On the Heat Partition Properties of (TiAl)N Compared with TiN Coating in High Speed Machining

[Link to publication record in Manchester Research Explorer](#)

Citation for published version (APA):

Akbar, F., Sheikh, M., & Mativenga, P. (2009). On the Heat Partition Properties of (TiAl)N Compared with TiN Coating in High Speed Machining. *Proceedings of the Institution of Mechanical Engineers - Part B: Journal of Engineering Manufacture*, 223(4), 363-375.

Published in:

Proceedings of the Institution of Mechanical Engineers - Part B: Journal of Engineering Manufacture

Citing this paper

Please note that where the full-text provided on Manchester Research Explorer is the Author Accepted Manuscript or Proof version this may differ from the final Published version. If citing, it is advised that you check and use the publisher's definitive version.

General rights

Copyright and moral rights for the publications made accessible in the Research Explorer are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

Takedown policy

If you believe that this document breaches copyright please refer to the University of Manchester's Takedown Procedures [<http://man.ac.uk/04Y6Bo>] or contact uml.scholarlycommunications@manchester.ac.uk providing relevant details, so we can investigate your claim.

On the heat partition properties of (Ti, Al)N compared with TiN coating in high-speed machining

F Akbar*, P T Mativenga, and M A Sheikh

School of Mechanical, Aerospace and Civil Engineering, The University of Manchester, Manchester, UK

The manuscript was received on 25 September 2008 and was accepted after revision for publication on 12 December 2008.

DOI: 10.1243/09544054JEM1365

Abstract: Heat flow into the cutting tool is one of the critical factors in metal cutting which can influence tool wear mechanisms, tool performance, and quality of the machined part, especially in high-speed machining. An investigation was undertaken to determine the fraction of heat that flows into the cutting tool for high-speed machining with coated tools. The cutting tests were performed over a wide range of cutting speeds during which the cutting temperatures were measured experimentally using an infrared thermal imaging camera. The sticking and sliding regions were established from an examination of the tool–chip contact region using scanning electron microscopy and energy-dispersive X-ray analysis. In the finite element model, a non-uniform heat flux was applied to match the experimental data. The heat partition results show that the use of coatings (Ti, Al)N may be more advantageous in high-speed machining than TiN coatings are.

Keywords: high-speed machining, heat partition, coatings, finite element method, contact phenomena

1 INTRODUCTION

High-speed machining (HSM) can be defined as machining at considerably higher cutting speeds and feed rates than is traditional practice. HSM processes enable high material removal rates, low cutting forces, reduction in lead times, and improved part precision [1, 2]. The challenge in HSM, however, is reduced tool life as a result of high cutting interface temperatures. Therefore, it is necessary to have an understanding of tool temperatures and heat partition in order to determine the optimum cutting conditions.

HSM requires special engineered cutting tool materials with extreme hot hardness and improved fracture toughness, as well as resistance to abrasion, thermal shock, adhesion, and diffusion. The use of advanced tool materials with sufficient heat isolation between the chip and the tool results in the development of dry machining for typical cutting operations. Currently coatings of different structures

containing layers of titanium carbide, titanium nitride (TiN), titanium carbonitride (Ti(C, N)), aluminium oxide (Al_2O_3), and titanium aluminium nitride ((Ti, Al)N) are mostly used in metal cutting [3, 4]. Over the past decades, TiN coatings have gained increasing importance for cutting tools, dies, and many mechanical parts to increase their lifetime and performance owing to their attractive properties such as high hardness, good wear resistance, and chemical stability [5, 6]. More recently, (Ti, Al)N coatings have been developed as hard coatings with excellent properties for high-temperature use [7, 8].

By 1995, as stated by Cselle and Barimani [9], there was an industrial trend towards using dry HSM. Nevertheless, major improvements in the performance of high-speed metal-cutting operations can only be achieved by understanding the full potential provided by cutting tool coatings. This requires attention to be focused on the role of the physical and thermal properties of the workpiece and tool materials in achieving the optimum tool–chip contact conditions including tribological and thermal relationships. For HSM which is associated with higher cutting interface temperatures, it is obvious that a more acceptable model must be developed for practical machining applications, in which the

*Corresponding author: School of Mechanical, Aerospace and Civil Engineering, The University of Manchester, Sackville Street Building, Manchester, Lancashire M60 1QD, UK. email: faraz.akbar@postgrad.manchester.ac.uk

temperature dependence of fundamental thermal properties is treated as one of the process variables.

It is well known [10–12] that heat generated during metal cutting is a critical factor which influences the performance of the cutting tool. According to Grzesik [7], the maximum working temperature for the tool can be increased by depositing (Ti, Al)N-based coatings because this hard layer maintains the hot hardness up to 800 °C. In contrast, the cutting speed for TiN coating with a substantially lower hardness should be reduced because its maximum working temperature is 600 °C. These values of maximum working temperature are established from the fact that TiN oxidizes intensively at a temperature higher than 600 °C, whereas (Ti, Al)N shows a high oxidation resistance up to 800 °C.

