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The influence of built-up layer formation on cutting performance of GG25 grey cast iron

Paolo Fiorini¹, Gerry Byrne¹ (1)

¹Advanced Manufacturing Science Research Centre, UCD School of Mechanical and Materials Engineering, University College Dublin, Belfield, Dublin 4, Ireland.

The success of high speed machining of grey cast iron relates to the protective built-up layer (BUL) that forms on the tool. The present work investigates BUL formation on pcBN tools for dry, high speed machining of GG25 grey cast iron (up to $v_c = 750$ m/min). This work suggests that the BUL distribution on the tool at high cutting speed ($v_c = 750$ m/min) is key to tool protection. Protection in the area of maximum cutting temperature is critical in preventing thermally driven wear modes, such as crater wear, found at low cutting speeds ($v_c = 250$ m/min).

Cubic boron nitride (CBN); Cutting tool; Grey cast iron

1. Introduction

Cast iron is widely used in industry as it offers a competitive strength-cost ratio, good castability and high machinability in terms of tool wear, cutting forces and power consumption [1]. The damping capacity of grey cast iron (GCI) makes it suitable for engine blocks, measurement equipment and the bases and frames of machine tools [2]. A census among 34 countries by Modern Casting in 2009 reported GCI to be the most cast metal [3].

High efficiency cutting of GCI is largely carried out using polycrystalline cubic boron nitride (pcBN) tooling as it exhibits superior tool life and higher cutting speeds ($v_c = 750$ – 1200 m/min [4]) under continuous and intermittent cutting conditions [5–7]. The successful combination of pcBN tooling and GCI can be largely attributed to the use of ‘High Speed Machining’ and ‘Dry Machining’ techniques, and the formation of a built-up layer (BUL) on the tool surface [4, 8]. A BUL is a thin, protective, regenerative layer that forms from workpiece material inclusions such as MnS and alumina-silicates – formation mechanisms and the benefit of such layers on tool protection during turning have been well clarified [9–11]. BULs are reported to act as both a solid lubricant and wear barrier thus reducing abrasion, oxidation and diffusion wear rates of the tool [4, 5, 7, 12–14].

It is often reported that a BUL forms more readily at higher cutting speeds ($v_c = 750$ – 2500 m/min) [4–7], and is reliant on an adequate workpiece composition and cutting zone temperature. Sufficient temperature is required to reduce the viscosity of the inclusion to facilitate transfer and deposition across the tool face [4, 15]. For example, Pereira *et al.* explored the influence of sulphur-content (0.065–0.18%) on the machinability of GG25 GCI ($v_c = 100$ – 200 m/min) with coated WC tools. The best tool life was found at the highest cutting speed and sulphur content, without a significant difference in workpiece properties [12].

Most studies that document BUL formation when cutting GCI typically focus on the resultant tool life and characterisation of the layer at the end of its tool life rather than analysing it throughout cutting. Furthermore, the high speed machining mechanisms understood to apply to most materials (i.e. those that form shear-localised chips) do not apply to GCI, which exclusively forms discontinuous chips [1]. For this reason, research is required to further understand the success of machining GCI in the high speed machining range which currently

points towards the formation of a BUL. This work therefore explores the following knowledge gaps and hypotheses:

1. To examine the progression of BUL formation during cutting.
2. The relationship between BUL formation and high cutting performance for high speed machining of GCI.
3. To explore the influence of Mn-content on BUL formation and cutting performance (S-content has been explored [12]).

2. Experimental setup

GG25 GCI, annular test-pieces were used for the present work. Straight, oblique turning was applied to the outer diameter (260 mm). Two batches were produced with low and high levels of Mn-content (0.57 and 0.80 wt%), see Table 1 for properties and composition. Chemical analysis was carried out using optical emission spectroscopy (OES), using an OBLF Spark Spectrometer ES-750-CA with 1–3% relative precision. Results presented in Sections 3 and 4 refer to test-pieces with 0.57 %Mn, while Section 5 reports on the comparison between batches with 0.57 and 0.80 %Mn. Using metallographic analysis, all batches were characterised as having graphite of Type I C 4 (ISO 945-1 (2008)), predominantly fine pearlite, steadite (Fc-C-P phase) and Type I MnS inclusions (highlighted in Figure 1). The 0.80 %Mn batch exhibited finer pearlite and smaller amounts of steadite at the grain boundaries which may explain its higher tensile strength.

