Zolgharni, M, Jones, Benjamin, Bulpett, R, Anson, A.W. and Franks, J

Energy Efficiency Improvements in Dry Drilling with Optimised Diamond-Like Carbon Coating

Archive version. Definitive version available at http://dx.doi.org/10.1016/j.diamond.2007.11.012

Energy Efficiency Improvements in Dry Drilling with Optimised Diamond-Like Carbon Coatings

M. Zolgharni[1], B.J. Jones[2,*], R. Bulpett[2], A.W. Anson[1], J. Franks[3]

1. Diameter Ltd, Brunel University, Uxbridge, UB8 3PH, UK
2. Experimental Techniques Centre, Brunel University, Uxbridge, UB8 3PH, UK
3. School of Engineering and Design, Brunel University, Uxbridge, UB8 3PH, UK

Abstract
We demonstrate enhancements of performance and energy efficiency of cutting tools by deposition of diamond-like carbon (DLC) coatings on machine parts. DLC was deposited on steel drill bits, using plasma enhanced chemical vapour deposition (PECVD) with the acetylene precursor diluted with argon, to produce a surface with low friction and low wear rate. Drill bit performance in dry drilling of aluminium was quantified by analysis of power consumption and swarf flow. Optimised deposition conditions produced drill bits with greatly enhanced performance over uncoated drill bits, showing a 25% reduction in swarf clogging, a 36% reduction in power consumption and a greater than five-fold increase in lifetime. Surface analysis with scanning electron microscopy shows that DLC coated drills exhibit much lower aluminium build up on the trailing shank of the drill, enhancing the anti-adhering properties of the drill and reducing heat generation during operation, resulting in the observed improvements in efficiency. Variation of drilling efficiency with argon dilution of precursor is related to changes in the microstructure of the DLC coating.

[*] *Corresponding author*: B. J. Jones, b.j.jones@physics.org +44 (0)1895 265409

1. Introduction

To maintain cost-effective volume production of cutting tools, low friction, thin film coatings applied to the surfaces of cutting tools will reduce friction effects and prevent fusion of metal debris to the tool surfaces which would otherwise lead to increased power consumption, tool wear, potential changes in micro or macro material properties and sub-optimal topographic properties. A number of candidate coatings are commercially available to improve cutting efficiency and increase tool life; several manufacturers produce products with titanium nitrides, oxides, carbides, ceramics and various diamond coatings [1, 2].

Diamond-Like Carbon (DLC) thin film coatings can be optimised to feature specific properties, in this case for lubricity and hardness. Changes in the properties of DLC thin-films are related to changes in the film structure, such as sp^2 / sp^3 bonding ratio, hydrogen content, sp^2 clustering and defect concentration; alterations are facilitated by changing process parameters which may consist of bias voltage, type of precursor gases, surface treatment and post-deposition processing [3-6].

This investigation demonstrates optimized DLC for dry-drilling applications; the rationale behind the use of DLC is to improve the transportation and removal of metal swarf through the helical drill form and to generate a sufficiently low friction tool surface, preventing fusion of the removed metal to the cutting tool. Eliminating coolants in metal cutting processes reduces costs and ecological burdens and simplifies logistics relating to metal and coolant recovery [7]. Reducing attachment of metal debris to the tool can result in improvements in topography of the cut surfaces.

2. Experimental

2.1 Film deposition and preliminary tribology

Diamond-like carbon films were deposited on steel drill bits by RF plasma enhanced chemical vapour deposition (PECVD) process in Diameter Ltd. The precursor gas was a mixture of acetylene, argon and tetramethylsilane (TMS). Drill bits, originally uncoated, were HSS/Co (high speed steel, 8% cobalt) with 135º point angle and diameter of 5 mm. Flute geometry of the drills was standard helix, thick web and Right Hand spiral. Prior to deposition, the samples were cleaned as described elsewhere [8]. Subsequently, the bias voltage was adjusted to V_2 and an interfacial layer was formed by adjusting argon flow rate to that used for the film deposition and introducing TMS with flow rate of 25 sccm. This layer enhances the adhesion of the film to the substrate. Once the interfacial layer was formed acetylene gas at 60 sccm was introduced into the chamber, the rate of TMS gas flowing into the system was reduced by half to form a transition layer, and finally cut off, allowing deposition of DLC from argon diluted acetylene at a bias voltage of V_2.

