Wear analysis of PVD-coated twist drills under MQL

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Abstract

Purpose – Deep drilling of hardened steels is a difficult machining operation because of the high wear level of tools. This paper aims to present the main wear mechanisms observed in physical vapor deposition (PVD)-coated twist drills during deep drilling of SAE4144M steel under minimum quantity lubrication, assessed in the production of injection holders.

Design/methodology/approach – Two PVD coatings were tested: TiAlN and AlCrN, industrially processed, the last one being a multilayer coating. The workpiece was heat treated for a hardness of 39 HRC to be applied in a diesel engine component. The tests were performed in an industrial environment for a fixed number of holes. Two levels of cutting speed and feed rate were selected for the experiments. In addition, minimum quantity of lubrication (MQL) was compared with conventional lubrication. Scanning electron microscope was used to reveal the wear mechanisms.

Findings – Spalling of PVD-coating was revealed for conventional lubrication, while adhesion was observed in MQL conditions. The use of multilayered AlCrN-based coating promoted a significant reduction of adhered material on the twist drill, which is the reason for this selection in industrial operation.

Practical implications – Results showed that the MQL regime can be applied for this industrial application.

Originality/value – A detailed description of wear mechanisms, which allows a suitable selection of coating and machining variables was found for a very difficult operation, using a more economic process in terms of lubrication.

Keywords Wear mechanism, Minimum quantity lubrication, PVD coatings

Paper type Research paper

Introduction

Drilling of deep and small boreholes using twist drills must be considered as one of the most difficult metal cutting operations (Heinemann *et al.*, 2006). The conditions in which it is performed involve the use of low rigidity drills and difficulty in chip removal. Moreover, tool degradation is one of the most serious production issues, largely driven by continuous work hardening. Drills degrade rapidly and fail under harsh thermal and mechanical loading conditions, despite the use of specially formulated drilling oil or coolant at high pressure (Woon *et al.*, 2014).

Because of the downsizing of components and the increasing power density demands, for example, in the automotive industry, the industrial relevance of deep holes with small diameters and high length-to-diameter-ratios is steadily increasing (Zabel and Heilmann, 2012). An application of the deep drilling process is the manufacture of injection holders for diesel injection systems that are used to carry fuel from the high-pressure pump to the combustion chamber. In general, the material used to manufacture injection holders is a low alloy steel based on the 41XX family, especially for the generations of more modern systems that work with injection pressures up to 2,300 bar. Within this family, the main grades are 4144 and 4150. However, deep drilling of these materials is a difficult operation. It presents problems related to chip clogging, tool breakage and low workpiece quality (Wosniak *et al.*, 2016).

Minimum quantity lubrication (MQL) is an established alternative to conventional flood cooling in some machining operations. Some examples of MQL application are grinding (Barros *et al.*, 2014), turning (Saini *et al.*, 2014) and drilling (Heinemann *et al.*, 2006), for some diverse classes of machined materials, such as Ni-base alloy (Wang *et al.*, 2014), titanium alloys (Deiab *et al.*, 2014), aluminum alloys (Cabanettes *et al.*, 2016) and tool steel (Zhang *et al.*, 2014). In the automotive industry, MQL is successfully applied in the machining of aluminum transmission prismatic parts, grey iron and aluminum engine blocks, aluminum engine heads and crankshaft oil and cross-holes (Tai *et al.*, 2014).

Bottlenecks of MQL fall in four areas: deep-hole drilling, energy intensive process, difficult-to-machine metals and special operations like honing and small-hole drilling. Although MQL has been reported to provide superior lubrication, it generally does not have comparable cooling and chip

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evacuation abilities of those found in wet machining. Without flood of cutting fluid, accumulated heat can wear the tool and thermally distort the part. Without cutting fluid flushing the cutting zone, chips can easily build up and clog in narrow operating regions. Thus, these issues can become major barriers that limit the MQL applications in the abovementioned areas (Tai *et al.*, 2014).

There are few investigations about the use of MQL detailing the tool wear mechanisms in addition to the tool life reports, especially for the machining of hardened steels, such as performed by Zeilmann *et al.* (2012). These studies paid attention to the surface integrity of machined steel, while here the focus is on the performance of coatings. In this fashion, the current investigation aims to present the wear mechanisms observed in PVD-coated twist drills during deep drilling of SAE 4144M steel under MQL, assessed in the production of injection holders.

Experimental

The machined steel was the forged and heat-treated SAE 4144M (C-0.44, Cr-1.26, Mo-0.25 per cent) with a hardness of 39 HRC.

