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Experimental Investigations on the Machinability of Aisi 304, Aisi 52100 and Aisi D2 Steel Materials

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Abstract: This paper explains the experimental investigations conducted on machining of hard – to – machine steel materials. AISI 52100 and AISI D2 steel of hardness 55 HRC were tested along with AISI 304 stainless steel. Multilayer coated carbides, cermets and alumina inserts of different tool geometries were experimented using three different levels of cutting speed, feed rate and depth of cut. To determine the influence of cutting fluids during machining, three classes of cutting fluids were used. Surface roughness, Flank wear, Temperature, Machining time and Metal removal rate are the output parameters considered. The influence of all the cutting (input) parameters on each of the output parameters is determined using the ANOVA technique. Generally, cutting speed, feed rate and depth of cut significantly affected all the output parameters. Graphical analysis of the variation of each of the output parameters with respect to the variation of the most significant cutting parameters has been done.

Key words: Machinability · Hard-to-machine steel · Tool Geometry

INTRODUCTION

Selection of cutting tools and the corresponding cutting conditions represent an essential element in process planning for machining. Such selection is normally done based on the experience of process planners utilizing data from machining handbooks and tool catalogues. Process planners still encounter problems due to the lack of performance data on the numerous new commercial cutting tools with different materials, coatings, geometry and chip-groove configurations for high wear resistance and effective chip breaking, etc. [1]. Many investigations have been performed on the turning process considering one or two materials at a time focusing on a few cutting parameters and recording two or three output parameters. The cutting parameters usually include cutting speed, feed rate and depth of cut. Only very few researchers have considered variations in cutting tool geometry, coating of inserts and cutting fluids for the experimentation. Only two or three of the output parameters like surface roughness, flank wear, tool life, cutting force, temperature, metal removal rate and machining time were investigated in most of the research work.

Arsecularatne *et al*. [2] experimentally investigated the machining of hard – to – cut material, AISI D2 steel of hardness 62 HRC with PCBN tools. They had considered only the cutting speed and feed rate as the turning (varying) parameters to measure flank wear on the tool. Davim and Luis [3] evaluated the machinability of AISI D2 at a hardness of 60 HRC with ceramic tools. A combined technique using orthogonal array and analysis of variance was employed to investigate the machinability. The machining parameters considered were cutting velocity, feed rate and cutting time to measure the flank wear, specific cutting pressure and surface roughness. Tool wear was reported to be greatly influenced by the cutting velocity; the surface roughness was influenced by feed rate and cutting time; feed rate strongly influenced the specific cutting pressure. Ozel *et al*. [4] investigated the surface finish and tool flank wear in finish turning of AISI D2 steel (60 HRC) using ceramic inserts. They employed three different cutting speeds and feed rates while maintaining a constant depth of cut for the experimentation. Ramon *et al*. [5] experimentally investigated hard machining of AISI D2 steel (60 HRC) with ceramic inserts. They used three different cutting speeds, feed rates and machining time while maintaining

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a constant depth of cut throughout the experiment to measure the tool wear. Lajis *et al*. [6] developed a tool life model in end milling of hardened steel AISI D2 (56 – 58 HRC) using PVD TiAlN – coated carbide cutting tool considering the input parameters of cutting speed, feed rate and depth of cut. Kishawy and Elbestawi [7] investigated the surface integrity of AISI D2 steel of 62 HRC machined with PCBN tools at high speeds. Cutting speeds used were in the range of 140 – 500 m/min, with feed rates of 0.05 – 0.2 mm/rev. and depth of cut 0.2 – 0.6 mm. At cutting speed above 350 m/min, the surface roughness was reported to increase with increase in tool wear. Lima *et al*. [8] presented results for hard turning of AISI D2 tool steel (58 HRC) using mixed alumina ceramic inserts with conventional nose radius geometry and achieved surface finishes equal to that produced by cylindrical grinding.

