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Evaluation of Chip-Tool Interface Temperature: Effect of Tool Coating and Cutting Parameters during Turning Hardened AISI 4340 Steel

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Abstract

In the present context of sustainable manufacturing, investigation of cutting temperature during machining is extremely valuable to address metal cutting issues such as dimensional accuracy, surface finish and tool life. In this study, average chip-tool interface temperature was investigated considering the effect of cutting parameters and the type of coating (coated tools), namely, PVD-applied single-layer TiAlN and CVD-applied multi-layer TiCN/Al_2O_3/TiN during turning of hardened steel. Mathematical model which can predict the average chip-tool interface temperature was developed based on experimental observations which were obtained in the wide range of cutting conditions. A calibration set-up based on tool-work thermocouple principle was developed to correlate the emf (electro motive force) and the interface temperature. R-squared value for the developed model found 0.9693, indicate that the developed model is reliable and could be used effectively for predicting the interface temperature within the domain of the cutting parameters for the given tool and work material pair. Experimental observations indicate that the interface temperature is higher for CVD-coated multi-layer coated tool in comparison to single-layer TiAlN, which get affected mostly by cutting speed followed by feed. However, depth of cut has negligible influence on interface temperature when using both the coated carbide tools.

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Keywords: Coated carbide tools; Interface temperature; Cutting parameters; Turning; Electro motive force (emf).

1. Introduction

In recent years, evaluation of the machining performance through predictive/simulation modeling to the progress of cutting technology is ingrained among users.The increasing trend toward maximizing productivity and higher

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material removal rates has generated the need for developing reliable predictive models and simulation methods of all manufacturing/machining processes. Manufacturing evolution, i.e. the design-to-manufacturing cycle is strongly driven by the database of information on process, tooling materials and workpiece requirements (Stein and Dornfeld, 1996). Evidently, process data and appropriate models can drive design and manufacturing decisions to achieve goals with increasing levels of complexity. In the machining area, predictive models, which are capable of predicting quantitatively the influence of the magnitude of one or more input parameters on the magnitude of one or more output parameters are of special importance.

Heat generated in machining operation is an important factor in addressing metal cutting issues like dimensional accuracy, surface integrity and tool life. In machining of hardened steels, higher workpiece hardness generates higher temperature in the cutting zone (Chinchanikar et al., 2013) which has a very strong influence on the tool wear rate through various tool wear mechanisms like abrasion, adhesion and diffusion. Therefore, evaluation and development of a mathematical model which can predict reliably average chip-tool interface temperature during machining considering the effect of cutting parameters for the given tool-work material combination will be extremely valuable.

Over the past century, several conduction techniques like tool-chip thermocouple, embedded thermocouple, thermo-colors and radiation techniques like infrared thermometry, pyrometry have been developed to evaluate the chip-tool interface temperature arising in the cutting zone during machining. However, tool-work thermocouple technique is widely used during metal cutting due to its ease of implementation and low cost as compared to other techniques (Aneiro et al., 2008; Grzesik, 1999; Korkut et al., 2007). Ren et al.(2004) evaluated the cutting temperature during hard facing of titanium alloy using thermocouples at tool–shim interface. Liu et al.(2002) measured the cutting temperature using a natural thermocouple during finish turning of bearing steel which were hardened at different levels of hardness varying between 30 to 64 HRC. They observed that the cutting temperature increases with increase in the workpiece hardness up-to 50 HRC. However, decrease in cutting temperature was observed by them beyond the value of workpiece hardness of 50 HRC. Casto et al. (1986) proposed a remote sensing technique for measurement of cutting temperature based on constant melting point of powders. Korkut et al.(2007) observed that increase in cutting speed, depth of cut, and feed rate causes increase in the chip back surface temperature. However, cutting speed and depth of cut were observed to have more influence relative to feed rate.

