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A review on the effect of mechanical drilling on polymer nanocomposites

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Abstract. Over the past decade, polymer nanocomposites have undergone intensive research and development ensued by its increasing implementation within commercial applications. Consequently, the full life-cycle performance and any health risks associated with these materials have become of major interest. Throughout its use, a nanocomposite will undergo industrial machining where drilling can lead to material damage and/or exposure to the potentially toxic nanoparticles. This study assesses the existing and perspective research on nanocomposite drilling. Currently, although considerable amount of studies have investigated machining on conventional composite materials, there is a lack in knowledge on the effect of drilling on nanocomposites. The data underlines the various drilling parameters that will affect and influence the damage to the material and nano-sized particles released. Importantly, previous studies have identified potential mechanical damage caused by drilling and the release-ability of toxic nanoparticles from nanocomposites. It is therefore crucial to develop a full understanding and characterization on the effect of drilling on polymer nanocomposites.

1. Introduction

Considered as 21st century advanced materials, nanocomposites are still relatively new to industry. Throughout its life-cycle, a composite material will undergo various machining processes to fabricate and regulate to its corresponding application. Within industry, drilling is a fundamental and significant machining process used during assembly operations. Various industries, such as the automotive and aerospace industry, have already established the use of nanocomposites within their structures [1]. An example of this is with a leading automotive manufacturer using 300,000 kg of nanoclay composites annually for exterior automotive parts, and according to a recent report, global consumption of nanocomposites is expected to grow from its current amount of around 225,060 metric tons in 2014 to 585,984 metric tons in 2019 [2]. Due to the multiphase structure within composite materials, damages can be introduced during drilling. Around 60% of rejected parts are due to defects introduced in holes [3]. As these defects can lead to a significant decrease in performance, which in some cases can be critical (e.g. aerospace industry), it is vital that the full effect of drilling on nanocomposites is understood.

Conventional polymer composites are fabricated using a selection of material fillers to improve the properties of the constituent polymer matrix. A nanocomposite is distinct from conventional composites, in that at least one dimension of the reinforcing filler material is in the nano range: i.e. less than 100 nanometres [4-6]. Many studies have established that the introduction of nano-sized



fillers can significantly further improve the properties of traditional polymer composite materials. Polymer nanocomposites are proven to potentially enhance mechanical [4], optical [6], electrical [6] and thermal [7] characteristics. These enhancements are due to the reinforcing phase having a particularly high surface to volume ratio and its exceptionally high aspect ratio [8]. These many advantages of nanocomposite materials have led to considerable research and as mentioned, the establishment within a variety of industrial applications; commonly for lightweight purposes.

Although considerable amount of studies have investigated composite drilling, there is still however very few studies on the effect of drilling on nanocomposites. This is due to the materials having only recently being established within the commercial industry. As stated, nanocomposites have different properties to conventional composite materials, and will consequently also perform differently under mechanical drilling. This work will present an overview on the work carried out on the effects of drilling on composite materials, followed by the existing studies on nanocomposite drilling and nanocomposite health risks.

2. Composite drilling

Drilling mechanics is a recognised discipline on its own, and has been thoroughly investigated and studied. The research so far however has been on more conventional materials that have been established within industries. Work done on traditional composite materials has identified several parameters during the drilling process that can affect the magnitude and amount of damage to the material. Damage distinctively associated to drilling on composites mainly investigates delamination mechanisms, as this is the leading and major cause of material failure [9]. Other damage modes induced by drilling include intralaminar cracking, fibre pull-out and fuzzing, matrix catering and thermal alterations [10].

A technique commonly used within literature on drilling assessment and optimization is to employ Taguchi's method to study the influence of process parameters such as the drill feed rate and speed on the thrust force, torque and damage factor [11-13]. In work done by Davim et al [13], through the use of Taguchi's method and the analysis of variance (ANOVA), the relationship between the feed rate and cutting speed with the delamination of a CFRP laminate was established. Other studies such as Enemouh et al [14] have demonstrated similar correlations for optimum drilling conditions on composite laminates.