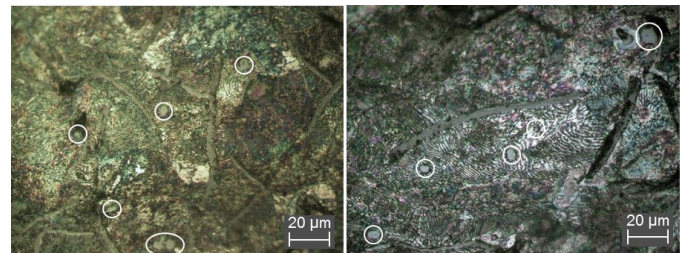


Figure 1. GCI with Mn-content of 0.57% (left) and 0.08% (right).

High-grade pcBN cutting inserts were used (SNMN 120404 020) in a carbide tool holder (DSSNL 2525M12). The pcBN material consisted of 90% cBN (10 µm grains) and 10% binder (aluminium nitrides and borides). The inserts were finished with a cutting edge radius of $r_\beta = 20$ µm, a chamfer land width of $b_\gamma = 200$ µm and a chamfer angle of $\gamma_f = 20^\circ$.

Oblique turning trials were carried out at low and high cutting speeds ($v_c = 250$ and 750 m/min) at a constant feedrate ($f = 0.3$ mm/rev) and depth of cut ($a_p = 1$ mm). Dry machining was carried out using a Colchester Mastiff 1400 (UK) lathe over a total cutting length of $l_c = 2.5$ km. Cutting forces were monitored using a Kistler dynamometer (9257B). The cutting tool was analysed after intervals of $l_c = 50, 100, 250, 500, 1500$ and 2500 m for:

- BUL thickness, crater wear and flank wear using optical profilometry (Nanovea PS50: vertical resolution of $0.012 \mu\text{m}$, lateral resolution of $0.1 \mu\text{m}$ and vertical accuracy of $0.06 \mu\text{m}$),
- morphology of the rake face using Scanning Electron Microscopy (SEM) with Backscattered Electron Imaging (BEI),
- and chemical analysis of the tool using ZAF corrected Energy-dispersive X-ray Spectroscopy (EDX). (FEI quanta 3d FEG: up to $\times 100,000$ magnification, 1.1 nm resolution).

A separate, orthogonal cutting test was carried out to assess the cutting temperature on the flank face. This used the same workpieces and tooling as the oblique trials. Temperature was measured during cutting using a VarioCAM 640hr thermal camera (0.08°C resolution and $\pm 2\%$ accuracy up to 2000°C).

Table 1 Mechanical and chemical properties of test-piece batches used.

Mechanical Properties:						
Batch	Tensile Strength (N/mm ²)		Brinell Hardness (HB)			
0.57%Mn	258		195			
0.80%Mn	317		196			
OES Chemical Composition (%):						
Batch	C	Si	Mn	P	S	Cr
0.57%Mn	3.720	2.420	0.570	0.001	0.021	0.020
0.80%Mn	3.940	1.930	0.800	0.001	0.021	0.130
	Mo	Ni	Al	Cu	Sn	Mn
0.57%Mn	0.050	0.050	0.004	0.240	0.015	0.017
0.80%Mn	0.020	0.050	0.004	0.310	0.015	0.017

3. Progressive built-up layer formation when machining GCI

The transfer of workpiece material to the tool surface was observed for all cutting conditions and at all cutting intervals ($l_c = 50$ – 2500 m). Fig. 2 presents SEM images of the primary cutting edge and nose, at the beginning and end of the cutting trials ($l_c = 50$ and 2500 m). It is clear from the SEM images that the BUL forms selectively across the tool with varying levels of coverage. The BUL thickness was determined using optical profilometry by comparing the difference in height of the tool in the area unaffected by the tool with the area of tool-chip engagement. The maximum BUL thickness was found to be $11.3 \mu\text{m}$ and $6.9 \mu\text{m}$ for cutting speeds of $v_c = 250$ and 750 m/min, respectively. The mean thickness for both cutting speeds was found to be below $2.5 \mu\text{m}$ over all cutting intervals tested, established within the first interval of cutting (50 m).

The BUL formed on tools at higher cutting speed ($v_c = 750$ m/min) is found to develop more closely to the primary cutting edge and the area of tool-chip contact. Tools used to machine at lower cutting speed ($v_c = 250$ m/min) form over a greater area on both the rake and flank faces (Fig. 2).