Sullivan and Cotterell(1987) measured the cutting temperature using embedded thermocouple and infrared techniques. They observed that the cutting temperature decreases with increase in cutting speed. However, cutting temperature and cutting forces increases as the tool wear progresses. An analytical model and numerical methods to predict cutting temperature (Cohen et al., 2012; Huang and Liang, 2003; Dogu et al., 2006) and investigation of the effect of cutting parameters on temperature, stress and shear angle using Finite Element Modeling are reported (Tang et al. 2011). However, prediction accuracy depends upon the basic assumptions and boundary conditions used in the study. Bahi et al. (2012) proposed a hybrid analytical-numerical based chip formation model for orthogonal cutting process. An analytical model was used to analyze the thermo-mechanical material flow in the primary shear zone, the tool-chip contact length, the local friction coefficient and the sliding-sticking zones. The temperature distribution in the chip was studied by numerical means.

Non-contact radiation techniques like infrared thermometry, pyrometry have been used to evaluate the chip-tool interface temperature (Muller-Hummel and Lahres, 1995; Saoubi and Chandrasekaran, 2004). However, accuracy of the results depends upon the exact values of the emissivity of the cutting tool material and temperature of the radiating surface. Further, when the chip flows at a high speed along the rake face, these methods give erratic results during the measurement of exact temperature on the rake/flank face with the help of infrared rays due to accessible issue. Metallographic techniques like observing the micro-structural changes of the cutting tool/workpiece after cutting can be used to find the temperature near the rake face. However, this technique is laborious and time consuming. Further, this technique is applicable to only those tool materials that exhibit a change in the micro-structure with temperature.

Trigger (1948) investigated the chip-tool interface temperature by thermocouple technique. Grezsik (1999) investigated the variations of the chip-tool interface temperature using standard thermocouple embedded in the workpiece. Interface temperature was observed to be more influenced by thermal properties of the workpiece and tool coating. A group of researchers investigated the effect of cutting parameters and variation in the nose radius on the interface temperature using tool-chip thermocouple/ embedded thermocouple technique (Aneiro et al., 2008;

Korkut et al., 2007; Findes et al., 2008; Choudhury and Bartarya, 2003; Abhang and Hameedullah, 2010). Most of the studies concluded that the tool-chip interface temperature increases with the increase in cutting speed, feed and depth of cut. However, interface temperature decreases with the increase in tool nose radius. Studies performed by embedded thermocouple technique also showed the increase in interface temperature with cutting parameters. 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 feed and depth of cut have negligible influence on interface temperature.

In view of probable effects of heat generated during machining on tool life, surface integrity and dimensional accuracy, development of a reliable model which can predict the chip-tool interface temperature will be extremely valuable. With this view, in present work, mathematical model, which was developed based on experimental results obtained in the wide range of cutting conditions, is presented and which could be used to predict chip-tool interface temperature during turning of hardened AISI 4340 steel (35 HRC) using PVD-applied single-layer TiAlN coated carbide tool. Correlation between the emf (electro motive force) and the interface temperature for the given tool-work material pair, which was obtained by developing a calibration set-up based on tool-work thermocouple principle, is presented. Finally, average chip-tool interface temperature which was evaluated considering the effect of cutting parameters and the type of coating (coated tools), namely, PVD-applied single-layer TiAlN and CVD-applied multi-layer $TiCN/Al_2O_3/TiN$ during turning of hardened steel is presented.

2. Experimental details and procedure

Turning tests were performed on hardened AISI 4340 steel (35 HRC). Hardness was maintained uniform throughout the cross section with a maximum variation of $\pm$ 2 HRC by a precisely controlled hardening and tempering process. The workpiece used has a length and diameter of 400 and 90 mm, respectively. Experiments were performed using PVD-applied single-layer TiAlN coated cemented carbide tools. Average chip-tool interface temperature obtained using single-layer TiAlN coated tool was compared with the chip-tool interface temperature obtained when using CVD-applied multi-layer $TiCN/Al_2O_3/TiN$ coated carbide tool from the earlier reported work (Chinchanikar et al., 2013). Details of the tool macro and micro-geometries, tool holder employed and coating architecture can be referred from the authors earlier reported work (Chinchanikar and Choudhury, 2013a).

