Available online at www.sciencedirect.com

ScienceDirect

Procedia Materials Science 6 (2014) 80 – 91

Procedia Materials Science

www.elsevier.com/locate/procedia

3rd International Conference on Materials Processing and Characterisation (ICMPC 2014)

Machinability Assessment through Experimental Investigation during Hard and Soft Turning of Hardened Steel

Awadhesh Pal[a],*, S.K. Choudhury[b],SatishChinchanikar[c]

[a]*Research scholar, Department of Mechanical Engineering, Indian Institute of Technology Kanpur, 208016, India*

[b]*Professor, Department of Mechanical Engineering, Indian Institute of Technology Kanpur, 208016, India*

[c]*Workshop Superintendent, Vishwakarma Institute of Information Technology, Pune-411048, India*

Abstract

In this study, experimental investigations were carried out to assess the machinability of hardened AISI 4340 steel during hard (55 HRC) and soft turning (35 and 45 HRC) using TiC mixed alumina ceramic tools. Mathematical models, which can predict the machining performances, namely, chip-tool interface temperature, cutting forces and surface roughness were developed based on experimental observations. Effect of workpiece hardness and cutting parameters, namely, cutting speed, depth of cut and feed on different responses were analyzed by performing ANOVA technique. Experimental observations indicate higher cutting forces, higher chip-tool interface temperature and lower values of surface roughness for harder workpiece. Feed value has been observed to have more prominent effect on surface roughness. However, the average chip-tool interface temperature has been observed to get more influenced with cutting speed and depth of cut. On the other hand, cutting forces, especially radial component of force which was largest in magnitude amongst the tangential and feed cutting forces, has been observed to get more affected with depth of cut followed by feed value.

Selection and peer review under responsibility of the Gokaraju Rangaraju Institute of Engineering and Technology (GRIET)

*Keywords:*Hard and soft turning; Chip-tool interface temperature; Cutting forces; Surface roughness; ANOVA.

1. Introduction

In recent years, with continuous development in cutting tool materials and cutting tool technology, it has become possible to machine harder materials having hardness up-to 70 HRC conventionally. Today, machining of workpiece material having hardness up-to 45 HRC is treated as soft machining. On the other hand, machining of workpiece having hardness in the range of 45-70 HRC is considered under hard machining.

* *Corresponding author*. Tel.: +91-8765675373; Fax: +91- 020- 26932500.
*E-mail address:*awadheshpal89@gmail.com

Selection and peer review under responsibility of the Gokaraju Rangaraju Institute of Engineering and Technology (GRIET)
doi:10.1016/j.mspro.2014.07.010

From last decade, hard turning is widely used in roller bearing, hydraulic, die, automotive and mold industries. A group of researchers carried out turning of hardened steel at different levels of hardness in view of evaluating the effect of workpiece hardness and cutting parameters on machining performances (Lima et al., 2005; Chinchanikar and Choudhury, 2013a; Luo et al., 1999). Chinchanikar and Choudhury(2013b) observed that higher cutting forces are employed during turning of harder workpiece with multi-layer coated carbide tool. In the same study, authors pointed out that abrasion is the dominant tool wear mechanism for harder workpiece and adhesion wear when turning softer workpiece with TiCN/Al_2O_3/TiN coated carbide tool. Determination of the temperature distribution and maximum temperature along the rake face of the cutting tool is also of particular importance, especially in hard turning because of its governing influence on quality of the machined part as well as tool life. Chinchanikar et al. (2013) observed that the average chip-tool interface temperature is predominantly affected with workpiece hardness and cutting speed. However, they reported that depth of cut has negligible influence on interface temperature.

Generally, temperature measurement techniques in metal cutting comprise of tool-work thermocouples, embedded thermocouples, radiation pyrometers and metallographic techniques (Grzesik, 2008). However, thermocouples have always been a popular and widely used technique. Embedded thermocouple measures the temperature along the tool rake face at the points where they are seated and inserted into the cutting inserts. However, they reduce the strength of the tool and restrict the heat flow. Moreover, it is difficult to drill holes in hard tool materials such as ceramics. Non-contact thermographic methods are also widely used for measuring the temperature. However, exact surface emissivity of the tool and workpiece surface should be known, as measured temperature is strongly affected by this factor.

Liu et al. (2002) studied the performance of PCBN tools during finish turning of bearing steel at different levels of hardness between 30 to 64 HRC. They observed that the cutting temperature increases with increase in workpiece hardness up-to 50 HRC. However, Temperature showed decreasing tendency with further increase in the workpiece hardness beyond 50 HRC. Korkut et al. (2007) study of analysis concluded that the cutting speed and depth of cut are dominant factors relative to feed rate on the chip back surface temperature. Senthilkumar and Tamizharasan(2012) found the relation between the interface temperature and flank wear by using taguchi technique during machining of the wheel axle of the ambassador car for different levels of hardness. Abhang and Hameedullah(2010) experimentally investigated the tool-chip interface temperature during turning of EN-31 alloy steel with tungsten carbide inserts employing a tool-work thermocouple technique. They found that the cutting speed as the main effecting factor on chip-tool interface temperature as compared to other factors.

Although, sufficient work has been reported on machinability of hardened AISI 4340 steel during turning, machining performance in terms of chip-tool interface temperature, cutting forces and surface roughness during hard and soft turning using TiC mixed alumina ceramic tools is rarely reported. Moreover, correlations developed based on experimental observations between different performance measures and cutting parameters will be more useful in evaluating and predicting the machining performance at different levels of workpiece hardness. With this view, in the present work, experimental investigations were carried out to assess the machinability of hardened AISI 4340 steel through mathematical modeling during hard (workpiece hardness $\geq$ 45 HRC) and soft turning (workpiece hardness $<$ 45 HRC) with TiC mixed alumina ceramic tools. Effect of workpiece hardness and cutting parameters, namely, cutting speed, depth of cut and feed on different responses, namely, chip-tool interface temperature, cutting forces and surface roughness were analyzed by performing ANOVA technique.