The bright deposit seen on the SEM images of the tool in Fig. 2 is identified by EDX to be mainly composed of Mn and S. To identify the BUL more accurately, the elements measured were restricted to known workpiece elements (Al, Si, Mn, S and Fe). Of these, it is noted that the cutting tool's binder also includes Al and Si. No significant trends in BUL composition were found between cutting intervals – in all cases the deposit on the tool was found to mainly consist of Mn and S with lower levels of Fe, Si and Al. Mn and S were found to be present to the approximate weight ratio of 2:1, Mn:S, suggesting a compound of MnS as reported by other

authors to be the MnS inclusions directly deposited on the tool [8, 12].

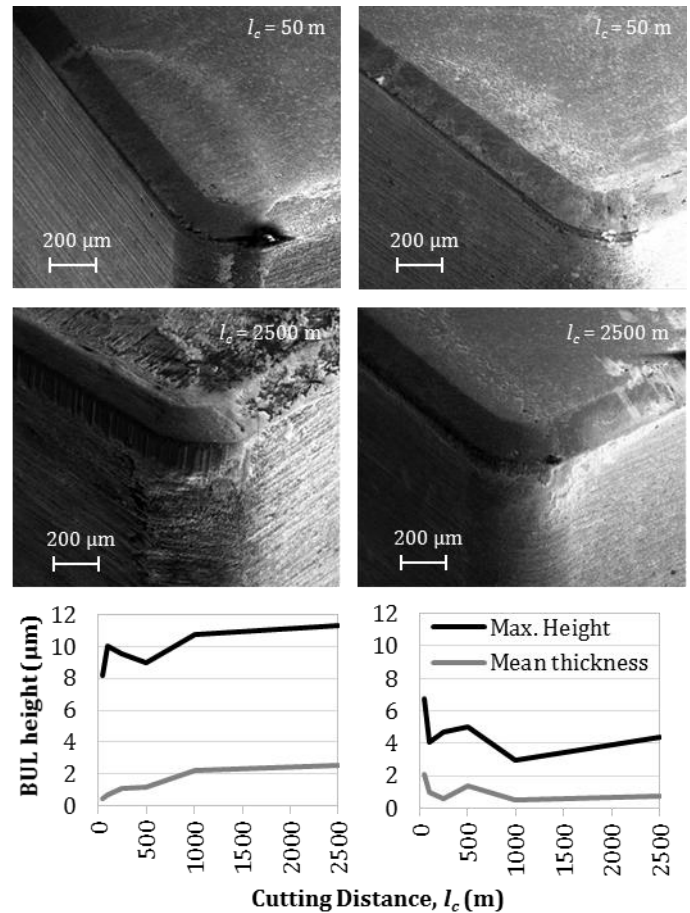


Figure 2. SEM (BEI) images and BUL data of pcBN tools after intervals of machining at $v_c = 250$ m/min (left) and $v_c = 750$ m/min (right).

4. The influence of cutting speed on BUL formation

The highest level of BUL coverage is found at $v_c = 250$ m/min along the cutting edge and in a crescent shape on the rake face (Fig. 3). The BUL observed at $v_c = 750$ m/min also forms in a crescent shape but closer to the cutting edge. This observation is associated with the chip length and the resultant chip-tool contact length which is found to reduce with increased cutting speed. A mean chip length of 4.23 mm (s.d. 0.70) and 0.80 mm (s.d. 0.13) was measured for $v_c = 250$ and 750 m/min, respectively.

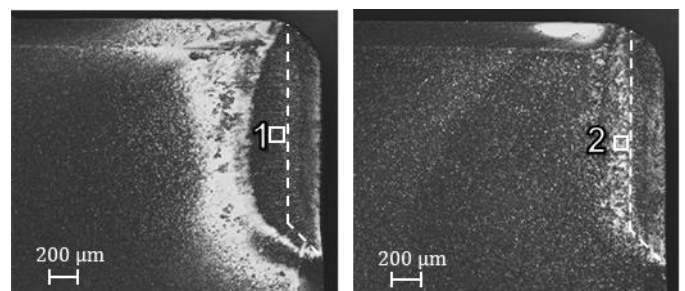


Figure 3. SEM (BEI) images of pcBN tool rake face after 2500 m of machining at $v_c = 250$ m/min (left) and $v_c = 750$ m/min (right).

