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# Cutting strategy of polymer composite material for aerospace engineering application.

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# Cutting Strategy of Polymer Composite Material for Aerospace Engineering Application

**Abstract** Despite the popular use of hybrid fibers in polymer composite in aerospace applications, it comes with a price where it is expensive and has a complex process to produce. A new alternative method of using nanocomposite using natural fiber such as Epoxy/Graphene is getting placed in the industry. However, the natural fiber has a hygroscopic characteristic. The minimum quantity lubrication (MQL) method was approached for this research to investigate the machinability behavior of the Graphene/Epoxy nanocomposite. The cutting force was also investigated to see the effect of different coatings material of the flat-end mill cutters when machining the Epoxy/Graphene nanocomposites. Despite having various acetone doses in the Epoxy/Graphene specimens, the results show that the MQL technique has a favorable impact on the surface finish and that the TiAlN-coated tungsten carbide tool has a constant cutting force during slot milling. Furthermore, the addition of acetone into the nanocomposite may assist in decreasing the build-up edge on the tool cutting edge, lowering the risk of the tool failure.

**Keywords** Epoxy · Flat-end milling · Graphene · MQL · Nanocomposite · Synthetic ester

## 1 Introduction

Polymer composite materials has been proven to be flexible and adaptable engineering materials for various type of engineering applications such as Aerospace engineering. The focus of aerospace engineering is the research and development of aircraft and spacecraft. Among the application of aerospace engineering that is widely used is the flight vehicle such as aeroplane, shuttles, etc. Composite materials are lightweight materials and thus, they are normally used for everything in structural applications and components of all aircrafts and spacecraft such as gliders, hot air balloon gondolas, fighter planes, space shuttles and passenger jets. The structure of the material used in this air vehicles demands high specific stiffness, high specific strength and high degree of dimensional stability to withstand under wide range of temperature and higher altitude atmospheric pressure as well as the applied structural load during operations.

In the recent decades, the use of air travel has been increased drastically worldwide. To meet the high demand, a higher production rate of the machining is compulsory. The most critical technique for producing better surface quality is the machining parameters of cutting speed, feed rate and cutting depth. Nicolais et al. states in their studies that for cutting and machining polymer composites, a combination of small depth of cut, smaller feed rate and high cutting force can produce better surface finish [1]. Meanwhile, for micro-milling of nano-polymer composites, Shyha et al. concluded in their studies that the feed rate influenced the cutting force while the cutting speed has little to no effect on cutting force [2]. Also, a negligible tool wear on cutting edge were obtained from the addition of nano-filler of up to 1% weight of filler fraction. The tool bits are also as much as important as those three parameters. According to studies by Xu et al., they highlighted that the TiAlN-coated tungsten carbide drill bit has better wear resistance to catastrophic failure than diamond-coated tungsten carbide drill bit despite having a similar cutting condition applied [3]. In terms of fiber orientation, studies by He et al. showed that the friction coefficient for milling dependent on fiber cutting angle [4].

John & Kumaran stated that, at constant feed rate, chilled air machining outperforms dry machining in terms of delamination and surface roughness [5]. Xu et al. investigated and found that a lower drilling torque and less energy consumption can be obtained under the minimum quantity lubrication (MQL) machining which was contributed by the lower frictional force occurred at the tool-hole wall interface [6]. MQL has been shown to have a positive influence on the geometric precision of composite holes.

Minimum Quantity Lubrication (MQL) or also known as Micro-lubrification is an alternative to the use of traditional metal working fluids in machining. When chips are ejected, the excellent lubricity of a good MQL lubricant guarantees that much of the heat generated from metal sliding friction is transmitted to the chip and departs the interface. This heat lubrication and transfer keeps the cutting tool cooler for longer and reduces tool wear. It is common for machinists to have double the tool life after using MQL. The swarf or chips from cutting with MQL are practically dry and can be recycled for greater benefit and without washing. With MQL, before secondary operations take place, sections also do not need any cleaning. Hydrogenbonded liquid media are more likely to induce environmental stress cracking (ESC) in polymers. Which also mean vegetable oil are more suitable for polymers since vegetable oil has little to less water content. Many MQL lubricants are highly distilled bio-based (plant) oils and are fully safe for skin contact and have the added advantage of organic and environmentally sustainable materials [7].