2. Tool-work thermocouple calibration setup

In present work, tool-work thermocouple principle was used to measure the average chip-tool interface temperature as this method is comparatively economical and widely used amongst the other methods during machining (Grzesik, 1999). However, to obtain the interface temperature, a thermoelectric relationship for the tool-workpiece material combination is to be established. With this view, in present study, the calibration set-up to obtain thermoelectric relationship for the ceramic tool-workpiece combination was developed as shown in Figs. 1-2. Fig. 1 shows the schematic of the set-up and photograph of the actual calibration set-up is shown in Fig. 2.

The set-up consists of an electrically insulated steel plate with a pocket at the centre, a digital temperature indicator with K-type thermocouple having temperature range of 0-1200^{0}C and an oxy-acetylene torch. Initially, a standard

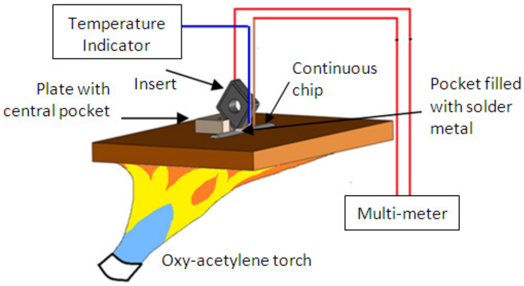


Fig. 1.Schematic of tool-work thermocouple calibration set-up.

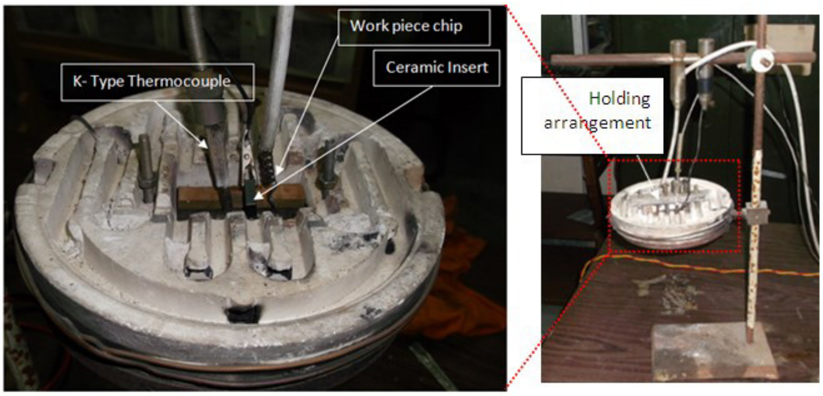


Fig. 2.Holding arrangement and enlarged view of marked rectangle showing process arrangement.

alumel-chromel thermocouple, cutting insert and one end of the continuous chip, which was obtained from the same workpiece were placed in the pocket as shown in Fig. 2. The soldering wire having composition of 60%tin and 40%lead having melting point of 183-188^{0}C was also placed in the pocket. When the plate was heated using an oxyacetylene torch, soldering wire was melted and a conductive path was formed between the ceramic cutting insert and one end of the continuous chip and a hot junction was formed between the tool and the continuous chip. Other end of the cutting insert and a long continuous chip acted as a cold junction.

Increasing temperature at the hot junction due to continuous heating by an oxyacetylene torch was recorded by a digital temperature indicator and a corresponding potential difference (emf) generated at different temperatures due to temperature gradient between hot and cold junctions was measured by multi-meter. Regression equations which describe the correlation between the potential difference (emf generated) (v) and the corresponding chip-tool interface temperature (θ) for the ceramic tool and hardened AISI 4340 steel combination were developed for different levels of workpiece hardness as given in Equations (1)-(3).

$$v = 10^{-6}\theta^2 + 0.006\theta - 0.447 \quad \text{[workpiece hardness: 35 HRC]} \tag{1}$$

$$v = 7\text{x}10^{-7}\theta^2 + 0.006\theta - 0.232 \quad \text{[workpiece hardness: 45 HRC]} \tag{2}$$

$$v = 7\text{x}10^{-7}\theta^2 + 0.005\theta - 0.243 \quad \text{[workpiece hardness: 55 HRC]} \tag{3}$$

3. Experimental set-up and procedure

Experiments were performed on centre lathe with step variable spindle speed and feed. Workpiece of diameter 90 mm and length of 120 mm hardened at different levels of hardness, namely, 35, 45 and 55 HRC was used for experiments. A TiC based Alumina ceramic insert having geometry CNMG 120408 was used as a cutting tool. Some rough cuts had been taken to remove the oxidized layer and surface irregularity. Experiments were performed by varying cutting speed, feed and depth of cut at five different levels as planned by using central rotatable composite design (CCD) technique (Cochran and Cox, 1957). Coded values and corresponding actual cutting conditions at different levels which were used during experiments is shown in Table 1. In present study, total 20 experiments at each level of workpiece hardness were carried out to assess and mathematically model the machinability responses, namely, cutting forces, surface roughness and chip-tool interface temperature. Cutting conditions were determined based on exploratory experiments, past experience and literature review.

Table 1. Values of cutting parameters as per DOE.