Preliminary tribological tests were conducted with pin-on-disk measurements on films deposited on steel coupons, with bias voltage ranging from 100 to 600V. This showed optimum friction and wear properties in the region V_2 = 400 to 550V, with wear rates and friction coefficients comparable to those of single-layer continuous DLC films found in other works [9, 10]. Based on these studies, a DLC film deposited with bias voltage (V_2) of 450V with zero argon was selected in order to evaluate the impact of the DLC film on the drill lifetime. For optimization of coating, two deposition parameters, bias voltage (V_2) and argon flow were varied in different deposition runs between 300-600V and 0-50 sccm (corresponding to fraction of 0% to 45%), respectively, to produce films of thickness 1.8 ± 0.2 µm.

2.2. Cutting performance
Drilling experiments were conducted using a 3-axis cnc milling machine (Sherline 5410 Deluxe Mill) in order to achieve consistent testing conditions. Workpiece material was aluminium alloy BS1474 HE30 (BSEN 754-5 608 2T6), which exhibits considerable adhesion to uncoated drills while drilling in dry conditions. The hole geometry was 5 mm in diameter and 10 mm deep blind. Drilling tests were conducted at moderate speeds; spindle speed of 2600 rpm and feed rate of 0.012 mm/rev. No lubricant was used and analysis of the results focussed on the drilling torque, power consumption of the spindle drive motor and the number of holes drilled before failure. Online monitoring of tool degradation is attractive economically and technically, and this experiment monitored the analogue current, which proportionally correlates to the drilling torque [11, 12]. Since the cutting parameters (i.e., spindle speed, feed rate, drill geometry) are similar during each run of experiment, the variation in current signals can be attributed solely to the drill condition.

Figures 1a and 1b show typical behaviour of the spindle current during drilling. The drilling process can be divided into four phases. In phase I and IV the drill is outside the material and motor is spinning free; phases II and III contain useful information about the cutting performance. In phase II the drill makes contact with the workpiece (point P1) and is moving downward; the power consumption increases as the drill tip penetrates further through the material and main cutting edges become fully engaged, until the end of the stroke (point P2). Figure 1a shows the signal from a well performing drill bit with smooth action. In contrast, figure 1b shows the signal from a drill bit close to failure; the current signal is considerably increased in phase II which implies a higher drilling force, and consequently higher friction coefficient. In phase III the drill is moving upward until it exits the workpiece (point P3). In this phase if there is low adhesion between tool and the swarf, there would be low torque on the spindle and the level of the current is similar to that of free-spinning zone when the drill is outside the workpiece, as in figure 1a. However, in the poorly performing drill, the level of current subsequent to point P2 is high, the spindle experiences an increased torque, although it is not in the cutting phase, and it can be inferred that the swarf removal process is disturbed. This torque reflects the engagement of the drill and is attributed to evacuation force. If the swarf flow is not smooth, the signal exhibits sudden changes and fluctuations. In order to quantify information from the recorded data, following indices were computed: The clogging incident index (C_I) is the area under current curve, indicated as "A" in figure 1b, which measures the severity of clogging incident for each hole. The lower the value of C_I , the better swarf flow. The power consumption (P) is the sum of current squared over the period of cutting process returns a value which is related to mechanical energy consumed during drilling a hole. This index can also offer a good evaluation of heat generation during tests [1].

