Machining of Nano-Structured Polymer Composites

Bao Le, Islam Shyha, and Dehong Huo

Abstract Nanocomposites have been discovered and researched for over 60 years due to their advanced characteristics such as mechanical, thermal and electrical properties compared to other materials (i.e., metals, ceramics and alloys). Among the most functional nanomaterials, polymer nanocomposites have found many industrial applications, especially as structural materials. Although near-net-shape (NNS) manufacturing processes could be employed to fabricate these materials, higher qualities in terms of machine surface and dimensional accuracy, especially in complex features are still required since they are crucial requirements in modern manufacturing. Therefore, machining seems to be an inevitable process and have found huge potential to generate high-precision products. However, machining of polymer nanocomposites is more severe than that of other materials due to their anisotropic, heterogeneous structure and high mechanical properties (i.e., high abrasiveness, fracture toughness, tensile strength) of their reinforcing constituents. These factors could result in low machined surface quality, typical damages introduced into the machined surfaces and tool wear acceleration. Therefore, investigation on machining behaviours of these polymer nanocomposites is necessary to provide suitable cutting conditions. This chapter addresses these materials' machinability when using major machining processes, including conventional, non-conventional, and micromachining.

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1 Introduction

Polymer nanocomposites have been applied widely due to their high properties per weight (specific properties) such as strength and stiffness compared to other materials (i.e., metals and their alloys). These characteristics provide enormous potential to manufacture light-weight products using these nanocomposites as structural materials. Conventional machining processes such as milling, turning, or drilling could be employed as a post-processing method to attain higher surface quality and dimensional accuracy. Applying these techniques to polymer nanocomposites shows high flexibility in choosing workpiece materials over other non-conventional methods (i.e., Electrical Discharge Machining (EDM), laser machining) maintaining comparable machining accuracy and productivity. However, the reinforcing materials mostly have higher strength, stiffness, fracture toughness (i.e., carbon nanotube (CNT), graphene) or hardness, abrasiveness (i.e., ceramic nano-fillers) over the matrix materials that make these materials hard to machine or low machinability. It leads to the machining behaviour of these polymer nanocomposites significantly depending on reinforcements' mechanical properties and matrix-filler interphase.

Consequently, critical machinability indicators, including surface roughness, tool wear and tool life have become the main concerns in machining polymer nanocomposites. This chapter will address both conventional and non-conventional machining processes of polymer nanocomposites (Fig. 1).

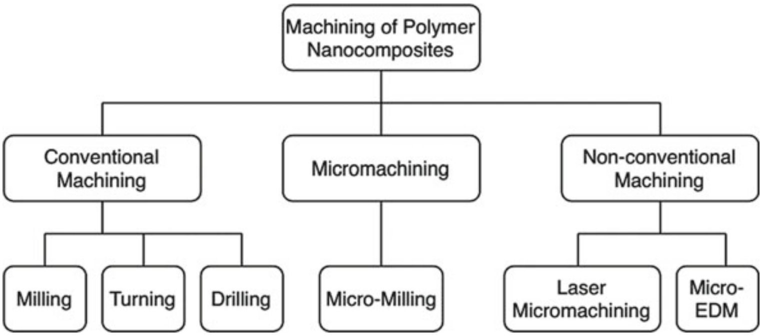


Fig. 1 Classification of machining of polymer nanocomposites

2 Machining of Polymer Nanocomposites

2.1 *Polymer Nanocomposites as High-Performance Engineering Materials*

The advancement of material science has observed metals and alloys' substitution by polymer composites, mostly fibre-reinforced based (FRP) as high-performance engineering materials. Carbon fibre reinforced polymers (CFRP), glass fibre reinforced polymers (GFRP), and aramid fibre reinforced polymers (AFRP) are the most common polymer composites that have been widely applied to manufacture primary structures in aerospace, marine or automotive industry. The demand for finding other lighter materials while providing comparable or even higher mechanical properties (i.e., stiffness, tensile strength, fatigue strength) than conventional metallic materials is the main reason for this replacement.

The near-net-shape methods (i.e., moulding, shaping) are mostly applied in the productions of FRPs. However, machining as a finishing process is still required if high dimensional accuracy and surface quality are concerned. Figure 2 shows an example of applying polymer composites machining in manufacturing aeroplane wing box structure (stringers and ribs). In this case, machining methods such as milling, or drilling are required to attain high dimensional accuracy (or low tolerance), and surface quality for assembly surfaces.

As the first polymer nanocomposites appeared in the past 50 years or so, these materials have been considered the successor of polymer composites in industrial applications. Polymer nanocomposites are considered as a branch of composite materials. The term "nanocomposite" indicates the size of filler in at least one dimension less than hundreds of nanometres. Similar to polymer composites with macro-sized fillers (hereafter called conventional composites), the most common filler form used in polymer nanocomposites is fibrous such as carbon nano-fibre (CNF), carbon

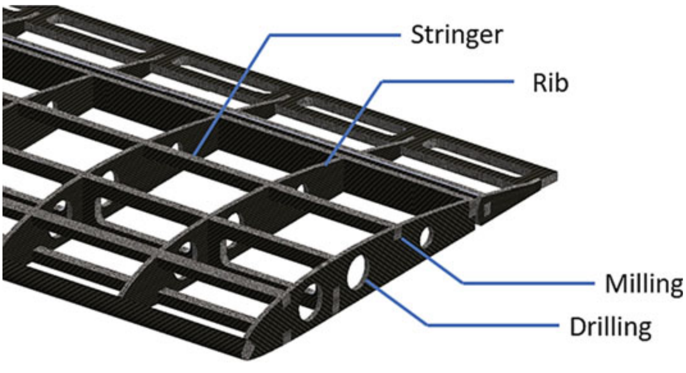


Fig. 2 An example of micromachining of polymer composites in manufacturing aircraft wing box structure

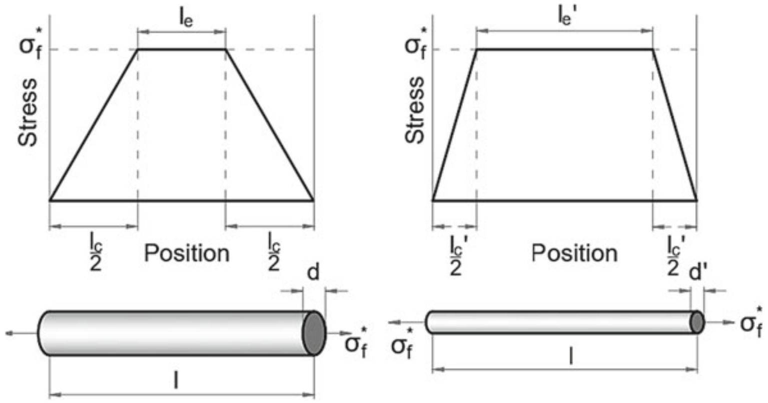


Fig. 3 Effect of fibre diameter on reinforcing efficiency of fibre

nanotube (CNT). Another sheet form like graphene is still considered as fibre. Due to the high mechanical reinforcing efficiency of the fibrous form (stiffness, strength) compared to particles. Fibre size reduction (diameter) can benefit the reinforcing efficiency of mechanical properties due to the aspect ratio (length/diameter). The strengthening efficiency of fibre can be identified based on the critical length:

$$l_c = \frac{\sigma.d}{2\tau} \quad (1)$$

where σ is the ultimate tensile strength of fibre, τ is the shear strength of the fibre-matrix bond, and d is the fibre diameter. For the same fibre length, reducing fibre diameter (d) can reduce the critical length, hence increasing the effective fibre length (l_e) (Fig. 3).