Cutting parameters	Coded levels				
	-1.682	-1.0	0	1.0	1.682
V (m/min)	100	120	150	180	200
f (mm/rev)	0.081	0.088	0.113	0.138	0.15
d (mm)	0.1	0.2	0.3	0.4	0.5

3.1. Force and surface roughness measurement

Cutting forces were measured with the help of a KISTLER piezoelectric dynamometer (type 9257 BA) with data acquisition card PC16024 (National instruments, USA). National LabView software was used to store and analyze the data. Through the interface board, analog signal obtained from dynamometer was converted into digital signals. Qualitest TR-100 surface roughness tester was used to measure surface roughness. The stylus of the instrument sensed the surface roughness by travelling a fixed length of 4mm along the axis of the workpiece. Cut-off length was taken as 0.8 mm. Surface roughness value at three different points was measured and average reading was noted.

3.2. Temperature measurement

An experimental set-up which was used for measurement of average chip-tool interface temperature during turning is shown in Fig. 3. One end of an iron rod was screwed to the workpiece mounted on a three jaw chuck and the other end was connected to a metallic disc (slip ring) dipped in mercury bath from where connection of cold junction was taken out to the computer with a LabView program installed. When the three jaw chuck holding the work piece rotates, metallic disk dipped in mercury also rotates and provides proper connection on the cold junction. Another wire was clipped to the tool insert connecting it with LabView program. The circuit was completed when the tool and work piece came into contact. Tool and work piece junction while machining acted as the hot junction and other ends of the work piece and tool at room temperature, acted as cold junction. To avoid parasitic emf, the work piece and tool were completely insulated from the rest of the machine by plastic sheet. For data acquisition in the present experimental setup PC 16024 a DOQ card (National instruments USA) was used. National LabView software was used to store and analyze the data. Through the interface board the analog signal from tool-work thermocouple was converted into digital signals. Thermocouple response namely emf was converted into temperature with the help of the calibration curve which was then fed to LabView software, and then the relation between the temperature and the time was plotted during turning.

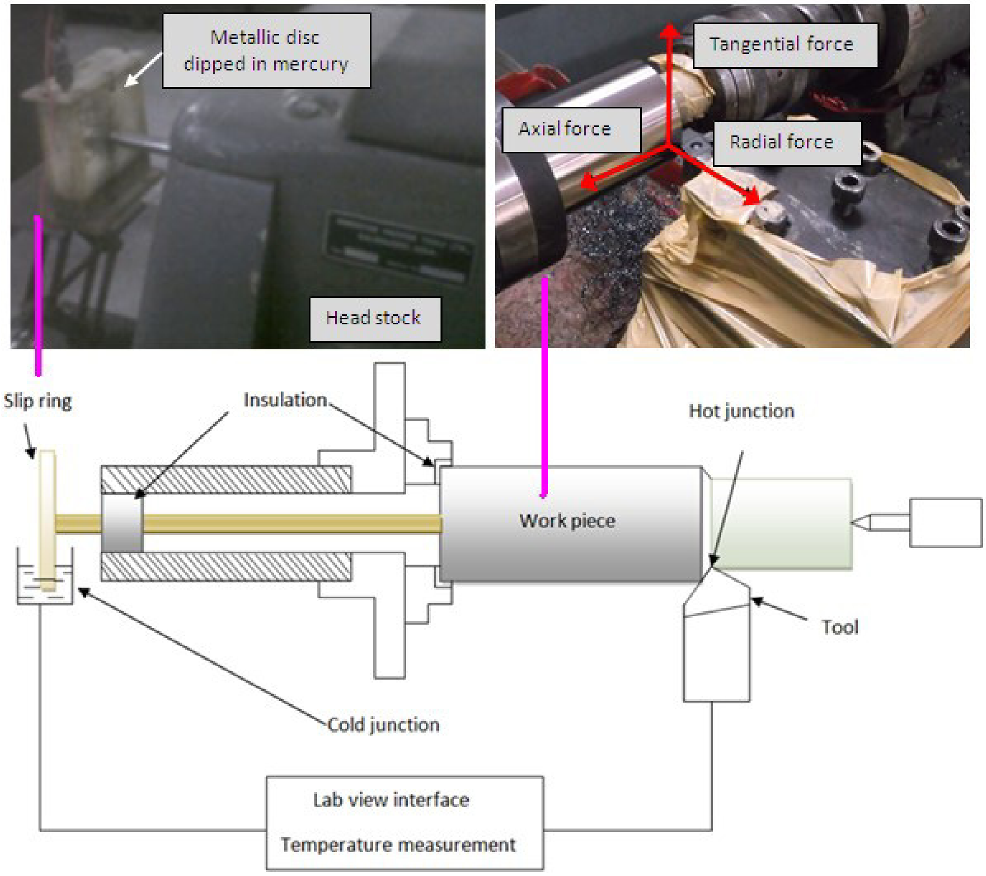


Fig. 3. Experimental set-up for interface temperature, cutting forces and surface roughness measurement: Schematic and actual photograph.

4. Results and discussion

Experimental values of cutting forces, surface roughness and interface temperature during turning of AISI 4340 steel hardened at three different levels of hardness, namely 35, 45 and 55 HRC, were obtained by varying the cutting conditions as per the plan of experiments (Table 1). Regression equations were developed based on experimental observations using Design Expert software (Version 8.0.7.1). The quadratic equation which was used for development of the model for three variables, namely, cutting speed (*V*), feed (*f*) and depth of cut (*d*), is expressed as below (Equation (4)).

$$y = K + a_1V + a_2f + a_3d + a_4Vf + a_5Vd + a_6fd + a_7V^2 + a_8f^2 + a_9d^2 \quad (4)$$

Where, y is the quadratic response function and a_1 to a_9 are regression coefficients of cutting variables. The constant values (*K*) and regression coefficients (a_1 to a_9) obtained for different responses during turning steel at different hardness levels are shown in Table 2.

Table 2. Values of constant (*K*) and regression coefficients obtained for different responses during turning steel at different hardness levels.