The tests were performed in a Fanuc Robodrill CNC machine with maximum spindle speed of 24,000 RPM with a MAS BT-30 with internal coolant-lubricant supply tool holder. The MQL system was a single channel V7 Lubrix unit. In the tests, the pressure in the pipeline was 10 bar and the oil flow rate was approximately 20 ml/h. EcoCut 610B (10 cSt at 40°C) was used in flood application tests and LubriOil E47 (47 cSt at 40°C) was selected for MQL ones.

Solid cemented carbide drills (K40 class) with 4-mm diameter (D) were used to drill 96-mm depth holes, resulting in a deep drilling condition of L/D = 24. Figure 1 shows a detailed design of tools.

The coatings were deposited using a physical vapor deposition (PVD) process, following industrial operations. The first test condition presented in Table I was used to establish the number of holes to be performed. In this case, the chip shape changed from curled spiral [Figure 2(a)] to tangled ribbon [Figure 2(b)] after 240 holes, representing a machined length of 22 m. In deep drilling, the shape of the chip is an important factor for the process stability. The alteration of a short chip to a long one due to a high tool wear usually leads to a tool breakage. To avoid this situation, the total number of holes was set to 200 for each test condition for safety reasons.

The wear mechanisms were revealed using a scanning electron microscope (SEM). To determine the local chemical composition of worn surfaces, an energy-dispersive X-ray spectroscopy system (EDX) was used. Each spectrum corresponds to an area of 0.04 × 0.06 mm^2, identified on images of 170 times of magnification.

Results and discussion

Figure 3 shows the worn surface of TiAlN coating, after tests under the condition 1 (pressurized oil, 62 m/min and 0.06 mm/rev). One can note that the PVD-coating was detached during the machining. An EDX analysis performed on two regions of Figure 4 confirms the composition expected for the cemented carbide in the bright area (Area 2). The spalling of coating (Area 1) can be associated to a thermal fatigue process.