An important aspect of dry machining when using coated carbide tools is the partition of the generated frictional heat between elements of the sliding tribopair, consisting of the chip and the coating/carbide substrate. The prediction of heat partition between the tool and the chip represents a big challenge. It was shown by König *et al.* [13] that thermophysical properties of Ti(C, N) and (Ti, Al)N coatings on high-speed steel substrate significantly influence heat flow in the coating system. They also suggested that (Ti, Al)N coating offers superior thermal protection to the substrate in turning because it carries the highest value of the heat transmission coefficient [13]. Additionally, since coatings can affect contact conditions, this gives the possibility of design of functionally graded coating systems [14]. Typical examples of such systems include composite films with an Al₂O₃ intermediate layer which act as a thermal barrier and hard/soft composites as a means of lowering friction. In particular, thermal conductivity and the thermal barrier effect have been found to be the key factors in chip curling [15] and controlling the heat partition in the chip-coating/substrate tribosystem [16]. In a recent investigation [1], it was reported that compared with uncoated carbide tools, the TiN coating resulted in a reduction in the percentage of heat transferred to the cutting tool.

Numerous investigations on coatings resistance from a mechanical point of view, i.e. abrasion, attrition, etc., exist [17]. However, few studies have treated the influence of coatings from a thermal point of view. Grzesik [18] reported that the use of an appropriate coating decreased the friction coefficient at the tool-chip contact area. Klocke *et al.* [14] also indicated that the coating modified the contact condition, reducing friction and adhesion. In addition, Akbar *et al.* [1] reported that the TiN coating modified the contact condition and reduced adhesion. Grzesik [16] proposed that the average tool-chip interface temperature and the fraction of heat transferred into

the tool depend on the thermophysical properties of the workpiece and the coating. Hence, an appropriate selection of metal-on-coating pair reduces the cutting temperature and allows heat transfer into the chip to be controlled. Grzesik [19] also highlighted that an Al₂O₃ coating can act as a thermal barrier. In related work, Du *et al.* [20] found a very slight influence of the Al₂O₃ coating on the temperature in the tool and explained this by its lower thermal conductivity compared with other coatings.

While the heat partition effects of coatings have been postulated in literature, very little quantitative evaluation has been reported. Heat partition values are usually assumed for finite element method (FEM) modelling using uncoated cutting tools. These values were reviewed by the present authors in an earlier publication [1], but there is no other work reported on (Ti, Al)N coating in the HSM regime. However, the robustness of FEM and other numerical models is strongly dependent on thermomechanical parameters such as heat partition into the cutting tool.

This paper has investigated and quantified the heat partition benefits of using (Ti, Al)N coating. Cutting experiments and numerical (FEM) simulations were used to quantify heat partition. The experiments were conducted on AISI/SAE 4140 high-strength alloy steel which was turned using TiN- and (Ti, Al)N-coated tools. One novelty of the approach is the application of non-uniform heat flux in the model obtained from an experimental quantitative determination of sticking and sliding zones along the tool-chip interface. The acquired data consisting of cutting forces, chip thickness, tool-chip contact area, and sticking and sliding lengths were used for heat source characterization which was applied in the finite element simulations.

2 EXPERIMENTAL INVESTIGATIONS

2.1 Experimental details

The cutting tests in the present investigation were conducted on a Dean Smith & Grace Lathes machine and a Kistler 9263 three-axis piezoelectric dynamometer was used to measure cutting forces. The cutting inserts had geometries designated as TCMW 16T304 (ISO specification) (triangular shape insert with 0.4 mm nose radius, 3.97 mm thickness, and 7° clearance angle). TiN and (Ti, Al)N coatings of 5 µm thickness were applied on two sets of inserts whose substrate material was carbide. The coating microhardness was measured experimentally on a Buehler 5114 microhardness-testing machine with 300 g load for both TiN and (Ti, Al)N coatings. The results are shown in Table 1. Figures 1(a) and (b) show the scanning electron microscopy (SEM) images of

cross-sectional views of the TiN- and (Ti, Al)N-coated tools respectively. In these images, TiN and (Ti, Al)N coatings and tungsten-carbide-based substrate materials show colour and brightness peculiar to the materials. The coating thickness was measured from cross-sectional views of the tools using SEM.

A prebored workpiece of AISI/SAE 4140 (Rockwell C hardness, 23.9 HRC) high-tensile alloy steel with an external diameter of 200 mm and a tube thickness of 2.5 mm was used in the cutting tests. The experimental set-up is shown in Fig. 2. AISI/SAE 4140 was chosen as it has many diverse applications in the manufacture of automobile components such as crankshafts, piston rods, steering components, axles, gears, and high-resistance screws. Experimental conditions were similar for both cutting tool materials. The cutting tests were performed at eight different cutting speeds of 100 m/min, 197 m/min, 314 m/min, 395 m/min, 565 m/min, 628 m/min, 785 m/min, and 880 m/min. These cutting speeds were set by the available spindle speeds on the conventional lathe. The feed rate and depth of cut were kept constant at 0.1 mm/rev and 2.5 mm respectively. The used tools were analysed using a scanning electron microscope equipped with an energy-dispersive X-ray analysis (EDXA) facility to quantify the sticking and sliding zones. The process parameters were

selected as appropriate to the cutting tests in the HSM range.

To analyse the surface quality of the freshly coated tools, the surface roughness was measured on the rake face of the new cutting inserts using a Wyko 1100 NT white-light interferometer equipped with image-processing software. The average surface roughness was calculated at regular intervals along the contact length of the inserts. These measurements indicated that TiN had a better average surface finish of $0.21\text{ }\mu\text{m}$ compared with the (Ti, Al)N which was $0.27\text{ }\mu\text{m}$.

