Improvement of drilling performance by overcoating diamond-like carbon films on diamond-coated drills for carbon fiber reinforced plastics processing

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ABSTRACT

The hardness and hydrogen content of diamond-like carbon (DLC) films vary depending on the film deposition methods and conditions. Carbon fiber reinforced plastics (CFRP), known as hard-to-machine materials, have been widely used for industrial aircrafts that require structural materials. In this study, the effects of the hardness and hydrogen content in DLC films on the drilling performance of CFRP drills were investigated. Various DLC films, prepared using the T-shaped filtered arc deposition method, were used to coat diamond-coated drills for CFRP processing. The drilling test of the CFRP plates revealed that the occurrence of burrs was suppressed using the drill coated with a hard DLC film containing small amounts of hydrogen, classified as a hydrogenated tetrahedral amorphous carbon (ta-C:H) film. The spherical polishing test of the CFRP plate using DLC-coated balls demonstrated that the DLC films containing hydrogen suppressed the adhesion of the resin material constituting the CFRP. The coating of hard DLC films containing small amounts of hydrogen, such as a ta-C:H film, significantly improved the drilling performance of diamond-coated drills for CFRP processing. The performance improvement of CFRP drills expands the range of CFRP processing conditions.

1. Introduction

Carbon fiber reinforced plastics (CFRP) are composite materials consisting of carbon fibers bound by a polymer matrix, such as a thermosetting resin (epoxy, polyester, phenolic, polyimide resins) or thermoplastic resin (polypropylene, Nylon 6.6, PMMA, PEEK) [1,2]. CFRP have been widely used for industrial aircrafts that require structural materials with superior properties such as high strength-to-weight and stiffness-to-weight ratios [1,2]. CFRP, which are regarded as hard-to-machine materials, are cut using diamond-coated drills made of tungsten carbide (WC). The polycrystalline diamond film on the drill acts as a protective film and enhances its performance and durability. Diamond-coated drills have been widely used for CFRP cutting; however, their cutting performance, in terms of accuracy and durability, has been insufficient. Coating diamond-coated drills with diamond-like carbon (DLC) films has been proposed to improve the cutting performance of drills [3]. The cutting performance of aluminum alloys of diamond-coated drills improves when coated with a DLC film as it provides a low surface-friction coefficient against the aluminum alloy. The coating is composed of a hydrogen-containing DLC film prepared by RF plasma chemical vapor deposition (CVD).

DLC films are hard amorphous carbon films that are used as...
functional films on sliding surfaces of cutting tools due to their low friction coefficient and low capacity to adhere to metals such as aluminum, copper, and brass [4–7]. DLC films are generally classified into four types according to their mechanical hardness and hydrogen content [8]. DLC films without hydrogen are categorized based on their hardness as tetrahedral amorphous carbon (ta-C) films and amorphous carbon (a-C) films, and those with hydrogen are categorized as tetrahedral hydrogenated amorphous carbon (ta-C:H) films and hydrogenated amorphous carbon (a-C:H) films. The ta-C films have extremely high mechanical hardness with nanoindentation hardness of 50 GPa or more [9]. These have been used as protective films preferred for cutting tools and molds [4,6,7]. However, even for DLC films with hardness similar to that of ta-C the wear characteristics differ depending on the hydrogen content in the films [10,11]. It is necessary to use each DLC film selectively, based on the application.

While DLC films have various properties, a suitable DLC film for CFRP cutting has not been successfully identified. This study investigates the drilling performance of diamond-coated drills, prepared with various DLC films, on CFRP. The DLC films are prepared using the filtered arc deposition method under different deposition conditions.

2. Experimental procedure

DLC films were prepared using the T-shaped filtered arc deposition (T-FAD) apparatus on diamond-coated drills (D-STAD, OSG Co., Ltd.) for CFRP processing [9,12–14]. As shown in Fig. 1, a plasma beam was scanned to coat a DLC film on a drill. Different types of DLC films were prepared by varying the flow rate of hydrocarbon gas introduced into a chamber under the following common conditions: a cathode target of graphite, an arc discharge current of 30 A, and a pulse substrate-bias voltage of −100 V. The characteristics of the prepared DLC films are summarized in Table 1. ta-C films, with nanoindentation hardness of 64 GPa, were fabricated in vacuum at a base pressure of 7.0 × 10⁻¹⁰ Pa. The ta-C films, with a nanoindentation hardness of 53 GPa and hydrogen content of 5 at.%, were fabricated under a C₂H₂ gas flow rate of 5 sccm and a gas pressure of 2.2 × 10⁻¹³ Pa in the chamber. The a-C films, with nanoindentation hardness of 18 GPa and hydrogen content of 29 at.%, were fabricated under a C₂H₂ gas flow rate of 50 sccm and a gas pressure of 1.8 × 10⁻¹³ Pa. The thickness of the DLC films was adjusted to approximately 500 nm. The drilling tests for a 5-mm-thick CFRP plate were performed using the DLC coated drills. A desktop computerized numerical control (CNC) milling machine (PSF-240-CNC, Prospec) equipped with a dynamometer (9272, Kistler) was used for the drilling test. A DLC coated drill was used to bore 12 holes on a CFRP plate. The Z-axis feed speed of the drill was varied from 600 to 100 rpm for each hole, and then from 100 to 600 rpm. The dynamometer measured the torque of the drills during the drilling tests.

