according to Taguchi's orthogonal array and ANOVA is performed to evaluate the significance of each of the input parameters on each of the output parameters. It is found that variation in work materials, and tool materials have significant effect on flank wear apart from cutting speed. Tool cutting edge geometry like nose radius and clearance angle influenced surface roughness apart from the cutting parameters. Variations in work material, cutting fluids and nose radius have considerable influence on tool-shim interface temperature.

***Keywords**: Turning, Difficult-to-machine steels, surface roughness, flank wear, tool-shim interface temperature.*

1 Introduction

The complexity of the turning process is compounded over the period of years due to the continuous development and introduction of new tool materials, work materials, service conditions / treatment on work materials and by the changes in machining conditions. In a practical machining situation, there is as yet lack of machining theory to provide adequate relationships between the machining performance (surface finish, flank wear and cutting zone temperature) and cutting conditions, tool geometrical parameters, and work and tool material properties. Ahmari [1] and, Ozel and Karpat [2] had mentioned the application of the following formula to determine surface roughness:
$Ra = f^2 / 32r$. Shaw [3] and Bhattacharyya [4] had derived and reported the theoretical model for surface roughness as follows: $Ra = f^2 / 8r$. It has been shown that the actual surface roughness in experiments with low feed rates does not match the theoretical surface roughness. There are two main effects that lead to the degradation of surface roughness: adhesion and ploughing. The frictional interaction between the tool and workpiece has a significant impact on surface quality [2]. Mozher [5] constructed a model for surface finish using regression analysis technique and is shown below: $Ra = 31.025f^{1.347} / v^{0.159}d^{0.159}r^{0.605.}$ Where, 'f' is the feed rate, 'r' is the nose radius, 'v' is cutting speed, 'd' is depth of cut. This equation indicates that surface roughness depends on cutting parameters such as cutting speed, feed rate and depth of cut, and cutting tool geometry namely nose radius.
The well-known Taylor [6] equation which, is the most widely used tool life relation to machining can be written as $VT^n = C$. The modified tool life equation used by various researchers is expressed as follows:
$VT^xf^yd^z = C$. Where, 'T' is tool life, 'V" is cutting speed, 'f' is feed rate, 'd' is depth of cut, x, y, z and C are the constants. It has been shown that for a given tool/work material combination, the above equations does not agree well with experimental results over wide ranges of cutting conditions [7]. This indicates that some other parameters also influence the tool life / wear. According to Mozher [5], the tool life 'T' is expressed as follows:

$T = 406.423\ r^{0.038} / V^{1.051} f^{0.289} d^{0.219}$ which shows that nose radius also influences the tool wear / life. Therefore it is evident from literature, that the surface roughness, tool wear (flank) and tool tip temperature are interrelated and depends on various factors. These factors include the tool cutting edge geometry, workpiece and tool material properties. Cutting edge geometry is important because much of the tool-workpiece interactions occur along the cutting edge. Workpiece properties are significant because the plastic deformation of the workpiece contributes to the surface generation and heat generation process [8]. Saglam et al. [9] reported that during cutting process, the tool tip was very close to the flowing chip and some of the heat was conducted to the workpiece. Hence it was not possible to obtain the real temperature exerted on the tool tip and for a reliable measurement a thermocouple should be embedded into the cutting insert.

From the literature, it is understood that there is no clear theory about the factors that affect the turning process. Researchers had also mentioned that tool and work material properties have some influence on the tool wear, surface roughness and cutting zone temperature. Further the capability of advanced tool materials like multi coated carbide, cermet and alumina inserts on machining of difficult to machine steels like AISI 304 stainless steel, hardened AISI 52100 and AISI D2 steel are not adequately investigated. Hence in this research work, apart from the cutting parameters like cutting speed, feed rate and depth of cut, the cutting tool geometry like nose radius, rake angle and clearance angle, variation in work and tool materials, and cutting fluids are considered for investigating the performance of the turning process.

2 Experimentation

Three work materials are considered for the experimentation viz. AISI 304 stainless steel, hardened AISI 52100 bearing steel (55 HRC) and hardened AISI D2 tool steel (55 HRC). Three different cutting tools namely carbide, cermet and alumina inserts of various combination of tool geometry are used. The input parameters in experimentation includes cutting speed, feed rate, depth of cut, tensile strength of work material, transverse rupture strength of tool, viscosity of cutting fluid, rake angle, clearance angle and nose radius. The three levels in each parameter identified for the trials are shown in Table 1. Each of the work piece specimens is 250 mm long with 200 mm of effective turning length and 50 mm in diameter. The machine tool used is Jobber XL CNC machine from ACE designer with Fanuc control system; variable speed motor 50 – 4000 rpm and 7.5 kW rating. After each trial the flank wear on the tool is measured using CARL ZIESS Optical Microscope having 50 X to 1500 X magnification, equipped with Clemex Vision Professional Edition Image Analysis Software. The surface roughness on the workpiece is measured using Mitutoyo Surface Roughness tester. Tool-shim interface temperature developed during the machining process is measured by a thermocouple, Iron - Constantan (J-Type) Tool Tip type with a temperature range of 30 - 400 º C, with sensitivity of ± 0.1ºC. The experimental plan and the corresponding observation made are presented in Table 2.

Table 1: Input Parameters and their levels

S.No	Parameter	Level 1	Level 2	Level 3
1	Tensile strength of Work material (t_s)	586 Mpa (AISI 304)	1736 Mpa (AISI D2)	2240 Mpa (AISI 52100)
2	Transverse rupture strength of Tool material (t_{rs})	1400 Mpa (Carbide)	1700 Mpa (Cermet)	700 Mpa (Ceramic)
3	Cutting speed (m/min)	100	140	180
4	Depth of cut (mm)	0.2	0.3	0.4
5	Feed rate (mm/rev)	0.1	0.15	0.2
6	Viscosity of Cutting fluid (η)	26.8 mPaS (Coconut oil)	1.63 mPaS (Soluble oil)	45.7 mPaS (Straight cutting oil)
7	Rake angle (deg)	6	18	0
8	Clearance angle (deg)	0	7	11
9	Nose radius (mm)	0.4	0.8	1.2