Qian *et al*. [9] compared cutting forces, temperature and residual stress in hard turning of AISI 52100 with CBN, TiAlN – coated carbide and ceramic turning inserts. Jeffrey *et al*. [10] investigated the effect of cutting edge geometry and workpiece hardness on surface roughness in the finish hard turning of AISI 52100 steel. Three different levels of hardness of workpiece, feed rate and cutting edge geometry were considered while maintaining cutting speed and feed rate at constant during the experimentation. Cutting edge geometry was reported to have a significant effect on surface generation in hard turning. Ozel and Karpat [11] developed a predictive modeling of surface roughness and tool wear in hard turning using regression and neural networks. Experiments were conducted by varying the cutting speed, feed rate, tool geometry and hardness maintaining depth of cut (0.254 mm) at a constant. Anderson *et al*. [12] developed a multivariate hybrid approach to optimize the turning process of AISI 52100 hardened steel (55 HRC). Cutting speed, feed rate and depth of cut were the three input factors considered for experimentation. The output factors considered were tool life, processing cost per piece, cutting time, total turning cycle time, surface roughness and metal removal rate. The results indicate that the multi-response optimization is achieved at a cutting speed of 238 m/min with a feed rate of 0.08 mm/rev and depth of cut of 0.32 mm. Attanasio *et al*. [13] conducted experiments to compare minimum quantity lubrication and dry cutting technique in turning 100 Cr6 normalized bearing steel. Triple coated carbide tip (TiN Al2O3 TiCN) was used and experiments were performed by varying the feed rate and cutting length while maintaining the cutting speed, depth of cut and entering angle at constant. Zhou *et al*. [14] investigated the effect of tool chamfer angle on cutting forces, tool flank wear and tool life when turning AISI 52100 steel of hardness 60 – 62 HRC. Testing was done at a depth of cut of 0.05 mm, feed rate of 0.05 mm/rev. and cutting speed of 160 m/min.

AISI 304 is generally regarded as a more – difficult – to machine steel on account of its high strength, high work hardening tendency and poor thermal conductivity [15]. AISI 304 possesses properties such as low thermal conductivity and high ductility which pose some difficulties in machining and are classified as poor machinability materials [16]. Anthony and Adithan [17] had investigated the performance of carbide inserts on machining of AISI 304 austenitic steel to determine the influencing factors of surface roughness and tool wear. It was reported that cutting speed and feed rate had remarkable influence on surface roughness and tool wear. Ihsan *et al*. [18] identified the optimum cutting parameters while machining AISI 304 austenitic steel. Tool wear was reported to decrease with increase in cutting speed up to 180 m/min., while surface roughness decreased with increase in the cutting speed. Multilayer coated cemented carbide cutting inserts were used. Feed rate and depth of cut were maintained at constant, while varying the cutting speed at 120, 150 and 180 m/min. Belluco and Chiffre [19] evaluated the performance of vegetable – based oils in drilling austenitic stainless steel. A commercial mineral based oil was used as the reference cutting fluid and five vegetable – based cutting oils at different levels of additivation were tested. All vegetable – based fluids reportedly performed better than the reference product in terms of increasing the tool life and reducing the thrust force. Ibrahim [20] performed experiments on machining of austenitic stainless steels using CVD multilayer coated cemented carbide tools. Turning tests were conducted at four different cutting speeds, while maintaining the feed rate and depth of cut at constant. The influence of cutting speed, cutting tool coating top layer and workpiece material on the machined surface roughness and cutting forces were investigated.

The large number of experiments necessary to establish an adequate functional relationship between the observed responses and the cutting parameters invariably makes the experimentation cost prohibitive. However, the current study considers the simultaneous variation of nine factors for experimentation and investigates their influence on five output factors. Design of experiments (DOE) methodology was adopted involving planning experiments to generate appropriate data for efficient statistical analysis, which in turn produces valid and objective conclusions [21].

Table 1: Chemical composition of the work materials

S. No	Element	AISI 52100 (Bearing Steel)	AISI D2 (Tool Steel)	AISI304 (Stainless Steel)
1	C	0.96	1.64	0.055
2	Si	0.20	0.29	0.64
3	Mn	0.43	0.4	1.66
4	P	0.012	0.014	-
5	S	0.007	0.003	-
6	Cr	1.48	11.4	18.2
7	Mo	0.052	0.73	0.092
8	Ni	0.10	0.26	9.11
9	V	-	0.95	0.046
10	W	-	0.15	0.048
11	Ti	-	0.005	0.006
12	Pb	-	0.001	0.015
13	Al	0.003	0.029	-
14	Cu	0.30	0.14	0.14

Table 2: Mechanical properties of the work materials

S. No	Characteristics	AISI 52100	AISI D2	AISI304
1	Density (kg/m^3)	7827	7770	7930
2	Poisson's ratio	0.277	0.285	0.285
3	Elastic Modulus (G Pa)	201.33	200	193
4	Tensile strength (M Pa)	2240	1736	586
5	Yield Strength (M Pa)	2030	1532	241
6	Hardness (HRC)	55	55	20

Nomenclature:

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 (ìm)
θ - Temperature (°C)
t - Machining time (sec.)
MRR - Metal Removal Rate (mm^3/min.)