The CFRP polishing test by the spherical polishing method was also performed to investigate the effect of the DLC type on the CFRP processing. Fig. 2 illustrates a cross-sectional schematic diagram of the spherical polishing test for a CFRP plate. A carotester (Calotest, CSM Instruments) was used in the spherical polishing test in which the diamond slurry was dropped between a CFRP plate and a DLC-coated SUJ2 ball. The CFRP plate surface was polished and worn by rotating the ball on the plate. To ensure comparability, the same DLC films that were used to coat the drills were coated on the balls. A small volume of 20 μL of the slurry was used with diamond particles, sized at 0.2 μm or less. A shaft rotation speed of 1000 rpm was used at a substrate angle of 60° for a polishing duration of 60 s. After the polishing tests, polishing marks on the CFRP plates and scratches on the ball surfaces were observed. An energy dispersive X-ray spectrometry (EDS) was conducted on the ball surfaces using a scanning electron microscope (SEM) equipped with an EDS analyzer.

3. Results and discussion

The occurrence of burrs on the holes in the CFRP plates was observed after the drilling tests. In this study, burrs indicate a piece of CFRP plate material left at the edges of the holes. While almost no burrs were observed when the holes were seen from the drill-entry side, these were observed on the drill-exit side. The occurrence state of the burrs varied depending on the drill used. Table 2 summarizes the burr occurrence on the drilling tests. A DLC non-coated drill indicates a drill with only diamond coating. Holes drilled using the DLC non-coated drill and the ta-C:H coated drill are shown in Fig. 3. In the DLC non-coated drill, burrs appeared regardless of the Z-axis feed speed, whereas almost no burrs were observed on the holes drilled using the ta-C:H coated drill. As presented in Table 2, the occurrence of burrs was significantly suppressed when the ta-C:H coated drill was used.
Fig. 4 shows the peel-off area ratio of the CFRP on the drill-exit-side surface. The peel-off area ratio, $F_D$, was calculated using the hole diameter, $D_{nom}$, and a CFRP peel-off diameter around the hole, $D_{max}$, as shown in the following equation [15,16].

$$F_D (\%) = \frac{D_{max} - D_{nom}}{D_{nom}} \times 100$$ (1)

There was no significant difference in the peel-off area ratio for the different DLC film types under the condition of low Z-axis feed speed, and the ratio was approximately 10%. The peel-off ratio of the holes using the ta-C coated drill increased with the feed speed. In contrast, the a-C:H and ta-C:H coated drills maintained a low peel-off area ratio even at a high feed speed. It was considered that the difference in the performance of the drills were significant when processing at a high Z-axis feed speed as the load on the drill increases with the Z-axis feed speed. At a Z-axis feed rate of 600 mm/min, the peel-off area ratio of the ta-C:H coated, a-C:H coated, and DLC non-coated drills were approximately 20%, while the that of the ta-C coated drill was 43%. The ta-C coating was found to have deteriorated the CFRP processing performance of the drill owing to higher peel-off area ratio of the ta-C coated drill, as compared to the DLC non-coated drill.

Table 3 shows the maximum torque of each drill during the CFRP drilling test. The maximum torque indicates the load on the drill during the test, and the low load represents the high sharpness of the drill used for CFRP processing. The maximum torque of the DLC non-coated drill...
was 79 Ncm. In the ta-C, ta-C:H, and a-C:H coated drills, the maximum torque observed was 84, 67, and 69 Ncm, respectively. It can be seen that the maximum torques of the ta-C:H and a-C:H coated drills were lower than that of the DLC non-coated drill, and the ta-C coated drill showed a slightly higher torque than that of the DLC non-coated drill. It was considered that the friction coefficient and load on the drill reduced because the a-C:H films wore aggressively owing to a soft film. The ta-C:H films were harder than the a-C:H films, with a hardness close to that of the ta-C film. The only difference between the ta-C and ta-C:H films was the hydrogen content in the films, indicating that the hydrogen in the DLC films might affect the frictional properties for the CFRP.