Dry cutting tests were carried out on a HMT-make (Hindustan Machine Tools) centre lathe. Desired cutting speeds were achieved by using different workpiece diameters and rotational speed available in the machine. During experiments, workpiece was held in a three jaw chuck and supported by a center in the tailstock. Tool geometry, Tool height and its overhang which were set to the required level with the help of gauges were kept constant. Before carrying out actual experiments, some rough turning pass was made in order to completely remove the surface irregularities and oxidized layer from the workpiece surface.

Experiments were planned in such a way that useful inferences could be drawn by performing minimum number of experiments. This can be done by using statistical techniques. In this study, a natural tool-work thermocouple principle was used to measure the interface temperature during turning of hardened AISI 4340 steel using PVD-coated single-layer TiAlN cemented carbide tool. Correlation between the cutting parameters with the average chip-tool interface temperature was developed by varying the cutting speed, feed and depth of cut as per the plan given by central composite rotatable design (CCRD) matrix with an alpha value of 1.6817 as shown in Table 1 (Cochran and Cox, 1957). Experiments were planned considering the replication of factorial points, axial (star) points and center points as one. Each numeric parameter of the input variable was varied over five levels: plus and minus alpha (axial points), plus and minus 1 (factorial points) and the center point. However, the correlations developed between the cutting parameters and the performance measures using Response Surface Methodology (RSM) technique can reliably predict the responses within the plus and minus one level only. To widen the scope of the model, eight additional experiments were performed at plus and minus alpha level (1.6817) of cutting speed. The ranges of three input variables were decided on the basis of practical machining conditions used while machining of these hardened alloy steels. In this study, total 23 experiments (as shown in Table 2) were performed to develop a chip-tool interface temperature model. Relationship between the electro motive force (emf) and the corresponding temperature was established using a tool-work calibration set-up which is discussed in more detail in next Section.

Table.1 Coded levels and corresponding actual values of cutting parameters

Parameters	Levels				
	- 1.6817	- 1	0	+ 1	+ 1.6817
Cutting speed (V) (m/min)	100	142	200	265	300
Feed (f) (mm/rev)	0.1	0.15	0.2	0.25	0.3
Depth of cut (d) (mm)	0.5	1	1.5	2	2.5

Table.2Experimental matrix showing coded levels and corresponding actual values of cutting parameters

Expt. No.	Coded levels			V (m/min)	f (mm/rev)	d (mm)	Expt. No	Coded levels			V (m/min)	f (mm/rev)	d (mm)
	V	f	d					V	f	d			
1	-1.6817	0	-1.6817	100	0.2	0.5	13	142	0.25	1	-1	1	-1
2	-1	-1	-1	142	0.15	1	14	265	0.25	2	1	1	1
3	0	0	1.6817	200	0.2	2.5	15	200	0.1	1.5	0	-1.6817	0
4	0	0	0	200	0.2	1.5	16	-1.6817	-1.6817	0	100	0.1	1.5
5	-1	-1	+1	142	0.15	2	17	-1.6817	1.6817	0	100	0.3	1.5
6	1	-1	1	265	0.15	2	18	-1.6817	0	-1.6817	100	0.2	0.5
7	1	1	-1	265	0.25	1	19	-1.6817	0	1.6817	100	0.2	2.5
8	0	0	-1.6817	200	0.2	0.5	20	1.6817	-1.68	0	300	0.1	1.5
9	0	1.6817	0	200	0.3	1.5	21	1.6817	1.68	0	300	0.3	1.5
10	1	-1	-1	265	0.15	1	22	1.6817	0	-1.6817	300	0.2	0.5
11	1.6817	0	0	300	0.2	1.5	23	1.6817	0	1.6817	300	0.2	2.5
12	-1	1	1	142	0.25	2							