2.2 Temperature measurements

Temperatures were measured using an infrared (IR) thermal imager FLIR ThermoCAM SC3000, which has a long-wave and self-cooling analysis system. This system allows extensive analysis of highly dynamic objects and events typically found in metal-machining

Table 1 Coatings and their mechanical properties

Coating	Vickers hardness (HV)	Coating thickness (μm)
TiN	1409	5
(Ti, Al)N	1800	5

Fig. 2 Experimental arrangement

Fig. 1 The SEM images of typical cross-sectional views of coating samples for (a) TiN and (b) (Ti, Al)N

research applications. The strong advantages for the present application are due to the small target size and the high spatial resolution achievable with IR cameras. The IR camera used within this study has a thermal sensitivity of 20 mK at 30 °C, an accuracy not better than 1 per cent or 1 °C for temperatures above 150 °C and less than 2000 °C. The quantum well infrared photon detector has a spectral range 8–9 µm with a resolution of 320 × 240 pixels. The system provides for automatic atmospheric transmission correction of temperature based on input distance from the object, atmospheric temperature, and relative humidity. A continuous electronic zoom (1–4 ×) is also provided. The system can acquire images in real time or at high speed (up to 750 Hz) with a reduction in the picture size so that each frame contains more than one image. The captured images are transferred to a dedicated personal computer with special built-in ThermoCAM analysis software (by FLIR Systems). The spatial resolution of the system depends essentially on the IR camera spectral range (8–9 µm for the camera used), the instantaneous field of view (IFOV) of the camera and the microscope lens. However, the limit of the camera's spectral range and the IFOV cannot be lowered irrespective of the lens magnification.

The IR thermal imager, FLIR ThermoCAM SC3000, was mounted near the machine turret and placed directly over the tool rake face during the cutting tests. The cutting tool temperatures were measured at three different points P₁, P₂, and P₃ on the tool rake face, as shown in Fig. 3. These three spots were appropriately selected as prominent observable locations on the rake face of the cutting tool. The thermal imaging system enabled the generation of thermal history of the cutting tool insert rake face at

Fig. 3 Temperature measurement locations of the specified multiple points (all dimensions are in millimetres)

distances away from the chip flow zone for points P₁, P₂, and P₃. The points were selected to observe the thermal images clearly and to avoid the effect of chip obstruction during machining.

The real temperature of an object depends strongly on the emissivity of the material, which is of particular concern when a thermal imaging camera is used. An accurate calibration of the thermographic system was carried out to find the emissivity values of the cutting tool surface materials (TiN- and (Ti, Al)N-coated inserts). Samples were heated to temperatures ranging from 100 °C up to 900 °C in an oven. A thermal imaging camera was used to read the inserts temperature and the emissivity was adjusted until the temperature reading of the thermal imager matched a thermocouple reading. 15 emissivity values were obtained at each temperature level. A mean of these values was then used for the camera setting. The average emissivities of TiN- and (Ti, Al)N-coated inserts were determined to be 0.21 and 0.45 respectively at 700 °C. Small variations in tool emissivity in the temperature range 450–900 °C given by 0.21 ± 0.00546 for TiN and 0.45 ± 0.00648 for (Ti, Al)N were observed.

3 NON-UNIFORM FRICTIONAL HEAT SOURCE ANALYSIS

A non-uniform frictional heat flux of the secondary heat source along the contact length cannot simply be treated as uniform owing to the presence of sticking and sliding zones which characterize the contact phenomena in machining. This distinction is highly dependent on the tool and the workpiece materials, as well as on cutting conditions. In the sticking zone, the shear stress (τ_{sh}) can be assumed to be constant along the entire sticking (seizure) contact length up to $x = l_{st}$, where x is the distance from the cutting tool edge. In the sliding zone, this shear stress reduces to zero at the point where the chip departs from the tool rake face. According to Wright *et al.* [21], the shear stress τ_{sh} in the sticking region can be computed from

$$\tau_{sh} = \frac{F_{fr}}{a_p(l_{st} + 0.5 l_{sl})} \quad (1)$$

where l_{st} is the sticking length of the tool–chip contact zone, l_{sl} is the sliding length of the tool–chip contact zone, a_p is the depth of cut, and F_{fr} is the frictional force which can be calculated from (Fig. 4)

$$F_{fr} = F_c \sin \gamma + F_f \cos \gamma \quad (2)$$

where F_c is the cutting force, F_f is the feed force, and γ is the rake angle. In this study, the heat flux $q(x)$ along the sticking zone is defined as $\tau_{sh} V_{ch}$ ($x \leq l_{st}$) which then linearly decreases to zero along the sliding contact zone ($l_{st} < x \leq l_{ch}$) [21–23].

Fig. 4 Forces acting on the considered system (F_c , cutting force; F_f , feed force; F_{fr} , frictional force; F_N , normal force on the tool face; F_R , resultant tool force; γ , rake angle)

4 FINITE ELEMENT SIMULATIONS

A heat transfer model of a three-dimensional tool was constructed using the commercial finite element analysis software, ABAQUS/Standard (6.6-1). A transient heat conduction analysis was carried out with adiabatic boundary conditions and an initial temperature of 25 °C. Convection boundary conditions were also applied, with relative air flow caused by workpiece rotations. The non-uniform frictional heat flux q at the tool rake face was calculated from cutting mechanics as described in section 3. The type of element used to model the whole cutting assembly was a four-noded tetrahedral heat transfer element DC3D4. The tool was modelled as a perfectly rigid body as tool materials have significantly high elastic moduli. The analysis was based on an estimated uniform or non-uniform heat flux as appropriate, applied over the experimentally established tool–chip contact area on the rake face of the cutting inserts. The actual geometries of the insert and the tool holder were used in the model. Figure 5 shows the finite element meshed model. In the meshing scheme, regions with large temperature gradients were refined considerably to improve the accuracy. Temperature-dependent thermal conductivity and specific heat values were used as given in Table 2. This is particularly essential for HSM where high temperatures are evaluated.