Additionally, the stiffness and strength of nano-fibres are much higher than their conventional counterparts. For example, single-walled carbon nanotubes (SWCNTs) have the stiffness five times higher than carbon fibres. It leads to a much better reinforcing efficiency of these nano-fibres. The rule of the mixture can theoretically estimate this efficiency:

$$E_c = E_m V_m + E_f V_f \quad (2)$$

E and *V* represent elastic modulus and volume fraction, respectively, whereas the subscript c, m, and f denote composite, matrix, and filler. Furthermore, the high filler-matrix bonding of polymer nanocomposites in the molecular level also contributes to these materials' advanced mechanical properties compared with conventional polymer nanocomposites.

However, these advanced properties also make enormous challenges for machining as they are hard to machine. The state-of-the-art machining of polymer nanocomposites has been observed a limited application despite nanocomposites' high potential as structural materials in many applications (e.g., aircraft components, automobile industry and sporting goods) and research studies had to be undertaken to investigate this in more detail. It is mostly due to their high production cost. Within this chapter's scope, some typical processes of polymer nanocomposites will be discussed, including conventional and non-conventional techniques. In general, surface roughness and surface damage (or integrity) indicate the machinability of materials. For conventional machining, cutting force, tool wear (or damage) should also be considered.

2.2 Milling of Polymer Nanocomposites

Milling is considered as the most common process among conventional machining techniques due to its high feasibility and flexibility when dealing with complex geometries and various materials. Therefore, this machining process is considered feasibly applied for polymer nanocomposites (Fig. 4). The machined surface quality is the most crucial objective when applying the machining process (Fig. 5). The primary adaption is to investigate the surface roughness respond concerning the variations of machining parameters. Feed rate, depth of cut (DoC) and cutting speed are mostly chosen as significant variables like cutting metallic materials.

Additionally, filler content is also considered because of its effect on workpiece structure and mechanical properties. The contributions of these inputs to the machined surface roughness are identified by applying Analysis of Variance (ANOVA) [1] or Taguchi method [2]. Feed rate is the most dominant factor affecting the surface roughness following by cutting speed and DoC while filler content shows the unobvious influence. The variations of surface roughness when milling different polymer nanocomposites as a function of feed rate is shown in Fig. 6.

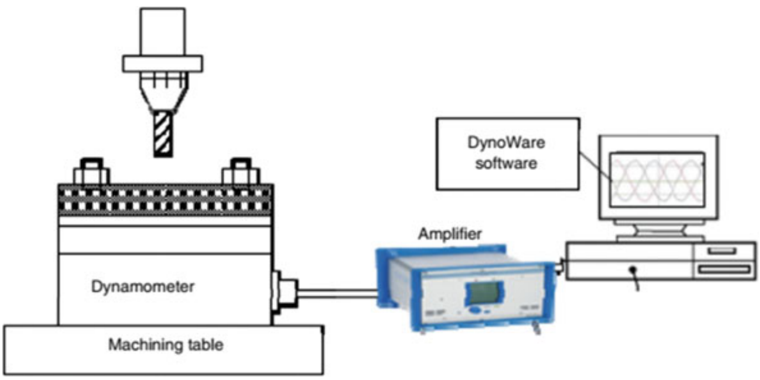


Fig. 4 A typical setup for milling of polymer nanocomposites. Open access from [3]

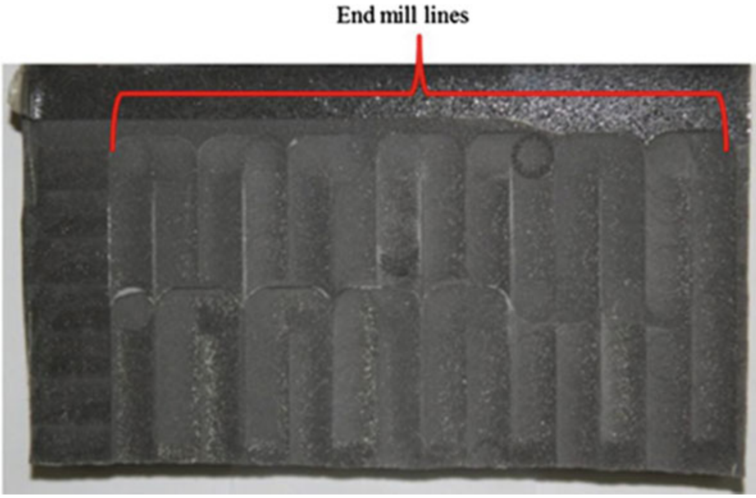


Fig. 5 An example of the machined surface of polymer nanocomposites using end-milling (open access from [2])

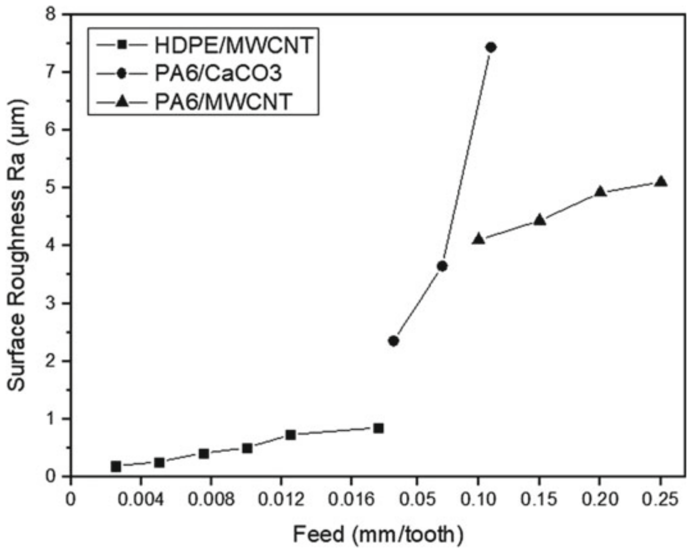


Fig. 6 Effect of feed rate on surface roughness when end-milling polymer nanocomposites (adapted from [4–6])

The behaviour of surface roughness variation when milling polymer nanocomposites is generally similar to metal cutting. The optimal surface quality can be obtained by cutting at low DoC and feed rate levels combined with high cutting speed. The small weight fraction of CNTs or graphene also contributes to surface quality improvement due to their lubricating nature [7]. Additionally, incorporating these nano-fillers into the matrix also plays a crucial role in improving polymer nanocomposites' thermal conductivity, consequently reducing the heat around the cutting area, hence reducing the roughness of the machined surface.

2.3 Drilling of Polymer Nanocomposites

As polymer nanocomposites' commercial applications are still limited due to their high production cost, the drilling applications (Fig. 7) mostly focus on hybrid polymer nanocomposites in which nano-fibres such as MWCNT, CNF are used as secondary reinforcing materials. Since the primary polymer composites are mostly CFRP or GFRP, the delamination is still the main challenge in this machining field. The small addition of nano-fibres (<1 wt.%) can reduce the drilling-induced delamination as they tend to bridge the crack between laminates (Fig. 8), hence improving internal laminate shear strength (ILSS) [8] and fracture toughness [9]. Figure 9 shows some reduction trends of delamination as a function of the nano-fibres addition. However, feed rate and cutting speed effect on these criteria are still dominant while cutting tool diameter shows unobvious influence [10]. In terms of cutting geometry, both twist and split point drills are suitable for this kind of machining (Fig. 10), but the

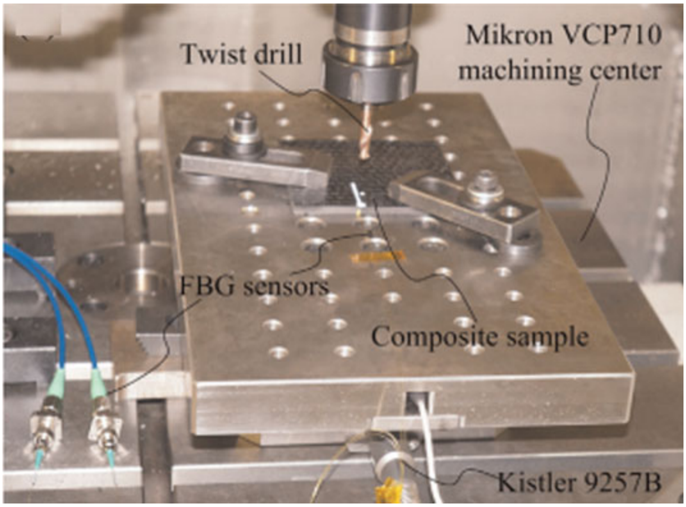


Fig. 7 A setup of drilling epoxy/carbon fibre/MWCNT nanocomposites. Copyright permission from [9]

