

# Experimental and numerical investigations on the temperature distribution in PVD AlTiN coated and uncoated Al<sub>2</sub>O<sub>3</sub>/TiCN mixed ceramic cutting tools in hard turning of AISI 52100 steel

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**Abstract.** Temperature generation in cutting tools is one of the major causes of tool failure especially during hard machining where machining forces are quite high resulting in elevated temperatures. Thus, the present work investigates the temperature generation during hard machining of AISI 52100 steel (62 HRC hardness) with uncoated and PVD AlTiN coated Al<sub>2</sub>O<sub>3</sub>/TiCN mixed ceramic cutting tools. The experiments were performed on a heavy duty lathe machine with both coated and uncoated cutting tools under dry cutting environment. The temperature of the cutting zone was measured using an infrared thermometer and a finite element model has been adopted to predict the temperature distribution in cutting tools during machining for comparative assessment with the measured temperature. The experimental and numerical results revealed a significant reduction of cutting zone temperature during machining with PVD AlTiN coated cutting tools when compared to uncoated cutting tools during each experimental run. The main reason for decrease in temperature for AlTiN coated tools is the lower coefficient of friction offered by the coating material which allows the free flow of the chips on the rake surface when compared with uncoated cutting tools. Further, the superior wear behaviour of AlTiN coating resulted in reduction of cutting temperature.

## 1. Introduction

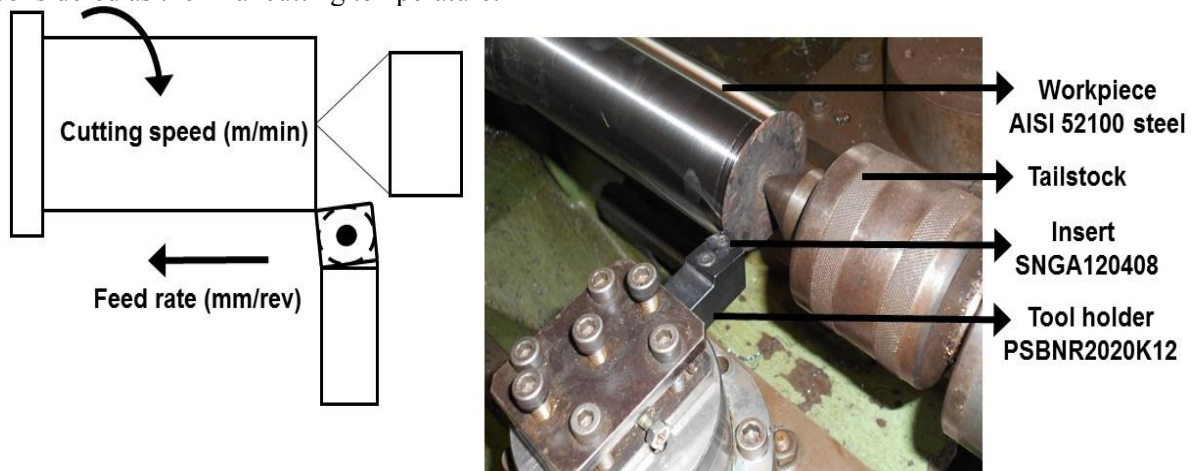
The finishing or semi-finishing machining operation of materials having hardness in the range of 45-70 HRC is termed as hard machining process. The advantages of hard machining is making it an imperative alternative to grinding process [1]. However, hard machining process is associated with elevated machining forces and temperature which demands excellent hot hardness and wear resistance for the employed cutting tools [2]. Thus, cutting tools manufactured from ceramics, mixed ceramics, polycrystalline cubic boron nitride (PCBN) or cubic boron nitride (CBN) that exhibit excellent thermal and chemical stability at elevated temperatures are employed for machining of hard materials [3]. Among these cutting tools, the popularity of alumina based mixed ceramic cutting tools in the industry and the research community is basically due to their economical nature. But the higher brittleness of these ceramic cutting tools make them more prone to brittle failure under impact or shock loads [4]. However, the progress made in the processing technology of ceramics [5] has generated the possibility of addition of certain ductile phases like TiCN and TiC to the brittle ceramic matrix to form a composite commonly termed as mixed ceramic or composite ceramic material. The addition of these phases impart additional fatigue and shock loading capacity, and wear resistance [6] to the ceramic cutting tools.