Table 2: Experimental plan and observation

S.No	Vc	f	d	t_s	t_{rs}	η	α	γ	R	Vb	Ra	θ
1	100	0.1	0.2	586	1400	26.8	6	0	0.4	0.082	1.65	278
2	100	0.1	0.2	586	1700	1.63	18	7	0.8	0.073	1.57	289
3	100	0.1	0.2	586	700	45.7	0	11	1.2	0.067	1.40	300
4	100	0.15	0.3	1736	1400	26.8	18	7	0.8	0.105	1.72	290
5	100	0.15	0.3	1736	1700	1.63	0	11	1.2	0.096	1.61	298
6	100	0.15	0.3	1736	700	45.7	6	0	0.4	0.088	1.84	285
7	100	0.2	0.4	2240	1400	26.8	0	11	1.2	0.115	1.70	307
8	100	0.2	0.4	2240	1700	1.63	6	0	0.4	0.106	1.92	296
9	100	0.2	0.4	2240	700	45.7	18	7	0.8	0.100	1.81	311
10	140	0.1	0.3	2240	1400	1.63	6	7	1.2	0.126	1.65	320
11	140	0.1	0.3	2240	1700	45.7	18	11	0.4	0.120	1.68	310
12	140	0.1	0.3	2240	700	26.8	0	0	0.8	0.111	1.70	318
13	140	0.15	0.4	586	1400	1.63	18	11	0.4	0.130	1.78	311
14	140	0.15	0.4	586	1700	45.7	0	0	0.8	0.125	1.82	319
15	140	0.15	0.4	586	700	26.8	6	7	1.2	0.118	1.75	308
16	140	0.2	0.2	1736	1400	1.63	0	0	0.8	0.131	1.91	315
17	140	0.2	0.2	1736	1700	45.7	6	7	1.2	0.122	1.88	330
18	140	0.2	0.2	1736	700	26.8	18	11	0.4	0.115	1.93	309
19	180	0.1	0.4	1736	1400	45.7	6	11	0.8	0.137	1.69	345
20	180	0.1	0.4	1736	1700	26.8	18	0	1.2	0.130	1.71	330
21	180	0.1	0.4	1736	700	1.63	0	7	0.4	0.124	1.80	328
22	180	0.15	0.2	2240	1400	45.7	18	0	1.2	0.132	1.81	360
23	180	0.15	0.2	2240	1700	26.8	0	7	0.4	0.126	1.92	338
24	180	0.15	0.2	2240	700	1.63	6	11	0.8	0.120	1.79	350
25	180	0.2	0.3	586	1400	45.7	0	7	0.4	0.134	2.06	318
26	180	0.2	0.3	586	1700	26.8	6	11	0.8	0.129	1.98	325
27	180	0.2	0.3	586	700	1.63	18	0	1.2	0.125	1.95	334

Vc: cutting speed (m/min.), f: feed rate (mm/rev.), d: depth of cut (mm), t_s: tensile strength of work material (Mpa), t_{rs}: transverse rupture strength of tool material (Mpa), η: Viscosity of Cutting fluid (mPaS), α: Rake angle (degrees), γ: Clearance angle (degrees), r: Nose radius (mm), Vb: Flank wear (mm), Ra: C. L. A. value of Surface roughness (μm), θ: Tool-shim interface temperature (˚C)

3 Analysis of variance (ANOVA)

Analysis of variance has been performed to estimate the actual influence of each input parameter on each of the output parameter. Table 3 summarizes the ANOVA performed for each output, i.e. the percentage influence of all the input parameters on each of the output parameter. For example, cutting speed has 23.4% influence, feed rate has 54.7% influence, nose radius has 13.1%, clearance angle has 6.5% influence and depth of cut has 1.2% influence on surface roughness. Likewise, the influence of all the input parameters on the other output parameters can be interpreted.

Table 3: Percentage influence of all input parameters on each output parameter

Output Parameters → / Input Parameters ↓	Surface roughness	Flank wear	Tool-shim interface temperature
Cutting speed	**23.4**	**71.6**	**75.71**
Feed rate	**54.7**	**7.1**	0.94
Depth of cut	**1.2**	**8.2**	**3.06**
Work material	0.2	**3.8**	**9.05**
Tool material	0.2	**9.2**	0.05
Cutting fluid	0.08	0.029	**3.05**
Rake angle	0.6	0.003	0.03
Clearance angle	**6.5**	0.003	0.32
Nose radius	**13.1**	0.029	**7.78**

(Figures in this table indicate the percentage values)

4 Results and Analysis

4.1 *Analysis on surface roughness*

ANOVA for surface roughness indicates that feed rate, cutting speed, nose radius and clearance angle have significant influence on surface roughness. From the experimental observations, graphs are plotted between surface roughness and the influencing parameters. Figure 1 indicates the plot between the surface roughness and feed rate for various tool nose radii. Feed rate is varied from 0.06 to 0.26 mm/rev. and the nose radius is varied as 0.4, 0.8 and 1.2 mm for each set of experiments. This figure presents the experimental results obtained during machining of AISI 52100 with carbide inserts with a constant cutting speed of 100 m/min., depth of cut; 0.2 mm, rake angle: 6º, clearance angle: 7º in the presence of soluble oil as cutting fluid. From the graph it is evident that surface roughness increases as the feed rate increases and the surface roughness decreases as the nose radius is increased. The finding is agreeable with Liu and Mittal, [10] who had reported that a surface comparable with a ground surface was realized using a tool with a large nose radius during hard turning process.

Figure 2 shows the graph between surface roughness and feed rate for various clearance angle. Feed rate is varied from 0.06 to 0.26 mm/rev. and the clearance angle is varied as 0º, 7º and 11º for each set of experiments. This figure presents the experimental results obtained during machining of AISI D2 with cermet inserts with a constant cutting speed of 100 m/min., depth of cut; 0.3 mm, rake angle: 6º, nose radius: 1.2 mm in the presence of soluble oil as cutting fluid. From the graph it is evident that surface roughness increases as the feed rate increases and the surface roughness decreases as the clearance angle is increased. Since all other parameters are kept constant a uniform increase in surface roughness is observed for any clearance angle. Minimum surface roughness is obtained at lower feed rate because at lower feed rates, the distance from peak to valleys on the machined surface is smaller resulting in better surface finish.