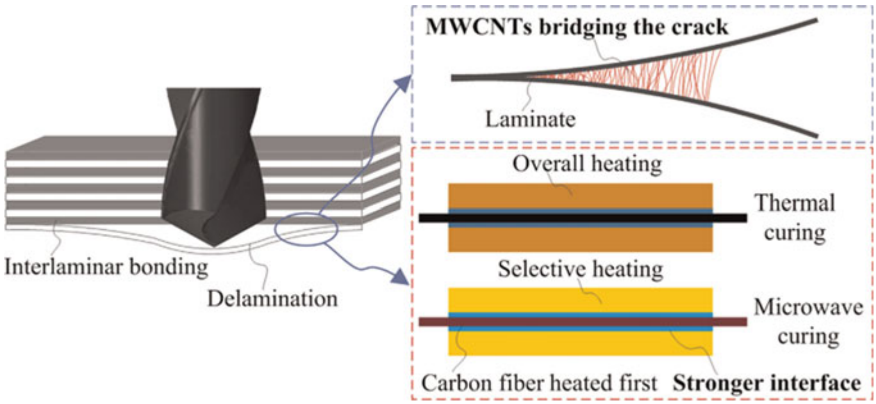


Fig. 8 The schematic represents the role of MWCNTs addition in reducing delamination by bridging the crack during drilling of epoxy/carbon fibre/MWCNT nanocomposites. Copyright from [9]

former type of drill seems to have better performance during the drilling process [11].

The reduction of delamination factor due to the presence of nano-fires consequently leads to better surface quality. Additionally, these hybrid nanocomposites' higher thermal conductivity can also contribute to less thermal damage on the machined surfaces than those without nano-fibres. In terms of machining parameters, feed rate and cutting speed are considered significant factors that affect the surface quality. The mechanism of surface roughness being affected by these variables is identical to drilling metallic materials. The cutting regime with low feed rates and high cutting speeds can generate low cutting forces and less built-up edge (BUE), hence improving the surface quality.

2.4 Turning of Polymer Nanocomposites

Surface roughness is the most critical objective when turning polymer nanocomposites, identical to other mechanical machining techniques (milling, drilling). This machining process shows similar surface roughness behaviour trends as a function of cutting parameters (cutting speed, feed rate, depth of cut) and filler loading. The high cutting forces due to the increase in the cross-sectional area at high feed rates lead to low surface quality. Therefore, the feed rate is considered the most influential factor in surface roughness when turning into polymer nanocomposites. However, the roles of MWCNTs in improving machined surface quality are not apparent although some of the nano-fillers such as MWCNTs [14] or $CaCO_3$ [15] nano-particles have been proved in reducing cutting forces due as lubricants. Figure 11 represents a typical setup for turning of epoxy/MWCNT nanocomposites.

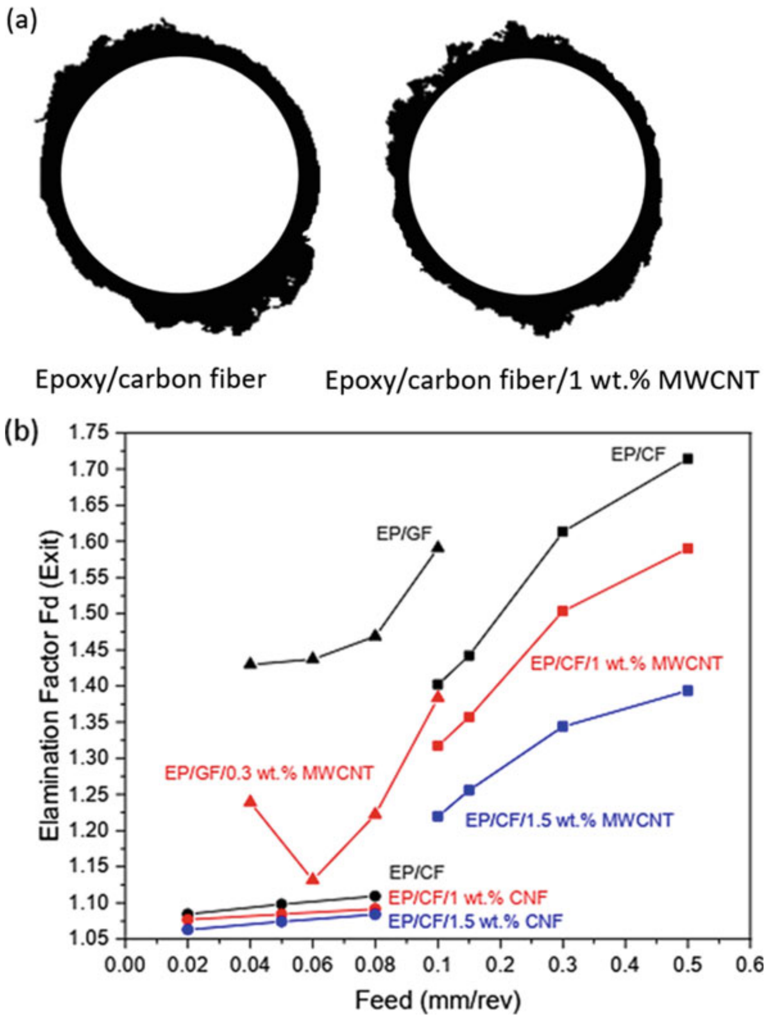


Fig. 9 Delamination in the drilling of polymer hybrid nanocomposites: **a** Computerised tomography depicts delamination from the drilling of epoxy/carbon fibre/MWCNT nanocomposites. Copyright permission from [9]); and **b** The reduction of delamination factor at the exit as a function nano-fibre content (adapted from [8, 12, 13])

3 Mechanical Micromachining of Polymer Nanocomposites

It is seen that the advancement of machining has aimed to improve two main features: (i) higher machining precision/lower tolerance and (ii) smaller feature size or miniaturization [16] which are critical requirements from modern manufacturing. The former refers to ultra-precision machining while the latter indicates mechanical micromachining. However, these two processes share some common