The objectives of this research are to compare the machinability behaviors of nanocomposites (Epoxy/Graphene) under various cooling and cutting conditions in terms of cutting force, surface quality and morphology as well as the build-up edge formation on the different coated flat-end mill cutters.

## 2 Methodology

There are three types of Epoxy/Multi-Layer Graphene Nanocomposites used as the material specimens in this work. A 0.1 wt.% of multi-layer graphene of 12 nm average thickness (purity 99.2%) was added in acetone at different concentrations of 0, 25 and 50 ml before being sonicated in a sonicating bath for 30 min prior mixing it with the epoxy resin. The preparation procedure is discussed thoroughly by Saharudin et al. in [8]. A monolithic (neat) epoxy is used as the control specimen sample in this investigation. Figure 1 shows the material specimens before the machining processes take place, which are (A) Monolithic Epoxy, (B) Epoxy/Graphene-0 ml Acetone, (C) Epoxy/ Graphene-25 ml Acetone and (D) Epoxy/Graphene-50 ml Acetone. Each specimen was in the shape of a cuboid with a dimension of 80 mm in length, 10 mm in width and 3 mm of thickness. The specimens were tested on a Vickers Micro-hardness Tester following the ASTM E384 standard for measuring the surface hardness of each specimen. The hardness test specifies an initial load, *P* of 0.05 kg divided by the indentation diagonal area, *A* in $mm^2$ after 20 s indentation time. Equation 1 depicts the Vickers microhardness calculation method according to the standard specification.

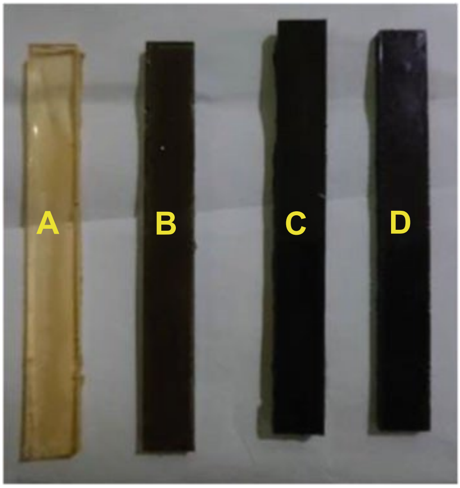


**Fig. 1** Material specimens of **a** Monolithic epoxy; **b** Epoxy/graphene-0 ml acetone; **c** Epoxy/graphene-25 ml acetone; and **d** Epoxy/graphene-50 ml acetone

**Table 1** Machining and MQL parameters

| Items | Description |
|---|---|
| End mills | 4 flute, Tungsten carbide |
| End mill diameter | 3 mm |
| Coatings | AlTiN (HRC50), TiSiN (HRC60), TiAlN (HRC55), Uncoated (HRC55) |
| Cutting speed, $v_c$ | 35 m/min |
| Feed rate, $f$ | 25 mm/rev |
| Axial depth of cut, $a_p$ | 0.5 mm |
| Cutting length | 10 mm per pass (4 passes each set) |
| MQL condition | Pressurized air, MQL-synthetic ester (MQL-SE) |
| MQL pressure and flowrate | 0.4 MPa at 15 ml/hr |

$$HV=100P/A \ldots\ldots\ldots (1)$$

Surface roughness of the specimens is measured using a perthometer (Surfcom Touch 50) both before and after the slot milling operations. The cut-off length, $\lambda_c$ was set at 0.8 mm with the measurement length of 5.6 mm according to the EN ISO 4287 standard.

Four different coatings of 4-flutes, 3 mm diameter tungsten carbide flat-end mill cutters are used for the machining tests. Table 1 depicts the cutting parameters of the slot milling experiments. For this experiment, the slot millings were conducted on MAKINO KE-55 CNC vertical milling machine which has a maximum power of 5.6 kW, maximum spindle speed of 4000 rpm, a positioning accuracy of 25–100 μm. The machine has a table width of 375 mm and a table length of 800 mm with traverse and crossing distances of 548.64 mm and 320.04 mm, respectively.