Figure 3 shows the graph between surface roughness and feed rate for various cutting speeds. Feed rate is varied from 0.10 to 0.20 mm/rev. and the cutting speed is varied as 180, 140 and 100 m/min for each set of experiments. This figure presents the experimental results obtained during machining of AISI 304 with alumina inserts with a constant depth of cut; 0.3 mm, rake angle: 6º, clearance angle: 7º, nose radius: 0.4 mm in the presence of soluble oil as cutting fluid. From the graph it is evident that surface roughness increases as the feed rate increases. In general surface roughness shows an increasing pattern for an increase in cutting speed. As the cutting speed is increased from 140 to 180 m/min, a difference in surface roughness is observed for a lower feed rate of 0.1 and 0.12 mm/rev. When feed rate is increased from 0.14 to 0.2 mm/rev the surface roughness almost remain same for both the cutting speeds of 140 and 180 m/min. Higher surface roughness value in AISI 304 can be explained by the highly ductile nature of austenitic stainless steels which increases the tendency to form a large and unstable built up edge (BUE). The presence of the large and unstable BUE causes poor surface finish. BUE and wear / chipping are closely associated with each other in the case of machining ductile materials. Both of them lead to increased surface roughness values. At lower / moderate cutting speeds, BUE becomes stronger than that formed at higher cutting speeds. At higher cutting speeds cutting zone temperature increases and this in turn, softens and decreases the strength of BUE. Therefore a lower adhesion force is observed between the BUE and cutting tool at higher speeds which results in detachment of BUE and chipping of cutting edge. Consequently a poor surface finish is obtained on the work piece.