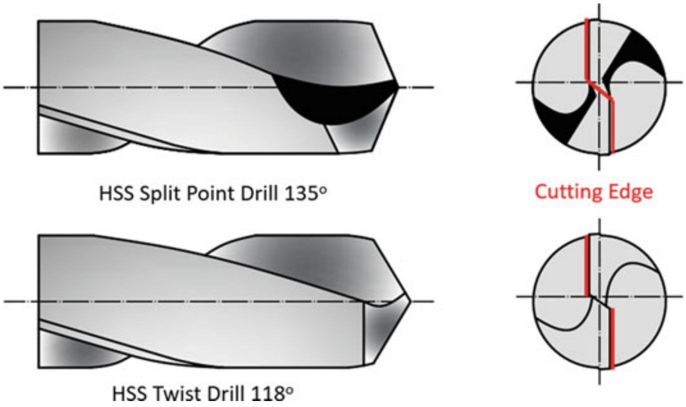


Fig. 10 Examples of tools used for drilling of polymer nanocomposites

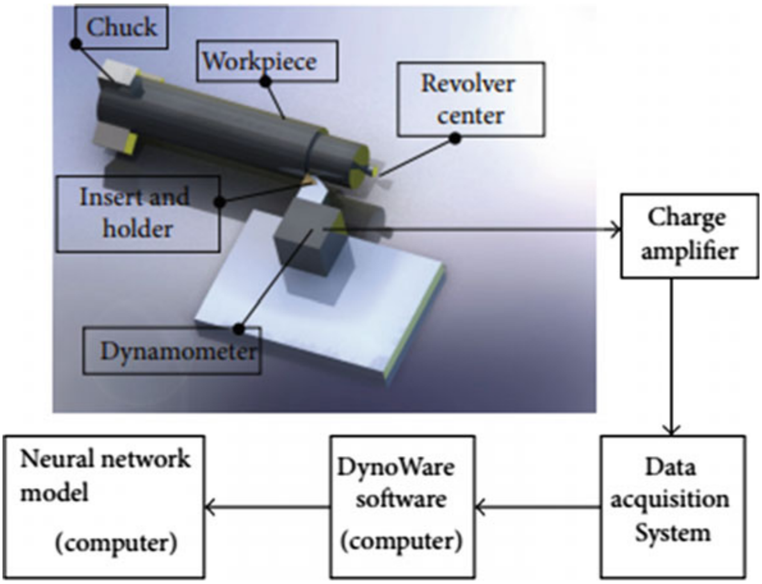


Fig. 11 A schematic represents the experimental setup of turning epoxy/MWCNT nanocomposites. Open access from [15]

characteristics such as uncut chip thickness (UCT), chip formation and specific cutting forces. Within the scope of this chapter, both terms will be referred to as micromachining. Some standard techniques, including micro-milling, micro-turning, and micro-drilling of polymer nanocomposites, are mentioned. In the context of nanocomposites being commercially applied, the needs of employing micromachining techniques to generate high-quality products in terms of dimensional accuracy, surface quality with from polymer nanocomposites deem to be necessary (Fig. 12).

Micromachining generally exhibits the same material removal mechanism as conventional machining with the physical contact between the mechanical cutting tool and workpiece. However, the miniaturization of a machine tool to attain micro-ranges of UCT leads to some critical differences called 'size effects' between these two techniques. Therefore, it seems necessary to illuminate the fundamentals of mechanical micromachining and its distinct features compared to conventional methods (drilling, turning or milling) (Sect. 3.1). The subsequent studies on micromachining of polymer nanocomposites are discussed in the next Sects. (3.2 to 3.4). The main conclusions and limitations from micromachining polymer nanocomposites research are indicated as their critical importance in prospects.

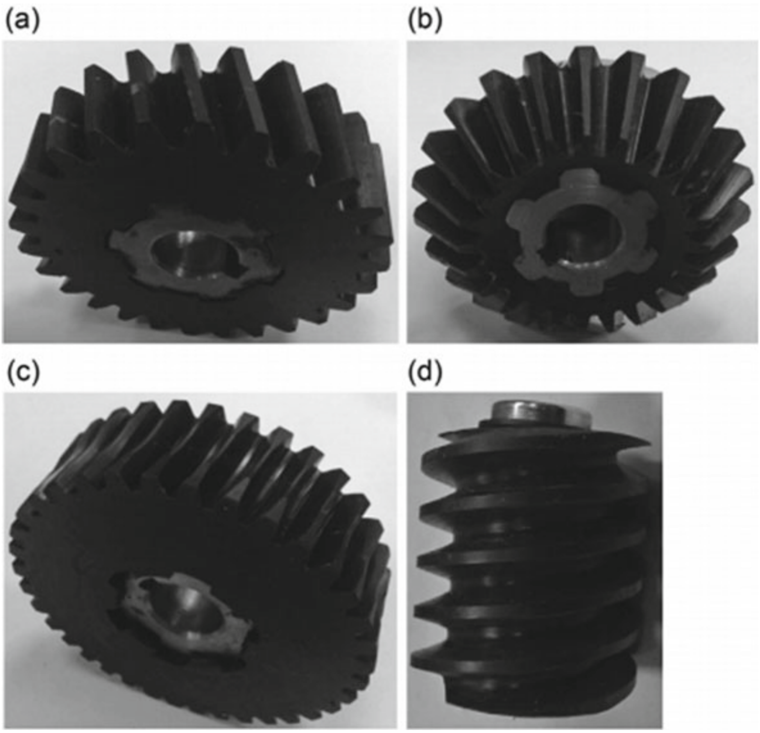


Fig. 12 Applications of micromachining of polymer nanocomposites: **a** a CNT/acetal helical gear, **b** a CNT/acetal bevel gear, **c** a CNT/acetal wheel gear, **d** a CNT/acetal worm gear. Copyright permission from [17]

3.1 Removal Mechanisms of Micromachining and Differences from Macro-Scale

In general, micromachining is considered a miniaturized version of conventional machining as they share the common kinematic cutting mechanism. However, some critical issues regarding the size effects appear when downscaling the UCT into comparable values with cutting edge radius or grain size. It leads to the dominant effects of workpiece microstructure and minimum uncut chip thickness (MUCT) which are usually neglected in macro-scale machining.

Microstructure Effect

In conventional machining at macro-scale, microstructure effect is mostly neglected as the material removal rate (MRR) is relatively high. Work-piece material, in this case, is assumed to be homogenous and isotropic. However, when the micro cutting-tool is employed in micromachining, the cutting edge radius approaches the grain size of material; hence this assumption is no longer valid. The required specific cutting force [18] or specific cutting energy [19] during the micromachining process, hence become higher due to the tool breaking individual grains bonding by atom forces (Fig. 13). It also leads to the cutting force variation as the tool passing between grain boundaries. The schematic representing these differences between micromachining and conventional machining in terms of microstructure effect is shown in Fig. 14. The grain boundary effects on cutting forces [20] or machined surface morphology

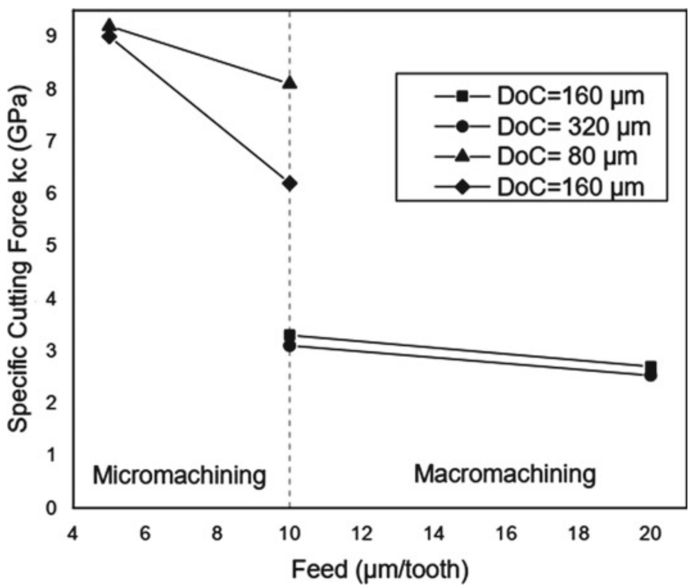


Fig. 13 Comparison of specific cutting force between micro and macro-milling of AISI 1045 Steel (adapted from [18])

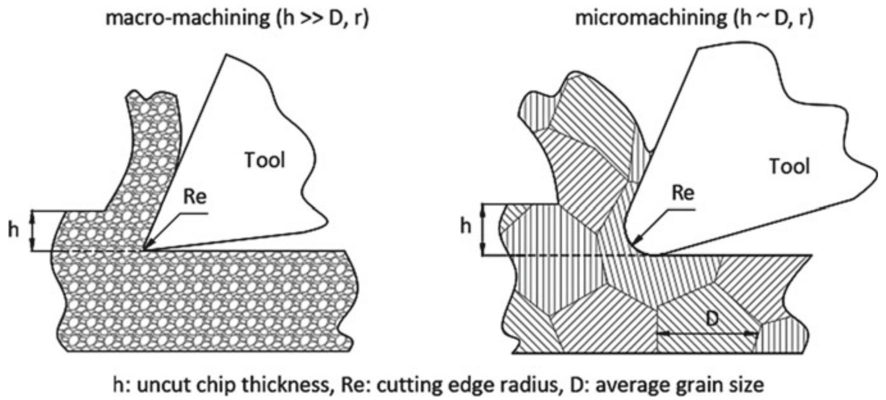


Fig. 14 Microstructure effect in micromachining resulting from the low ratio between UCT to cutting edge radius and grain size. adapted from [22]

[21] have also been investigated. Micromachining of single-phase materials and multiphase materials has been investigated to clarify the microstructure's effects on machining key indicators.