3. Results

3.1. Failure Experiments

In order to study the effect of films on the tool life, one uncoated and one coated drill were used and power consumption, clogging incidence and the total number of holes drilled before failure were measured. The drills were assumed to have failed when the drilling torque approached a predefined limit, i.e. power consumption reached unacceptable levels.

Graphs showing current drawn over 25 holes drilled at different levels of usage for both coated and uncoated drills are shown in Figure 2. Current magnitudes over the first 25 holes are almost similar with a slightly higher level in the uncoated drill. After drilling 650 holes the motor current of the uncoated drill shows a considerable increase, which is due to the high cutting torque on the spindle (see figures 2c and 2d). Also, sharp changes at the end of the hole depth were observed which are associated with the poor swarf evacuation in the uncoated drill. Finally, in figure 2f current values for the coated drill are plotted after drilling 3600 holes, where the coated drill was still performing better than the uncoated drill at 650 holes.

P and C_I were computed as the mean values over 690 holes and normalized to that of the uncoated drill. The power consumption of the coated drill was 68% of the uncoated and clogging incidence was reduced by 15%. Greater than five times more holes could be drilled using the coated drill than the uncoated counterpart - it was still showing a better performance when the test was stopped after 3667 holes. The surface quality of the drilled holes was also improved.

3.2 Optimization experiments.

The performance of different coated drills and one uncoated drill was investigated using indices explained in the previous section.

All drills tested showed similar performance over the first 10-20 holes. Thereafter, the torque magnitude increased as the tool gradually deteriorated. In the case of coated drills both torque magnitude and its trend have a lower level which corresponds to lower friction coefficient and degradation rate, respectively. In addition, the cutting force exhibited a more stable and consistent behaviour in coated drills.

The average of clogging incidence and power consumption values were normalized to that of uncoated drill. For films deposited in the range of bias voltage 400-500V, power consumption of coated drills was 82 ± 6 % of the power consumed by the uncoated drill; swarf flow was also improved by these films, C_I reduced to 89 ± 4 % of that of the uncoated drill. Outside this bias range there was little statistically significant improvement. The addition of argon to the precursor mix further improved the performance, with the optimum 20 sccm argon, C_I was improved by 25% and power consumption 36% over the uncoated drill. As argon incorporation is increased past this level, the power consumption and clogging incidence rise.

3.3. Surface properties

A Zeiss Supra field effect scanning electron microscope (SEM) operated at 20kV was used to make comparative examination and analysis of two drills representing 1) an uncoated drill that had been worked past the failure point and completed a total 900 holes, and 2) the drill coated with DLC deposited with 0 Ar at bias voltage of 450V, that had completed 3667 holes.

The secondary electron image of the uncoated drill that had completed 900 drilling operations, figure 3a, shows the trailing edge close to the drill tip. A substantial build up of aluminium has developed on the drill shank and smaller island-like deposits have adhered to the rough inner surface of the drill flute.

The corresponding energy dispersive (ED) X-ray maps for aluminium, figure 3b, recorded from the same field of view shows clearly where thick deposits of aluminium have become quite firmly attached to the surface of the steel drill.

In contrast an SEM examination of the same area of the DLC coated drill that had completed 3667 drilling operations, figure 3c and the X-ray map for aluminium, figure 3d, shows a line of deposits of aluminium at the trailing edge and a small region of build up further down the shank. Isolated deposits of aluminium were also identified in the drill flute, in addition to those observed on the trailing edge.

4. Discussion

As the temperature rises in cutting zone, material adhesion to the drills will become more likely, leading to formation of a built-up layer. Poor swarf evacuation also makes the generation and growth of this layer more probable, which gradually reduces cutting efficiency. The DLC film has a positive effect on reducing build up of material on the drill bit, improving both energy efficiency and swarf evacuation. Owing to lower cutting force less consumed mechanical energy is turned to thermal energy thus the temperature in cutting zone decreases and swarf is less prone to adhere to the drills. Moreover, the reduction of cutting forces with the coated drill can also increase tool life directly.