3. Results and discussion

3.1 Calibration set-up

In order to establish the relationship between the emf generated and the corresponding temperature, a calibration set-up was developed as shown in the schematic of the set-up (Fig. 1) and actual photographs showing chip-tool junction point in contact with heater in Fig. 2(a) along with actual photograph of the calibration set-up in Fig. 2(b). In this set-up, tool-work thermocouple junction was formed using a coated carbide tool and a long continuous chip taken from the same workpiece as being used for the experiments. A heating coil was used for heating the junction point of coated insert and chip. A standard K-type thermocouple wire was mounted just near the junction point and connected to temperature indicator. Electro motive force (emf) generated between the hot junction and cold junction was monitored by a digital multi-meter. The linear relationship obtained for the coated carbide tool and hardened workpiece (35 HRC) is shown in Fig. 3. Both the workpiece and the tool were insulated properly during turning and calibration process to avoid the generation of secondary emf.

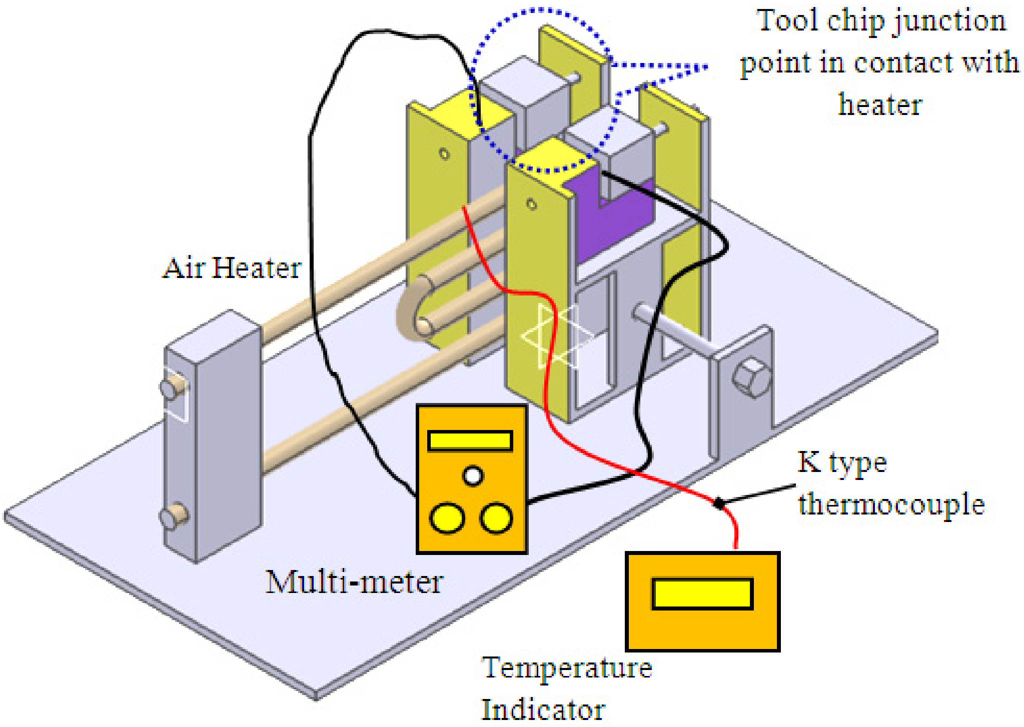


Fig. 1. Schematic tool-work calibration set-up.