Reviewing some of the studies carried out on the effect of drilling on polymer composites, a table has been produced to identify the parameters most commonly assessed in the drilling process when investigating composite damage. This is shown in Table 1.

Table 1. The drilling process parameters assessed for damage effects on composite materials from a sample selection of literature available

Composite tested	Drill Speed	Feed rate	Drill type	Drill diameter	Drill angle	Reference
GFRP Epoxy	x	x				[15]
CFRP Epoxy	x	x		x		[16]
GFRP Epoxy	x	x				[11]
CFRP Epoxy	x	x		x		[12]
CFRP Epoxy	x	x	x			[13]
GFRP Epoxy	x	x			x	[17]
CFRP Epoxy	x	x	x		x	[18]
GFRP Polyester	x	x		x		[19]
GFRP Polyester & GFRP Epoxy	x	x				[20]

The sample data presented in table 1 show a dominant focus on investigating the drill speed and feed rate as parameters for drilling operations on composite materials. From the chosen studies, the feed rate was observed to have the greatest effect on the damage caused to the mechanical structure of the material. With an increase in feed rate, an increase in delamination damage at any given speed was cited throughout all of the studies. However, the drill speed also observed to have an incremental effect on delamination damage, except for one of the composites tested by Kashaba et al [20], where the inverse effect was evident.

Importantly, the experimental observations have shown that careful consideration is necessary when drilling on composite materials. The selection of drill parameters will have major implications on the damage, surface finish and degradation qualities of the holes [11-20].

3. Nanocomposite drilling

As nanocomposites are a relatively newly established material, few studies have been produced on the drilling on polymer nanocomposites. As shown in the previous section however, mechanical drilling has demonstrated to undesirably damage composite materials, thus it is therefore necessary to evaluate the effect of drilling on nanocomposites.

From the literature available, only three studies have investigated drilling on nanocomposites. The generic development and assessment of polymer nanocomposite properties is also considerably scarce within literature. Baker et al [21] utilised drilling to evaluate coating wear resistance, but there is a lack in other studies assessing the damage caused by mechanical drilling on nanocomposites. Several studies have investigated damage caused to nanocomposites from other machining methods [22]. Previous studies that have evaluated the effect of mechanical drilling on nanocomposites are summarized in Table 2.

Table 2: Overview of parameters assessed in current studies on the effect of drilling on nanocomposites

Reference	Material Damage	Nanoparticle Release		
		Number of Nanoparticles	Nanoparticle Concentration	Nanoparticle Characterization
Sachse et al. [23]		x	x	
Bello et al [24]		x	x	x
Sachse et al. [25]		x	x	x

From the limited studies on nanocomposite drilling, the research has solely focused on investigating nanoparticles release due to the drilling. This highlights that there are currently no studies assessing the material damage due to drilling on nanocomposites. The three works appeared to have no common or standardized set of parameters used to assess the drilling effect. In the drilling studies carried out by Sachse et al [23] [25], a manually controlled 10mm diameter angle drill was used with a maximum speed of 1800 min^{-1} . The setup for these experiments is shown in Figure 1.

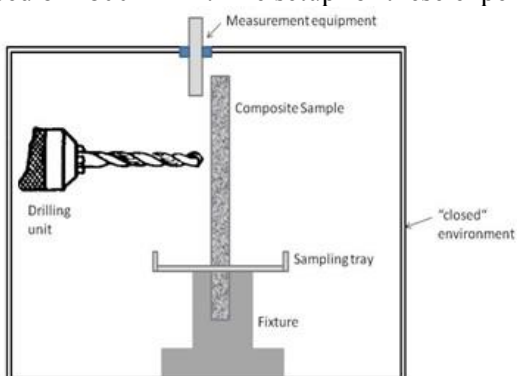


Figure 1. Apparatus and setup used for chamber experiments on investigating nanoparticle release due to drilling on nanocomposites [25]

Bello et al [24] specified two diamond drill diameters, 1/4" (6.35mm) and 3/8" (9.525mm) along with investigating two drill speeds of 725min-1 and 1355min-1. This study investigated the use of CNT, alumina and graphite-epoxy composites, whereas the studies by Sachse [23][25] investigated PA6 and PP-silica nanocomposites. Apart from diverse nanocomposites being investigated, the differences in setups for the two studies demonstrate the need for a standardized set of drilling parameters to allow for a feasible comparison.