The boundary conditions were applied to the model for thermal analyses as follows: the cutting insert, shim seat, and tool-holder interaction surfaces were assumed to be smooth and held together with a

Fig. 5 Finite element mesh model of a cutting tool system generated in ABAQUS

rigid clamping system and were assumed to be in perfect contact. Initially the whole model was set at a room temperature of 25 °C. For non-interactive surfaces of the cutting insert, shim seat, and workpiece, heat losses due to heat convection were calculated using a convective heat transfer coefficient $h = 20 \text{ W/m}^2 \text{ K}$ [24].

4.1 Determination of heat partition (R_T) into the cutting tool

FEM was used in an inverse procedure aimed to identify the heat (R_T) flowing into the cutting tool. The aim of the algorithm was to minimize the difference between the predicted and the experimental steady state temperatures at multiple points (see Fig. 3). Heat partition into the cutting tool was obtained using the hybrid FEM–experimental technique, which was recently presented by the present authors [1]. For clarity, a brief description of this approach is summarized here.

1. For each experimental test, compute the non-uniform heat flux at the tool–chip interface.
2. In the finite element model, apply 100 per cent of the heat flux (uniform or non-uniform depending on contact phenomenon) as a thermal load on the tool–chip contact area.
3. Reduce the applied heat flux in the model until the measured and simulated temperatures are matched at three points. The fraction of this heat flux resulting in multiple-point temperature matching is taken as heat partition into the cutting tool.

This approach was used for a complete set of experimental tests discussed in section 2. For each test, the convergence on the minimum difference was found after a few iterations.

Table 2 Summary of the temperature-dependent mechanical and thermal properties of the coated cutting tools, the substrate, and the tool-holder material [1, 25–32]

		Value at the following temperatures				
		100 °C	300 °C	500 °C	700 °C	900 °C
<i>Properties of the TiN coated cutting tool</i>						
Young's modulus (GPa)	250					
Poisson's ratio	0.25					
Density (kg/m ³)	5420					
Thermal conductivity (W/m K)		21	22	23.0	24.38	25.50
Specific heat (J/kg K)		702.60	783.40	818.9	846.39	857.60
<i>Properties of (Ti, Al)N-coated cutting tool</i>						
Young's modulus (GPa)	370					
Poisson's ratio	0.22					
Density (kg/m ³)	1892					
Thermal conductivity (W/m K)		12.61	14.01	15.41	16.81	18.21
Specific heat (J/kg K)		639.89	727.28	769.46	794.29	810.67
<i>Properties of the substrate (tungsten-based carbide)</i>						
Young's modulus (GPa)	534					
Poisson's ratio	0.22					
Density (kg/m ³)	11 900					
Thermal conductivity (W/m K)		40.15	48.55	56.95	65.35	73.75
Specific heat (J/kg K)		346.01	370.01	394.01	418.01	442.01
<i>Properties of the tool holder (AISI 1045)</i>						
Young's modulus (GPa)	207					
Poisson's ratio	0.3					
Density (kg/m ³)	7844					
Thermal conductivity (W/m K)		50.70	45.30	38.10	30.10	25.75
Specific heat (J/kg K)		470.40	571.20	672.00	772.80	873.60

5 RESULTS AND DISCUSSION

5.1 Cutting forces

Figure 6 shows the variation of cutting forces with cutting speed. The cutting force decreases when the cutting speed is increased from 100 m/min to 314 m/min, marginally increases with the cutting speed up to 395 m/min, and subsequently decreases in the high-speed cutting region for TiN-coated tools. On the other hand, for (Ti, Al)N-coated tools, cutting forces gradually decrease when the cutting speed is increased from 100 m/min to 880 m/min. In general, the experimentally measured cutting and feed forces values for the TiN-coated tools are slightly higher than for the (Ti, Al)N-coated tools over the whole range of cutting speeds. The feed force also decreases gradually when the cutting speed is increased in all the cutting tests for both TiN- and (Ti, Al)N-coated tools.

Fig. 6 Variation in the cutting forces with the cutting speed

5.2 Shear angle and tool-chip compression ratio

The shear angle ϕ and the chip compression ratio λ_h can be computed from [33]

$$\phi = \tan^{-1} \left(\frac{\cos \gamma}{\lambda_h - \sin \gamma} \right) \quad (3)$$

where γ is the rake angle and λ_h is the chip compression ratio given by

$$\lambda_h = \frac{t_c}{t} \quad (4)$$

where t_c is the chip thickness after cutting and t is the undeformed chip thickness. Figures 7 and 8 show the variations in the chip compression ratio λ_h and shear

Fig. 7 Variation in the chip compression ratio with the cutting speed

Fig. 8 Variation in the shear angle with the cutting speed

angle ϕ with the cutting speed. For TiN-coated cutting tools, the chip compression ratio decreases while the shear angle increases when the cutting speed is increased from 100 m/min to 880 m/min. This is due to a decrease in the deformed chip thickness t_c . For (Ti, Al)N-coated cutting tools, a similar trend is observed; i.e. the chip compression ratio decreases while the shear angle increases for the whole range of cutting speeds. In general, the chip compression ratio is an important variable which is used in evaluating the amount of deformation of the chip and the shear angle. An increase in the shear angle reduces the area of the shear plane, thereby concentrating heat generation in a narrow zone and hence raising the temperature of the primary deformation zone.