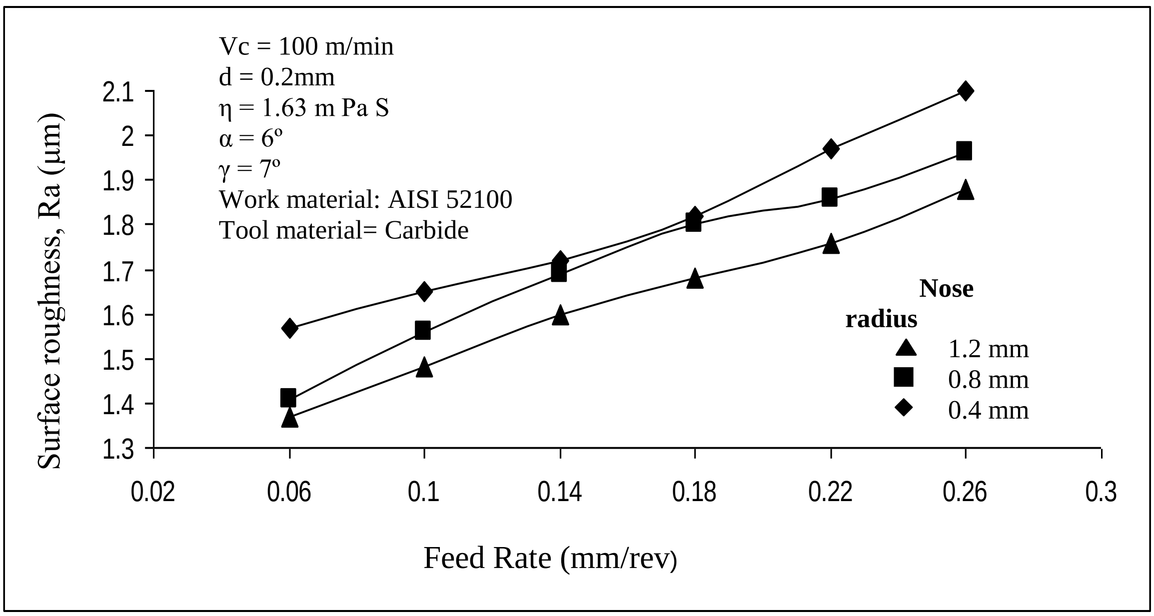

Figure 1: Surface roughness Vs Feed rate for various nose radius

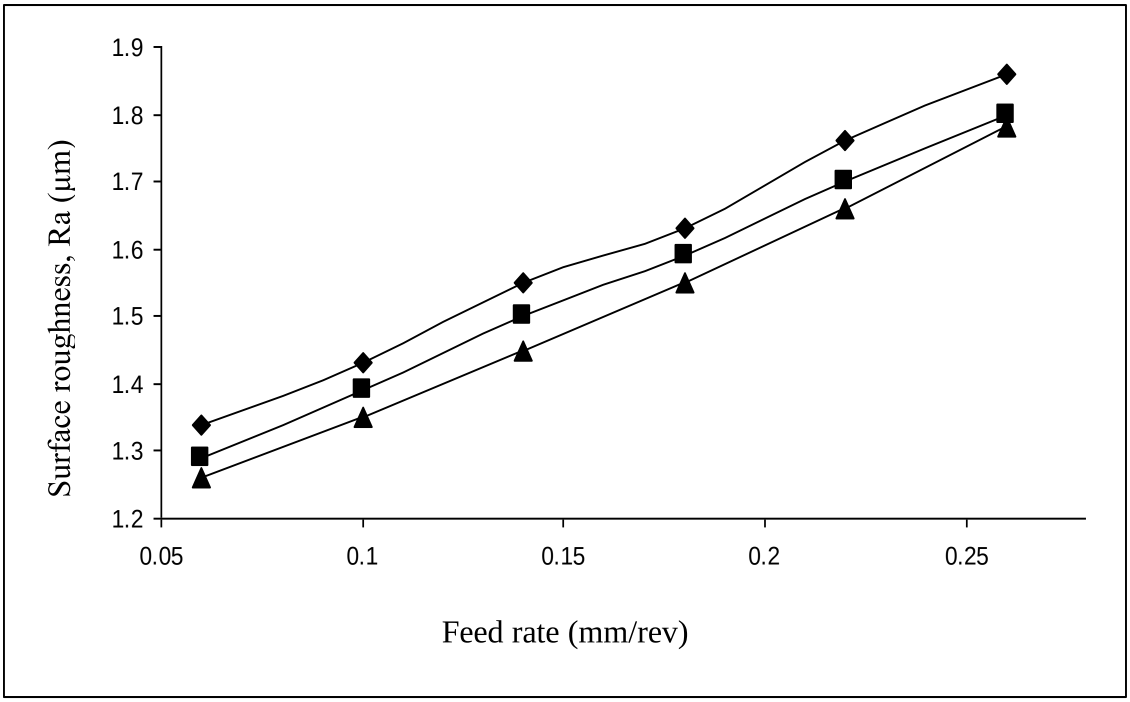

Figure 2: Surface roughness Vs Feed rate for various clearance angle

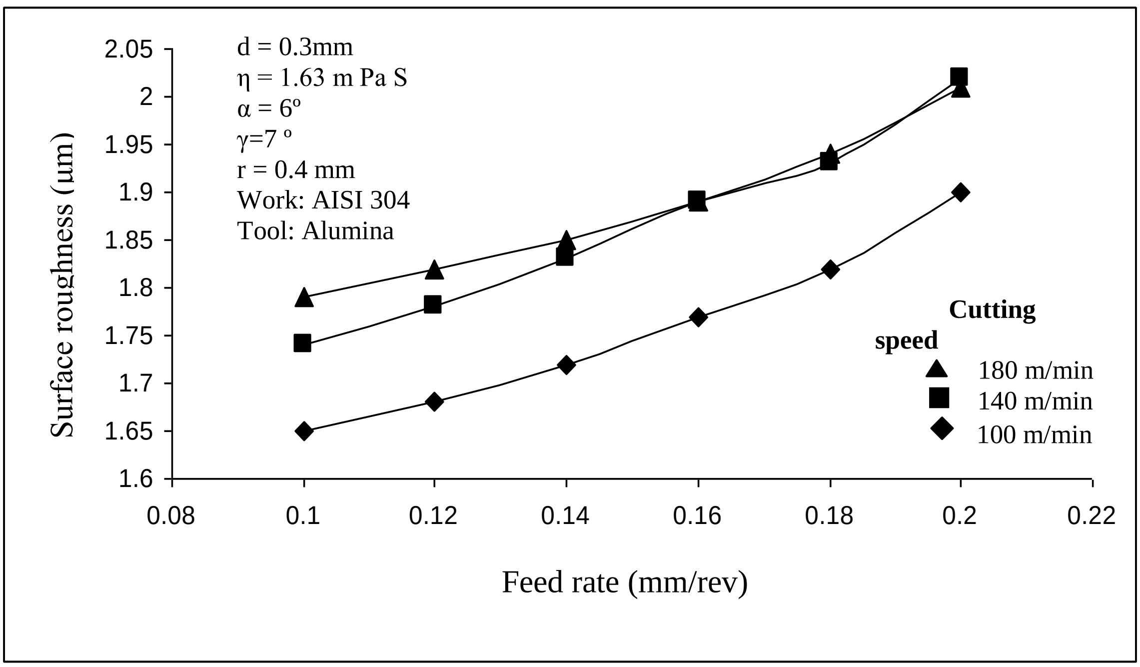

Figure 3: Surface roughness Vs feed rate for various cutting speed

4.2 *Analysis on flank wear*

ANOVA for flank wear indicates that cutting speed, feed rate, depth of cut, variation in work material and tool material have significant influence on flank wear. Hence, it is evident that different tool material encounter different rate of wear while machining various materials. From the experimental observations, graphs are plotted between flank wear and the influencing parameters. Figure 4 indicates the plot between the flank wear observed on each of the three tool material and the cutting speeds. Since cutting speed greatly influences tool wear, it is varied from 80 to 180 m/min. This figure presents the experimental results obtained during machining of AISI D2 with carbide, cermet and alumina inserts with a constant feed rate: 0.15 mm/rev, depth of cut; 0.3 mm, rake angle: 6º, clearance angle: 7º, nose radius: 0.8 mm in the presence of soluble oil as cutting fluid. From the figure it is evident that the tool wear gradually increases with increase in cutting speed irrespective of the tool material. As the cutting speed increases, carbide tool wears faster than the cermet and alumina inserts. Alumina inserts performs better than cermet and carbide inserts with respect to wear resistance for the entire range of cutting speeds. For carbide inserts, at the initial stages of wear, the coating layers protect the WC-Co from the high temperature caused by tool-work piece friction. It also contributes to chemical stability and a low frictional force resulting in slow tool wear. Even though the wear at 80 m/min is high when compared to cermet and alumina inserts, the presence of Al_2O_3 coating on the insert offers resistance to wear. Beyond the cutting speed of 140 m/min due to high temperature developed in the machining zone, the coating layer is delaminated and tool wear then increases rapidly. Beyond the cutting speed of 140 m/min the wear rate in alumina insert is less than cermet because due to the presence of TiC (30%) in alumina inserts, it posses very good resistance to thermal and mechanical shocks, and improved resistance to crack initiation and propagation. (Cermet inserts contain only 10% TiC)

Figure 5 indicates the plot between the flank wear observed on alumina inserts while machining the three work material and the range of cutting speeds considered i.e. from 80 to 180 m/min. This figure presents the experimental results obtained during machining of AISI D2, AISI 304 and AISI 52100 with alumina inserts with a constant feed rate: 0.15 mm/rev, depth of cut; 0.3 mm, rake angle: 6º, clearance angle: 7º, nose radius: 0.8 mm in the presence of soluble oil as cutting fluid. The tool wear observed while machining AISI 304 is considerably less when compared to the wear observed on machining the other two materials. The tool wear observed while machining AISI D2 and AISI 52100 is almost close to each other for the entire range of cutting speeds considered because the hardness of both these material is same. In spite of the difference in the properties of the three work materials tested, the higher hardness value is responsible for the accelerated wear rate in AISI 52100 (55 HRC) and AISI D2 (55 HRC) compared to AISI 304 (20 HRC). Abrasion is the important wear mechanism giving a significant contribution to flank wear, probably owing to the presence of hard carbide particles in the hardened steel materials.

Figure 6 indicates the plot between the flank wear and cutting speeds for the variation in depth of cut. Cutting speed is varied form 80 m/min to 180 m/min and the depth of cut is varied as 0.2, 0.3 and 0.4 mm. This figure presents the experimental results obtained during between the tool and work piece and thus intensifying heating as well as wearing of the tool.