The different elastic recoveries [23], unbalance plastic strains [24], or the burr formations at the grain boundary [25] in these multiphase materials were claimed to be the main reasons for high cutting force variations as well as low surface quality (Fig. 15).

Minimum Uncut Chip Thickness (MUCT) and Cutting Edge Radius

Uncut chip thickness (UCT) and its correlation with cutting edge radius identify the fundamental distinction between macro and micro-machining. UCT is miniaturized in micro-machining; its values become comparable with cutting edge radius, leading to the difference in cutting mechanism from conventional machining. If these values are below a minimum uncut chip thickness (MUCT), there is no material being removed and subsequently, no chip formation.

It is observed from Fig. 16 that when UCT is much greater than MUCT and cutting edge radius in case of macro-machining, the cutting mechanism mostly occur as shearing. Due to the meagre ratio between cutting edge radius and UCT (r/h), the cutting tool is considered as ideally sharp, and the effect of cutting edge radius is ignored. However, when reducing UCT into micro-range in micro-machining. UCT, in this case, becomes comparable with cutting edge radius. The workpiece material is now both sheared and ploughed due to the considerable effect of cutting edge radius. A further reduction of UCT values below MUCT (hm) makes the material removal unfeasible, leading to the ploughing-dominant regime.

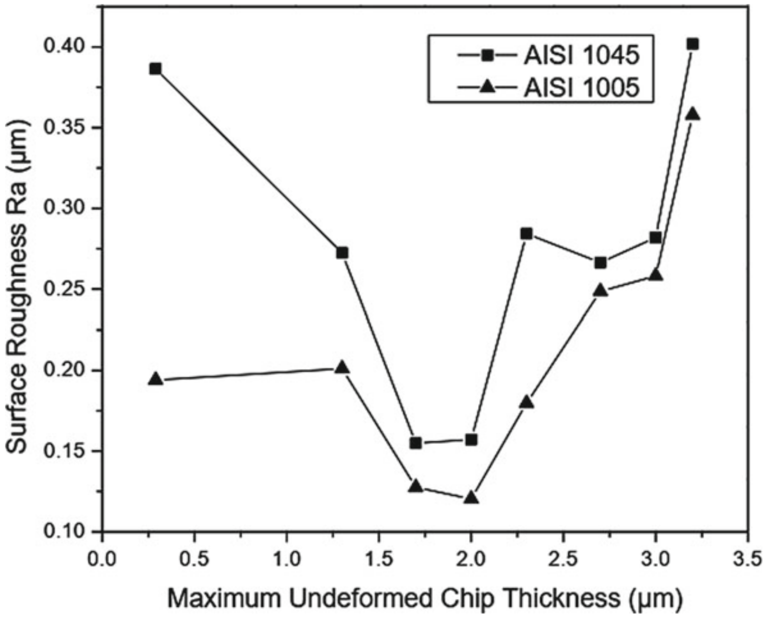


Fig. 15 Effect of microstructure on surface quality when micro-milling steel at a spindle speed of 30,000 rpm and DoC of 75 μm adapted from [23]

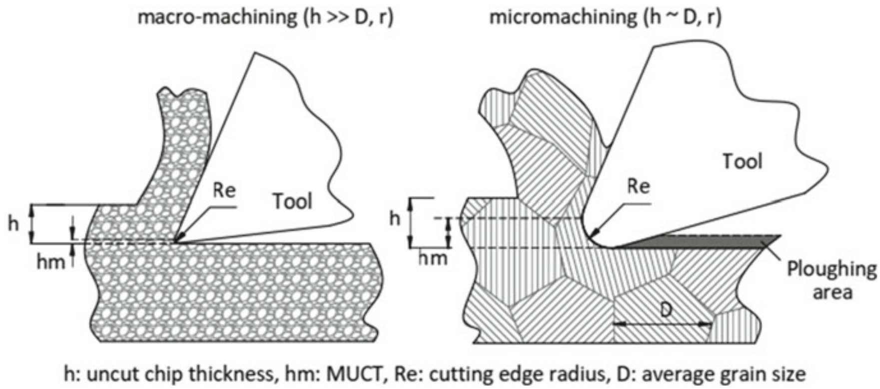


Fig. 16 Size effect affecting cutting mechanism as uncut chip thickness being reduced. adapted from [22]

3.2 Micromachining of Polymer Nanocomposites

Despite many polymer nanocomposites being commercially used, micromachining applications on these materials have only focused on carbon nanotube (CNT)-based

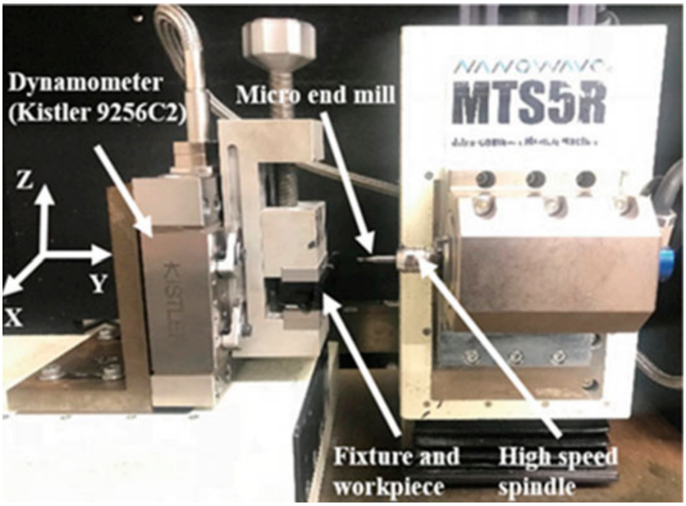


Fig. 17 Micro-milling of polyester/halloysite nano-clay nanocomposites using miniature machine tool (Open access from [26])

and graphene-based nanocomposites, using micro-milling. Figure 17 shows a typical setup for micro-milling of polymer nanocomposites using a miniature machine tool.

For that reason, this section of the chapter will discuss the micromachining behaviour of polymer nanocomposites reinforced by CNT and graphene. The main objectives include cutting forces, machined surface generation, chip formation and tool wear during micro-milling processes. The most important factors that affect these categories will be highlighted with the cutting mechanisms or models (if available) to explain nanocomposites' micromachining.

