Chapter 7
Health and Safety Aspects in Machining FRPs

Even though fully cured composites are considered inert, their machining raises concerns about health and safety due to exposure to dust and decomposition compounds. Therefore, it is necessary to evaluate the byproducts of both traditional and nontraditional machining of composites in order to assess the potential of harming the operator's health due to exposure. Assessment of machining byproducts is also necessary for devising effective measures for eliminating hazardous exposures. Both traditional machining and nontraditional machining processes are considered. Among the nontraditional machining methods, laser beam cutting was subject to the most investigation because it poses the greatest potential of exposure to hazards. Abrasive waterjet machining has the advantage of being carried out under water and the water jet entrapping and washing away most of the dust generated. However, exposure to high levels of noise remains a concern that must be addressed.

The intention of this chapter is to make the reader aware of the potential harm to health and safety related to machining fiber-reinforced composites. The chapter will also report on studies that characterize the morphology and chemical composition of machining byproducts, the influence of machining process parameters, and common protection methods against these hazards. It is worth noting that this chapter is not intended as an authoritative and accurate source in the subject of occupational health and safety. For more accurate detailed listing of toxicity, reactivity, and health and safety data for composites and their constituents the reader is advised to consult detailed material safety data sheets (MSDS) provided by the material suppliers. The reader is also advised to consult local and federal government regulations concerning the safe handling of composite materials and the legally accepted exposure levels.

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7.1 Hazard Sources and Routes of Exposure

Hazard is the potential that a material, process, or equipment will cause an adverse health effect (injury) under the conditions in which it is produced or used. In machining fully cured and polymerized composites the sources of hazard are associated with direct handling of the material as well as dust and gaseous emissions caused by machining. Since the composites are fully cured, they are considered chemically inert and their direct exposure to skin does not pose a threat. However, glass and carbon fiber ends protruding from a composite part are often stiff and sharp enough to penetrate skin. Aramid fibers do not exhibit these characteristics and therefore pose no danger of skin penetration. In addition, thermal decomposition of cured epoxy produces volatile vapors that are allergic, toxic, or carcinogenic [1–3]. Table 7.1 provides a general listing of the hazards generated from machining composites and the routes of exposure to the human body. It is noted that the major routes of exposure involve both dermal and inhalation, while the major sources of exposure include aerosols, dust, and gaseous compounds.

An aerosol is a group of particles suspended in a gaseous medium. In the context of occupational hygiene the gaseous medium is usually air. Aerosols are frequently classified according to their physical form and source. Aerosols consisting of fibers, fiber fragments, and particulates (e.g., coal, wood, graphite) are designated dusts. Aerosols consisting of liquid droplets (e.g., oil, water, solvents) are called mists. Aerosols containing submicrometer particles that are formed from condensation or combustion processes are generally called fumes or smokes. The actual impact of exposure to these hazards on health and safety depends greatly on their morphology, chemical properties, concentration, and length of exposure.

Dusts are solid particles, ranging in size from below 1 μm up to at least 100 μm, which may be or become airborne, depending on their origin, physical characteristics, and ambient conditions. For most occupational hygiene situations, the particle size is expressed in terms of aerodynamic diameter, defined as the diameter of a hypothetical sphere of density $1\,\mathrm{g/cm^3}$ having the same terminal settling velocity in calm air as the particle in question, regardless of its geometric size, shape, and true density. It is generally accepted that particles with aerodynamic diameter greater than 50 μm do not usually remain airborne very long. Dust is further classified according to particle size as inhalable dust, thoracic dust, and respirable dust.

Table 7.1 Hazards and routes of exposure in machining FRPs

Hazard	Operation	Exposure route			
		Inhalation	Skin contact	Eye contact	Injection
Exposed protruding fibers	Handling	–	–	–	x
Dust	Traditional machining	x	x	x	–
Fumes	Laser machining, EDM, traditional machining	x	x	x	–

Inhalable dust is that size fraction of dust which enters the body though the nose and mouth. Particles with median aerodynamic diameter greater than about 30 μm are trapped in the nose, throat, and upper respiratory tract. Thoracic dust is that fraction that can penetrate the head airways and enter the airways of the lungs. The larger size particles of this dust ($>10\,\mu$m) will deposit in the tracheobronchial airway region and may later be eliminated by mucociliary clearance. Respirable dust refers to those dust particles that are small enough to penetrate deep into the alveolar region of the lung, the region where inhaled gases can be absorbed by the blood. Only about 1% of 10 μm particles gets as far as the alveolar region, so 10 μm is usually considered the practical upper size limit for penetration to this region. Insoluble particles that penetrate deep into the alveolar region are engulfed by macrophage cells (phagocytes), which can either then travel to the ciliated epithelium and then be transported upward and out of the respiratory system, remain in the pulmonary space, or enter the lymphatic system. Certain particles, such as silica-containing dusts, are cytotoxic; i.e., they kill the macrophage cells [4].