5.3 Tool–chip contact area

The tool–chip contact area along the rake face of the cutting tool can affect the mechanics of machining, heat generation, and heat partition into the cutting tool. In this study, the tool–chip contact area of the worn TiN- and (Ti, Al)N-coated inserts was obtained at different cutting speeds from a scanning electron microscope equipped with image-processing software. Sample SEM images of the used inserts are shown in Fig. 9. Figure 10 presents the calculated tool–chip contact area obtained from the SEM images of the worn inserts at different cutting speeds for TiN- and (Ti, Al)N-coated tools. It is observed that the contact area is affected by the cutting speed. For TiN-coated tools, there is a consistent decrease in the contact area when the cutting speed is increased from 100 m/min to 880 m/min. On the

Fig. 9 SEM images of the tool–chip contact area at a cutting speed of 880 m/min for (a) TiN-coated and (b) (Ti, Al)N-coated tools

Fig. 10 Variation in the tool-chip contact area with the cutting speed

other hand, with (Ti, Al)N-coated tools, the contact area decreases with increasing cutting speed in both conventional and HSM regions. However, it should be noted that numerical results for the (Ti, Al)N-coated insert present a larger contact area for all cutting speeds compared with the TiN-coated inserts. These results clearly show that, for most cutting speeds, TiN coatings mitigate the expansion of contact area compared with the (Ti, Al)N-coated tools.

5.4 Determination of the sticking and sliding regions

SEM and EDXA were used to distinguish between the sticking and the sliding regions from an examination of the tool-chip contact region for carbide tools. The worn inserts were examined by SEM using a back-scattered imaging mode for all cutting speeds. The contact length was scanned for evidence of iron (Fe) transfer from the chip. The evaluation of this Fe transfer intensity was taken on a cross-sectional plane of the contact area for both TiN- and (Ti, Al)N-coated tools in the direction of chip flow.

Figures 11(a) to (f) show the EDXA maps of Fe concentration on the rake face of the cutting inserts for TiN- and (Ti, Al)N-coated tools for three cutting speeds of 100 m/min, 565 m/min, and 880 m/min. All the micrographs show a low concentration of Fe about the cutting edge and this can be attributed to the effect of the tool edge radius. For TiN-coated tools, Fig. 11(a) shows that at 100 m/min the tool rake face is not dominated by Fe transfer from the workpiece, hence providing evidence that seizure does not occur at this cutting speed. As the cutting speed is increased to 565 m/min (Fig. 11(b)), the nature of the contact remains the same and the tool rake face is not dominated by a significant amount of Fe transfer, thereby suggesting that the tribological phenomenon

of sliding takes place. For a higher cutting speed of 880 m/min, slightly high peaks of Fe appear near the edge of the rake face within the contact length (Fig. 11(c)). These Fe peaks support a slightly dominant sticking condition. In summary, it can be concluded from Figs 11(a) to (c) that, for TiN-coated cutting tools, no significant sticking or seizure occurred for 100 m/min and 565 m/min, with 32 per cent sticking and 68 per cent sliding at 880 m/min.

For (Ti, Al)N-coated tools, at a low cutting speed of 100 m/min, no significant concentration of Fe is present (less than 10 per cent), indicating the absence of material transfer or sticking and hence supporting a dominant sliding condition (Fig. 11(d)). When the cutting speed increases to 565 m/min, still no dominant Fe concentration is present (Fig. 11(e)), again supporting a prevalent sliding condition. At the highest cutting speed of 880 m/min (Fig. 11(f)), about 48 per cent of the contact area shows a significant Fe transfer, and hence a 48 per cent sticking (seizure) and 52 per cent sliding is established for this case. It is worth noting that TiN-coated tools reduce the sticking of the work material compared with the (Ti, Al)N-coated tools in the HSM region.

5.5 Heat partition into the TiN- and (Ti, Al)N-coated cutting tools

Figure 12 shows typical simulation results for temperature distribution at the cutting insert for a non-uniform heat input at a cutting speed of 565 m/min for TiN- and (Ti, Al)N-coated tools. These distributions clearly show the presence of high temperature gradients near the cutting edge. Very high temperatures are obtained, as expected, owing to the high strength of the machined workpiece alloy and high depth of cut which was set at 2.5 mm.

In the estimation of heat partition into the cutting tool with the hybrid FEM-experimental approach, a slight disagreement was observed between 'single-point' and 'multiple-point' temperature matching for both TiN- and (Ti, Al)N-coated tools. The tool temperatures obtained from the simulations were compared with the experimentally measured temperatures for uncoated tools. These are presented in Table 3 for three locations P_1 , P_2 , and P_3 defined in Fig. 3. The errors due to location uncertainty in measurements are considered small because the temperature gradients at these locations are rather insignificant. These results indicate that the tool-chip contact area is more sensitive to heat partition and temperature response than it is to the measurement locations. A systematic analysis has shown that a difference of 10 per cent in temperature values at the specified measurement locations produces a 16 per cent change in heat partition obtained from the corresponding simulations. It is also noted that

Fig. 11 EDXA Fe density maps along the tool rake face of TiN- and (Ti, Al)N-coated tools for cutting speeds of (a) 100 m/min, (b) 565 m/min, and (c) 880 m/min

temperature reductions obtained from the simulations are between 5°C and 10°C, similar to the variation in the experimental measurements. This variation could be because, when one point is selected for temperature matching, the thermal plane does not capture the complete variation in the non-uniform heat flux. Furthermore, it is likely that this

non-uniform heat flux also varies in the depth of cut direction, driven by chip curl.