Deposition with bias voltage 400-500V provides optimum films which correlates with the lower friction coefficient of these films observed in preliminary tribological tests. Coated drills deposited at bias voltages outside this range showed no significant improvement compared to the uncoated drill. The variation in tribological properties relates to the influence of bias voltage on the hydrogen content and sp^2/sp^3 ratio in the a-C:H films. Below this bias range, polymer-like films with a high fraction of hydrogen and fully saturated sp^3 groups can be deposited [13] whereas as bias exceeds this range, the graphite structure becomes dominant which leads to a decrease in hardness and wear resistance.

Argon dilution of precursor enhances the performance further; the best performance was obtained with DLC deposited with argon dilution of 20 cc/min and bias voltage 450 V, showing an enhancement of 36% in power consumption and 25% in swarf flow. Jones [8] shows the increase of Ar in the precursor mix leads to greater sp^2 clustering, but also an increase in surface roughness, this leads to the low optimum level of argon for this application, where the low roughness allows the swarf to exit smoothly along the flute.

5. Conclusions

We demonstrate improved performance and energy efficiency of standard drill bits by coating with diamond-like carbon (DLC) deposited with plasma enhanced chemical vapour deposition (PECVD).

DLC coating at bias voltage of 450V and argon dilution of acetylene of 1:3 produces the most suitable films for dry drilling applications; measurements show DLC coated drills operate with significantly improved power efficiency. Our DLC coated drill continues to draw less current after 3600 drilling operations than an uncoated drill after 650 drilling operations. This is related to reduction in build up of aluminium on the drill bit, and increased ease of swarf removal.

This preliminary work has been continued with industrial partners, with a larger sample size and high speed machining, which verifies the improved lifetime of optimized-DLC coated drills in both aluminium and stainless steel machining.

Acknowledgements

This project was funded by Diameter Ltd and ETCbrunel. We acknowledge the assistance of M Azimi for development of software and electronics.

References

[1] D.G Flom, R Komanduri, M Lee *Annual Review of Materials Science*, **14** (1984) 231
[2] A. Rivero, G. Aramendi, S. Herranz, L.N. Lopez de Lacalle, *J. Adv. Manuf. Technol.* **28** (2006) 1
[3] J.W. Zou, K. Reichelt, K. Schmidt, B. Dischler, *J. Appl. Phys*. **65** (1989) 3914
[4] J. Robertson *Mat. Sci. Eng: R* **37** (2002) 129
[5] L. Valentini, J.M. Kenny, G. Mariotto, P. Tosi, G. Carlotti, D. Fioretto, L. Lozzi, S. Santucci, *Diamond Relat. Mater*. **10** (2001) 1088
[6] R.U.A. Khan, J.D. Carey, S.R.P. Silva, B.J. Jones and R.C. Barklie *Physics Review B* **63** (2001) 121201(R)
[7] P.S. Sreejith, B.K.A. Ngoi, *J. Mater. Process. Technol.* **101** (2000) 287
[8] B.J. Jones, S Wright, R.C. Barklie, J Tyas, J Franks, A.J. Reynolds *Diamond Relat. Mater*. This volume (submitted)
[9] W. Zhang, T.A. Tanaka, B.S. Xu, Y. Koga, *Diamond Relat. Mater*. **14** (2005) 1361
[10] J.M. Dasch, C.C. Ang, C.A. Wong, Y.T. Cheng, A.M. Weiner, L.C. Lev, E. Konca, *Surf. Coat. Technol.* **200** (2006) 2970
[11] E. Jantunen, *Journal of Machine Tools & Manufacture* **42** (2002) 997
[12] X. Li, S.K. Tso, *Wear* **231** (1999) 172
[13] Y.H. Cheng, Y.P. Wu, J.G. Chen, X.L. Qiao, C.S. Xie, B.K. Tay, S.P. Lau, X. Shi, *Surf. Coat. Technol.* **135** (2000) 27