The performance of these tools can further be improved by deposition of hard coatings [7–11]. The literature apparently indicates that the AlTiN coated tools exhibit excellent thermal stability [12] which is a must condition in hard machining where large amount of heat is generated. Further, temperature generation in cutting tools is one of the major causes of tool failure especially during hard machining where machining forces are quite high resulting in elevated temperatures [1]. Thus, the present work investigates the temperature generation during hard machining of AISI 52100 steel (62 HRC hardness) with uncoated and PVD AlTiN coated  $\text{Al}_2\text{O}_3/\text{TiCN}$  mixed ceramic cutting tools. Further, a finite element model has been adopted to predict the temperature generated during the hard machining process for comparative assessment with the measured temperature.

## 2. Experimental methodology

AlTiN coating was deposited on to the  $\text{Al}_2\text{O}_3/\text{TiCN}$  (designation: SNGA120408) based mixed ceramic cutting tool using Oerlikon Balzers rapid coating machine (RCM) in cathode arc evaporation mode. The detailed coating process has been elaborated by Kumar and Patel [2]. After deposition of coating on the ceramic substrates, the coated and uncoated cutting tools were subjected to continuous turning tests under dry cutting environment on a heavy duty lathe machine provided by HMT Ltd., India (see Fig. 1) by mounting the cutting tools on a tool holder with the specification as PSBNR2020K12. Each experiment was carried out 3 times to avoid machining errors. The machining parameters used for the turning tests are listed in Table 1. The temperature measurements were performed during each experimental run with the help of a non-contact infrared thermometer (Make: HTC, Model: IRX-65) that has the capability to measure the temperature of a 1 mm spot from a distance of 30 mm. The temperatures were recorded after every 2 min during each experimental run and an average was considered as the final cutting temperature.



**Fig. 1** Experimental setup for turning tests

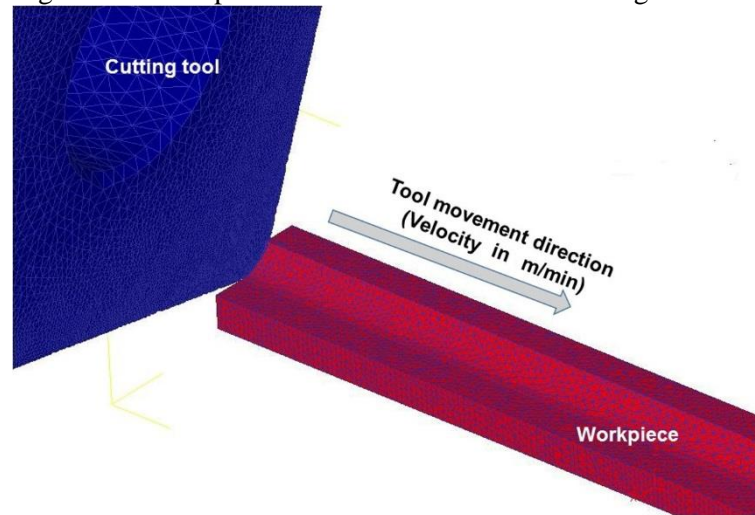
**Table 1** Machining parameters for turning tests

Experimental run	Cutting speed (m/min)	Feed rate (mm/rev)	Depth of cut (mm)
1	110	0.12	0.5
2	145	0.12	0.5
3	180	0.12	0.5

## 3. Finite element analysis

In the present work, Deform 3D finite element analysis and modelling software for the numerical analysis of the temperature generation during dry and hard turning of AISI 52100 steel. All the simulations were performed using  $\text{Al}_2\text{O}_3/\text{TiCN}$  based mixed ceramic inserts as cutting tools in coated

and uncoated condition. A thickness of 3  $\mu\text{m}$  was considered for the AlTiN coating. The separation of the chips has been defined using Lagrangian approach in the numerical modelling process. A linear simplified workpiece model as illustrated in Fig. 2 has been implemented for the present study. The tool has been considered as rigid whereas the workpiece was considered as visco-plastic. The cutting tool and the workpiece were meshed with 1,55,000 and 90,000 tetrahedral thermally coupled elements respectively. For the purpose of precisely investigating the cutting zone, a very fine mesh has been defined at the cutting zone for the cutting tool. The heat transfer coefficient and air convection on the free surface were assumed as per the considerations from Özel et al. [13]. Also, all the simulations were performed considering an initial temperature of 20  $^{\circ}\text{C}$  for both the cutting tool and the workpiece.