Today, very little information exists on the toxicological properties of inhaled composite aerosols. Research on the medical hazards of cured composite dust involving investigations into pulmonary toxicity have shown inconclusive evidence of adverse effects on human respiratory system [2, 5]. It has also been shown that the accumulation of large enough burdens of insoluble particles in the lungs leads to impaired clearance. This so-called "dust overload" condition may occur as a result of prolonged occupational exposures, even at relatively low levels [4]. It is widely accepted, however, that composite dust remains a serious irritant to skin, eyes, and lungs. The US Department of Labor, Occupational Safety and Health Administration (OSHA) lists the airborne composite dust as "nuisance dust" [6]. This term suggests that the human body's natural clearance mechanisms will eliminate most of the dust and that the dust has no pathological significance. The American Conference of Governmental Industrial Hygienists (ACGIH) classifies composite dust as Particles Not Otherwise Specified (PNOS). This includes low toxicity particles (i.e., not cytotoxic, genotoxic, or otherwise chemically reactive with lung tissue, not radioactive or a sensitizer, or toxic other than by inflammation or the mechanism of "lung overload") [7].

Permissible exposure levels (PELs) are set by health authorities in order to establish levels of exposure to which the vast majority of workers may be exposed without experiencing adverse health effects. These legally acceptable exposure levels vary from one country to another and over time. As knowledge of the interaction of workplace hazards with the human body is acquired, the permissible exposure limits may be adjusted accordingly. In the United States, the primary sources of environmental evaluation criteria for the work place are OSHA Permissible Exposure Limits (PELs) [6], ACGIH Threshold Limit Values (TLVs) [7], and the National Institute for Occupational Safety and Health (NIOSH) Recommended Exposure Limits (RELs) [8]. ACGIH established TLVs for PNOS is $3\,\mathrm{mg/m^3}$ for respirable dust and $10\,\mathrm{mg/m^3}$ for inhalable dust. In addition, MSDS provided by the supplier contains essential information for the safe handling of the material. This information includes physical and chemical properties, PELs, toxicity, reactivity, fire and explosion hazards, and health hazards. The following sections discuss the effects of FRP constituent aerosols on the human body. The phenomena of aerosol generation in mechanical edge trimming and laser cutting are discussed in separate sections.

7.1.1 Matrix Material

Most of the health hazards associated with manufacturing polymer composites involve uncured thermosetting resins, cross-linking agents and other additives. Thermoplastic matrices and fully cross-linked thermoset polymers are basically inert and considered harmless. Their dust is particulate in nature and is thermally stable up to 250 °C. However, excessive heating of the polymer matrix may result in decomposition into airborne and potentially toxic substances that are respirable. Chemical decomposition is one of the material removal mechanisms in laser machining and EDM because the processing temperatures are extremely high. Excessive heating may also result under certain processing conditions during traditional machining. These conditions must be avoided in order to protect the health of the workers and integrity of the machined parts.

The decomposition products from thermal processing depend on processing temperature and pyrolysis mechanisms. The decomposition products may condensate out of the vapor phase or remain gaseous. The condensation particles first form as nuclei out of supersaturated vapor phase. The particle nucleus then grows by processes like coalescence and agglomeration. At the particle surface, further substances like polynuclear aromatic hydrocarbons (PAH) can condense. In most cases particles are solid. However, laser processing of polyamides generates viscous particles that can easily stick together. Haferkamp et al. [3] have shown the size of particles generated from laser processing of polymers have a normal distribution on a log-normal scale and that 90% of the particles are smaller than aerodynamic diameter of 1 µm. The particles have a spherical shape and form agglomerates. Mazumder et al. [9] have found that resin aerosol particulates generated by evaporation–condensation process have a mass median aerodynamic diameter (MMAD) of approximately 0.77 µm. The aerosol was generated by treating the composite dust at a temperature above 400 °C. Due to this small size, the particles are highly respirable. The gases and volatile organic compounds generated from laser processing of plastics affect the respiratory tract when inhaled. Most of these gases are allergic toxic or carcinogenic [3]. The TLVs recommended for aerosol particles is the same as that for PNOS ($3\,mg/m^3$ for respirable dust and $10\,mg/m^3$ for inhalable dust). The PELs for the gaseous phases are given by gas species as shown in Table 7.2. The reader is advised to consult NIOSH publication [8] for definitive information and more exhaustive coverage.