To help explain this further, Fig. 4 illustrates the cutting interaction between the chip and the tool, adapted from Trent [1] for this cutting set up. It shows the area engaged by the chip as controlled by the feedrate (f) indicated by the dashed lines in both Fig. 3 and 4. It also describes the areas of seizure and intermittent contact as the chip moves along the rake face and

away from the cutting tool. The contact between the tool and chip adjacent to the cutting edge is highly intimate such that the chip forms under intense pressure resulting in conditions of seizure and high shearing rather than traditional sliding friction [1]. Conditions of sliding are typically observed at the boundary where the chip comes away from the tool. The area of seizure is typically greater than the area imposed by the feedrate contact and the shape and size of these areas is dependent on the cutting parameters and chip geometry [1].

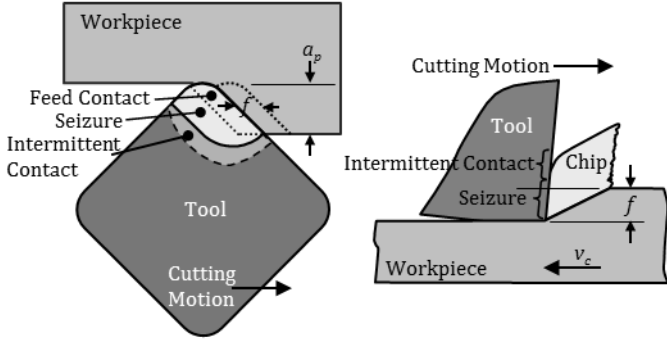


Figure 4. Areas of tool-chip interaction for turning (adapted from [1]).

SEM and EDX analysis was carried out in areas 1 and 2 in Fig. 3. By comparison, a greater level of BUL coverage is observed in this zone for high cutting speed ($v_c = 750$ m/min) supported by the higher level of Mn and S detected by EDX, as presented in Fig. 5. Therefore, while tools machining at $v_c = 750$ m/min seem to exhibit less overall BUL coverage, they actually feature better coverage in areas 1 and 2. This observation is understood to be critical when further considering where the area of BUL coverage coincides with the locations of crater wear and maximum temperature, which will now be explained.

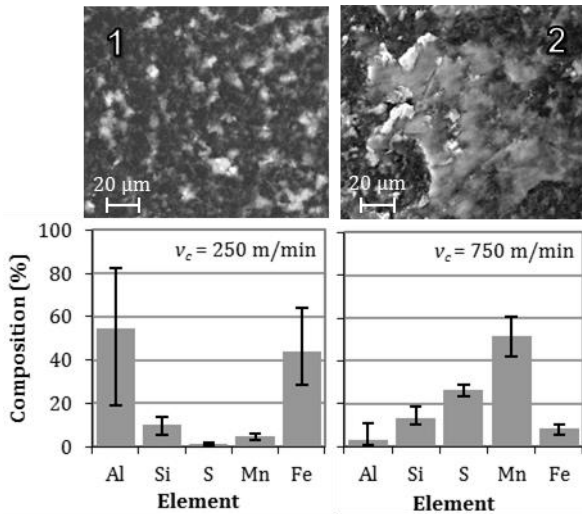


Figure 5. Elemental composition of the BUL in locations 1 and 2 from Fig. 3, for $v_c = 250$ m/min (left) and $v_c = 750$ m/min (right). Minimum-maximum bars quantify the range taken over all cutting intervals.

Fig. 6 presents higher magnification images of the flank face and primary cutting edge at the end of the cutting trials. It is evident that machining at lower cutting speed ($v_c = 250$ m/min) results in more BUL formation and higher tool wear. Crater wear and flank wear is plotted against cutting distance in Fig. 7 which are both found to be higher for $v_c = 250$ m/min. After 2500 m of machining, the tool used at $v_c = 250$ m/min approaches the suggested end of tool life criterion of $VB_B \text{ max.} = 0.6$ mm given by ISO 3685:1993. Furthermore, significant grooving in the flank face is observed at lower speeds (Fig. 7). Grooves form perpendicularly to the cutting

edge and parallel to the cutting motion. Grooving occurs through mechanical abrasion by hard particles (such as steadite, iron carbide and loose cBN tool particles) which take the path of least resistance and is typically enhanced by higher cutting temperatures that reduce the strength and hardness of the tool.