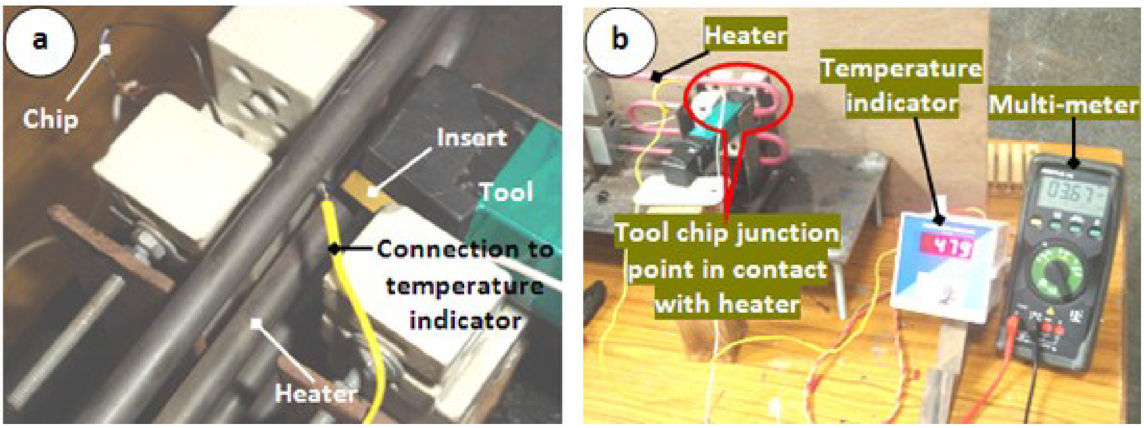


Fig.2.(a) actual photograph showing chip-tool junction point in contact with heater and (b) actual photograph of calibration set-up.

Relationship between the electro-motive forces (emf) generated during turning and the interface temperature was established using a set-up as shown in Fig. 4(a) and (b). One wire from the rear end of the workpiece (cold junction) through carbon brush and another wire, screwed to the cutting insert (hot junction), were connected to a multi-meter. Circuit was completed when the tool came in contact with the workpiece. For each cutting test, thermo-electric emf was measured and average chip-tool interface temperature for the corresponding cutting condition was calculated using the linear relationship as shown in Fig. 3.

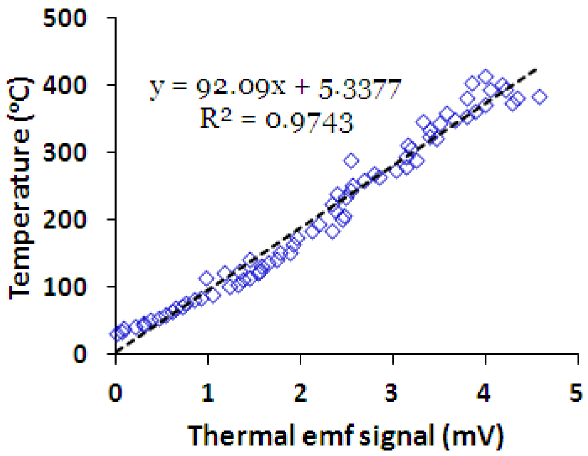


Fig.3.Calibration curve for PVD-coated single-layer TiAlN tool and AISI 4340 steel (35 HRC).