Table 7.2 NIOSH recommended exposure limits for hazardous agents [8]

Hazardous agent	NIOSH REL	Health effect
Benzene	Ca; 0.1 ppm (0.32 mg/m^3), 8-h TWA 1 ppm (3.2 mg/m^3) ceiling (15 min)	Cancer (leukemia)
Fibrous glass	3 million fibers/m^3 TWA (fibers $\leq$ 3.5 μm in diameter and $\geq$ 10 μm long); 5 mg/m^3 TWA (total fibrous glass)	Eye, skin and respiratory effects
Ethyl benzene	100 ppm (435 mg/m^3) TWA 125 ppm (545 mg/m^3) STEL	Eye, skin, and upper respiratory irritation
Indene	10 ppm (45 mg/m^3) TWA	Mucous membrane and lung irritation; in animals, liver and renal necrosis, spleen injury
Naphthalene	10 ppm (50 mg/m^3) TWA 15 ppm (75 mg/m^3) STEL	Hemolysis and eye irritation that causes cataracts
Phenol	5 ppm (19 mg/m^3) TWA (skin) 15.6 ppm (60 mg/m^3) ceiling (15-m) (skin)	Skin, eye, CNS, liver, and kidney effects
Styrene	50 ppm (215 mg/m^3) TWA 100 ppm (425 mg/m^3) STEL	Nervous system effects, eye and respiratory irritation, reproductive effects
Toluene	100 ppm (375 mg/m^3) TWA 150 ppm (560 mg/m^3) STEL	CNS depression
M, p-Xylene	100 ppm (435 mg/m^3) TWA 150 ppm (655 mg/m^3) STEL	CNS depression, respiratory and eye irritation

Definitions:
Ca Agent recommended by NIOSH to be treated as a potential occupational carcinogen;
Ceiling The exposure that shall not be exceeded during any part of the workday. If instantaneous monitoring is not feasible, the ceiling shall be assessed as a 15-min TWA exposure (unless otherwise specified) that shall not be exceeded at any time during a workday;
CNS Central nervous system;
ppm Parts of contaminant per million parts of air at 25 °C and 1 atm. of pressure;
STEL Short-term exposure limit. Unless otherwise noted, the STEL is the 15-min TWA exposure that shall not be exceeded at any time during a workday;
TWA time-weighted average. Unless otherwise noted, TWA concentrations of a contaminant for up to 10 h/day during a 40-h workweek

7.1.2 Reinforcement Fibers

Carbon fibers which typically have diameters from 6 to 8 μm may splinter lengthwise during machining producing fibrils with diameters less than 6 μm. Therefore a significant fraction of the total dust generated may be respirable. The fiber fragments are irregular in shape and may have sharp ends. Mazumder et al. [9] have shown that mechanical chopping of virgin carbon fibers generates a wide distribution of particulate size with a MMAD of approximately 4.0 μm. Grinding of carbon–epoxy composite produced aerosol particles consisting of resinous material and fiber fragments with a MMAD of approximately 2.7 μm. The primary health effect of exposure to fiber reinforcement materials, including carbon and glass fibers, is mechanical irritation of the eyes, skin, and upper respiratory tract. Animal and bacterial tests suggest that pitch-based carbon fibers are biologically active, whereas PAN-based fibers produce negative results. The pitch-based carbon fibers may be associated with an increased risk of cancer, although the evidence is weak [10].

Aramid fibers have diameters in the range from 12 to 15 μm, which makes it difficult for the fiber dust to reach deep into the respiratory system. However, aramid fibers are capable of splitting along its axis forming fibrils of diameters in the respirable range. Industrial monitoring shows that airborne respirable fibril levels are low in typical operations. Aramid fibers show no potential skin sensitization and low potential for irritation in animal and human skin tests [10].

The diameter of all glass fibers are larger than 6.0 μm which make them nonrespirable. Continuous filament glass fibers do not possess cleavage planes, which would allow them to split lengthwise to smaller diameter fibrils. Therefore, machining operations break the fibers only in shorter fragments of the same diameter. Like carbon fibers, glass fibers cause mechanical irritations to human organs such as skin, eyes, nose, and throat. Human epidemiology studies have categorized continuous filament glass fibers as noncarcinogenic [11–13].

Moreover, reinforcement fibers are commonly coated with sizing a sizing material to improve handling and enhance properties of the fiber–epoxy composite. This sizing material may be epoxy resins or other organic compounds. These materials may be biologically active and cause irritation or sensitization [14].

7.2 Dust Generation in Dry Machining

The aerodynamic and morphological properties of advanced composites dust have been studied by a few researchers [9, 15, 16]. Mazumdar et al. [9] investigated the morphology of dust particles generated from grinding carbon FRP laminates and chopping virgin carbon fibers. Dust samples examined under scanning electron microscope revealed that it consisted of carbon fibers and resin particles. A significant number of the fiber fragments were found to be of irregular shape, showing sharp ends in a number of fibers. It was also evident that some particles have a diameter that is less than that of the carbon fiber. This is due to the fibers splitting along their axis and forming fibrils. This property is also evident in machining aramid FRPs, but is absent in machining glass FRPs. The aerosol particles have an enormously wide geometric size distribution. The MMAD of the composite aerosol was approximately 2.7 μm. Boatman et al. [15] examined the dust generated from machining different fiber-reinforced epoxies by light and electron microscopy, thermogravimetry (TGA), gas chromatography (GC), and mass spectrometry (MS). It was found that less than 3% of the total mass of bulk samples were respirable dust with particles aerodynamic diameters ranging from 0.8 to 2.0 μm. Microscopic examination of the bulk particles showed that their size ranged from 7 to 11 μm in diameter, with mean aspect ratios from 4:1 to 8:1.