Figure 1 Design of tested tools

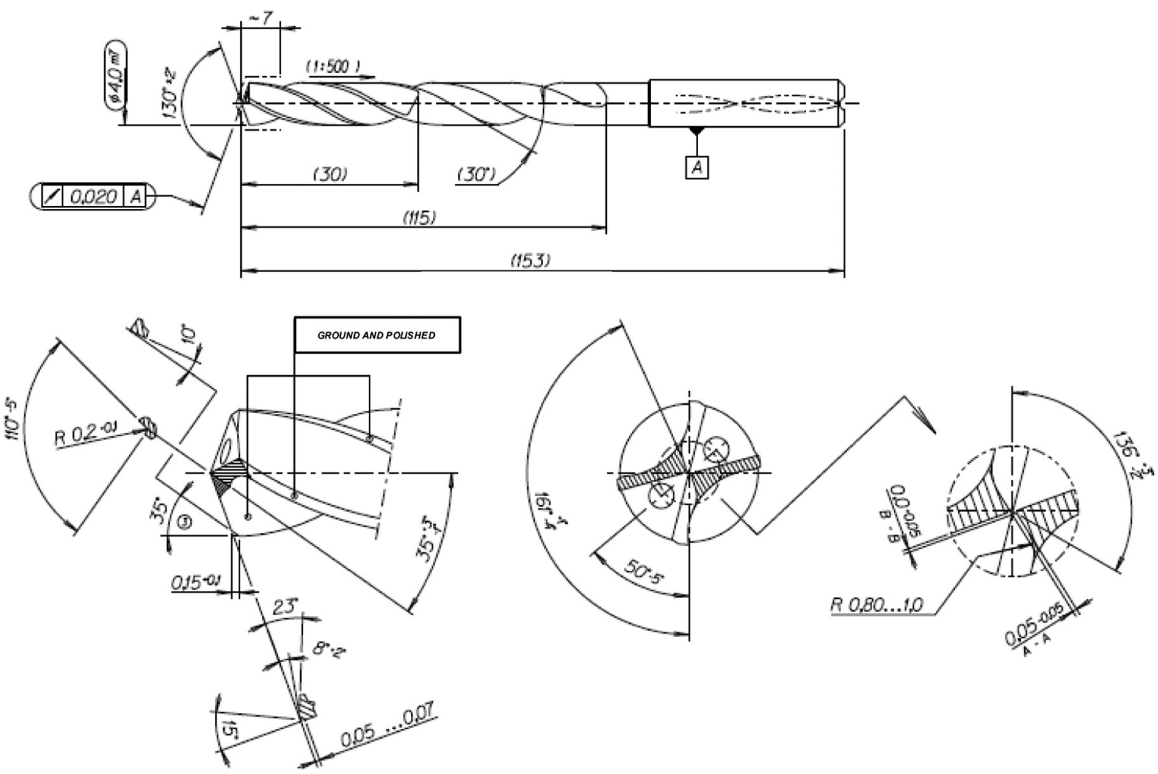

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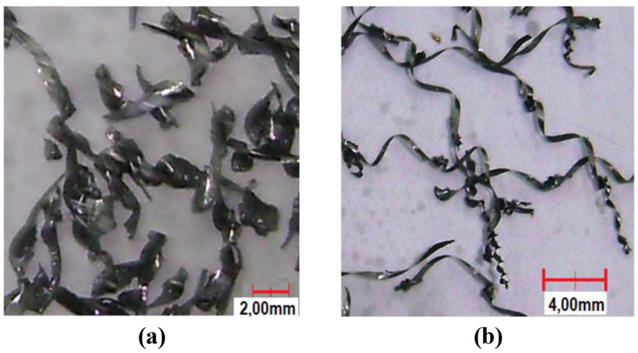
Table I PVD coatings, lubrication systems and cutting parameters used in the deep drilling experiments

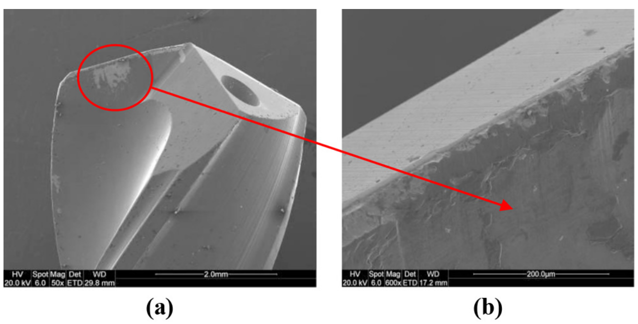
Condition	Coating	Lubrication System	Cutting speed, Vc (m/min)	Feed rate, f (mm/rev)
1	TiAlN	Pressurized oil	62	0.06
2	TiAlN	MQL	62	0.06
3	TiAlN	MQL	45	0.14
4	AlCrN-based	MQL	45	0.14

Figure 2 Formed chip samples through drilling



Notes: (a) Few holes; (b) after 240 holes

Figure 3 Worn surface of tool coated with TiAlN, after tests with pressurized oil, Vc 62 m/min and f 0.06 mm/rev



Notes: (a) General view; (b) detailed view. Note the spalling of coating

The temperature during drilling in the flooded condition is lower compared to the MQL, because of the higher rate of heat transfer. A large amount of heat is then transferred for the chips. However, the temperature at the interface between the chip and the tool is still high when the oil reaches it, promoting a thermal shock (Zeilmann and Weingaertner, 2006). Consequently, tensile stresses are developed, which can be higher than the limit strength of coating.

Figure 5 shows the worn surface of TiAlN coating, after tests under the condition 2 (MQL, 62 m/min and 0.06 mm/rev). In this case, a small absence of coating on tool cutting edge can be observed, where probably the coating was removed by abrasion. The small tool chamfer (0.05 to 0.07mm 15°) reinforces the drill cutting edge, thus reducing chipping. However, when lower feed rates are employed, as in this case, all shearing of material occurs in this region, increasing the tool edge wear.

Adhered material can be seen on the drill rake surface; in this case, the occurrence of this mechanism has been increased when compared to the flooded coolant condition. Local chemical analysis of the adhered material at the worn surface revealed a large amount of iron (approximately 53 per cent). At higher temperatures, there is an increase of the adhesion affinity and a decrease of the chip breakage ability of the material. Thus, the use of MQL system increased the adhesion mechanism, aggravated by a higher temperature, combined with a higher friction on tool-chip interface.

Zeilmann *et al.* (2012) also observed a significant material adhesion on the drill flank, after drilling of P20 steel under MQL. They compared this machining condition with two others, an emulsion and dry machining. Microchipping was only observed in the emulsion and MQL experiments. The challenge in terms of drilling is most significant in this investigation, comparing our 96-mm depth hole with the 22-mm one studied by Zeilmann *et al.* (2012).

As will be possible to see for another tested condition, the wear caused by multiple pileup layers is analogous to that identified by Qin *et al.* (2012), who pointed out that the extensive heat disturbs the adhesion, carrying away material from the cutting edge, becoming the fresh substrate more vulnerable to adhesion again.

Figure 6 shows the worn surface of TiAlN coating, after tests under the condition 3 (MQL, 45 m/min and 0.14 mm/rev).