The finite element thermal analysis of heat partition into the cutting tool is validated by its comparison with the experimentally measured temperatures with thermal imaging camera at three different spots P_1 , P_2 , and P_3 . In general, good agreement between

Fig. 12 Temperature distribution results at a cutting speed of 565 m/min for (a) TiN- and (b) (Ti, Al)N-coated tools

Table 3 Comparison between simulation and measured tool temperatures for TiN-coated cutting tools ($a_p = 2.5$ mm; $f = 0.1$ mm/rev)

Cutting speed (V_c) (m/min)	Simulation temperature ($^{\circ}\text{C}$)			Measured temperature ($^{\circ}\text{C}$)		
	P_1	P_2	P_3	P_1	P_2	P_3
100	146	202	131	140	199	128
314	132	248	125	139	256	125
565	115	199	109	122	208	104
785	123	214.5	109	125	224	112
880	131	230	111	130	241	114

Table 4 Comparison between simulation and measured tool temperatures for (Ti, Al)N-coated cutting tool ($a_p = 2.5$ mm; $f = 0.1$ mm/rev)

Cutting speed (V_c) (m/min)	Simulation temperature ($^{\circ}\text{C}$)			Measured temperature ($^{\circ}\text{C}$)		
	P_1	P_2	P_3	P_1	P_2	P_3
100	160	191	136	158	188	130
314	130	240	121	129	240	120
565	120	186	110	125	224	112
785	124	220	107	125	225	111
880	130	240	108	130	241	114

temperatures is obtained. The difference in the temperature values at P_3 is higher than at the other two measured locations because P_3 is furthest away from the tool–chip contact area zone. Generally, the simulations underestimate temperatures at the beginning of turning at low speeds but in high-speed regions the temperatures are overestimated. Over the range of cutting speeds, the percentage difference is less than 5 per cent, which is reasonable for the three different thermal imaging camera locations P_1 , P_2 ,

and P_3 . In summary, good agreement between experimentally measured and finite element temperatures at three different locations throughout the turning process validates the proposed hybrid FEM–experimental approach to predict heat partition into the coated cutting tool. The tool temperatures for (Ti, Al)N-coated tools obtained from the simulations are compared with the experimentally measured temperatures. These are presented in Table 4 for the three measurement

locations P_1 , P_2 , and P_3 . Like TiN-coated tools, these results also indicate that the thermal properties and tool-chip contact area are more sensitive to heat partition and temperature response than to measurement locations.

Figure 13 compares heat partition into the cutting tool for TiN- and (Ti, Al)N-coated tools following the hybrid FEM-experimental approach and multiple-point temperature matching. For both TiN and (Ti, Al)N coatings the graph shows a notable change in trend at 400 m/min. The mechanism for the change in heat partition when the cutting speed approaches 400 m/min needs further investigation. However, the contact area has been found to be a dominant influence on heat partition. The cutting speed of 400 m/min represents the HSM transition zone where the trend for a reduction in the contact length with increasing cutting speed, as experienced in conventional machining [34, 35], changes and starts to increase. This is driven by the change in the sliding contact phenomenon. This trend has been reported in earlier work by Abukhshim *et al.* [36].

For TiN-coated tools, heat partition varies from 35 per cent down to 9.5 per cent. A continuously decreasing trend for heat partition into the cutting tool is observed with TiN-coated tools for the whole range of cutting speeds. For (Ti, Al)N-coated tools, in the conventional cutting speed range from 100 m/min to 395 m/min, the heat partition coefficient obtained varies from 38 per cent down to 16 per cent. When the cutting speed is increased above 395 m/min in the HSM region, the nature of the contact changes and the tool-chip contact length and hence the contact area decrease for (Ti, Al)N tools. As a consequence, Fig. 13 shows that the fraction of heat flowing into the (Ti, Al)N-coated tool gradually decreases with increasing cutting speed and reaches 9.2 per cent at 880 m/min. In summary, this implies that the use of single-layer TiN-coated tools compared with the (Ti, Al)N-coated

tools can cause a reduction in heat partition into the cutting tool at a conventional cutting speed but does not do so in the HSM region. In the HSM region, the reduction of heat partition is more dominant for (Ti, Al)N-coated tools. Therefore, it can be concluded that the benefits of reduction in heat partition due to the (Ti, Al)N coating are more pronounced in HSM than in conventional machining.

Thermal effects caused by coatings have an important influence on the tribological behaviour between the cutting tool and the chip. The amount of thermal energy transferred into the chip depends on the thermal conductivity of the coating film deposited on the cutting tool insert. When the thermal conductivity of the cutting tool is low, the temperature in the chip is high, and consequently the fraction of heat entering the cutting tool is low. Furthermore, there is a direct correlation between the tool-chip contact length, the properties of the cutting tool, and the performance of the cutting process. Cutting tool materials with a low thermal conductivity produce more curled chips because of a thermal bimetallic effect. As presented earlier, Table 2 gives the temperature-dependent thermal conductivity values for TiN and (Ti, Al)N cutting tool materials. A more conductive layer would allow higher heat flux to be conducted through it, resulting in a lower temperature at the tool-chip interface. It can be seen from Table 2 that the thermal conductivity values for (Ti, Al)N coating are lower than for TiN tools. It should be noted that (Ti, Al)N film applied to tungsten-based carbide provides the lowest values of heat partition in the HSM region compared to TiN-coated tools. In fact, the (Ti, Al)N coating provides the highest contact temperatures, which allows the friction force to be reduced owing to the formation of an Al_2O_3 layer from the chip material. It is reasonable to conclude that Al_2O_3 will only be formed at high cutting temperatures, i.e. at high cutting speeds. This study suggests that this could happen above 395 m/min cutting speeds (crossover point for TiN and (Ti, Al)N heat partition in Fig. 13).