**Fig. 2** Simplified linear finite element meshing model for turning simulations

The equivalent flow stress for the workpiece material has been defined with the help of Johnson-Cook (J-C) material flow stress model. J-C model applied by Kim et al.[3] has been implemented for the present numerical study. J-C model indicating the equivalent stress has been shown in Equation 1.

$$\bar{\sigma} = [A + B \cdot \varepsilon^n] \left[ 1 + C \cdot \ln \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \right] \left[ 1 - \frac{T - T_{\text{Room}}}{T_{\text{Melt}} - T_{\text{Room}}} \right]^m \quad (1)$$

where A, B, n, C,  $\varepsilon$ ,  $\dot{\varepsilon}$ ,  $\dot{\varepsilon}_0$ ,  $T_{\text{Room}}$ ,  $T_{\text{Melt}}$  and m are material model constants. The values of model constants and temperature dependent material properties for workpiece are adopted as implemented by Kumar and Patel [1]. The model constants used for the present work are illustrated in Table 2

**Table 2** J-C material constitutive model constants for AISI 52100 steel (62 HRC)

A (MPa)	B (MPa)	n	C	m	$T_{\text{Melt}}$ (K)
774.78	134.46	0.371	0.0173	3.171	1760

The researchers have employed various friction models that are basically based on Coulomb's coefficient of friction or shear friction factors [14–16] but there is scarcity of studies that involve implementation of hybrid models. Thus, the present work involves implementation of a hybrid model which has been shown in Equation 2.

$$s_f = \begin{cases} \alpha \sigma_n, & \text{if } \alpha \sigma_n < v \bar{\tau} \\ v \bar{\tau}, & \text{if } \alpha \sigma_n \geq v \bar{\tau} \end{cases} \quad (2)$$

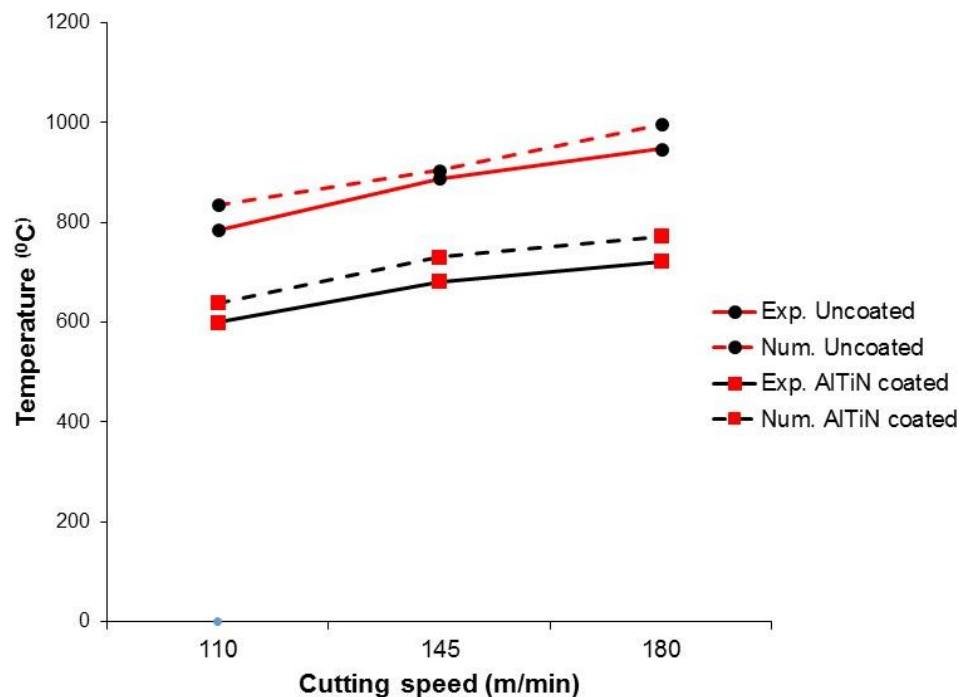
where  $s_f$  is the frictional shear stress,  $\alpha$  is the Coulomb's coefficient of friction,  $\sigma_n$  is the normal stress,  $v$  is the shear friction factor and  $\bar{\tau}$  is the shear flow stress of workpiece material which is further expressed as

$$\bar{\tau} = \frac{\bar{\sigma}}{\sqrt{3}} \quad (3)$$

The values of shear friction factor and Coulomb's coefficient of friction have already been elaborated by Kumar and Patel [2]. The present model tries to explore the sliding and sticking zones of friction during the machining process.