Fig. 5 shows the results of the spherical polishing tests. The polishing marks on the CFRP plates formed using the ta-C:H coated ball were clear, and the CFRP plate was worn. However, the surface of the CFRP plates, polished using the ta-C and a-C:H coated balls, were only slightly worn, indicating that the ta-C:H films contributed to the efficient processing of CFRP. The results of the SEM observation and EDS analysis of the ball surface after the spherical polishing tests are summarized in Fig. 6. A scratched line was observed on the surface of the ta-C coated ball, as seen in the SEM photograph in Fig. 6(a). However, no significant scratches were observed on the surfaces of the ta-C:H and a-C:H coated balls, as seen in the SEM photographs in Fig. 6(b) and (c). The EDS analysis detected carbon on every ball surface that originated from the DLC film coated on the surface of the balls. As shown in the images of the EDS analysis in Fig. 6(a), oxygen was detected with carbon on the scratched line on the surface of the ta-C coated ball. As CFRP are composites of carbon fibers and resin material, the resin material in the CFRP plate was considered to have adhered to the scratched line, and the oxygen in the resin material was detected using EDS analysis. As seen in the images of the EDS analysis in Fig. 6(b) and (c), the hydrogenated DLC films, such as ta-C:H and a-C:H, exhibited high adhesion resistance to the resin material as no oxygen was detected in the hydrogenated DLC films. The difference in resin adhesion between hydrogen-free DLC and hydrogenated DLC films was believed to be caused by the number of dangling bonds of carbon in the DLC films. DLC films are an amorphous film and with dangling bonds in the films. Particularly, it was speculated that the hydrogen-free DLC films have a considerable number of carbon dangling bonds in the films. When a DLC film is worn due to drilling or polishing, the surface of the DLC film is scraped continuously, and a new surface of the film is exposed. A large number of carbon dangling bonds on the newly exposed surface combine with the oxygen and carbon contained in the resin materials, adhering to the ta-C:H films. Most of the carbon in the hydrogenated DLC films terminate with hydrogen because the films were prepared in hydrogen or hydrocarbon atmospheres. Thus, even when a new surface of the DLC films is exposed, owing to abrasion, the carbon dangling bonds on the DLC surface are less in number, suppressing the adhesion of the resin to the ta-C:H and a-C:H films. The low adhesion resistance of the ta-C:H films to the resin materials may be resulting in the lack of improvement in the CFRP processing performance of the drills coated with ta-C:H films. Additionally, the peel-off area ratio and the maximum torque observed indicate a reduction in the drill performance owing to the coating of the ta-C:H film. The ta-C:H film cannot be expected to improve the friction properties of the drilling surface for the CFRP. The diamond edges on the drill are smoothed by overcoating the ta-C:H film. The difficulty in cutting the carbon fibers in CFRP was assumed to be due to the smoothing of the diamond edges.

Based on the EDS analysis showed in Fig. 6(b) and (c), it is seen that the a-C:H films exhibited high adhesion resistance to the resin materials, similar to the ta-C:H films. However, the scratch performance of the a-C:H films was lower than that of the ta-C:H films (Fig. 5(c)). During polishing it is observed that a soft film wears out sooner compared to a material such as CFRP. Thus, the soft a-C:H films were worn out during the polishing test, rather than the CFRP, resulting in the lack of improvement in the drilling performance. DLC films that are effective in improving the performance of CFRP processing need to be hard and have a high resin adhesion resistance. Thus, ta-C:H was found to be a suitable type of DLC film for CFRP processing.

4. Conclusions

Various DLC films prepared using the T-shaped filtered arc deposition method were coated on diamond-coated drills for CFRP processing. Drilling tests were used to test their performance. The effects of the DLC coating on the CFRP drilling performance were also assessed based on spherical polishing tests on CFRP plates using various DLC coated balls. The key results are summarized as follows.
The drills coated with a ta-C:H film, with a hardness of 53 GPa, and a hydrogen content of 5 at.%, had significantly fewer burrs compared to the other DLC films and DLC non-coated drills. Additionally, the hydrogenated DLC film coating reduced the load on the drills during the CFRP processing.

The hydrogenated DLC films suppressed the adhesion of the resin materials on the drilling surface. The difference between the adhesion characteristics of the hydrogen-free DLC films and the hydrogenated DLC films with the resin was considered to be related to the number of carbon dangling bonds in the films. Among the hydrogenated DLC films, the hard DLC films exhibited a high scratch performance for CFRP.

The hardness and hydrogen content of a DLC film affected the wear resistance and resin adhesion resistance as a surface protective film on cutting tools, respectively. It was observed that the ta-C:H films, which had excellent wear resistance owing to high hardness, and suppressed resin adhesion, due to its hydrogen content, were a suitable DLC type for CFRP drilling.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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