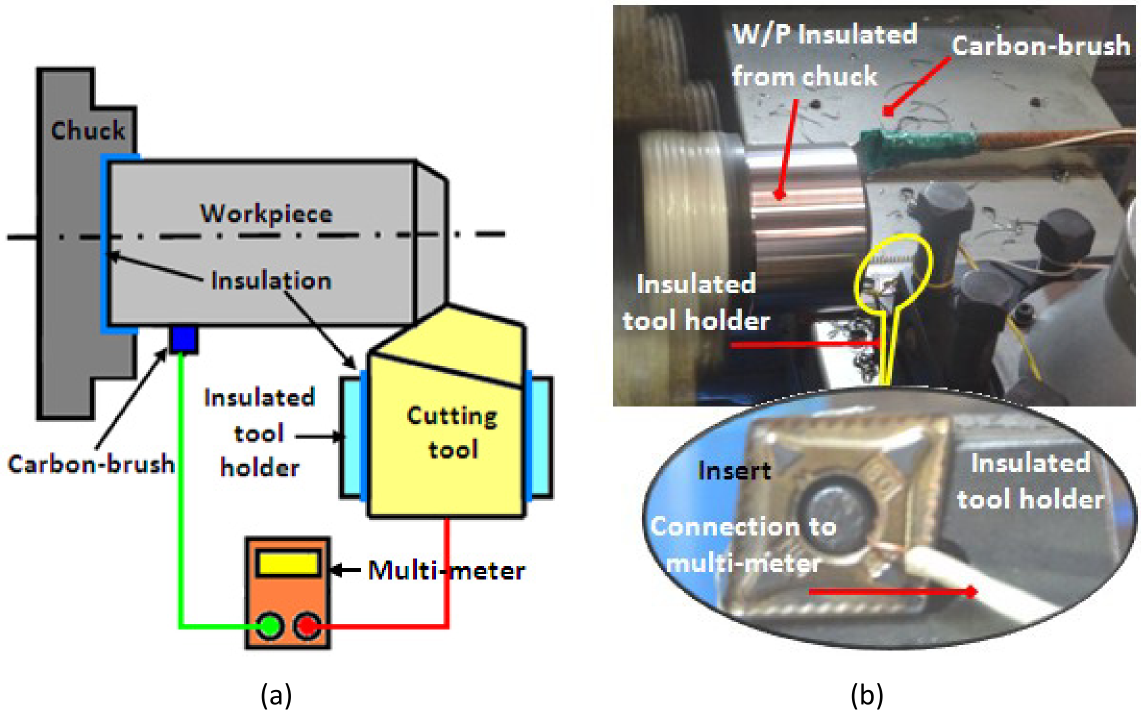


Fig.4. Chip-tool interface temperature measurement set-up (a) schematic and (b) actual photograph.

3.2 Modeling of interface temperature

Average chip-tool interface temperature was expressed in terms of cutting parameters, namely, cutting speed, feed and depth of cut. In general form it can be expressed as follows:

$$\text{Response function} = c_1 \; V^p f^q d^s \quad (1)$$

The unknown coefficients, namely, exponents of cutting speed, feed, and depth of cut and constant involved in (1) were determined by minimizing the least squares error between experimental and predicted results obtained within the range of cutting conditionsusing Data-Fit software (version 8.1). Developed model of average chip-tool interface temperature along with their R-Squared values is given below.

$$T_{in} = 154.54 V^{0.3275} f^{0.1334} d^{0.0527} \quad (R^2 = 0.9693) \quad (2)$$

The correlation coefficient (R-Squared value) found 0.9693 showed that the developed model is valid and could be used reliably for predicting the average chip-tool interface temperature for the given tool and work material combination and within the domain of the cutting parameters.Plot showing the predicted values of average chip-tool interface temperature (obtained using **(**2) along with the experimental values is shown in Fig. 5.