Micromachining of CNT-Based Nanocomposites

The incorporations of CNTs into polymer matrix mostly improve various characteristics such as mechanical, thermal, and electrical properties of polymer nanocomposites. However, within this section's scope, only thermomechanical properties will be analysed since they have shown significant influences on micromachining behaviour when micro-milling of polymer nanocomposites. CNTs play a positive role in dissipating heat generating from the cutting zone, reducing burr formation and improving the dimensional accuracy when micro-milling polymer nanocomposites (Fig. 18). Furthermore, the addition of CNTs into the polymer matrix is also the main reason for cutting forces and better-machined surface quality [27] (Fig. 19). It is due to incorporations of CNTs improved both mechanical and thermal properties of nanocomposites, hence leading to the dominance of strengthening effects and the subordination of thermal softening effects (especially at high feed rates) and consequently, cutting force increments during micro-milling process following by

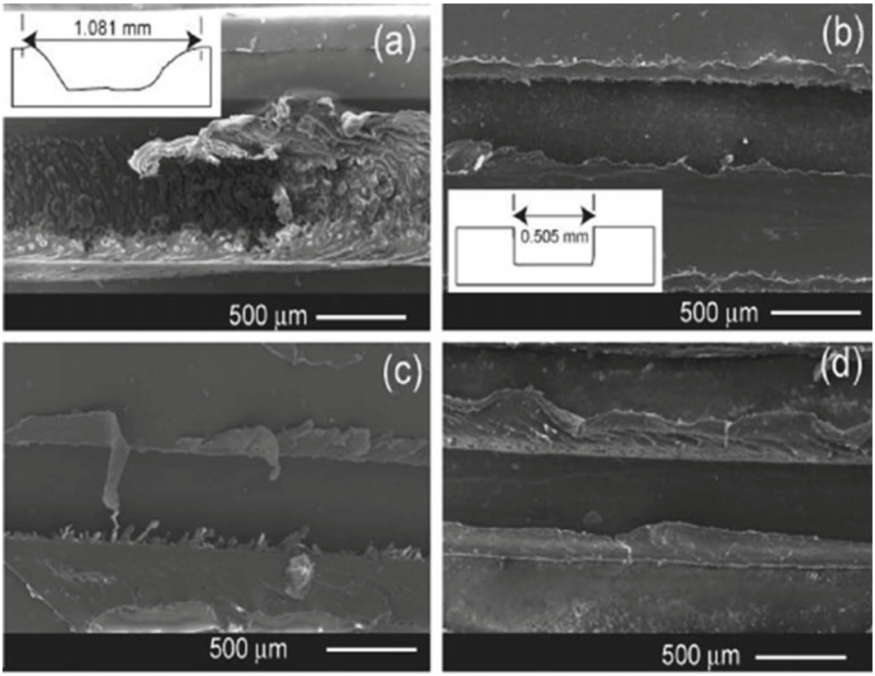


Fig. 18 SEM images of machined slots when micro-end milling of: **a** Plain PC, **b** PC/2 wt.% xGNP-M-5, **c** PC/2 wt.% xGNP-M-25, and **d** PC/1 wt.% xGNP-M-5/1 wt.% MWCNT nanocomposites (cutting speed of 80 m/min and FPT of 3 μm). Copyright permission from [27]

the reductions of surface roughness. These analyses are supported by the investigations on chip formation with discontinuous morphology compared to continuous chips in a micro-milling neat polymer.

A mechanistic micro-milling model [28] was applied to explain the mechanism of cutting force variations in the consideration the effects of CNT addition and fibre orientation when micro-milling of MWCNT reinforced polystyrene (PS) nanocomposites (PS/MWCNT) (Fig. 20). The radial force (dF_r) and tangential force (dF_t) acting on a small element of cutting edge with its height of dz can be obtained as follows:

$$dF_t = \begin{cases} (K_{tc}(\psi)h + K_{te}(\psi))dz & \text{when} \quad h \geq h_m \text{ (shearing)} \\ \left(K_{tp}(\psi)A_p + K_{te}(\psi)\right)dz & \text{when} \quad h < h_m \text{ (ploughing)} \end{cases}$$
$$dF_r = \begin{cases} (K_{rc}(\psi)h + K_{re}(\psi))dz & \text{when} \quad h \geq h_m \text{ (shearing)} \\ \left(K_{rp}(\psi)A_p + K_{re}(\psi)\right)dz & \text{when} \quad h < h_m \text{ (ploughing)} \end{cases} \tag{3}$$

K_{tc}, K_{rc}, K_{re} and K_{te} are the tangential and radial cutting and edge coefficients. K_{tp} and K_{rp} are ploughing constants. These coefficients are expressed as a function

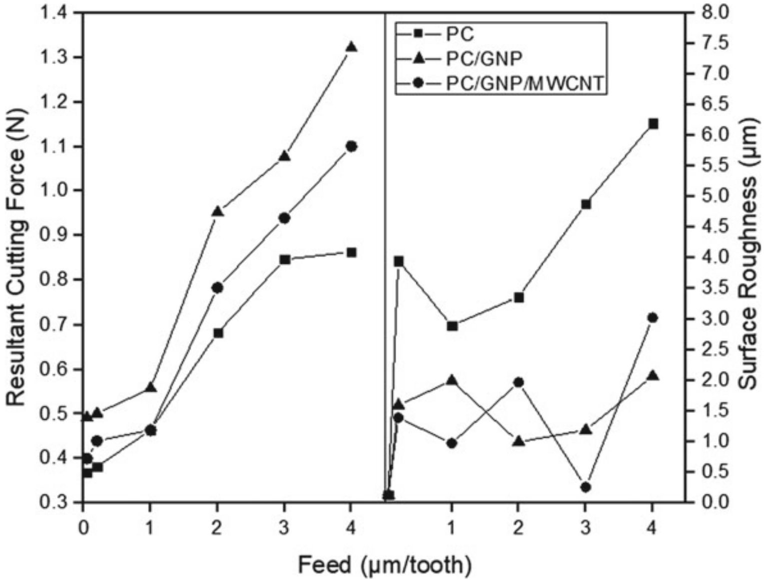


Fig. 19 The variations of surface roughness and cutting forces at various FPTs when micro-milling different polymer nanocomposites. Adapted from [27]

of CNT fibre orientation angle (Ψ). The cutting coefficients refer to shearing of the workpiece while the edge coefficients specify the friction between the cutting tool and workpiece. These coefficients can be obtained from experiments with different chip thicknesses/ feed rate and cutting force compensations [29] using the Kalman filter (KF) method [30]. They are identified via a nonlinear curve fitting as the following equation:

$$e = \sum_{i=1}^{n} \sum_{j=1}^{m} \left(F_{expi,j} - F_{theo}\right)^2 \tag{4}$$

where n is the level number of feed rates, m is the number of samples, F_{exp} is the experimental results regarding the cutting forces, and F_{theo} is their theoretical results. The UCT (h) can be obtained from the chip thickness model [31] in the consideration the effects of MUCT, elastic recovery, and tool vibration (Fig. 21) as follow:

$$h = \max(0, \left\| C_i^j F_i^j \right\| - \left\| C_i^j I_i^{j-1} \right\|) \tag{5}$$

The superscript (j) is the tooth path number, and the subscript (i) is the rotation angle. C, F represent the tool centre positions and cutting edge location, respectively, while I denotes the intersection between $C_i^j F_i^j$ and tool path j-1. In the case of UCT