Figure 7 indicates the plot between the flank wear and cutting speeds for the variation in feed rate. Cutting speed is varied form 80 m/min to 180 m/min and the feed rate is varied as 0.1, 0.15 and 0.2 mm/rev. This figure presents the experimental results obtained during machining of AISI D2 with cermet inserts with a constant depth of cut: 0.2 mm, rake angle: 0º, clearance angle: 11º, nose radius: 0.4 mm in the presence of soluble oil as cutting fluid. From the figure it is evident that the flank wear gradually increases with increase in cutting speed. For any cutting speed, lower flank wear is observed for a lesser feed rate and as the feed rate is increased the flank wear also increases accordingly.

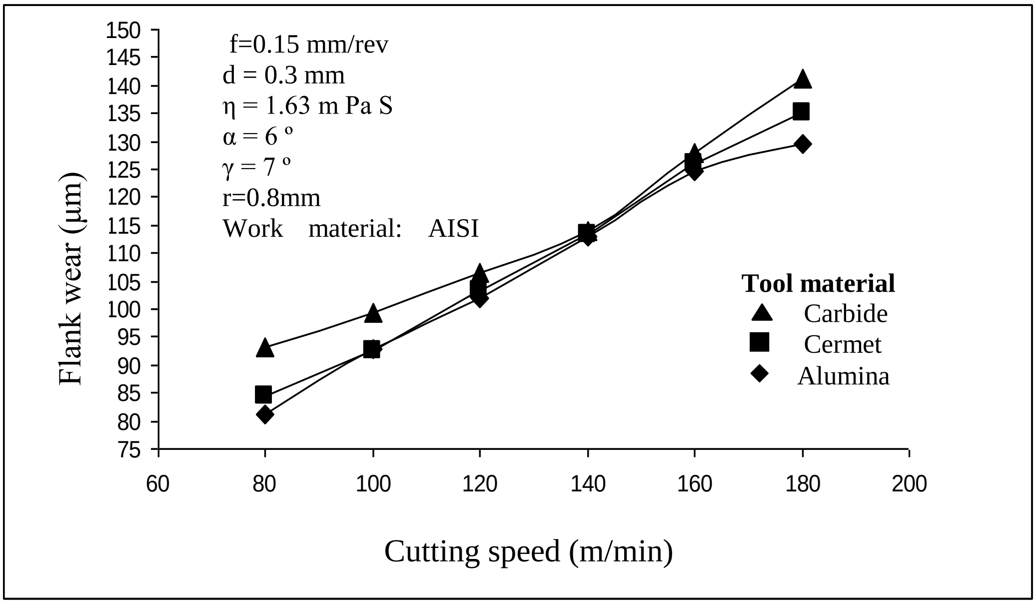

Figure 4: Flank wear Vs Cutting speed for various tool materials

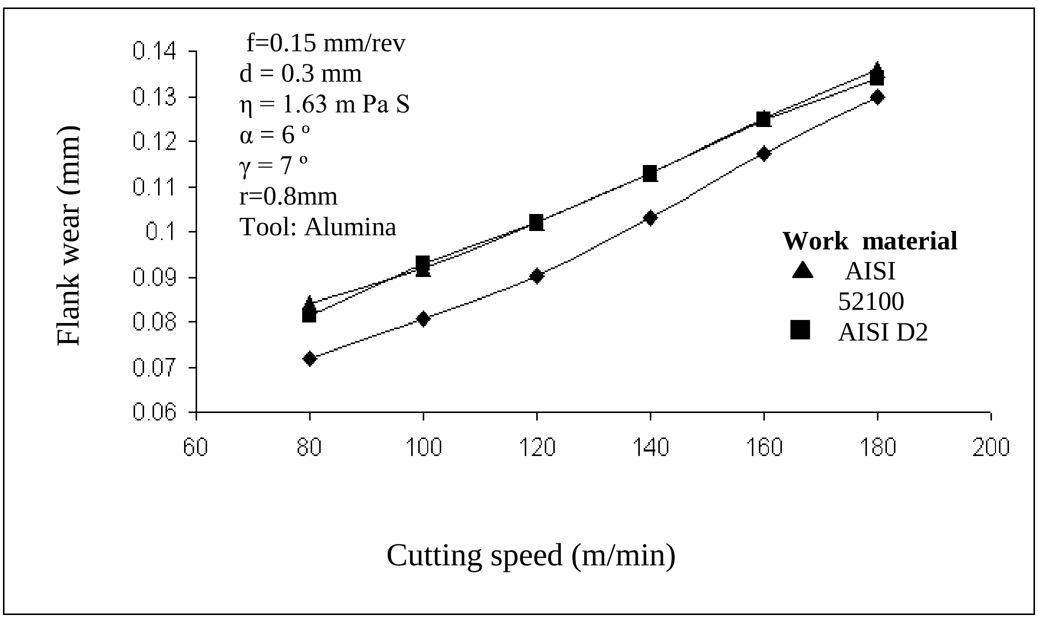

Figure 5: Flank wear Vs Cutting speed for various work materials

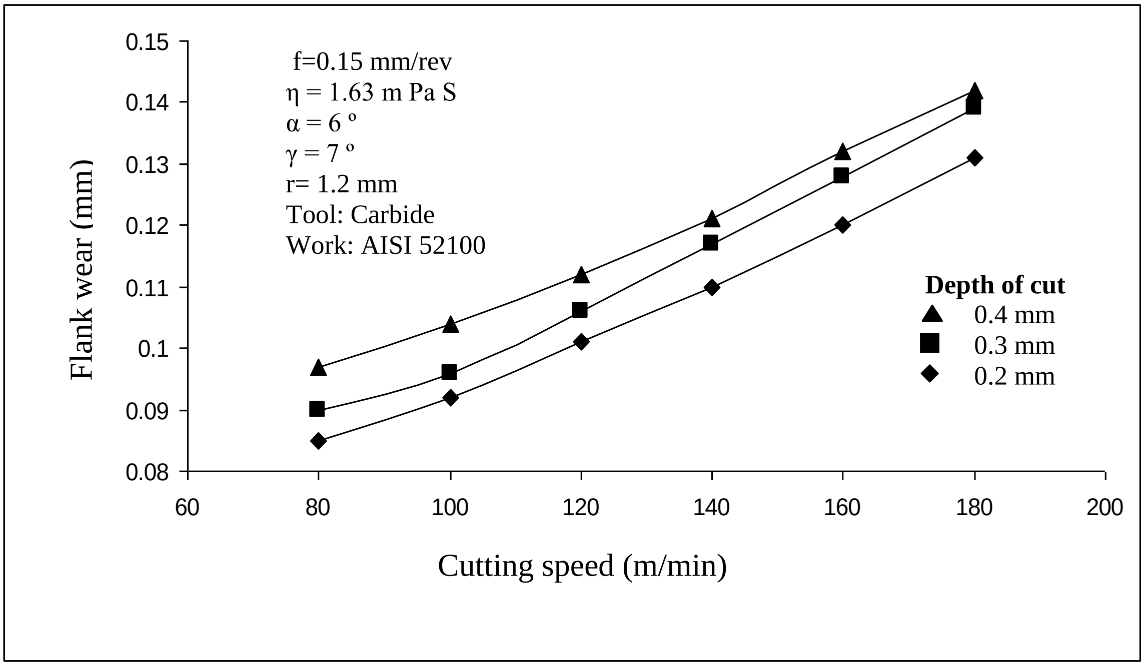

Figure 6: Flank wear Vs Cutting speed for various depth of cut

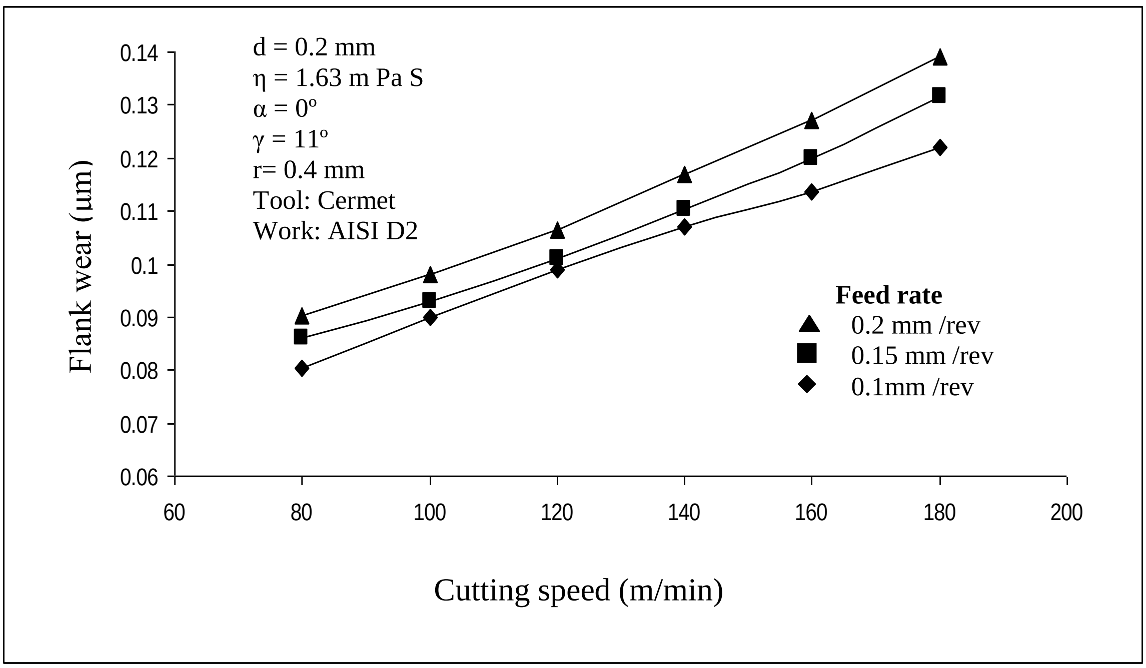

Figure 7: Flank wear Vs cutting speed for various feed rate

4.3 *Analysis on tool-shim interface temperature*

ANOVA for tool-shim interface temperature indicates that cutting speed, depth of cut, nose radius, variation in work material and type of cutting fluid have significant influence on tool-shim interface temperature. Figure 8 indicates the plot between the tool-shim interface temperature observed while machining each of the three work material and the cutting speeds. Since cutting speed greatly influences tool-shim interface temperature, it is varied from 80 to 180 m/min. This figure presents the experimental results obtained during machining of AISI D2, AISI 52100 and AISI 304 with alumina inserts with a constant feed rate: 0.15 mm/rev, depth of cut; 0.3 mm, rake angle: 6º, clearance angle: 7º, nose radius: 0.8 mm in the presence of soluble oil as cutting fluid. The temperature developed while machining AISI 304 is less when compared to the temperature developed while machining the other