Experimentation: Three work materials were considered for the experimentation viz. AISI 52100, AISI D2 and AISI 304. The chemical composition and the mechanical properties of the work materials are presented in Table 1 and 2 respectively.

Three different cutting tools namely carbide, cermet and alumina inserts of various combination of tool geometry are used. The insert type, description and grade, the tool holder recommended are listed in Table 3. Fig. 1 shows the tool inserts and their corresponding tool holders.

Fig. 2 indicates the turning process which presents the controllable input parameters and the measurable output parameters. 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 4. 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 (shown in Fig. 3) 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 was 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 was measured using Mitutoyo Surface Roughness tester. Temperature developed during the machining process was measured by a thermocouple, Iron - Constantan (J-Type) Tool Tip type with a temperature range of 30 - 400°C, with sensitivity of ±0.1°C. Metal removal rate was calculated using the standard formula shown in equation 1.

Fig. 1: Tool inserts and Tool holders

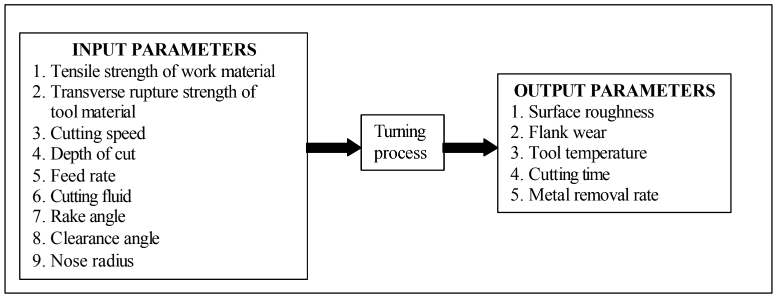

Fig. 2: Schematic diagram of the turning process

Fig. 3: CNC Machine tool used in the experimentation with the display panel

Table 3: Tool insert specifications and the corresponding tool holders

	Tool Insert Type,	Grade and	Description	
S.No	Carbide, TT1500 TiN-TiCN-AL2O3-TiN	Cermet, PV 3010 TiN COATED	Alumina, AB30 AL2O3-TiC	Tool Holders
1	TNMG 160404	TNMG 160404	TNGA 160404	TTJNR 2525 M16
2	TNMG 160408	TNMG 160408	TNGA 160408	TTJNR 2525 M16
3	TNMG 160412	TNMG 160412	TNGA 160412	TTJNR 2525 M16
4	TPUN 110304	TPGN 110304	TPGN 110304	CTFPR 2020 K11
5	TPUN 110308	TPGN 110308	TPGN 110308	CTFPR 2020 K11
6	TPUN 110312	TPGN 110312	TPGN 110312	CTFPR 2020 K11
7	CCMT 09T304	CCMT 09T304	CCMT 09T304	SCLCR 2525 M09
8	CCMT 09T308	CCMT 09T308	CCMT 09T308	SCLCR 2525 M09
9	CCMT 09T312	CCMT 09T312	CCMT 09T312	SCLCR 2525 M09

Table 4: 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 5: Experimental plan and observation