Figures

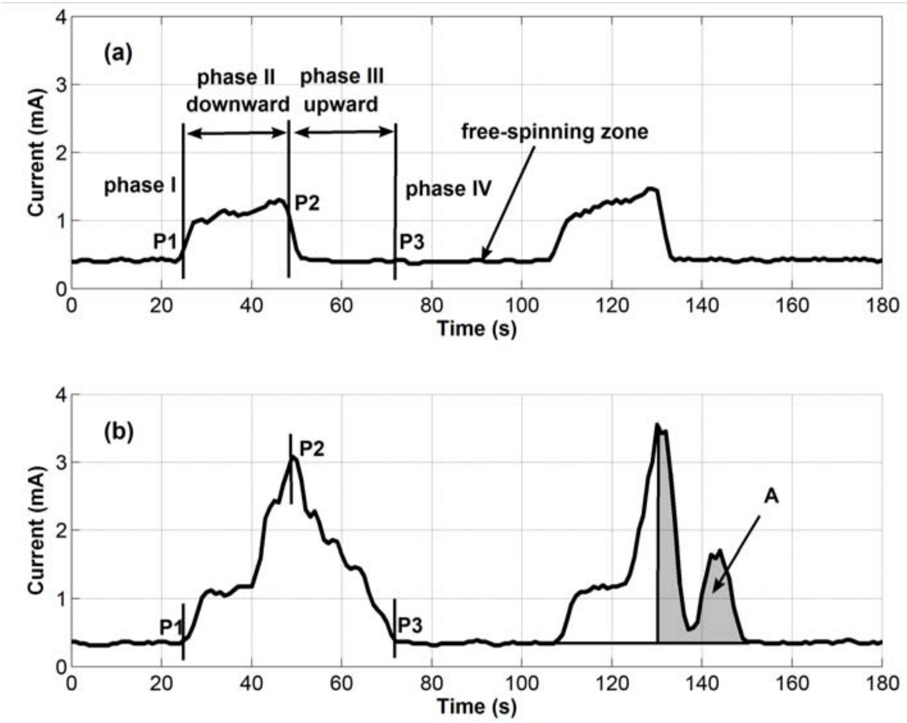

Figure 1. A sample of recorded signal; (a) coated drill after drilling 270 holes, (b) uncoated drill close to failure. P1-P3 represents key points in the signal and A is the area under current curve in phase III.