4. Why study nanoparticle release due to drilling?

As mentioned, due to the use of nano-sized particles, nanocomposites introduce a potential toxicological and eco-toxicological hazard. Research is comprehensively investigating the potential nanoparticle release and exposure to humans and the environment. Drilling on nanocomposites has the ability of unintentionally releasing these nanoparticles into the environment.

Studies in toxicology have shown that particles within the nano scale are potentially hazardous to humans. The advantages of the nanoparticle physiochemical properties employed for the use within materials also render potential unique toxic effects within biological systems [4]. Due to their small size, nanoparticles have the ability of penetrating the bloodstream and translocate throughout the body at which larger particles could not. Studies show that nanoparticles within the body can cross biological barriers such as the blood-brain and the blood-testis barrier and therefore treacherously reach highly protected organs [26]. Published data from in vitro studies, suggests that nanoparticles have the aptitude to induce cell growth inhibition [27], cell death [28], inflammatory response [29], DNA damage [30] and the generation of free radicals and reactive oxygen species. The toxicological effect is different for each type of nanoparticle, although the specific relationship between the chemical structure of every particle and the toxic implementations are still unknown [4]. It is also important to note that some nanoparticles appear to be non-toxic [31], and others may even possess health benefits [32].

The type and characterization of the nanoparticles measured from release scenarios varies in most studies. In work by Bello et al [33], epoxy based nanocomposites were considered during laboratory cutting. Particle release measurements were taken and compared for both an unmodified and a carbon nanotube reinforced epoxy. The studies observed that nanoparticles were detected regardless of the composite type and presence of the carbon nanotube fillers. 1-10% of particles released were shown to be within the nanometre range (<100nm), whilst 71-89% were in the 1-10µm range. When examined using scanning electron microscopy (SEM) and transmission electron microscope (TEM), the released nanoparticles exposed no clearly distinguishable carbon nanotubes. The data suggests the nano-fillers continue to be merged within the polymer resin. However, in a different study by Huang et al, multi-walled carbon nanotubes were detected in the released nanoparticles from the composite matrix during sanding [34]. Multiple other studies have investigated the release of nanoparticles from carbon nanotube reinforced polymer nanocomposites due to mechanical influences. In most cases, nanoparticles have been observed to be released, but there is no universal conclusion on the quantity of exposure [35].

In the work carried out by Sachse et al [25], on drilling on PA6 and PP based nanocomposites, the data showed that the silica reinforced nanocomposite introduced fifty-six times more nanoparticles released than the neat polyamide. In a similar study, but with the use of montmorillonite as a nanofiller for the polyamide 6 resin, reverse data was observed. The reinforced nanocomposite was seen to release twenty times fewer nanoparticles than the neat polyamide [23].

In the study on the effect of drilling performed by Bello et al [25], the research appeared to exhibit aggregates of the carbon nanotubes in the released nanoparticles. Whereas in a comparative study also done by Bello et al [33] the same nanocomposites undergoing cutting did not show the aggregates of the carbon nanotube. This study highlights the effect of the machining process rather than the nanocomposite composition in production of nanoparticles released from nanocomposites.

The release of nano-sized particles from nanocomposites has been broadly researched [36]. So far however there is no standardized method established to simulate the release scenarios. From the

literature available, including the studies performed on nanocomposite drilling, it can be said that most studies illustrated that nano-sized particles are released during some of the scenarios, but to a certain extent while laboratory experiments repeatability remains challenging.

5. Conclusions

The benefit of the nanoparticle fillers has caused a surge in investment and research across the world. From the literature available however, there is currently a lack of knowledge on the effect mechanical drilling has on polymer nanocomposites. Although considerable amount of studies have demonstrated that drilling can structurally damage conventional composite materials, no work has investigated the effects on nanocomposites. Along with assessing the damage drilling can cause on various polymer nanocomposites, it is crucial that any potential health or environmental risks associated with the materials are fully understood and characterized.

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