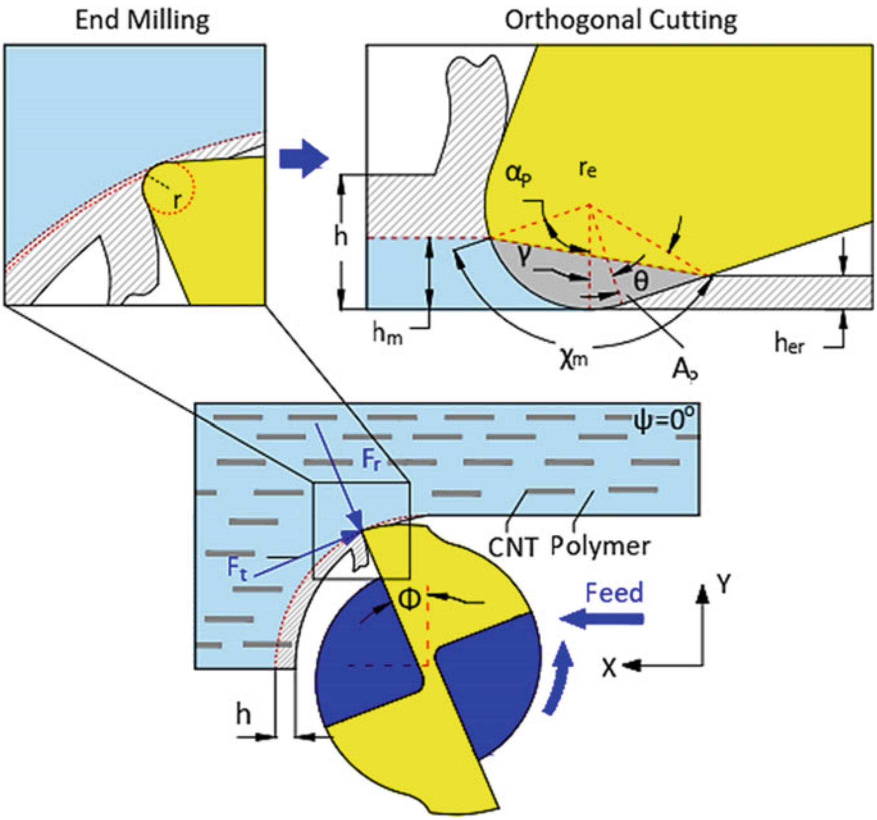
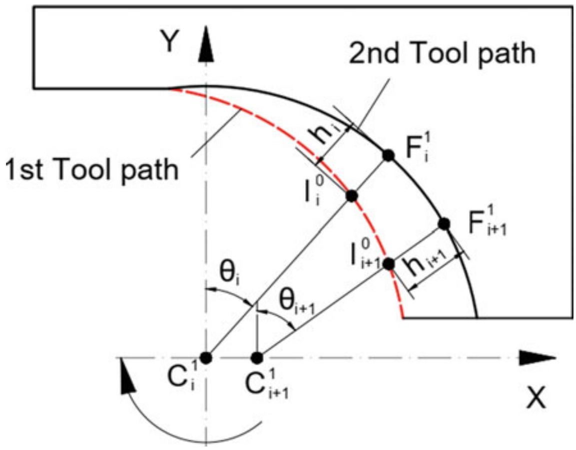


Fig. 20 Schematic representing the mechanistic model for micro-milling of Polymer/CNT nanocomposites. adapted from [28]

Fig. 21 Schematic representing chip thickness model in micro-milling



being infinitesimal compared to the micro-milling tool diameter, the variation of UCT is inconsiderable.

Therefore, it could be considered to be equivalent to feed rate by simplifying the 2D micro-milling to orthogonal cutting (top of Fig. 20). The ploughing area (A_P) can be identified as follow:

$$A_P \approx \frac{1}{2} r_e^2 (\alpha_P + \gamma) + \frac{1}{2} r_e (l_1 - l_2) \tag{6}$$

where

$$l_1 \approx \left(\frac{h_{er} - r_e(1 - \cos\gamma)}{\sin\gamma} \right)$$

$$l_2 \approx \sqrt{r_e^2 + l_1^2} \sin(\alpha_P + \gamma + \theta); \ \theta = \tan^{-1}\left(\frac{l_1}{r_e}\right)$$

The effective rake angle (α_P) is identified from:

$$\alpha_P = \cos^{-1}\left(1 - \frac{h}{r_e}\right) \tag{7}$$

The elastic recovery ratio (h_{er})can be obtained from the experimental data by applying scratching tests with a conical tool (apex angle of 90° and edge radius of 15 μm) [29]. The MUCT (h_m) is determined by the minimum energy method [32]. Its value is obtained when a transition from shearing to ploughing is recognized as the minimum cutting energy is attained. The MUCT can also be approximated from the following equation:

$$h_m = r_e(1 - \cos\chi_m) \quad \text{where} \quad \chi_m \approx \beta_s \tag{8}$$

The friction angle (β_s) is determined from the orthogonal cutting test using a cutting tool with 0° rake angle. This model exhibited high agreement with the experimental data regarding the cutting force variation in ploughing and shearing dominant regimes as a function of CNT content and CNT fibre orientation. A significant increase of cutting force and tool wear can be seen at a high CNT load due to high interaction between the cutting tool and CNT. This was confirmed by the high cutting coefficients when micro-milling at CNT based nanocomposites compared to other materials. Besides, small and debris chip formation can be observed from micro-milling at high CNT loading due to these materials' high brittleness.

The continuous and curly chip formations have been observed when micro-milling PC/CNT nanocomposites at every feed rate [33]. It is due to the presence of CNT as a lubricant, reducing the friction coefficient between tool rake face and workpiece, hence eliminating chip formation from being broken during the micro-cutting process. Additionally, better chip surface quality has been observed from micro-milling of PC/CNT nanocomposites compared to those of neat PC with adiabatic shear bands on chip surfaces, indicating low thermal conductivity of these neat polymers. Subsequently, higher heat concentration in the cutting area led to the formation of built-up-edge (BUE) along tool rake face, resulting in low machined surface quality when micro-milling neat PC compared to that of micro-milling of PC/CNT nanocomposites.

There is a ductile-to-brittle transition of workpiece material property as CNT additional content reaching a certain threshold, for example, 5 wt.% [34], thereby reducing MUCT magnitudes micromachining brittle high-filler-content nanocomposites. Additionally, the presence of CNT exhibited significant influence on improving machined surface quality due to high thermomechanical properties of these nanocomposites that have been highlighted in the studies as mentioned earlier. On the other hand, cutting forces were significantly influenced by cutting speed regardless of the CNT loadings. Based on that, it could indicate that the incorporation of CNTs improves micro-machined surface quality. Simultaneously, its influences on cutting force and chip formation when micromachining CNT-based polymer nanocomposites are still unapparent with different experimental results and explanations.

In general, the reinforcements in terms of thermomechanical properties due to CNT addition, MUCT, cutting edge radius and microstructure effects have been addressed to explain micro-machining behaviours of CNT-based polymer nanocomposites. However, CNT content's roles, cutting speed or feed rate have been still minor controversy with different claims from relevant studies. It reconfirms the high complication of micromachining of polymer nanocomposites that requires further investigation in the future aspects.

Micromachining of Graphene-Based Nanocomposites

Like CNT-based polymer nanocomposites, the micromachining of graphene-based polymer nanocomposites showed better performance [35], in terms of low cutting force and high surface quality due to the addition of graphene compared to neat polymer (Fig. 22). These phenomena' explanations are similar to those of CNT additions in thermomechanical improvements, leading to strain hardening dominance/thermal-softening subordination and lubricating effect of graphene, resulting in less tool-chip fraction.

However, as graphene content increasing, the high specific area of graphene nanoplatelets (GNP) attributes to considerable GNP-tool interaction. It is associated with high interlocking between GNP and polymer matrix due to GNP's rough and wrinkled surfaces resulting in high cutting force when micro-milling polymer/GNP nanocomposites. Figure 23 shows different variations of cutting forces considering the effect of graphene addition.

In general, micro-milling of graphene-based polymer nanocomposites shows similar machinability behaviour to their CNT-based counterparts. It is possibly due to the similarities in terms of mechanical properties between graphene and CNT. The roles of graphene in micro-machining of these nanocomposites have been highlighted.