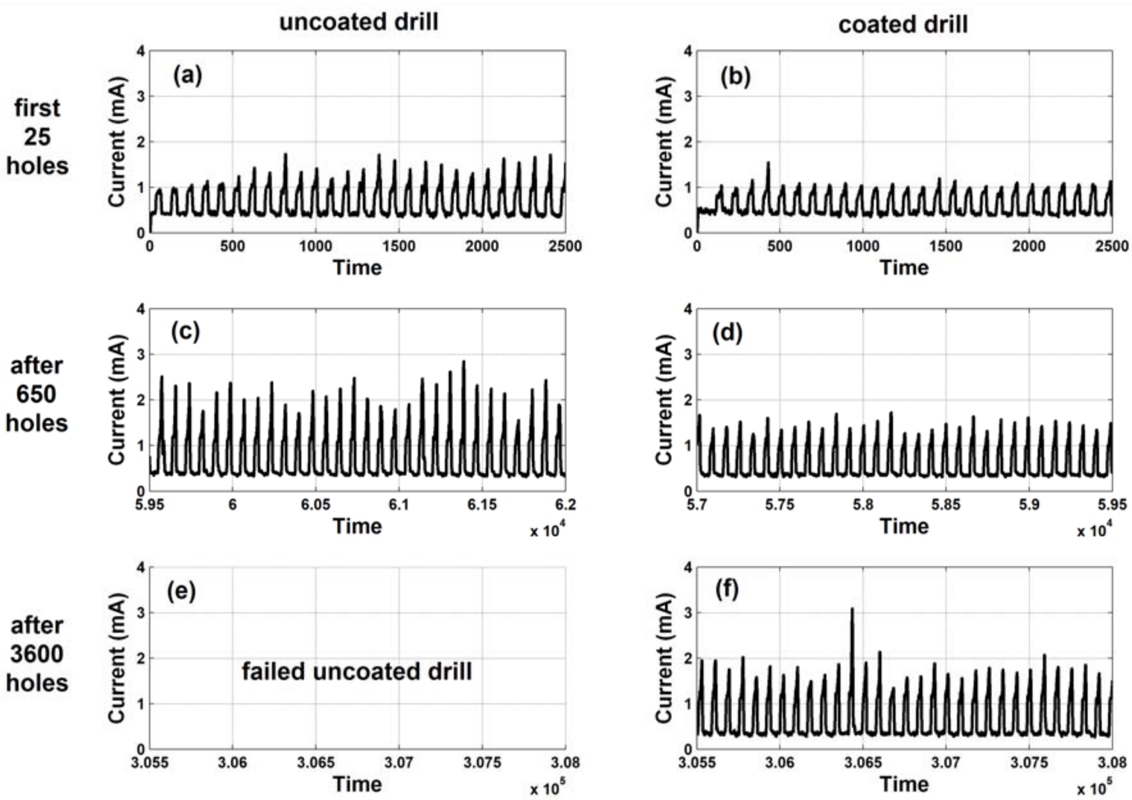

Figure 2. Current plots for uncoated (a,c,e) and coated (b,d,f) drills over 25 holes at different levels of usage. (a-b) first 25 holes, (c-d) after drilling 650 holes, (f) after drilling 3600 holes.

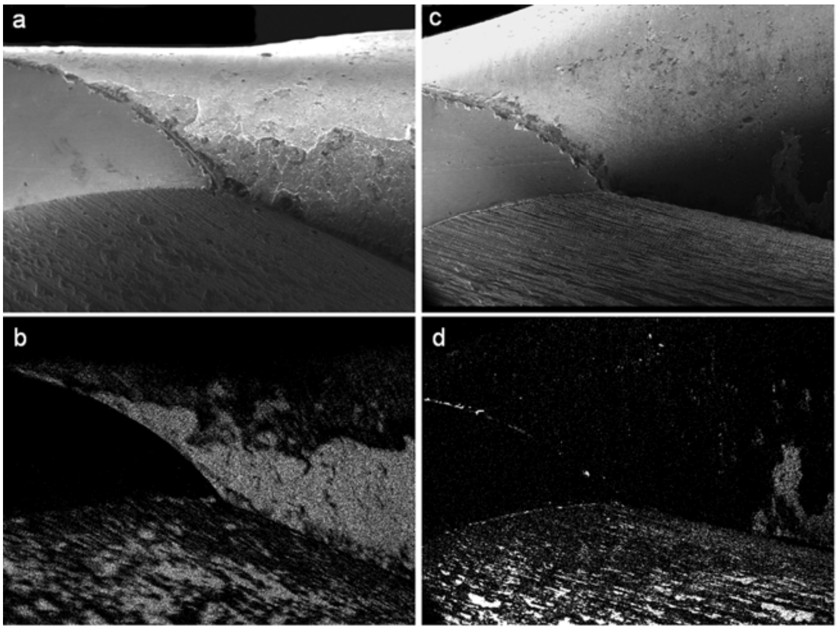

Figure 3. SEM examination of drills: a) shows electron image and b) Aluminium X-ray map of uncoated drill after 900 drilling operations, showing build up of aluminium on trailing flank and flute. c) and d) show electron image and aluminium X-ray map respectively, of DLC coated drill after 3667 drilling operations, showing isolated aluminium deposits on trailing edge and flute.