All four different types of Graphene/Epoxy nanocomposites will undergo a total of 16 sets of experiment following the machining parameters shown in Table 1. For each set of experiment a new specimen and tool bit are used. The first 12 sets of experiments use the three coated cutting bits with pressurized air while the last four will use the uncoated milling cutter lubricated by the Synthetic Ester (SE) through the MQL condition as the lubrication method. The pressurized air and the microlubrication of SE is delivered to the cutting zone using a MQL device (Kuroda Ecosaver KEP-WR) through a nozzle orifice diameter of 2.5 mm and the distance from the nozzle tip to the tool cutting edge between 50 to 55 mm. Figure 2 illustrates the machine configuration of the milling operations. The machining process starts at the entry region towards the end point (negative X-direction) with the up-milling procedure is taken place at the entry point (conventional milling).

All the test specimens and the tool bits are then analyzed with video measuring microscope and digital microscope to capture the tool morphologic and surface topography before and after the machining tests.


**Fig. 2** Machining setup, nozzle distance and cutting path

## 3 Results and Discussion

The surface hardness and roughness results of the material specimens are shown in Figs. 3 and 4, respectively. According to Saharudin et al., the hardness of the nanocomposite prepared without acetone is higher compared to the Vickers microhardness of the monolithic epoxy [9]. The initial surface roughness of the specimens recorded a different results variation. The monolithic epoxy has a rougher surface compared to the other nanocomposites and the smoother surface is shown by the nanocomposite prepared without acetone, specimen B.

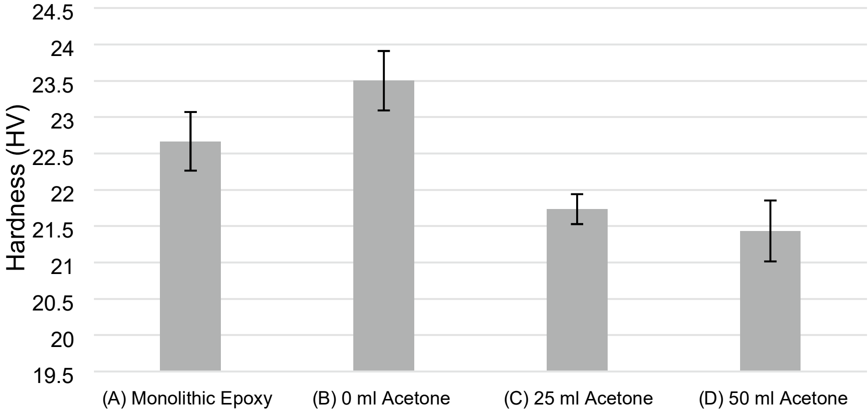


**Fig. 3** Vickers hardness of monolithic epoxy and its nanocomposites

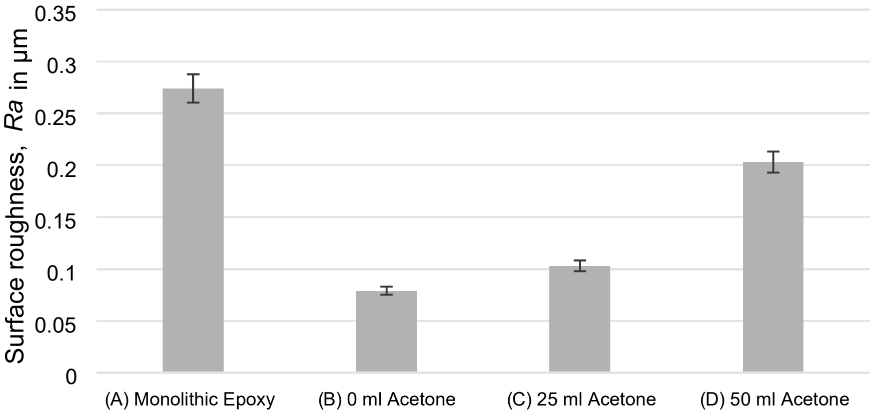


**Fig. 4** Surface roughness results of the specimens before milling

The cutting force results of all specimens during milling operation using different coatings of flat-end mill cutters are presented in Fig. 5. The specimen of Epoxy/Graphene-25 ml Acetone (specimen C) shows that the cutting forces remain at a constant trend of below 6 N for all coated and uncoated tungsten carbide tools compared to the other results. In addition, the milling with MQL-SE lubrication using uncoated tools presented a consistent trend of low cutting forces (between 3.9

and 5.6 N) for all specimen materials. This finding also corroborates with the report from Skopp and Klaffke, whereby low cutting forces were produced when cutting using uncoated tungsten carbide tool under MQL condition [10]. It can be noted that MQL does have a positive influence on nanocomposite machining.