S.No	Vc	f	d	t_s	t_{rs}	η	A	γ	r	Vb	Ra	θ	t	MRR
1	100	0.1	0.2	586	1400	26.8	6	0	0.4	0.082	1.65	278	181	1996
2	100	0.1	0.2	586	1700	1.63	18	7	0.8	0.073	1.57	289	179	2006
3	100	0.1	0.2	586	700	45.7	0	11	1.2	0.067	1.40	300	178	2004
4	100	0.15	0.3	1736	1400	26.8	18	7	0.8	0.105	1.72	290	121	4490
5	100	0.15	0.3	1736	1700	1.63	0	11	1.2	0.096	1.61	298	120	4494
6	100	0.15	0.3	1736	700	45.7	6	0	0.4	0.088	1.84	285	118	4497
7	100	0.2	0.4	2240	1400	26.8	0	11	1.2	0.115	1.70	307	91	7982
8	100	0.2	0.4	2240	1700	1.63	6	0	0.4	0.106	1.92	296	89	8015
9	100	0.2	0.4	2240	700	45.7	18	7	0.8	0.100	1.81	311	88	7984
10	140	0.1	0.3	2240	1400	1.63	6	7	1.2	0.126	1.65	320	129	4192
11	140	0.1	0.3	2240	1700	45.7	18	11	0.4	0.120	1.68	310	128	4197
12	140	0.1	0.3	2240	700	26.8	0	0	0.8	0.111	1.70	318	126	4197
13	140	0.15	0.4	586	1400	1.63	18	11	0.4	0.130	1.78	311	86	8383
14	140	0.15	0.4	586	1700	45.7	0	0	0.8	0.125	1.82	319	85	8412
15	140	0.15	0.4	586	700	26.8	6	7	1.2	0.118	1.75	308	83	8383
16	140	0.2	0.2	1736	1400	1.63	0	0	0.8	0.131	1.91	315	65	5588
17	140	0.2	0.2	1736	1700	45.7	6	7	1.2	0.122	1.88	330	64	5620
18	140	0.2	0.2	1736	700	26.8	18	11	0.4	0.115	1.93	309	63	5609
19	180	0.1	0.4	1736	1400	45.7	6	11	0.8	0.137	1.69	345	101	7186
20	180	0.1	0.4	1736	1700	26.8	18	0	1.2	0.130	1.71	330	99	7209
21	180	0.1	0.4	1736	700	1.63	0	7	0.4	0.124	1.80	328	97	7186
22	180	0.15	0.2	2240	1400	45.7	18	0	1.2	0.132	1.81	360	67	5390
23	180	0.15	0.2	2240	1700	26.8	0	7	0.4	0.126	1.92	338	66	5416
24	180	0.15	0.2	2240	700	1.63	6	11	0.8	0.120	1.79	350	66	5394
25	180	0.2	0.3	586	1400	45.7	0	7	0.4	0.134	2.06	318	50	10780
26	180	0.2	0.3	586	1700	26.8	6	11	0.8	0.129	1.98	325	50	10788
27	180	0.2	0.3	586	700	1.63	18	0	1.2	0.125	1.95	334	49	10801

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 (ìm), θ: Temperature (?C), t: machining time (Sec.), MRR: Metal Removal Rate (mm^3/min.)

$$MRR = \pi DNfd \ (mm^3/min.) \quad (1)$$

where D is the diameter of the workpiece, N is the spindle speed in rpm, f is the feed rate in mm/ rev. and d is the depth of cut in mm. The actual machining time was observed from the machine display for every trial. The experimental plan and the corresponding observation made are presented in Table 5.

ANOVA: Analysis of variance has been performed to estimate the actual influence of each input parameter on each of the output parameter. Tables 6, 7, 8, 9 and 10 indicate the ANOVA for flank wear, surface roughness, temperature, machining time and metal removal rate. Although, the metal removal rate is calculated using equation 1, ANOVA is performed to determine the influencing parameters. Reportedly the depth of cut, feed rate and cutting speed has a significant effect on metal removal rate. Table 11 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.

Mathematical Modeling: Multiple linear regression models were developed for flank wear, surface roughness, temperature, machining time and metal removal rate using Minitab15 software. The response variables (output parameters) are flank wear, surface roughness, temperature, machining time and metal removal rate whereas the predictors (input parameters) are cutting speed, feed rate, depth of cut, tensile strength of work materials, transverse rupture strength of the tool materials, viscosity of the cutting fluids, rake angle, clearance angle and nose radius. The viscosity of each cutting fluid at 40°C was considered for the mathematical modeling. Accordingly the equations of the fitted model for various output parameters are given below.