Responses	*K*	Coefficient of								
		V	*f*	*d*	*Vf*	*Vd*	*fd*	V^2	f^2	d^2
		a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9
Axial force (*Fx*)										
Fx_{35HRC}	-45.56	0.23	261.2	270.3	-0.82	-0.5	243.7	≈ 0	99.1	109.9
Fx_{45HRC}	47.15	-0.42	-131.5	211.7	0.82	-0.33	243.7	≈ 0	588	223.8
Fx_{55HRC}	50.98	-0.26	-164.1	113.9	≈ 0	0.42	365.6	≈ 0	1745	236.7
Radial force (*Fy*)										
Fy_{35HRC}	-278.2	0.17	4063	682.1	≈ 0	≈ 0	≈ 0	≈ 0	-13865	-451.5
Fy_{45HRC}	-306.9	0.29	4386.4	724.1	≈ 0	≈ 0	0.6	≈ 0	-14911	-475.6
Fy_{55HRC}	-295.9	0.18	4226.4	808.1	1.23	-0.25	-365.6	≈ 0	14459	-441.6
Tangential force (*Fz*)										
Fz_{35HRC}	-206.7	-0.36	3714.6	549.4	-2.87	0.08	-609.3	≈ 0	-9126	-429.8
Fz_{45HRC}	-73.29	-0.85	2451.1	411	≈ 0	≈ 0	≈ 0	≈ 0	-6016	-272.5
Fz_{55HRC}	-102	-0.78	2889	440.5	≈ 0	≈ 0	≈ 0	≈ 0	-7483	-296.6
Surface roughness (*Ra*)										
Ra_{35HRC}	-0.21	≈ 0	7.53	0.99	≈ 0	≈ 0	-3.04	≈ 0	8.6	-0.31
Ra_{45HRC}	-0.11	≈ 0	5.43	0.31	≈ 0	≈ 0	≈ 0	≈ 0	8.83	0.14
Ra_{55HRC}	0.04	≈ 0	4.34	0.16	≈ 0	≈ 0	≈ 0	≈ 0	11.38	0.21
Chip-tool interface temperature (θ)										
θ_{35HRC}	148.24	4.27	1078.4	357.3	-4.1	-0.5	-853	≈ 0	505	-9.45
θ_{45HRC}	171.43	5.94	-822.96	374.8	0.41	-0.58	-1096	-0.01	6212.7	29.31
θ_{55HRC}	485.78	2.48	441.25	266.9	3.28	-0.33	-731.2	≈ 0	-1678	34.15

For all the developed models, R^2 (correlation coefficient) values found close to 1, indicating that the developed models could be reliably used to predict the responses during hard and soft turning of hardened AISI 4340 steel within the domain of the cutting parameters selected in this study. Effect of cutting parameters on responses, namely, cutting forces (axial, radial and tangential), surface roughness and chip-tool interface temperature,during turning of different hardened work piece materials, observed by plotting curves varying one of the input parameters within the domain of the cutting conditions selected and keeping the other parameters constant at the central level. Response curves were drawn using the developed regression equations.

4.1. *Effect of cutting parameters on cutting forces*

Effect of cutting speed on cutting force components namely; axial(*Fx*), radial (*Fy*) and tangential force (*Fz*) is illustrated in Figs. 4(a), (b) and (c), which are plotted using depth of cut of 0.3 mm and feed value of 0.113 mm/rev while turning steel at three different hardness levels. It can be seen that all the components of cutting forces decrease with the increase in cutting speed. This is because of the fact that with increase in cutting speed shear plane energy and frictional energy increases therefore the temperature at the shear plane increases and material becomes softer.