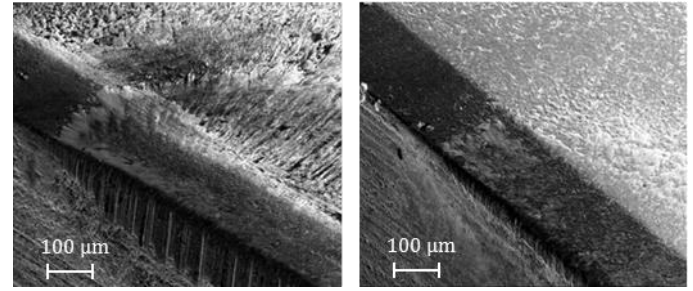


Figure 6. SEM (BEI) images of pcBN tool on the primary cutting edge after 2500 m of machining at $v_c = 250$ m/min (left) and $v_c = 750$ m/min (right).

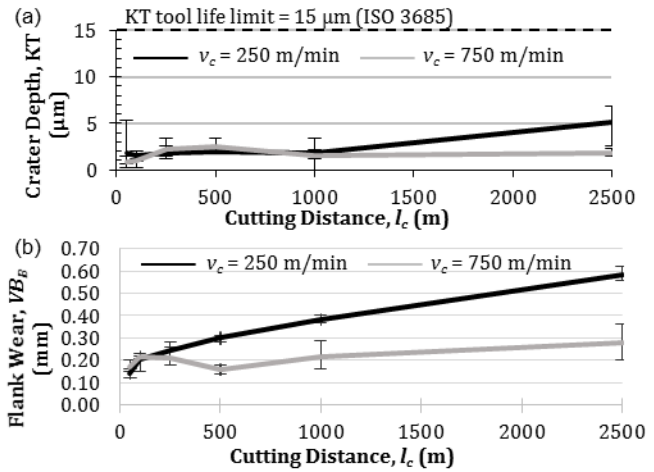


Figure 7. (a) Crater depth (KT) and (b) flank wear (VB_B) plotted against cutting distance for $v_c = 250$ and 750 m/min.

Tool profiles are plotted in Fig. 8 demonstrating the crater wear observed in Fig. 6 when machining at $v_c = 250$ m/min. The lowest point of the crater is measured at approximately 0.3 mm from the cutting edge.

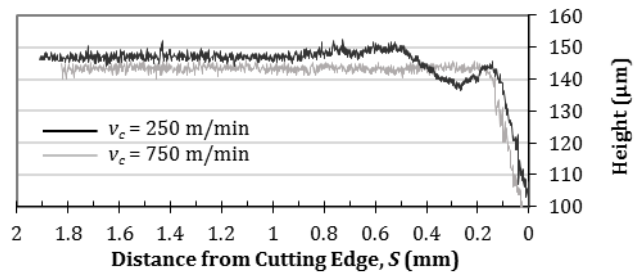


Figure 8. Rake face and chamfer surface profiles for $v_c = 250$ and 750 m/min, the cutting edge begins at 0 mm.

From the second set of experiments (orthogonal cutting), Fig. 9 plots the location of the maximum temperature along the tool-chip interface as measured from the cutting edge against cutting speed. Maximum temperatures of 777 and 696 °C were measured for $v_c = 250$ and 1000 m/min, respectively. The maximum temperature was found to locate closer towards the primary cutting edge, S , with increased cutting speed. During steady-state cutting, the location of maximum temperature moves from 0.27 to 0.13 mm, from the cutting edge, as the cutting speed is increased from $v_c = 250$ to 1000 m/min (Fig. 9). Reviewing Fig. 3, it is observed that the location of maximum temperature and

cratering at low speeds ($v_c = 250$ m/min) coincide with very low BUL formation. On the contrary, the tool used to machine at $v_c = 750$ m/min exhibits much higher BUL coverage in the area of maximum temperature, and no evidence of crater wear. This analysis supports the observation of accelerated crater wear at low cutting speeds ($v_c = 250$ m/min) and the benefit of machining GCI at high cutting speeds with pcBN tooling.