The application of Condition 3 meant a reduction of adhered material in comparison with Condition 2. The variation of both feed rate and cutting speed has a direct influence on the machining time of the process. For higher feed rate, the effective time of drilling is reduced, diminishing the temperature at the interface. According to Biermann *et al.* (2012), the lower the feed rate the higher is the heat flow into the workpiece and, consequently, the resulting temperature. The reason for this behavior can be found in the long duration of the deep hole drilling process. The heat flow rate into the workpiece rises because of the high speed of heat propagation and the small uncut chip thickness. Thus, more material that is heated remains in the front of the drilling tool within the next revolution. Because of the lower feed rate the friction at the flank faces as well as the corresponding heating of the workpiece increase, because the number of spindle revolutions for drilling a borehole and, hence, the path length because of primary motion rise (Biermann *et al.*, 2012).

Moreover, according to Kulkarni *et al.* (2014), for small feed rates, the friction at the chisel edge has a significant influence on the feed force because of the small non-deformed chip thickness. When the drilling is performed with higher feed rates, the dependence on cutting speed becomes minor, as the

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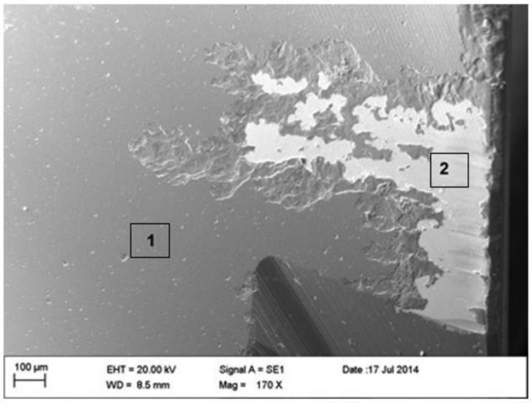
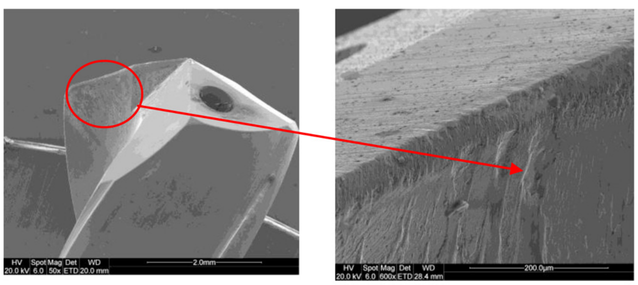
Figure 4 Detailed of region shown in Figure 3(b), revealing features of coating spalling



	Area 1 (wt. %)	Area 2 (wt. %)
Ti	24	2
Al	12	-
N	32	6
W	-	56
C	-	20
Co	-	5

Notes: Region 1: TiN coating; Region 2: WC-Co substrate

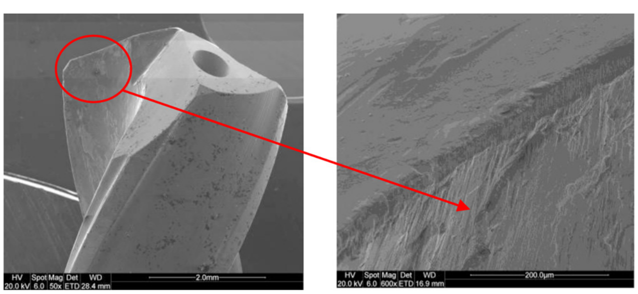
Figure 5 Worn surface of tool coated with TiAlN, after tests with MQL, Vc 62 m/min and f 0.06 mm/rev



(a) (b)

Notes: (a) general view; (b) detailed view. Note the strong adhesion at the coating surface

Figure 6 Worn surface of tool coated with TiAlN, after tests with MQL, Vc – 45 m/min and f – 0.14 mm/rev



(a) (b)

Notes: (a) General view; (b) detailed view. Note the adhesion at the coating surface

undeformed chip thickness at the major cutting edge as well as the effective rake angle increase (Kulkarni *et al.*, 2014). Therefore, the use of a higher feed rate in Condition 3 probably resulted in a lower temperature and, consequently, in a lower tool wear compared to Condition 2, despite its lower cutting speed.