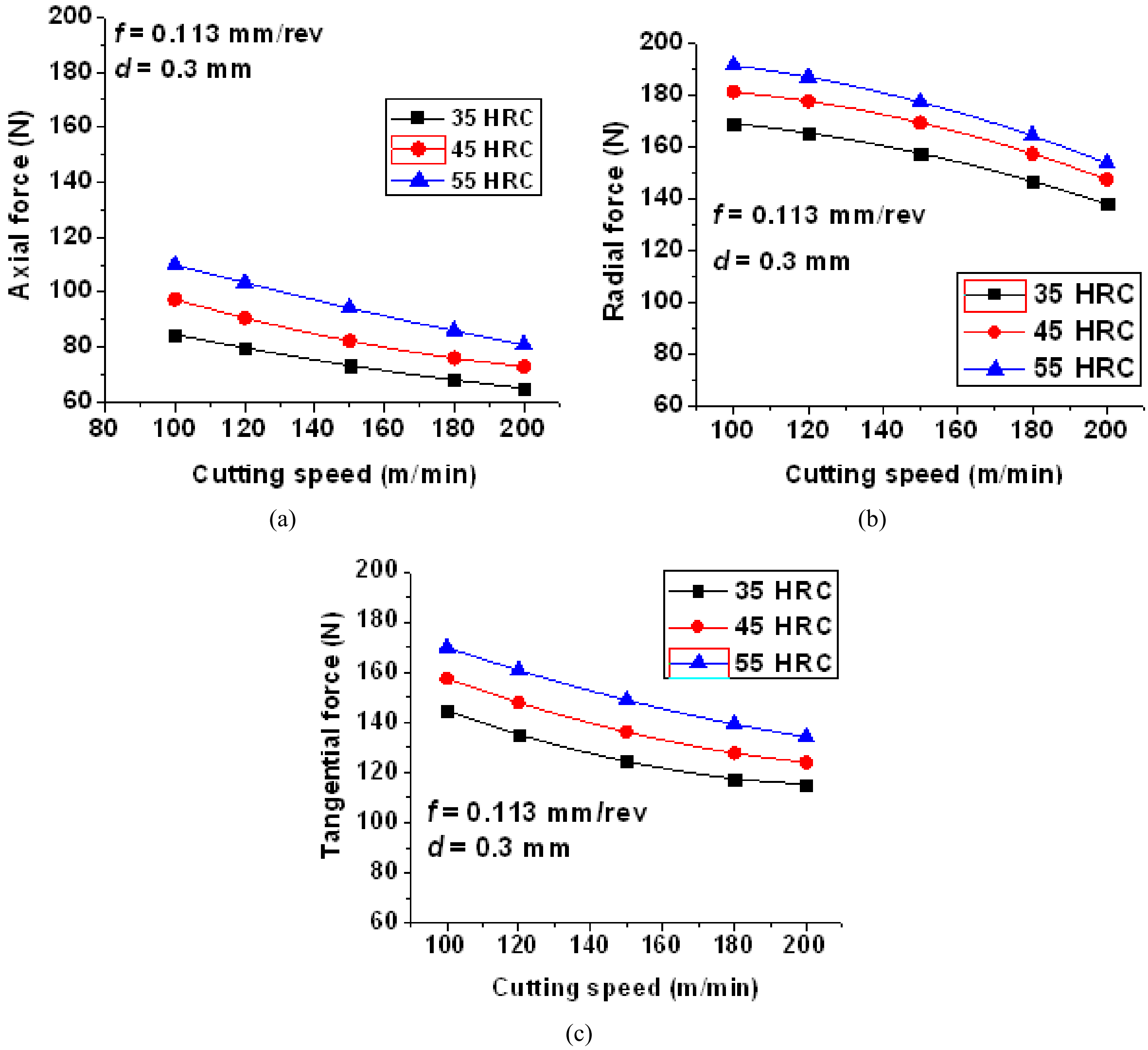


Fig. 4. Effect of varying cutting speed on (a) axial force (b) radial force and (c) tangential force.

Similarly, effect of depth of cut on cutting forces is illustrated in Figs. 5(a), (b) and (c), which are plotted using cutting velocity of 150 m/min and feed value of 0.113 mm/rev while turning of steel at different hardness levels. It can be seen that all the components of cutting forces increases with the increase in depth of cut. This is because of the fact that with increase in depth of cut, the shear plane area increases and forces required for cutting increases. Effect of feed on cutting forces is illustrated in Figs. 6(a), (b) and (c), which are plotted using depth of cut of 0.3 mm and cutting speed of 150 m/min while turning steel at different hardness levels. It can be seen that all the components of cutting forces increases with the increase in feed .This is because of the fact that with increase in feed shear plane area of the chip increases and forces required for cutting increases. It can be seen from Fig 6(c) that the tangential forces get saturated beyond the feed value of 0.13 mm/rev for all hardened workpieces. This is because of the fact that when feed value increased beyond 0.13 mm/rev, type of chip formed during cutting was changed from continuous to serrated type of chip resulting in decrease in tangential cutting force. This can be also attributed to the fact that when the chip shape transforms from ribbon to serrated type, adiabatic shear instability occurs resulting in the softening of the work material in the primary shear zone due to high adiabatic temperature. This result in decrease in deformation resistance and hence, decease in the tangential force.