In addition, the Al_2O_3 layer contributes to the reduction in temperature on the substrate, thereby offering a stronger thermal barrier. Additionally the Al_2O_3 layer has a lower thermal conductivity and therefore less heat can go to the substrate.

6 CONCLUSIONS

In the machining of AISI/SAE 4140 steel, the use of higher cutting speeds leads to thinner chips, reduced length of the shear plane, and increased thermal loads and hence temperatures. Thus, thermal effects are critical in HSM and hence the selection of an appropriate cutting tool coating system is required.

Fig. 13 Variation in the heat partition (R_T) into the cutting tool with the cutting speed

A numerical model has been used in this study which in conjunction with experimental results quantifies heat partition into the cutting tools. The results show that a TiN coating causes a larger reduction in heat partition into the cutting tool compared with the (Ti, Al)N-coated tool at conventional cutting speeds. In the HSM region, on the other hand, the (Ti, Al)N coating is more advantageous than the TiN-coated tool and causes a larger reduction in heat partition into the cutting tool. It may be concluded that, in comparison with the TiN-coated tools, (Ti, Al)N coatings improve the tribological phenomena in the HSM region, by providing a lower thermal conductivity for the tooling systems and ultimately reducing heat partition into the cutting tool.

REFERENCES

- 1 Akbar, F., Mativenga, P. T., and Sheikh, M. A. An evaluation of heat partition in high-speed turning of AISI/SAE 4140 steel with uncoated and TiN-coated tools. *Proc. IMechE, Part B: J. Engineering Manufacture*, 2008, **222**(B7), 759–771.
- 2 Fallbohmer, P., Rodriguez, C. A., Ozel, T., and Altan, T. High-speed machining of cast iron and alloy steels for die and mold manufacturing. *J. Mater. Processing Technol.*, 2000, **98**, 104–115.
- 3 Prengel, H. G., Pfouts, W. R., and Santhanam, A. T. State of the art in hard coatings for cutting tools. *Surf. Coatings Technol.*, 1998, **102**, 183–190.
- 4 Klocke, F. and Krieg, T. Coated tools for metal cutting-features and applications. *Ann. CIRP*, 1999, **48**(2), 515–525.
- 5 Wallen, P. and Hogmark, S. Influence of TiN coating on wear of high speed steel at elevated temperature. *Wear*, 1989, **130**, 123–135.
- 6 Akbar, F., Mativenga, P. T., and Sheikh, M. A. An investigation of the tool-chip interface temperature and heat partition in high-speed machining of AISI/SAE 4140 steel with TiN-coated tool. In Proceedings of the 35th International MATADOR Conference, Taipei, Republic of China, 18–20 July, 2007, pp. 215–218 (Springer, London).
- 7 Grzesik, W. Friction behaviour of heat isolating coatings in machining: mechanical, thermal and energy-based considerations. *Int. J. Mach. Tools Mf.*, 2003, **43**, 145–150.
- 8 Rech, J., Djouadi, M. A., and Peer, J. Wear resistance of coatings in high speed gear hobbing. *Wear*, 2001, **250**, 45–53.
- 9 Cselle, T. and Barimani, A. Today's applications and future developments of coatings for drills and rotating cutting tools. *Surf. Coatings Technol.*, 1995, **76–77**, 712–718.
- 10 Boothroyd, G. and Knight, W. A. *Fundamentals of machining and machine tools*, 2nd edition 1989 (Marcel Dekker, New York).
- 11 Trent, E. M. *Metal cutting*, 3rd edition 1991 (Butterworth, London).
- 12 Akbar, F., Mativenga, P. T., and Sheikh, M. A. An evaluation of heat partition models in high speed machining of AISI/SAE 4140 steel. In Proceedings of the Sixth International Conference on Manufacturing Research (ICMR08), Uxbridge, Middlesex, 9–11 September 2008, Vol. 1, pp. 13–21 (Brunel University Press, London).
- 13 König, W., Fritsch, R., and Kammermeier, D. New approaches to characterizing the performance of coated cutting tools. *Ann. CIRP*, 1992, **41**(1), 49–54.
- 14 Klocke, F., Krieg, T., Gerschwiler, K., Fritsch, R., Zinkann, V., Pohls, M., and Eisenblatter, G. Improved cutting processes with adapted coating systems. *Ann. CIRP*, 1998, **47**(1), 65–68.
- 15 Balaji, A. K., Sreeram, G., Jawahir, I. S., and Lenz, E. The effects of cutting tool thermal conductivity on tool-chip contact length and cyclic chip formation in machining with grooved tools. *Ann. CIRP*, 1999, **48**(1), 33–38.
- 16 Grzesik, W. The influence of thin hard coatings on frictional behaviour in the orthogonal cutting process. *Tribology Int.*, 2000, **33**, 131–140.
- 17 Gu, J., Barber, G., Tung, S., and Gu, R. J. Tool life and wear mechanism of uncoated and coated milling inserts. *Wear*, 1999, **225–229**, 273–284.
- 18 Grzesik, W. An integrated approach to evaluating the tribo-contact for coated cutting inserts. *Wear*, 2000, **240**, 9–18.
- 19 Grzesik, W. Experimental investigation of the cutting temperature when turning with coated indexable inserts. *Int. J. Mach. Tools Mf.*, 1999, **39**, 355–369.
- 20 Du, F., Lovell, M. R., and Wu, T. W. Boundary element method analysis of temperature fields in coated cutting tools. *Int. J. Solids Structs*, 2001, **38**(26–27), 4557–4570.
- 21 Wright, P. K., McCormick, S. P., and Miller, T. R. Effect of rake face design on cutting tool temperature distributions. *Trans. ASME, J. Engng Industry*, 1980, **102**(2), 123–128.
- 22 Tay, A. E., Stevenson, M. G., and DeVahl Davis, G. Using the finite element method to determine temperature distribution in orthogonal machining. *Proc. Inst. Mech. Engrs*, 1974, **188**, 627–638.
- 23 Huang, Y. and Liang, S. Y. Cutting temperature modeling based on non-uniform heat intensity and partition ratio. *Machining Sci. Technol.*, 2005, **9**, 301–323.
- 24 Yen, Y. -C., Jain, A., Chigurupati, P., Wu, W. -T., and Altan, T. Computer simulation of orthogonal cutting using a tool with multiple coatings. In Proceedings of the Sixth CIRP International Workshop on *Modeling of machining operations*, Hamilton, Ontario, Canada, 2003, pp. 119–130 (McMasters University Hamilton, Ontario, Canada).
- 25 Yen, Y. -C., Jain, A., Chigurupati, P., Wu, W. -T., and Altan, T. Computer simulation of orthogonal cutting using a tool with multiple coatings. *Machining Sci. Technol.*, 2004, **8**(2), 305–326.
- 26 Reginaldo, T. C., Ng, E. -G., and Elbestawi, M. A. Tool wear when turning hardened AISI 4340 with coated PCBN tools using finishing cutting conditions. *Int. J. Mach. Tools Mf.*, 2007, **47**, 263–272.
- 27 Abukhshim, N. A., Mativenga, P. T., and Sheikh, M. A. Investigation of heat partition in high speed turning of high strength alloy steel. *Int. J. Mach. Tools Mf.*, 2005, **45**, 1687–1695.