The cutting forces produced by TiAlN-coated tools with pressurized air show a comparable good trend of results with the uncoated tools. TiAlN is reported to have

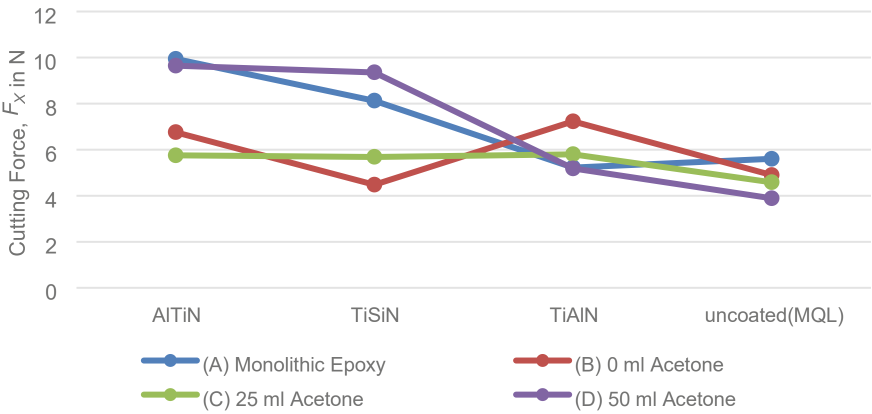


**Fig. 5** Cutting Force, $F_X$ with respect to different tool coatings

a very high thermal stability of up to 1000 °C, thus this coating can sustain high cutting temperature generated at the cutting zone, which subsequently resulted in lower tool wear rate and cutting forces as compared to the other coated and uncoated flat-end mill tools [11]. Additionally, Ji et al. [12] reported that lower cutting energy consumption can be obtained under MQL condition with TiAlN coated-tool due to the reduced frictional forces acting at the tool-hole wall interface.

The surface roughness, $R_a$ results after the milling operation can be seen in Fig. 6. The machined surface of the specimen A using AlTiN-coated carbide tool has a rougher surface compared when using other cutting tools. At high cutting speed of 35 m/min, the AlTiN-coated carbide tool experiences extreme frictional conditions that results in rapid tool wear as well as higher cutting forces compared to TiAlN and the uncoated+ MQL-SE [11]. With TiSiN-coating, the slotted surface was found with clean cut alongside with uncoated tungsten carbide tool under MQL-SE condition. As for the machined surface using TiAlN-coated flat-end mill cutter, minor thermal damage is found at the exit of the slot as shown in Fig. 7. Different coating materials provide different tribo-mechanical interactions between the tool-workpiece sliding interfaces, which indicate the difference in surface friction produced by the coatings material on the tool-workpiece sliding surfaces [13].

Thermal damages can be seen on the machined surfaces of specimen B despite having been machined using different type of coated flat-end mill cutter especially when using the TiAlN-coated tungsten carbide tool. A better surface finished is presented on specimen C when using TiAlN-coated cutting tool in high pressurized air condition as well as when using the uncoated tool in MQL-condition as shown in Fig. 7. The TiAlN coated carbide tool may reduce the sliding friction between the TiAlN coated surfaces while cutting the workpiece specimen C (dispersed in 25 ml

Acetone) compared to the material that has 0 ml Acetone dispersant (specimen B). The highly concentrated multi-layered graphene nanoparticles in the epoxy of specimen B may increase the frictional behavior of the workpiece when being cut by the different coated carbide tools [13].