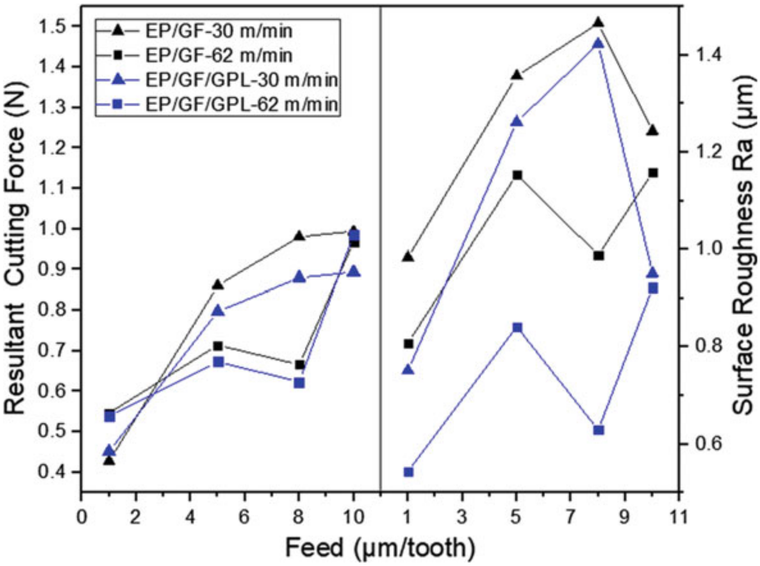


Fig. 22 Cutting force and surface roughness versus feed rate when micro-milling Epoxy/0.8 vol.% GF composites and Epoxy/0.8 vol.% GF/0.2 wt.% GPL hybrid nanocomposites. adapted from [36]

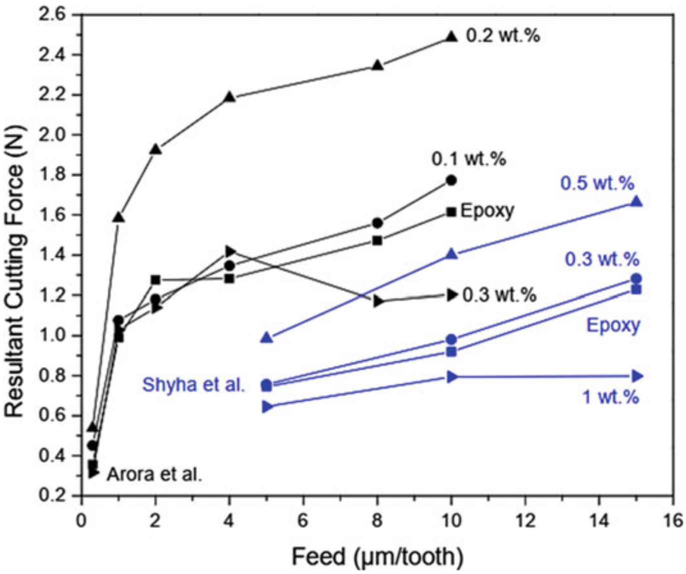


Fig. 23 Different trends of cutting forces as a function of graphene addition when micromachining graphene reinforced polymer nanocomposites. adapted from [22]

3.3 Tool Wear in Micromachining of Polymer Nanocomposites

Beside machined surface roughness, tool wear is also considered a vital machinability indicator in the manufacturing cost aspect. The tool wear study in micromachining of polymer nanocomposites primarily focuses on the effect of nano-filler addition such as graphene or CNTs. The most common variation of tool wear behaviour as a function of nano-fibres addition is being reduced in the beginning then accelerating at high filler contents. This trend can be explained based on various mechanism including (i) the improvement of the thermo-mechanical properties of polymer nanocomposites as a result of nano-fibre additions, (ii) the nature of nano-fibres, and (iii) the dominance of micro-structure effect in micromachining. First, the incorporation of CNTs or graphene improves mechanical properties and thermal conductivity of polymer nanocomposites. This thermo-mechanical improvement significantly affects the micro-cutting characteristics, including tool wear. As conduction materials, CNTs or graphene stimulate faster heat dissipation around the cutting area during the machining process, reducing the workpiece debris smearing on the clearance surfaces. Additionally, the strengthening effect of these nano-fibres also restricts polymer chains' relative sliding, hence reducing the elastic recovery exhibited on the clearance face. These effects minimize the rubbing between tool and clearance face, which consequently reduce the tool wear. Second, both CNTs and graphene are considered as lubricants [37, 38]. It leads to a decrease in the effective coefficient of friction between cutting tool and workpiece, contributing to tool wear reduction. However, the agglomeration tends to appear as high concentrations of nano-fibres being employed. In micromachining where microstructure effect becomes more influential (Sect. 3.1), this could lead to the tool being trapped by nano-fibre bundles, hence increases the tool wear. Figure 24 shows an example of tool wear when micro-milling of epoxy/graphene nanocomposites.

4 Non-Conventional Micromachining of Polymer Nanocomposites

While the mechanical micromachining has been applied to manufacture mechanical micro-components (i.e., micro-gears, micro-wheels), non-conventional micromachining of polymer nanocomposites exhibits high feasibility in micro-electronic productions, especially laser micromachining. This method could be employed to cut a wide range of different features from thin films, arrays to complex 3D structures in multifunctional capacitors [40]. Additionally, micro-electrical discharge machining (EDM) is also feasible for polymer nanocomposites with high conductive fillers (i.e., CNT, graphene). Similarly, this technique can also produce micro-features with

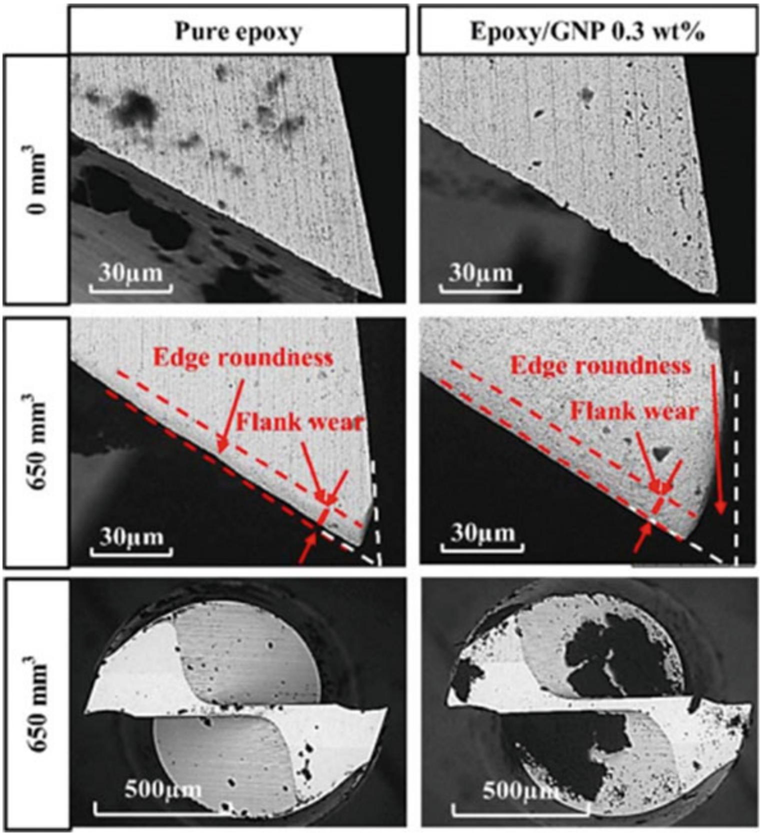


Fig. 24 SEM images of tool wear when micro-milling of epoxy/graphene nanocomposites and neat epoxy. open access from [39]

high complexity [41]. However, the high loading of reinforcement could lead to machined defects. Besides, the low material removal rate also makes it less efficient than mechanical micromachining.

5 Review Questions

(1) What are the main reason behind applying machining of polymer nanocomposites in the industry?

(2) What are the current reasons that make the commercial applications of machining of polymer nanocomposites limited?

(3) What are the main reasons that make the machining of polymer composites more complicated than metals or alloys?

(4) Discuss the general classification machining of polymer nanocomposites.
(5) Show the main objectives of machining of polymer nanocomposite
(6) Discuss the most applied techniques for machining of polymer nanocomposite
(7) What are micromachining and its differences from ultra-precision machining?
(8) Discuss the differences in terms of material removal mechanism between micromachining and macro-machining.
(9) What are the main reason behind applying the micromachining of polymer nanocomposites in the industry?
(10) What are the current reasons for the research limitations of machining of polymer nanocomposites?
(11) What are the most applied polymer nanocomposites in micromachining?
(12) What are the most common objectives for micromachining of polymer nanocomposite research?
(13) What are the main reasons that make micromachining of polymer nanocomposites complicated than conventional machining of other materials?
(14) Discuss mechanisms, equations, theories and models that can explain the micromachining of polymer nanocomposites.

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