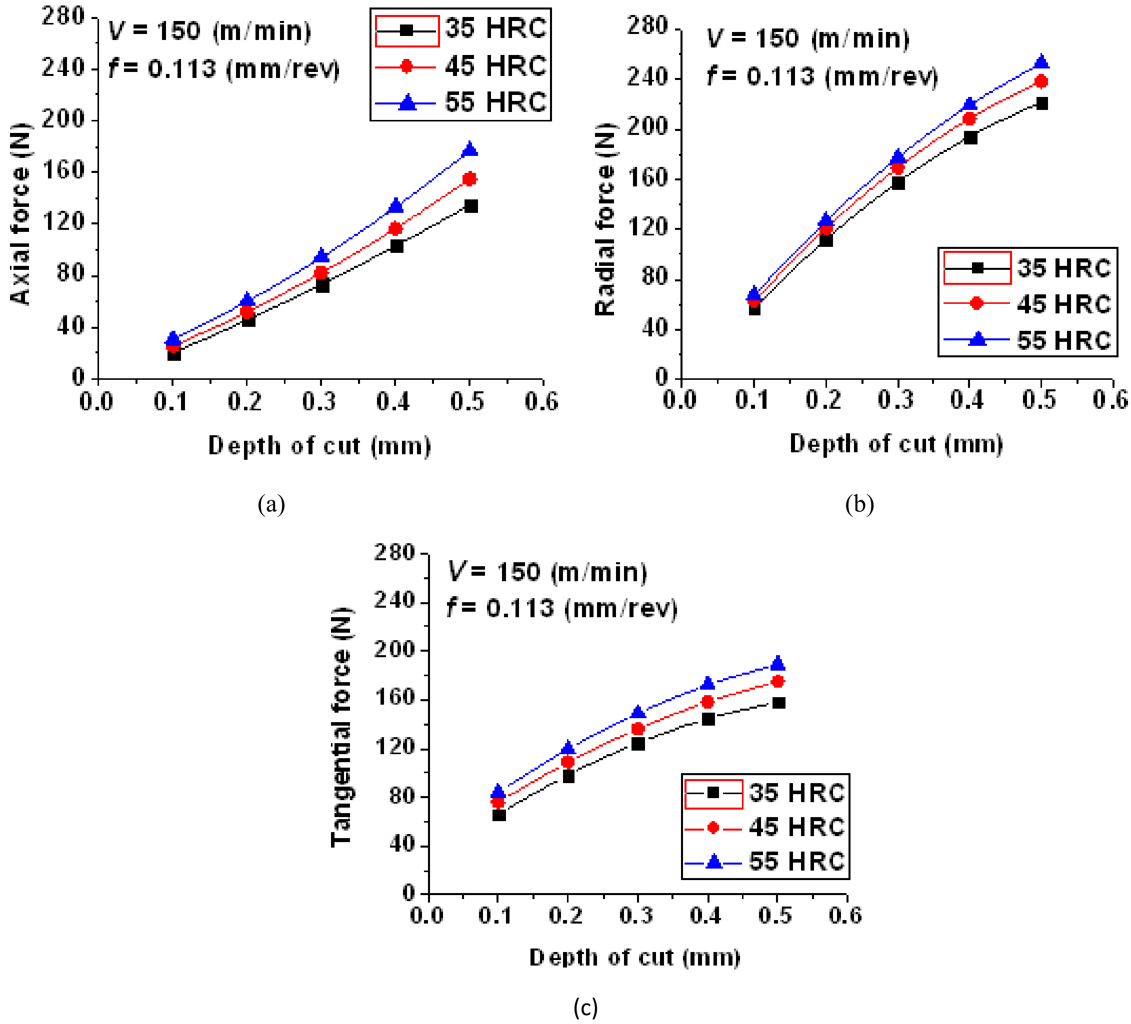
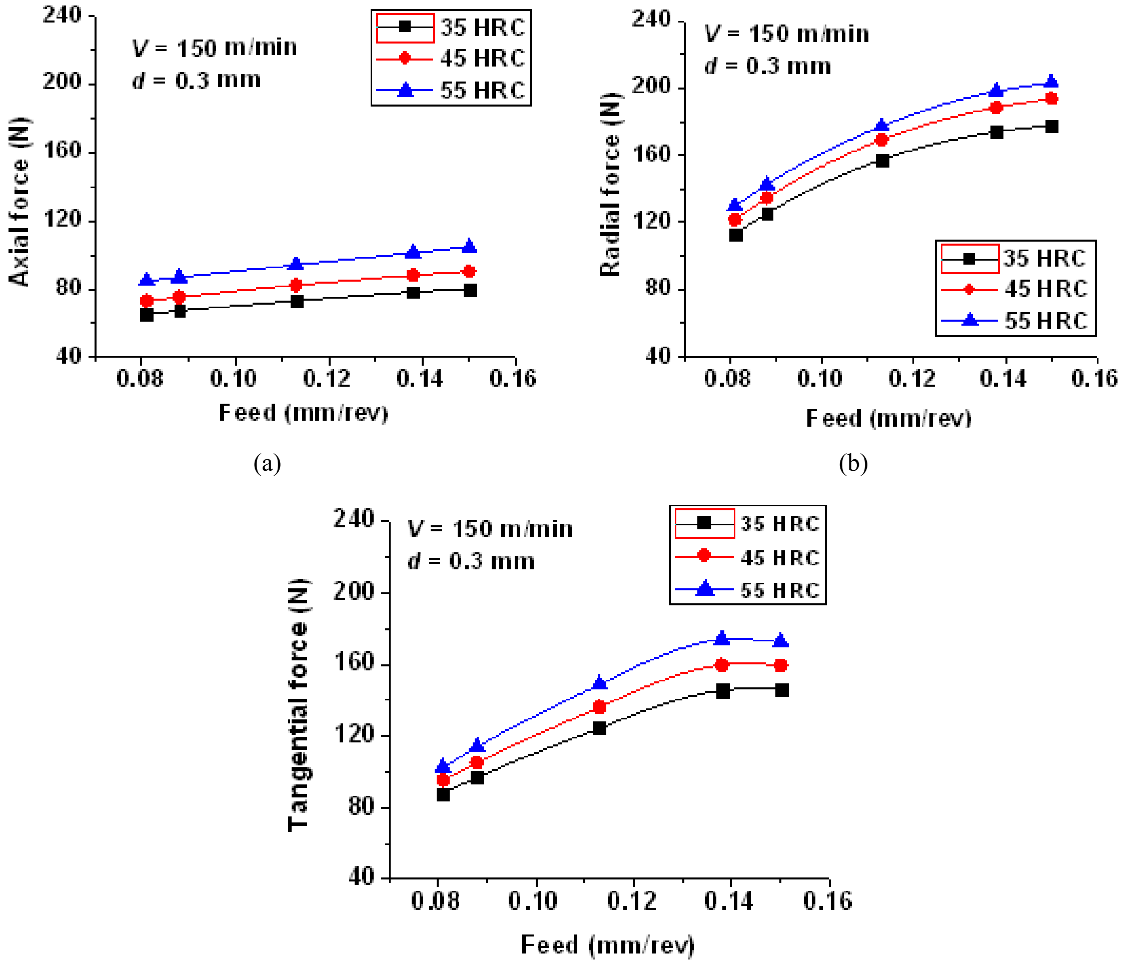


Fig. 5. Effect of varying depth of cut on (a) axial force (b) radial force and (c) tangential force.

It can be seen that the magnitude of the radial force is about 15-20 % higher than that of the tangential force and about 102-112 % higher than that of axial force. Higher values of the radial force can be attributed to the ploughing effect which is obtained under the condition of small depth of cut in the range of 0.1-0.5 mm, small feed value of 0.081-0.15 mm/rev compared to nose radius of 0.8 mm and a negative rake angle of 5^0 (Lalwani et al., 2008).Similar observations were reported by a group of researchers during hard turning (Koenig et al., 1984; Chinchanikar and Choudhury, 2013b). It can be also seen that the magnitude of the cutting forces increases with the increase in workpiece hardness due to higher shear strength of the harder workpiece.