Table 6: ANOVA for Flank Wear

S.No	Factors	DOF	Sum of Squares	Mean Squares	Variance Ratio	% Contribution
1	Cutting speed	2	2.22	1.11	18893.62	71.75
2	Feed rate	2	0.22	0.11	1872.34	7.15
3	Depth of cut	2	0.25	0.13	2127.66	8.09
4	Work material	2	0.12	0.06	1021.28	3.88
5	Tool material	2	0.28	0.14	2382.98	9.06
6	Cutting fluid	2	8.98×10^{-4}	4.49×10^{-4}	7.64	0.03
7	Rake angle	2	8.41×10^{-5}	4.21×10^{-5}	0.72	0.005
8	Clearance angle	2	8.41×10^{-5}	4.21×10^{-5}	0.72	0.005
9	Nose radius	2	8.98×10^{-4}	4.49×10^{-4}	7.64	0.03
	Total	18	3.092			
	Error	8	0.00047	5.88×10^{-5}		

Table 7: ANOVA for Surface Roughness

S.No	Factors	DOF	Sum of Squares	Mean Squares	Variance Ratio	% Contribution
1	Cutting speed	2	0.0415	0.02075	12.73	23.39
2	Feed rate	2	0.0970	0.04850	29.75	54.68
3	Depth of cut	2	0.0021	0.00105	0.64	1.18
4	Work material	2	0.0004	0.00020	0.12	0.23
5	Tool material	2	0.0004	0.00020	0.12	0.23
6	Cutting fluid	2	0.0001	0.00005	0.03	0.06
7	Rake angle	2	0.0011	0.00055	0.34	0.62
8	Clearance angle	2	0.0116	0.00580	3.56	6.54
9	Nose radius	2	0.0232	0.01160	7.12	13.07
	Total	18	0.1774			
	Error	8	0.013	0.00163		

Table 8: ANOVA for Tool Temperature

S.No	Factors	DOF	Sum of Squares	Mean Squares	Variance ratio	% Contribution
1	Cutting speed	2	2589.63	1294.82	39.78	75.71
2	Feed rate	2	32.23	16.12	0.50	0.95
3	Depth of cut	2	104.76	52.38	1.61	3.06
4	Work material	2	309.65	154.83	4.76	9.05
5	Tool material	2	1.8	0.90	0.03	0.05
6	Cutting fluid	2	104.34	52.17	1.60	3.05
7	Rake angle	2	0.92	0.46	0.01	0.03
8	Clearance angle	2	11.04	5.52	0.17	0.32
9	Nose radius	2	266.07	133.04	4.09	7.78
	Total	18	3420.44			
	Error	8	260.43	32.55		

Table 9: ANOVA for Machining Time

S.No	Factors	DOF	Sum of Squares	Mean Squares	Variance ratio	% Contribution
1	Cutting speed	2	5148.70	2574.35	24.78	32.72
2	Feed rate	2	7121.29	3560.65	34.27	45.25
3	Depth of cut	2	3246.04	1623.02	15.62	20.63
4	Work material	2	209.38	104.69	1.01	1.33
5	Tool material	2	9.8376	4.92	0.05	0.06
6	Cutting fluid	2	0.0243	0.01	0.0001	0.0014
7	Rake angle	2	0.1695	0.08	0.0008	0.0021
8	Clearance angle	2	0.6954	0.35	0.0034	0.0044
9	Nose radius	2	0.1695	0.08	0.0008	0.0021
	Total	18	15736.31			
	Error	8	831.14	103.89		

Table 10: ANOVA for Metal Removal Rate

S.No	Factors	DOF	Sum of Squares	Mean Squares	Variance Ratio	% Contribution
1	Cutting speed	2	13306440.17	6653220.09	12.92	25.76
2	Feed rate	2	20240314.77	10120157.38	19.65	38.28
3	Depth of cut	2	18941000.91	9470500.46	18.39	35.94
4	Work material	2	3128501.43	1564250.72	3.04	0.018
5	Tool material	2	542.32	271.16	5.2×10^{-4}	0.0017
6	Cutting fluid	2	2.99	1.49	2.9×10^{-6}	0.55×10^{-5}
7	Rake angle	2	3.06	1.53	2.9×10^{-6}	0.55×10^{-5}
8	Clearance angle	2	90.47	45.23	8.8×10^{-5}	24×10^{-5}
9	Nose radius	2	25.58	12.79	2.5×10^{-5}	4.9×10^{-5}
	Total	18	55616921.7			
	Error	8	4119835.67	514979.46		