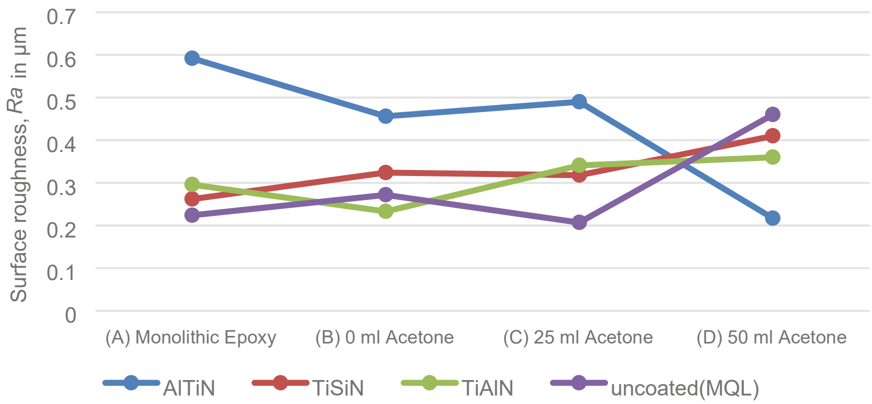


**Fig. 6** Surface roughness results on the machined surfaces for all specimens after milling

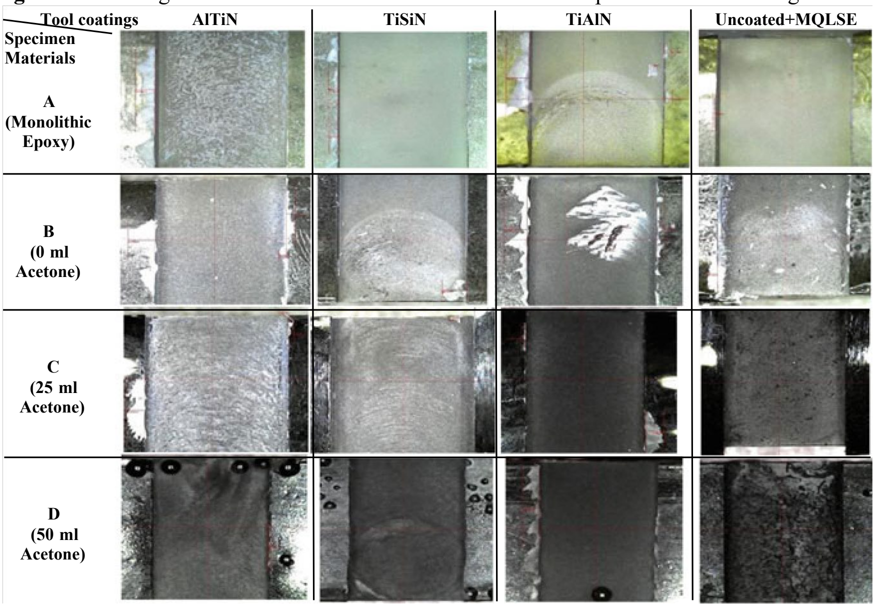


**Fig. 7** Optical images of the machined surfaces at 4th pass on all specimens' materials

The machined surfaces on specimen D is seen to be having a similar pattern of surface damage when compared to all the other cutting conditions. The presence of higher acetone volume in the specimen D reduces the dynamic storage modulus, $E'$ as well as contributing to the presence of high porosity, which could degrade the mechanical properties of the specimen [8]. However, the topographical image after machining with the uncoated tungsten carbide tool in MQL-SE condition shows a rougher surface compared to the other cutting tools as presented in Figs. 6 and 7. The uncoated tool may increase the material adhesion of specimen D at the chiptool interface as the cutting temperature increases while removing the workpiece material, thus increases the tool wear and material's build-up at the cutting zone, which produces rougher surface conditions (0.46 μm) compared to that of the other coated cutting tools that cut the same specimen's material [13].

## 4 Conclusion

In this paper, a comparative study was performed on the machinability properties of Epoxy/Graphene nanocomposites under various tool coatings and lubrication conditions in terms of cutting force, surface quality and morphology on different specimen materials using flat-end milling processes. Based on the results and findings acquired, the conclusion can be summarized as follows:

- Less cutting force and lower surface roughness were obtained from MQL-SE condition machining except for Epoxy/Graphene-50 ml Acetone (specimen D).
- Cutting Epoxy/Graphene-25 ml Acetone (specimen C) with uncoated tungsten carbide in MQL-SE condition give the best surface finish (0.207 μm).
- Epoxy/Graphene-25 ml Acetone (specimen C) is much easier to cut compared to other specimens even using different coated carbide cutting tools.
- The TiAlN-coated tungsten carbide tool produces a more consistent cutting forces compared to the other coated cutting tools despite having to cut different material specimens.
- AlTiN, TiSiN and TiAlN-coated flat-end mill cutters produce better surface finish compared to the uncoated cutting tool when cutting the Epoxy/Graphene-50 ml Acetone (specimen D).
- Acetone volume influenced the material adhesion on the tool-workpiece interfaces with higher acetone dosage being added in the nanocomposite, less material adhesion is found on the cutting tool's edge.

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