two materials because the hardness and tensile strength of AISI 304 is lesser than the other two materials. The temperature developed while machining AISI D2 and AISI 52100 is almost same for the cutting speeds between 100 and 140 m/min and for other cutting speeds the temperature developed while machining AISI 52100 is slightly more than that of AISI D2. This is because the hardness of both the materials are maintained at same level and the tensile strength of AISI 52100 is more than that of AISI D2.

Figure 9 indicates the plot between the tool-shim interface temperature observed while machining AISI 304 material using alumina inserts in the presence of three cutting fluids and the range of cutting speeds considered i.e. from 80 to 180 m/min. This figure presents the experimental results obtained during machining of AISI 304 using alumina inserts with a constant feed rate: 0.15 mm/rev, depth of cut; 0.2 mm between the tool and work piece and thus intensifying

rake angle: 0º, clearance angle: 11º, nose radius: 0.8 mm in the presence of all the cutting fluids. The temperature observed while machining in the presence of soluble oil is considerably less when compared to the temperature observed while machining in the presence of the other two cutting fluids for the entire range of cutting speeds considered. This is due to the presence of water content in soluble oil which would increase the rate of cooling. Further the cooling ability of coconut oil is in between the soluble oil and straight cutting oil because the viscosity of it lies between the two cutting fluids. The evaporation enthalpy of water, coconut oil and mineral oil is 2260 KJ/Kg, 431 KJ/Kg and 210 KJ/Kg correspondingly. The specific heat capacity for water, coconut oil and mineral oil is 4.2 KJ/Kg.K, 2.1 KJ/Kg.K. and 1.9 KJ/Kg.K. Since the evaporation enthalpy of water is very high, evaporation of even a very small quantity of water is sufficient to create significant cooling [11]. This is reason for soluble oil containing around 95% of water resulting in comparatively low temperature.