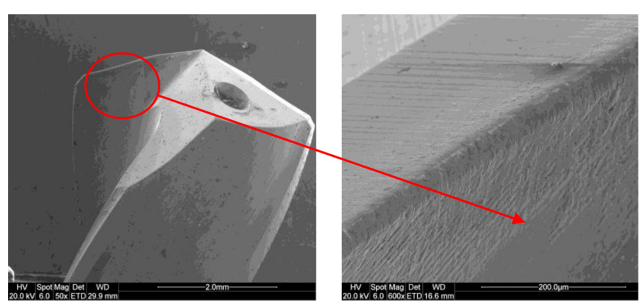
Figure 7 shows the worn surface of AlCrN-based coating, after tests under Condition 4 (MQL, 45 m/min and 0.14 mm/rev).

Comparing Figure 7 with those that described for Conditions 2 and 3, Condition 4 is that where the smallest amount of adhered material at the worn surface was observed. A detailed analysis shows that the wear mechanisms of abrasion and adhesion were present in a uniform way (Figure 8).

Area 1 contains a considerable amount of iron (approximately 37 per cent) and Mn as well, both elements resulting from adhesion. This finding can mean that multiple layers of chips are deposited along the tool, and they are subsequently removed by abrasion, which can reduce at the same time the coating thickness. This mechanism is like the previously described for Condition 2, but obviously in a much lower degree in this case.

Mo *et al.* (2013) showed that the AlTiN coating suffered more severe abrasive wear compared to the AlCrN one, although both coatings have similar hardness. This result corroborates the more frequent presence of AlCrN coating at the tool worn surface than that observed when TiAlN was tested (Condition 3). According to Fox-Rabinovich *et al.*

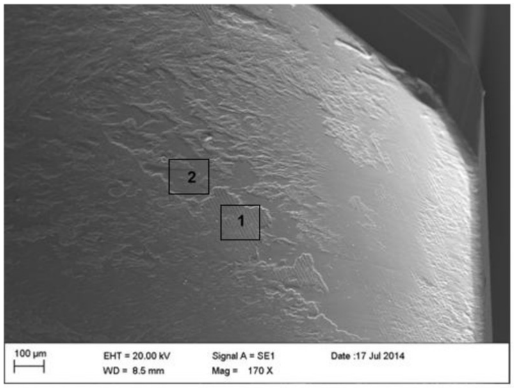
Figure 7 Worn surface of tool coated with AlCrN, after tests with MQL, Vc – 45 m/min and f – 0.14 mm/rev



(a) (b)

Notes: (a) General view; (b) detailed view. Note the adhesion at the coating surface

Figure 8 Detailed view of Figure 7(b)



	Area 1 (wt. %)	Area 2 (wt. %)
Ti	12	31.3
Al	1.4	8.8
N	-	10
Mn	16.1	-
Cr	13.5	17.4
Fe	36.8	5.2

Notes: Region 1: abrasion marks on the adhered material; Region 2: coating with low surface modification

(2012), for a deep drilling of hardened steels, the coating should adapt in a slightly different way, mostly because of its ability to sustain heavy loads at elevated temperatures and its low cycling fatigue. Another interesting result comparing the performance of different coating systems is because of Paiva *et al.* (2013). They found less flank wear of Cr-based coatings after drilling of compacted graphite iron, compared to TiAlN/TiN system, for example. Finally, when the thermal behavior of coatings is improved with protective tribofilms, as investigated by Fox-Rabinovich *et al.* (2010), a large fraction of heat is transferred into the chip, which enhanced the metal flow at the tool/chip interface and, consequently, the frictional conditions are improved (Fox-Rabinovich *et al.*, 2010).

The mild wear mechanisms observed for AlCrN coating revealed in the current investigation followed the trends reported by the literature, but the most important aspect is to solve a critical situation related to a deep drilling of a hardened steel.

Conclusions

A minimum quantity lubrication system was used to deep drilling of a quenched and tempered steel. In general way, the worn surfaces of tested tools presented large amounts of adhered material; this condition was not observed when pressurized oil was applied. Changes in machining parameters reduced this amount of adhered material, as well as the change of PVD-coating. AlCrN-based coating presented less adhesion than that observed for TiAlN one. On the other hand, when a pressurized oil was applied, the spalling of coating limited the tool life, probably associated to a thermal fatigue process.

In summary, MQL could be successfully applied for industrial conditions, despite the wear mechanisms presented in the current investigation. A combination of a high feed-rate, relative low cutting speed and AlCrN-based drill coating allowed increasing the tool life in deep drilling of 4144M hardened steel under a MQL regime. Higher tool life provided cost-savings and reduced the number of tool changes, which in turn decreased the overall cycle time, increasing productivity. Once the MQL is applied for a high-volume machining, significant costs can be avoided by replacing coolant systems. There are also gains in terms of sustainable manufacturing process by reducing energy consumption and hazardous waste.

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