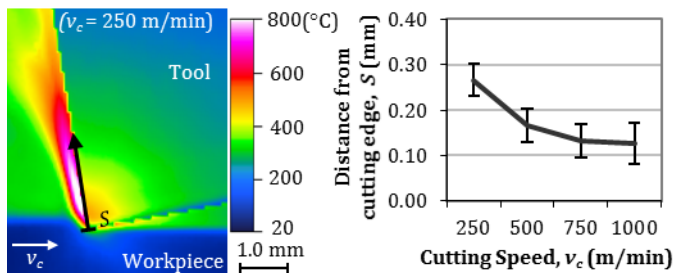


Figure 9. Distance from the cutting edge, S, of maximum temperature from thermograph (left) plotted against cutting speed (right).

5. The influence of Mn-content on BUL formation

In this work, increasing the Mn-content of GG25 GCI from 0.57% to 0.80% was found to increase the size of the manganese sulphide inclusions, maintain the same material hardness (195 HB) and increase the tensile strength from 250 to 317 N/mm².

Oblique cutting trials carried out on test-pieces with low and high Mn-content (0.57 and 0.80 wt%) found no significant difference within this range of Mn-content in terms of BUL formation (coverage and thickness), tool wear patterns and cutting forces. The morphology of cutting tools machined at $v_c = 250$ and 750 m/min is given in Fig. 10 for test-pieces with 0.80 %Mn, and observed to be very similar to those in Fig. 3 for test-pieces containing 0.57 %Mn.

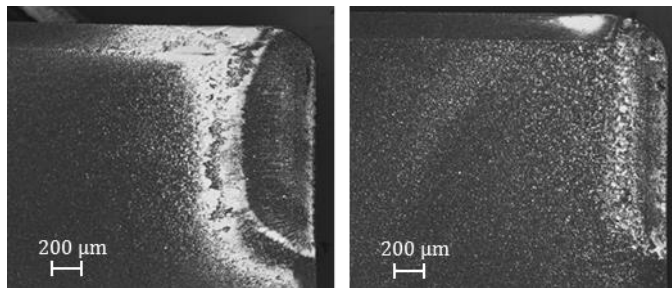


Figure 10. SEM (BEI) images of pcBN tool rake face after 2500 m of machining at $v_c = 250$ m/min (left) and $v_c = 750$ m/min (right).

6. Conclusion and outlook

A BUL, mainly consisting of Mn and S, is found to form and regenerate on the pCBN cutting insert for both cutting speeds tested ($v_c = 250$ and 750 m/min) at all cutting intervals ($l_c = 50, 100, 250, 500, 1000$ and 2500 m). This is suggested to be MnS through elemental characterisation. The maximum height of the BUL is found to be 11.29 μm . The BUL typically forms to a thickness below 2.5 μm .

PcBN cutting inserts machining at $v_c = 250$ m/min exhibit accelerated wear. At the end of the cutting trial ($l_c = 2500$ m) flank wear of VB_B of 0.50–0.60 mm is observed. Tools used to machine at $v_c = 750$ m/min, exhibit reduced wear rates and VB_B of 0.20–0.35 mm. Significant craters (up to $KT = 10.9$ μm) were only detected for tools used to machine at $v_c = 250$ m/min. Therefore machining at the higher cutting speed of $v_c = 750$ m/min is favourable in terms of maximising tool life as reported by other authors [5–7].

The BUL is observed to form in the area of tool-chip contact on the tool's rake face, nose and along the minor and major cutting edges, extending across the flank faces. Largest deposits are found to form in the area of intermittent tool-chip contact (as defined by Trent [1]). The BUL forms over a greater area on the rake and flank faces at lower cutting speed ($v_c = 250$ m/min). Crater wear at lower cutting speeds is associated with the point of maximum temperature coinciding with an area of poor BUL coverage at $v_c = 250$ m/min. While tools machining at $v_c = 750$ m/min seem to exhibit less BUL coverage, they actually feature better coverage over the area of maximum temperature, and intimate tool-chip contact, which is critical in terms of wear. Therefore the evidence suggests that the location and coverage of the BUL on the tool, coupled with the chip length and cutting temperature at high cutting speed are the reasons for extended tool life. This represents a beneficial, more complex cutting system involving the chip, tool and importantly, the intermediary BUL.

BUL distribution was found to be key to tool protection. Protection in the area of maximum temperature is critical in preventing thermally driven wear modes such as crater wear. A study into the preferential deposition of the BUL would be of benefit, carried out on a thermo-mechanical basis or through exploring different cutting tool geometries and chemical influences.

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