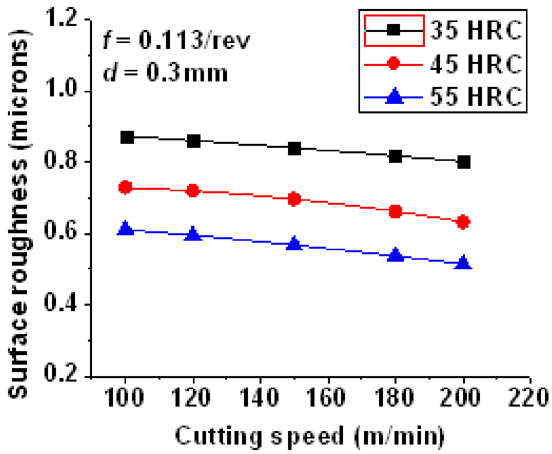


(c)

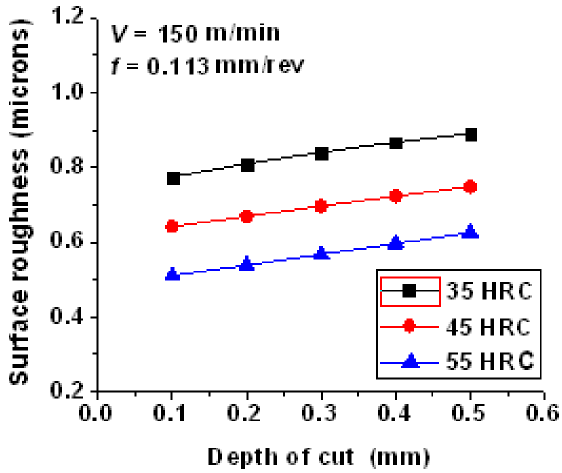
Fig. 6. Effect of varying feed on (a) axial force and (b) radial force and (c) tangential force.

4.2. Effect of cutting parameters on surface roughness

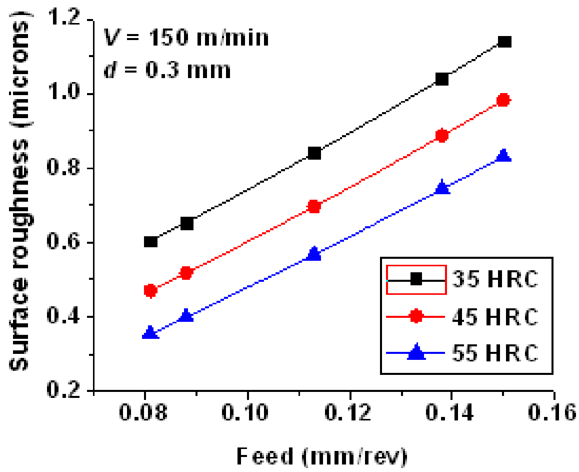
Effect of cutting parameters on surface roughness is illustrated in Figs. 7(a), (b) and (c). It can be seen that the roughness value of the machined surface increases sharply with the increase in feed (Fig. 7(c)). This is because increase in feed leads to produce feed marks on the turned surface resulting in the increase in the roughness value. However, with the increase in cutting velocity, the temperature increases as discussed in Section 4.3, making the work material softer which tends to decrease the components of cutting forces and hence resulting in better surface finish (Fig. 7(a)). On the other hand, it can be seen that the increase in depth of cut leads to increase in radial forces more prominently (Fig. 5(b)) resulting in more lateral vibrations of tool and hence, increase in roughness value of the turned surface. Also, it can be seen that surface roughness decreases with increase in hardness level of workpiece. It is due to the fact that with increase in hardness of the workpiece, the grain size of the workpiece decreases resulting in smaller size of the craters on the turned surface due to removal of grains and hence, decrease in roughness value.



(a)



(b)

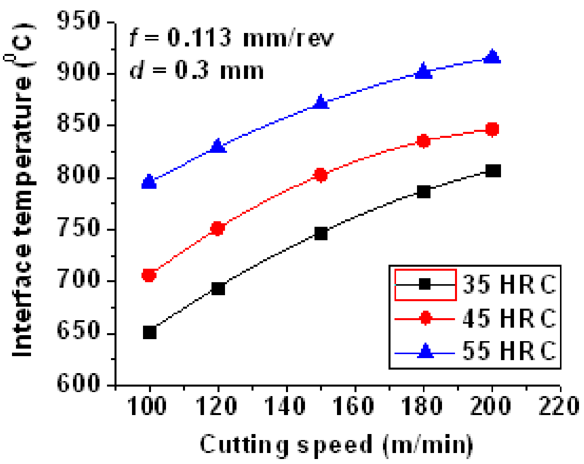


(c)

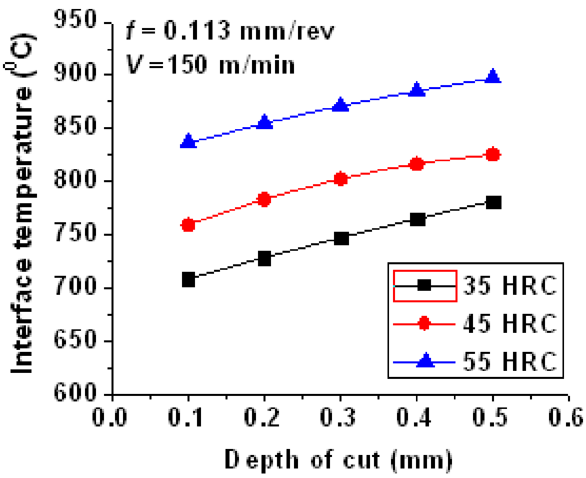
Fig. 7. Effect on surface roughness varying with (a) Cutting speed, (b) depth of cut and (c) feed.