Figure 10 indicates the plot between the tool-shim interface temperature and cutting speeds for the variation in depth of cut. Cutting speed is varied form 80 m/min to 180 m/min and the depth of cut is varied as 0.2, 0.3 and 0.4 mm. For any cutting speed, lower temperature value is observed for a lesser depth of cut and as the depth of cut is increased the temperature also increases accordingly. This indicates that as the depth of cut is increased it results in larger contact surface between the part and the tool. Consequently more friction is induced between the tool and work piece which results in increase in temperature. For a cutting speed up to 120 m/min the increase in temperature is gradual for all the depth of cut considered. Beyond 120 m/min of cutting speed, there is a rapid increase in temperature for any depth of cut due to the combined effect of higher speed and more depth (larger contact surface area).

Figure 11 indicates the plot between the tool-shim interface temperature and cutting speeds for the variation in nose radius. Cutting speed is varied form 80 m/min to 180 m/min and the nose radius is varied as 0.4, 0.8 and 1.2 mm. This figure presents the experimental results obtained during machining of AISI D2 with carbide inserts with a constant feed rate: 0.15 mm/rev, rake angle: 18º, clearance angle: 0º, depth of cut: 1.2 mm in the presence of soluble oil as cutting fluid. From the figure it is evident that the temperature gradually increases with increase in cutting speed. For any cutting speed, lower temperature value is observed for a smaller nose radius and as the nose radius is increased the temperature also increases accordingly. This indicates that as the nose radius is increased the contact area between the tool and the work piece is increased which results in more friction and the temperature between the tool and work piece.

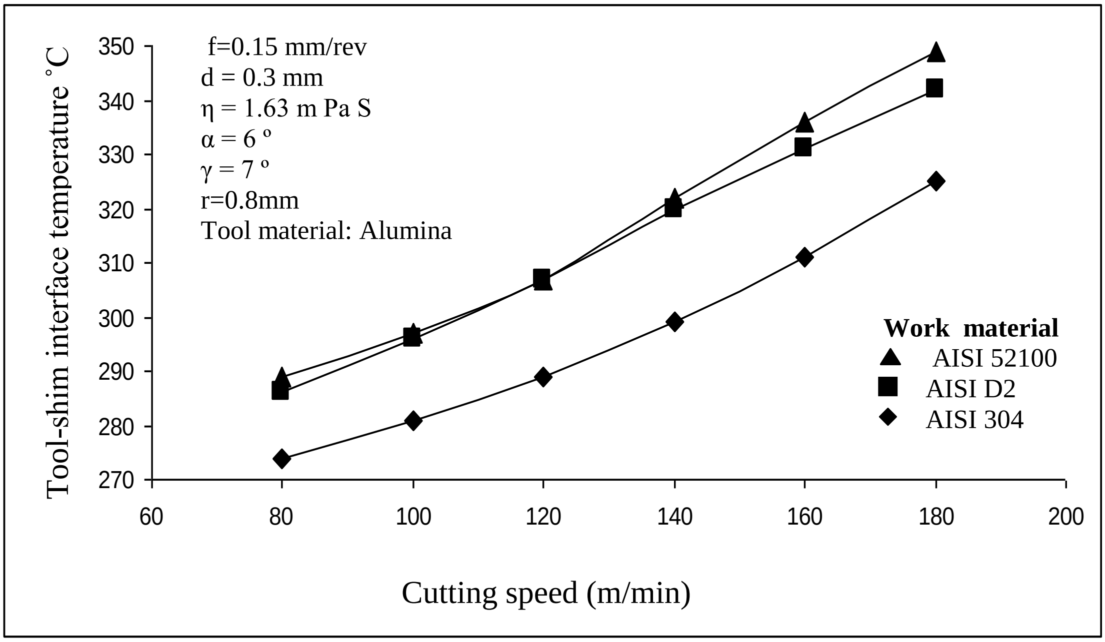

Figure 8: Tool-shim interface temperature Vs Cutting speed for various work materials

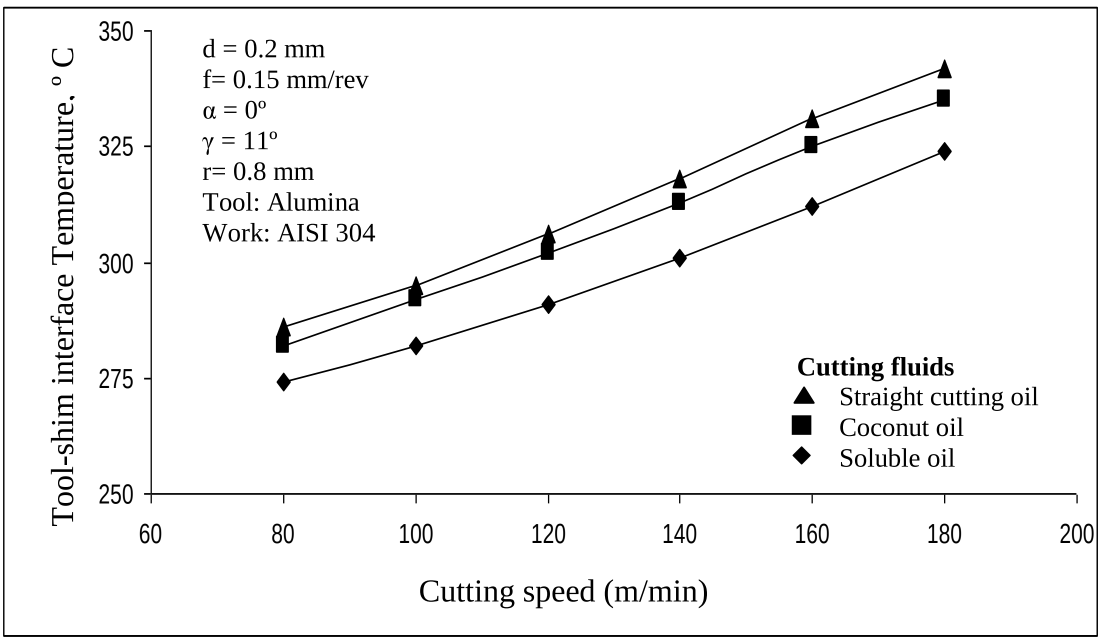

Figure 9: Tool-shim interface temperature Vs cutting speed for various cutting fluid