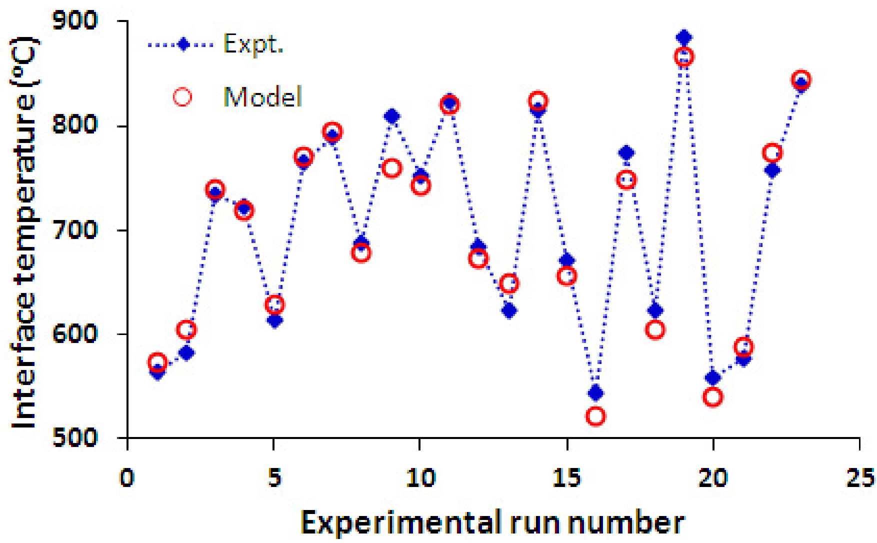


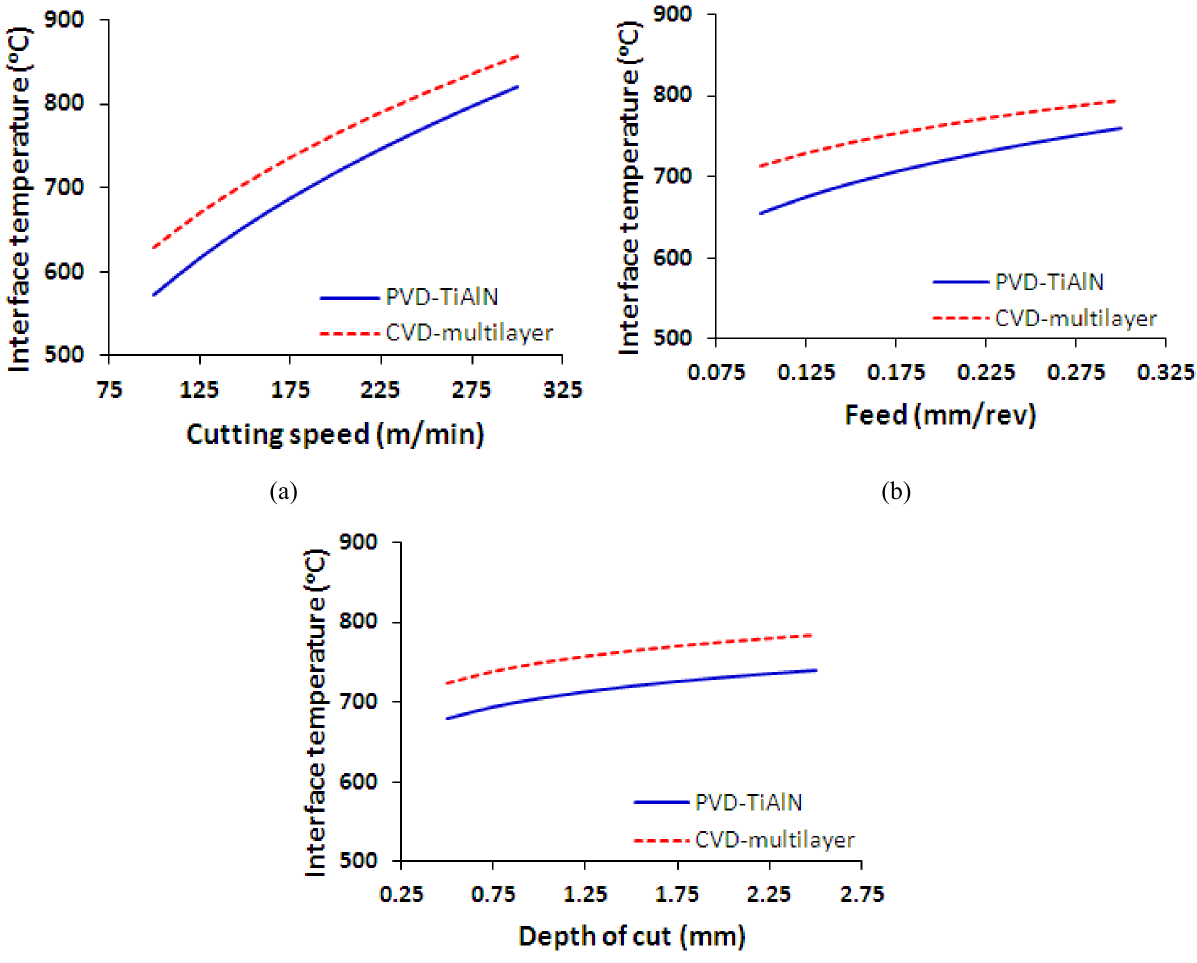
Fig.5. Experimental and predicted values of average chip-tool interface temperature.