4.3. Effect of cutting parameters on average chip-tool interface temperature

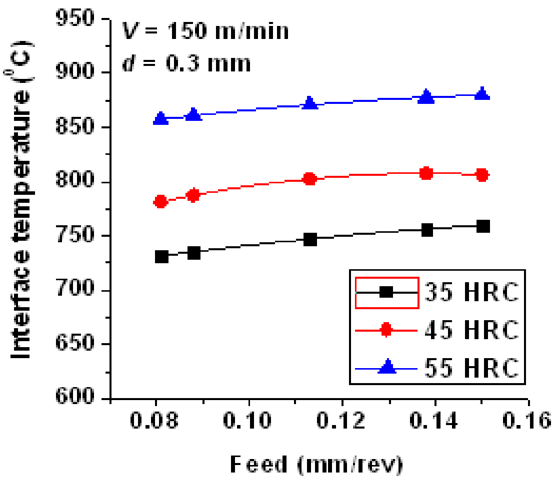
Effect of cutting parameters on average chip-tool interface temperature is illustrated in Figs. 8(a)-(c). It can be seen that the average chip-tool interface temperature produced during turning increases sharply with the increase in cutting speed (Fig. 8(a)). This is because, increase in cutting speed leads to increase in shear and frictional energy which in turn increases the temperature at the chip-tool interface. It can be seen that with increase in depth of cut and feed value, shear plane area and hence, cutting forces increases which in turn increases the frictional energy resulting in increase in the chip-tool interface temperature (Figs. 8(b) and (c)). However, feed and depth of cut can't be seen as prominent factors on interface temperature as cutting speed because with increase in feed and depth of cut values, large amount of heat is carried away with the chip instead of getting penetrated into the tool due to increase in cross sectional area of the chip.



(a)



(b)



(c)

Fig. 8. Effect on average chip-tool interface temperature varying with (a) cutting speed, (b) depth of cut and (c) feed.

5. Conclusions

In this study, machinability of hardened AISI 4340 steel during hard and soft turning using TiC mixed alumina ceramic tools was assessed by experimental investigations through mathematical modeling. For all the developed models, R^2 (correlation coefficient) values found closer to 1, indicating that the developed models could be reliably used to predict the responses, namely, chip-tool interface temperature, cutting forces and surface roughness during hard and soft turning of hardened AISI 4340 steel within the domain of the cutting parameters selected. It has been observed that the magnitude of the radial forces are about 15-20 % higher than that of tangential forces and about 102-112 % higher than that of axial forces. It has been also observed that the magnitude of the cutting forces increases with the increase in the workpiece hardness, feed and depth of cut. However, the tangential cutting forces were observed to get saturate beyond the feed value of 0.13 mm/rev due to changing behavior of the type of chip formed from continuous to serrated type of chip. Surface roughness was observed to increase sharply with the increase in feed value. Further, it has been observed to decrease with increase in hardness of the workpiece. Average value of the chip-tool interface temperature was observed to increase prominently with increase in cutting speed. Also, it has been observed that interface temperature increases with increase in workpiece hardness.

References

Abhang, L.B., Hjameedullah, M., 2010.Chip-tool interface temperature prediction model for turning process. International Journal of Engineering Science and Technology 2(4), 382–393.

Chinchanikar,S., Choudhury, S.K.,2013a. Effect of work material hardness and cutting parameters on performance of coated carbide tool when turning hardened steel: An optimization approach.Measurement 46, 1572- 1584.

Chinchanikar,S., Choudhury, S.K.,2013b. Investigations on machinability aspects of hardened AISI 4340 steel at different levels of hardness using coated carbide Tools. International Journal of Refractory Metals and Hard Materials 38, 124-133.

ChinchanikarS., Choudhury, S.K. and Kulkarni,A.P., 2013. Investigation of chip-tool interface temperature during turning of hardened AISI 4340 alloy steel using multi-layer coated carbide inserts. Advanced Materials Research 701, 354-358.

Cochran, W.G., Cox, G.M., 1957. Experimental Designs, John Wiley and Sons Inc., New York.

Grzesik, W., 1999. Experimental investigation of the cutting temperature when turning with coated Index able inserts. International Journal of Machine Tools and Manufacture 39, 355–369.

Grzesik, W., 2008. Advanced machining processes of metallic materials, Elsevier.

Koenig, W.A., Komanduri, R., Toenshoff, H.K., Ackeshott, G., 1984. Machining of hard metals.Annals of the CIRP 33(2), 417–427.

Korkut, I., Boy, M., Karacan, I., Seker, U., 2007. Investigation of chip-back temperature during machining depending on cutting parameters. Materials and Design 28, 2329–2335.

Lalwani, D.I., Mehta, N.K., Jain, P.K., 2008. Experimental investigations of cutting parameters influence on cutting forces and surface roughness in finish hard turning of MDN250 steel. Journal of Materials Processing Technology 206, 167–179.

Lima, J.G., Avila, R.F., Abrao, A.M., Faustino, M., et al., 2005. Hard turning: AISI 4340 high strength alloy steel and AISI D2 cold work tool steel. Journal of Materials Processing Technology 169(3), 388–395.

Liu,X.L., Wen, D.H., Li,Z.J., Xiao, L. and Yan, F.G., 2002. Cutting temperature and tool wear of hard turning hardened bearing steel.Journal of Materials Processing129, 200-206.

Luo, S.Y., Liao, Y.S., Tsai, Y.Y., 1999. Wear characteristics in turning high hardness alloy steel by ceramic and CBN tools, Journal of Materials Processing Technology 88, 114–121.

Senthil Kumar,N. and Tamizharasan, T., 2012. Impact of interface temperature over flank wear in hard turning using carbide inserts. J.Procedia Engineering 38, 613 – 621.