Table 11: Percentage influence of all input parameters on each output parameter

	Output Parameters				
Input Parameters	Surface roughness	Flank wear	Tool temperature	Machining time	Metal Removal rate
Cutting speed	23.39	71.75	75.71	32.72	25.76
Feed rate	54.68	7.15	0.95	45.25	38.28
Depth of cut	1.18	8.09	3.06	20.63	35.94
Work material	0.23	3.88	9.05	1.33	0.018
Tool material	0.23	9.06	0.05	0.06	0.0017
Cutting fluid	0.06	0.03	3.05	0.0014	0.55×10^{-5}
Rake angle	0.62	0.005	0.03	0.0021	0.55×10^{-5}
Clearance angle	6.54	0.005	0.32	0.0044	24×10^{-5}
Nose radius	13.07	0.03	7.78	0.0021	4.9×10^{-5}

(Figures in this table indicate the percentage values)

$$Ra = 1.23 + 0.00207\ Vc + 2.54\ f + 0.0667\ d + 0.000003\ t_s + 0.000011\ t_{rs} + 0.000043\ \eta - 0.000040\ \alpha - 0.00699\ \gamma - 0.156\ r$$

$$Vb = -0.0056 + 0.000451\ Vc + 0.119\ f + 0.0650\ d + 0.000005\ t_s + 0.000009\ t_{rs} - 0.000014\ \eta + 0.000008\ \alpha - 0.000013\ \gamma + 0.00083\ r$$

$$\theta = 214 + 0.519\ Vc + 30\ f - 7.8\ d + 0.00792\ t_s - 0.00070\ t_{rs} + 0.0792\ \eta + 0.025\ \alpha + 0.174\ \gamma + 15.8\ r$$

$$t = 326 - 0.722\ Vc - 677\ f - 61.1\ d - 0.00661\ t_s + 0.00174\ t_{rs} - 0.0024\ \eta + 0.009\ \alpha + 0.032\ \gamma + 0.28\ r$$

$$MRR = -8542 + 37.1\ Vc + 36660\ f + 17621\ d - 0.794\ t_s + 0.007\ t_{rs} + 0.03\ \eta + 0.1\ \alpha - 0.7\ \gamma - 1r$$

After omitting the parameters with negligible coefficients the equations can be rewritten as follows.