- 28 Gale, W. F. and Totemeier, T. C. (Eds) *Smithells metals reference book*, 2004 (Elsevier, Amsterdam).
- 29 Childs, T., Maekawa, K., Obikawa, T., and Yamane, Y. *Metal machining theory and applications*, 2000 (Arnold, London).
- 30 Lengauer, W., Binder, S., Aigner, K., Ettmayer, P., Guillou, A., Debuigne, J., and Groboth, G. Solid state properties of group IVb carbonitrides. *J. Alloys Compounds*, 1995, **217**, 137–147.
- 31 Barsoum, M. W., Rawn, C. J., El-Raghy, T., Procopio, A. T., Porter, W. D., Wang, H., and Hubbard, C. R. Thermal properties of Ti_4AlN_3 . *J. Appl. Physics*, 2000, **87**(12), 8407–8414.
- 32 Finkel, P., Barsoum, M. W., and El-Raghy, T. Low temperature dependencies of the elastic properties of Ti_4AlN_3 , $\text{Ti}_3\text{Al}_{1.1}\text{C}_{1.8}$, and Ti_3SiC_2 . *J. Appl. Physics*, 2000, **87**(4), 1701–1703.
- 33 Merchant, M. E. Mechanics of the metal cutting process. I. Orthogonal cutting and type 2 chip. *J. Appl. Physics*, 1945, **16**(5), 267–275.
- 34 Gad, G. S., Armarego, J. A., and Smith, A. J. R. Tool–chip contact length in orthogonal machining and its importance in tool temperature predictions. *Int. J. Prod. Res.*, 1992, **30**(3), 485–501.
- 35 Sadik, M. I. and Lindstrom, B. The role of tool–chip contact length in metal cutting. *J. Mater. Processing Technol.*, 1993, **37**, 613–627.
- 36 Abukhshim, N. A., Mativenga, P. T., and Sheikh, M. A. An investigation of the tool–chip contact length and wear in high-speed turning of EN19 steel. *Proc. Instn Mech. Engrs, Part B: J. Engineering Manufacture*, 2004, **218**, 889–903.

APPENDIX

Notation

a_p	depth of cut (mm)
f	feed rate (mm/rev)
F_c	cutting force (N)
F_f	feed force (N)
F_{fr}	frictional force at the rake face (N)
h	convective heat transfer coefficient (W/m ² K)
l_{ch}	tool–chip contact length (mm)
l_{sl}	sliding length of the tool–chip contact zone (mm)
l_{st}	sticking length of the tool–chip contact zone (mm)
q	non-uniform heat flux along the tool–chip interface (W/mm ²)
R_T	fraction of the heat conducted into the coated cutting tool
t	undeformed chip thickness (mm)
t_c	actual chip thickness (mm)
V_c	cutting velocity (m/min or m/s, as defined)
V_{ch}	chip velocity (m/s)
γ	rake angle (deg.)
λ_h	chip compression ratio = t_c/t
ϕ	shear angle (deg.)
τ_{sh}	shear stress (N/mm ²)