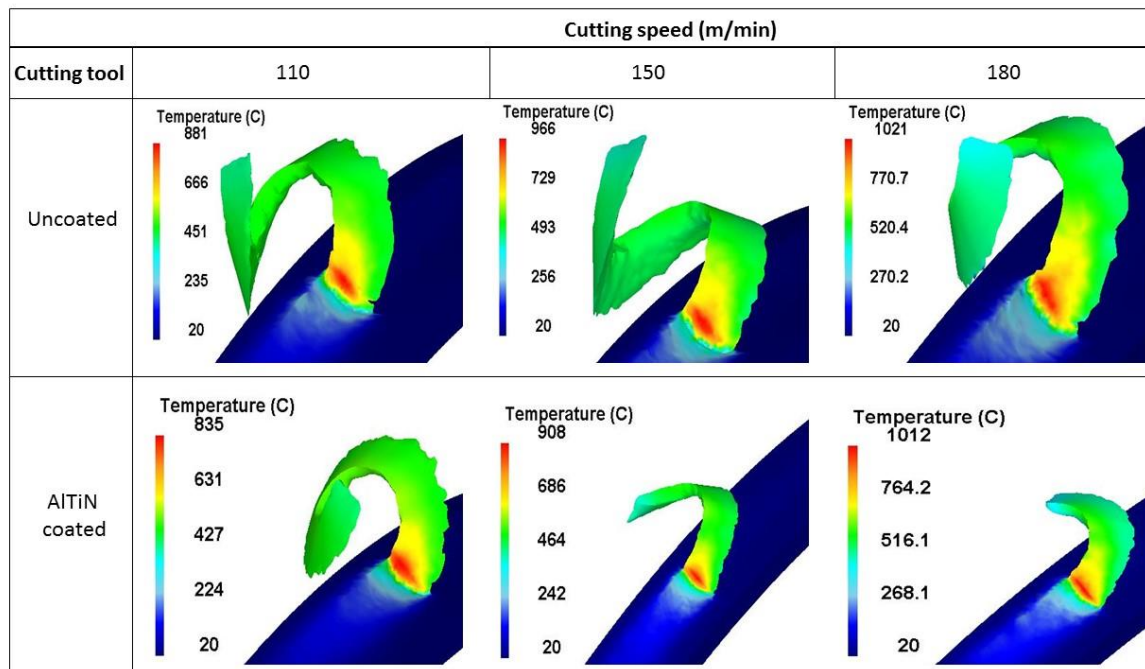
#### 4. Results and discussions

Fig. 3 represents the variation of cutting temperature with cutting speed for coated and uncoated cutting tools respectively. The dashed lines represent the corresponding numerically predicted cutting temperatures while machining of AISI 52100 steel at 62 HRC hardness under dry cutting environment. It was observed that the measured cutting temperatures were less as compared to the numerically predicted cutting temperatures. These lower readings during experimental procedure have accounted due the hindrance offered by the moving chips and thus, the exact cutting zone could not be explored. Therefore, the temperatures recorded were only of the top surface of the chips. However, owing to the high thermal conductivity of workpiece material and small thickness of the chips, there would not be much difference in the cutting zone temperature and the temperature of the top surface of the chips. This phenomenon has also been discussed by Kumar and Patel [1,2].



**Fig. 3** Variation of temperature with cutting speed

The investigation of temperature generation revealed that the cutting zone temperature reduced drastically while machining with AlTiN coated tools when compared with uncoated cutting tools. Numerical results also reveal similar trend, though the temperatures are on the higher side due to the reasons mentioned above. However, the temperature gain by the workpiece is almost same when machining with coated and uncoated cutting tools which indicates that the energy required for material removal from a specimen remains almost constant (see Fig. 4). The reduction in temperature generation during machining with AlTiN coated tools is mainly due to the lower friction offered by the coating material as compared to uncoated cutting tool [2]. Further, higher hardness of AlTiN coating when compared with uncoated cutting tool, provides it with added wear resistance.



**Fig. 4** Numerically predicted temperature distribution in the workpiece material during turning of AISI 52100 steel

## 5. Conclusions

The present work investigated the machining behavior of AlTiN coated and uncoated  $\text{Al}_2\text{O}_3/\text{TiCN}$  based mixed ceramic cutting tools during turning of hardened AISI 52100 steel (62 HRC). Deposition of AlTiN coating on the mixed ceramic substrate resulted in the reduction of cutting temperature. The lower coefficient of friction and superior wear resistance offered by the AlTiN coating led to the reduction of temperature generation during the machining process.

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