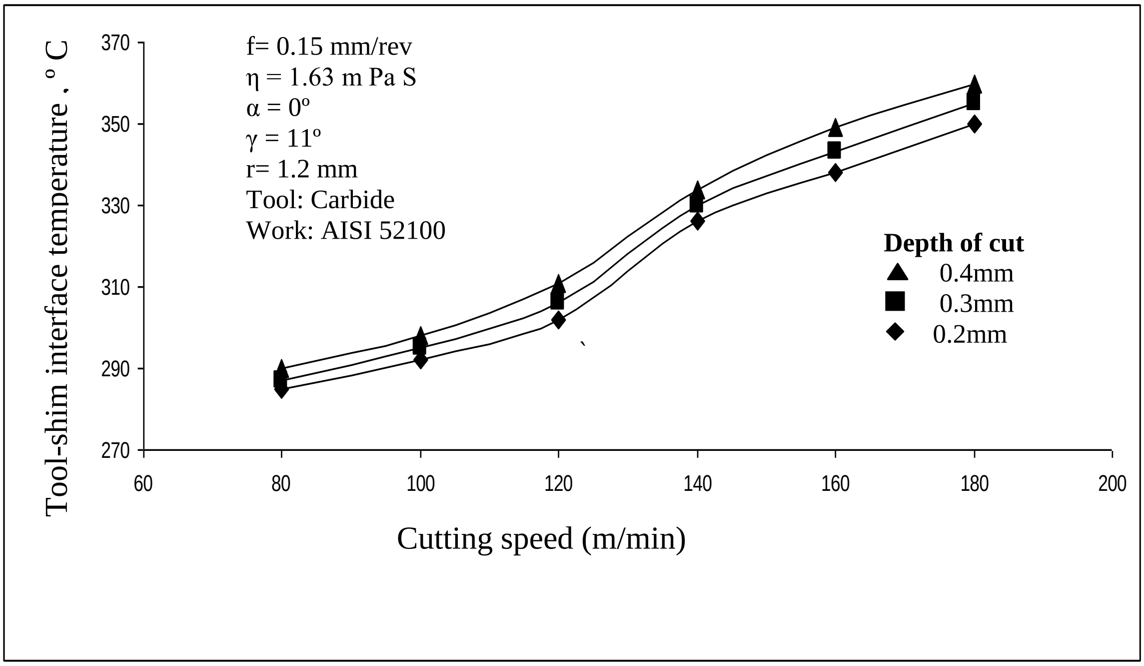

Figure 10: Tool-shim interface temperature Vs cutting speed for various depth of cut

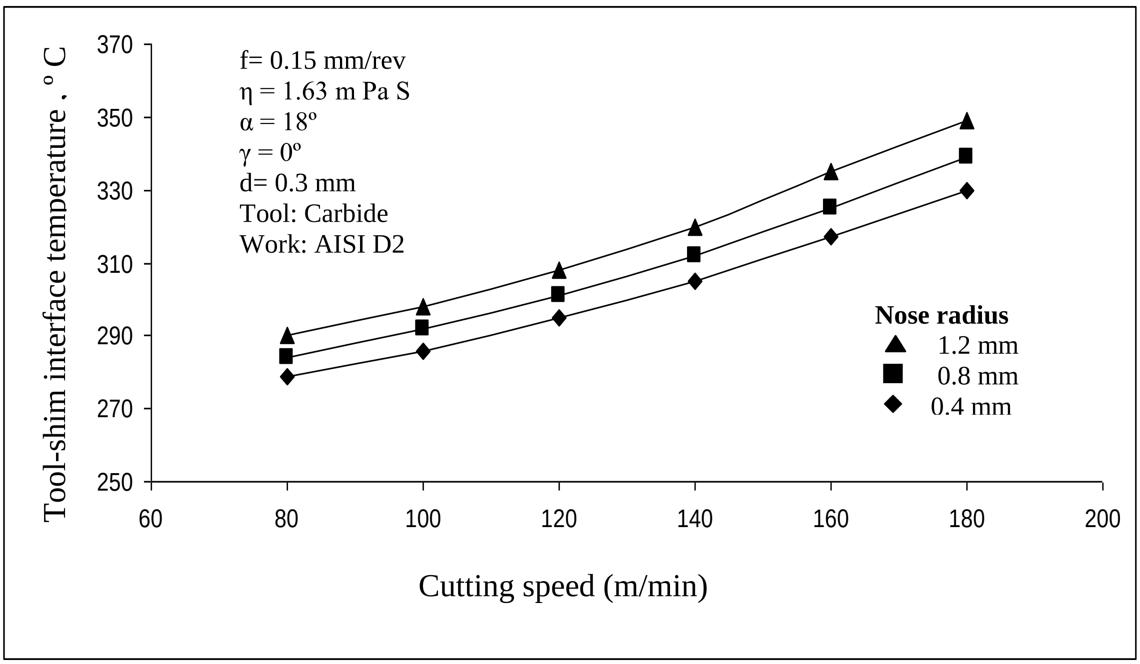

Figure 11: Tool-shim interface temperature Vs Cutting speed for various nose radius

5 Conclusions

Cutting speed is found to be the most significant parameters that influences flank wear and tool-shim interface temperature. Variation in work materials has considerable influence on both flank wear and tool-shim interface temperature. Nose radius and clearance angle have remarkable influence on surface roughness apart from the cutting parameters like cutting speed, feed rate and depth of cut. Cutting fluid is found to have influence only on temperature developed during the turning process. It should be emphasized that cutting speed, tool wear and temperature are closely interdependent during turning process, owing to the fact that a change in cutting speed involves a change in temperature and a heat diffusion within the tool probably causing variations of its mechanical characteristics vis-à-vis wear processes. As wear evolves with cutting times, it results in larger contact surfaces between the part and the tool, and the surface roughness also increases.

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