$$Ra = 1.23 + 0.00207\ Vc + 2.54\ f + 0.0667\ d - 0.00699\ \gamma - 0.156\ r$$

$$Vb = -0.0056 + 0.000451\ Vc + 0.119\ f + 0.0650\ d$$

$$\theta = 214 + 0.519\ Vc + 30\ f - 7.8\ d + 15.8\ r$$

$$t = 326 - 0.722\ Vc - 677\ f - 61.1\ d$$

$$MRR = -8542 + 37.1\ Vc + 36660\ f + 17621\ d$$

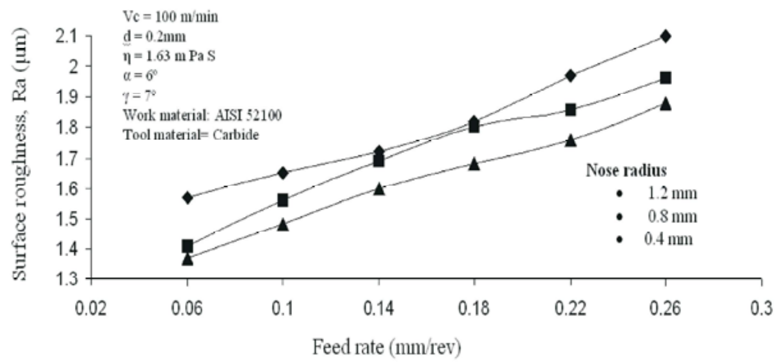

Fig. 4: Surface roughness Vs Feed rate for various nose radius

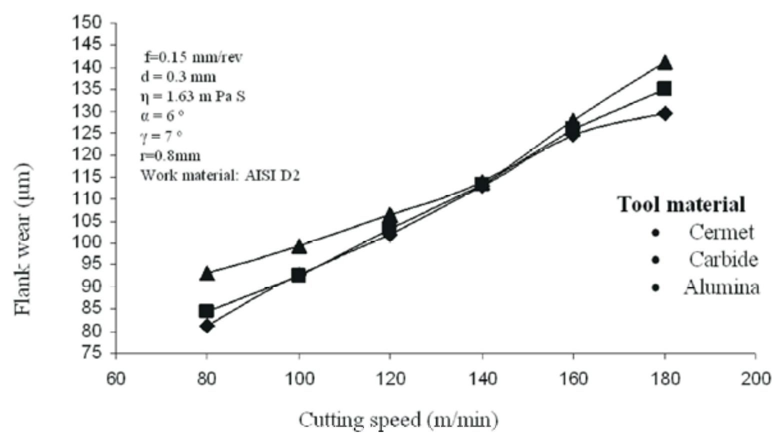

Fig. 5: Flank wear Vs Cutting speed for various tool materials

RESULTS AND DISCUSSION

The actual influence of the cutting parameters on each of the output parameters is obtained from ANOVA. Based on the information further experimentation was carried out by varying the most significant parameters and maintaining the other parameters at constant. From the experimental values detailed graphical analyses are performed. Experiments are conducted on AISI 52100 with carbide tools by maintaining constant cutting conditions such as rake angle, clearance angle, depth of cut, cutting speed and soluble oil as the cutting fluid. Although, cutting speed, feed rate, clearance angle and nose radius have significant effect on surface roughness, the response of variation in feed rate and nose radius alone is considered. 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. Fig. 4 indicates the plot between the surface roughness and feed rate for various tool nose radii. 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.

Experiments are conducted on AISI D2 material by maintaining cutting conditions such as feed rate, depth of cut, rake angle, clearance angle, nose radius and soluble oil as cutting fluid constant. Since cutting speed greatly influences tool wear, it is varied from 80 to 180 m/min. Three sets of observations are made (each set with one type of cutting tool) using cermet, carbide and alumina inserts respectively. Fig. 5 presents the plot between tool wear and cutting speed for various tool materials. From the graph it is evident that the tool wear gradually increases with increase in cutting speed irrespective of the tool material. All the three cutting inserts wear at a uniform rate between the cutting speed range of 120 to 160 m/min. As the cutting speed increases, cermet wears faster than the carbide and alumina inserts. Alumina inserts performs better than cermet and carbide inserts with respect to wear resistance for the entire range of cutting speeds

Further it has been found that cutting speed has more influence on temperature, so experiments are performed by varying the cutting speed from 80 to 180 m/min while maintaining other parameters constant. Three sets of experiments are conducted on three different materials