3.3 Effect of tool coating and cutting parameters on interface temperature

In this Section, average chip-tool interface temperature employed during turning of hardened steel is discussed considering the effect of cutting parameters and the type of coating, namely, PVD-applied single-layer TiAlN and CVD-applied multi-layer TiCN/Al_2O_3/TiN with the help of developed mathematical models.Authors of the present study have already developed a mathematical model to predict the average chip-tool interface temperature using CVD-coated multi-layer TiCN/Al_2O_3/TiNtool during turning of AISI 4340 steel (35 HRC) within the same domain of the cutting parameters as used in the present study (Chinchanikar et al., 2013) , expressed as:

$$T_f = 196.9V^{0.2818} f^{0.09818} d^{0.05024} \qquad (3)$$

From exponent and constant values of average chip-tool interface temperature from (2) and (3), respectively, it can be seen that cutting speed followed by feed become the most influencing parameters on chip-tool interface temperature. However, this effect can be seen as more prominent for PVD-coated tool, showing by higher values of exponents than for CVD-coated tool, which can be also seen from the curves plotted using (2) and (3) for PVD and CVD-coated tools, respectively, as shown in Figs. 6(a) to (c). Curves showing the interface temperature are plotted based on the developed regression equations by varying one of the input parameters and keeping the other parameters constant. Fig. 6(a) depicts the variation of interface temperature with cutting speed, plotted using feed value of 0.2 mm/rev and depth of cut of 1.5 mm. Similarly, Figs. 6(b) and (c) depict the variation in interface temperature with feed and depth of cut, respectively, plotted using the values of other parameters, as, V = 200 m/min and d = 1.5 mm, for Fig. 6(b) and V = 200 m/min and f = 1.5 mm/rev, for Fig. 6(c).



(c)

Fig.6. Average chip-tool interface temperature with varying (a) cutting speed, (b) feed and (c) depth of cut.

It can be seen that the average chip-tool interface temperature is lower for PVD-coated single-layer TiAlN carbide tool in comparison to CVD-coated multi-layer TiCN/Al2O3/TiN carbide tool during turning of hardened AISI 4340 steel (35 HRC). It can be seen that the average chip-tool interface temperature get affected mostly by cutting speed followed by feed. However, effect of cutting parameters can be seen as more prominent for PVD-coated tool. Authors of this study observed that the PVD-coated tools are more sensitive to cutting conditions in comparison to CVD-coated tools during turning of hardened AISI 4340 steel (35 HRC) (Chinchanikar and Choudhury, 2013b). Depth of cut having the negligible influence on chip-tool interface temperature for both the coated tools could also be observed. These observations are in line with the earlier findings of the present authors while machining of hardened steel at different levels of hardness using multi-layer coated tool (Chinchanikar et al., 2013).The lower average interface temperature with single-layer TiAlN coated carbide tool can be attributed to the characteristicsof the PVD-applied coating process. PVD-applied coating gives rise to minimum friction between the tool face and the chips resulting in lower cutting forces (Venkatesh et al., 1991) and hence resulting in lower cutting temperature.

4. Conclusions

In this study, in view of probable effects of heat generated during machining on tool life, surface integrity and dimensional accuracy, a mathematical model which could predict reliably average chip-tool interface temperature during turning of hardened AISI 4340 steel (35 HRC) using single-layer PVD-coated TiAlN carbide tool was developed based on experimental observations.The unknown coefficients in the model, namely, exponents of cutting speed, feed, and depth of cut and constant were determined by minimizing the least squares error between experimental and predicted results obtained within the range of cutting conditions. A calibration set-up was developed to correlate the emf (electro motive force) generated and the corresponding temperaturebased on tool-work thermocouple principle. During turning for each cutting test, thermo-electric emf was measured and average chip-tool interface temperature for the corresponding cutting condition was calculated using the linear relationship obtained for the given tool-work material pairby the calibration set-up. Effect of cutting parameters and the type of coating, namely, PVD-applied single-layer TiAlN and CVD-applied multi-layer TiCN/Al_2O_3/TiN on average chip-tool interface temperature was discussed with the help of developed mathematical models. Ithas been observed that cutting speed followed by feed become the most influencing parameters on chip-tool interface temperature. However, this effect was more prominent for PVD-coated tool. Lower interface temperature was observed for PVD-coated tool in comparison to CVD-coated tool. Depth of cut having negligible influence on chip-tool interface temperature was observed for both the coated tools.

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