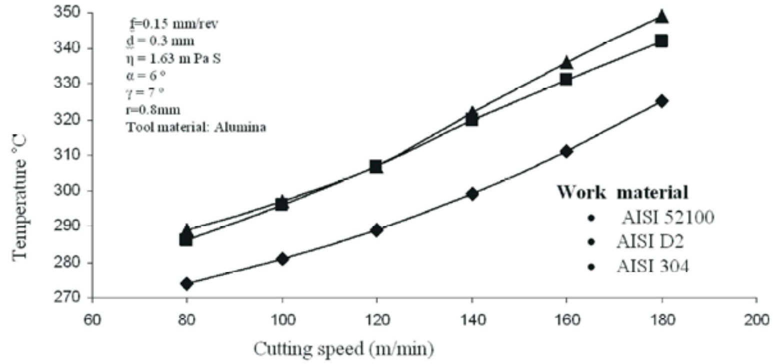

Fig. 6: Temperature Vs Cutting speed for various work materials

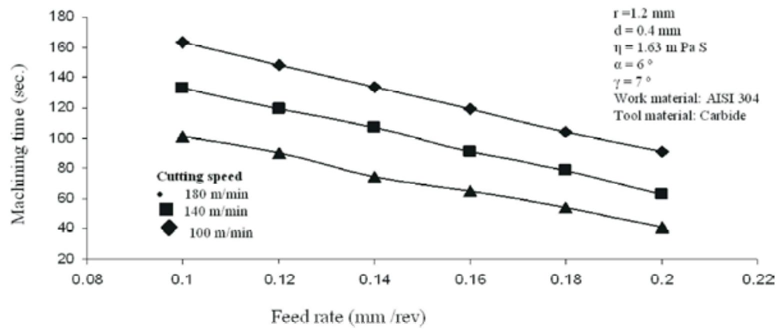

Fig. 7: Machining time Vs Feed rate for various cutting speed

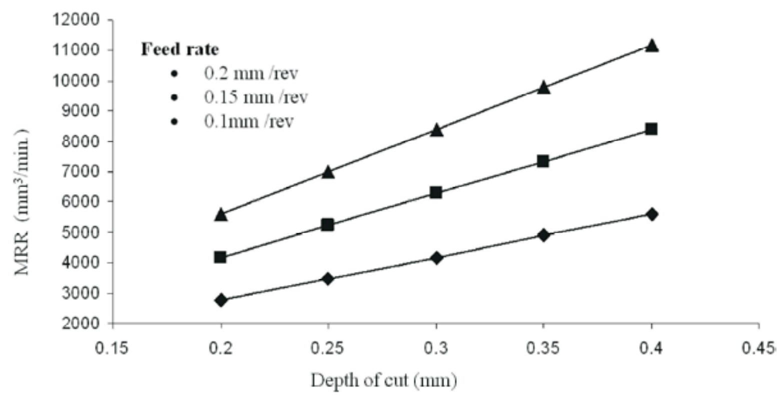

Fig. 8: MRR Vs Depth of cut for various feed rate

using alumina inserts. Feed rate, depth of cut, rake angle, clearance angle, nose radius and cutting fluid are maintained constant for all the trials. Fig. 6 indicates the plot between cutting speed and temperature for the three work materials. It is observed that the temperature rose during machining of AISI 52100 and AISI D2 are almost close to each other, but the temperature that developed during machining of AISI 304 is quite low as compared to the other two materials. As the cutting speed increases the temperature also increases gradually for all the materials. From ANOVA the feed rate and cutting speed evidently show a significant effect on machining time. Thus experiments are conducted by varying the feed rate from 0.1 to 0.2 mm/rev for three cutting speeds, viz. 100, 140 and 180 m/min. Machining trials are performed on AISI 304 using carbide tool by maintaining depth of cut, rake angle, clearance angle, nose radius and cutting fluid a constant. Fig. 7 presents the plot between machining time and feed rate for varying cutting speed. As the feed rate increases, the actual machining time decreases. For any cutting speed there is a decreasing trend of machining time as the feed rate is increased. It is also observed that as the cutting speed is increased from 100 to 180 m/min there is a drastic reduction in machining time. Lowest machining time is achieved for the highest feed rate and cutting speed.

Although, the metal removal rate is calculated using the formula, depth of cut, feed rate and cutting speed are observed to have significant effect on metal removal rate. Three sets of calculations are made by utilizing three feed rates viz. 0.1, 0.15 and 0.2 mm/rev. For each feed rate the depth of cut is varied as 0.2, 0.25, 0.3, 0.35 and 0.4 mm. Fig. 8 indicate the plot between metal removal rate and depth of cut for varying feed rates. As the depth of cut increases a steady increase in metal removal rate is observed and when the feed rate is increased the rate of increase is quite high. There is a drastic increase in metal removal rate at the highest feed rate and depth of cut when compared to the lowest feed rate and depth of cut.

CONCLUSION

Experimental investigations were conducted by considering nine cutting parameters as input variables which include variation in work material, tool material, cutting fluid, cutting speed, feed rate, depth of cut, clearance angle, rake angle and nose radius. ANOVA was performed to identify the influence of all the input parameters on output variables like surface roughness, flank wear, temperature, machining time and metal removal rate. Based on the ANOVA, graphical analysis was performed to correlate the output parameter with the most significant input parameters. Generally, cutting speed, feed rate and depth of cut show a significant effect on all the output parameters. Variations in work material considerably affect all the output parameters except for surface roughness. Tool material variations exhibit a reasonable influence on flank wear only. The wear rate varies for the tool materials at cutting speeds between 80 and 100 m/min and also between 160 and 180 m/min. But the wear rate was almost uniform for all the three cutting tool materials between cutting speed ranges of 120 and 160 m/min. Clearance angle and nose radius have 6.54% and 13.07% influence on surface roughness correspondingly. As the nose radius was increased from 0.4 to 1.2 mm surface roughness decreased for all the feed rates. Nose radius has 7.78% influence on the temperature developed during machining. The temperature developed during machining of AISI 52100 and AISI D2 is almost the same and higher than the temperature developed during machining of AISI 304. Concerning machining time and MRR machining time decreases when cutting speed, feed rate and depth of cut are increased, while MRR increases as the cutting parameters are increased.

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