Milling operations on reinforced thermosetting plastics have been shown to produce mostly coarse (nonrespirable) dust particles [16]. Only up to 1% of total dust is small enough to be considered as respirable. There is less dust formation when thermoplastic FRPs are machined because the fibers are retained in the matrix due to its high fracture strain. The concentration of fine dust was found to depend largely on the cutting tool geometry and the cutting parameters. Increasing the chip per tooth (e.g., reducing the cutting speed while maintaining the feed constant) results in lower concentration of respirable dust. Tool selection is also an important factor. Tools with less number of cutting edges will also produce coarser and less harmful dust particles. This is clearly demonstrated in Fig. 7.1 for the routing of aramid-fiber-reinforced epoxy machined with opposing helix tool and split helix tool. When a split helix tool with larger flutes was used, there was a clear shift in particle size concentration from fine (respirable) to coarse [16].

Investigation of the effect of cutting conditions on total airborne dust emissions in milling medium density fiberboard lead to similar findings [17]. The airborne dust was determined as the fraction of dust where aerodynamic particle size is 100 μm or less. A vertical elutriator was used to separate the airborne dust particles. It was found that the cutting speed is the most influential factor on dust emission. Airborne dust emissions decreased up to 60% when cutting speed decreased from 19 to 8 m/s. Depending upon the tool type and the material to be cut, decreasing of feeding speed caused decreasing of airborne dust emission or did not have any clear effect on airborne dust emission. An apparent relationship exists between the dust emissions and average chip thickness where an increase in the average chip thickness leads

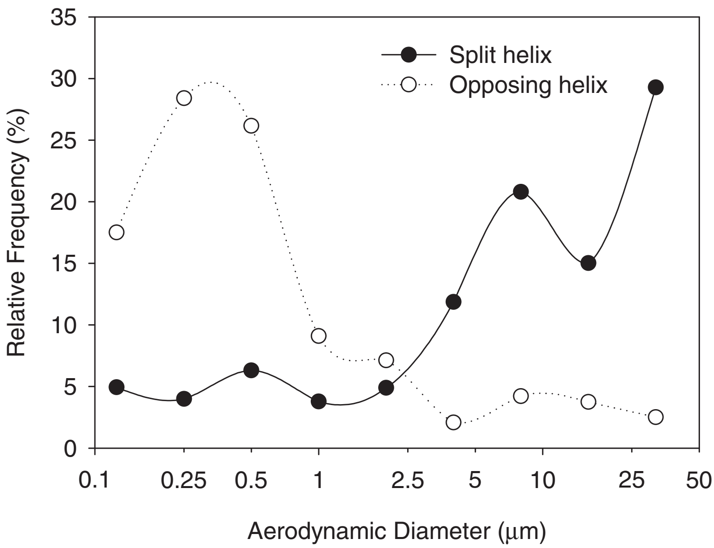

Fig. 7.1 Particle size distribution in milling aramid FRP. $v = 200\,\mathrm{m/min}$, $v_f = 1\,\mathrm{m/min}$ [16]

to a significant decrease of dust level. Increasing the cutting speed while the feed speed is held constant would lead to an increase of absolute dust emission and in the same way the average chip thickness would be decreased.

7.3 Aerosol Emissions in Laser Machining

Aerosol formation in laser cutting of FRPs results from thermal decomposition of the constituents. Thermal decomposition for epoxy resins takes place at 250–350 °C, for aramid fibers at 550 °C, for glass fibers at 1,300 °C and for carbon fibers at 3,600 °C. Aerosol formation in laser machining of aramid, carbon, and glass FRPs was investigated by [1, 18]. Morphological analysis of the particles obtained from laser cutting of GFRP shows agglomerates of spherical glass beads consisting of primary particles of 1 μm diameter. This agglomeration may have formed from condensation of organic material on the glass beads which helps the glass beads to stick together [3]. Figure 7.2 shows the size distribution of aerosol particles resulting from laser machining of aramid and glass FRPs. It is apparent that the bulk of aerosol particles generated are in the respirable range. It was also shown that the size distribution for aramid FRP exhibited nearly no change when cutting parameters were changed. On the other hand, the size distribution for glass FRP exhibited significant dependence on laser power and cutting speed. The median aerodynamic

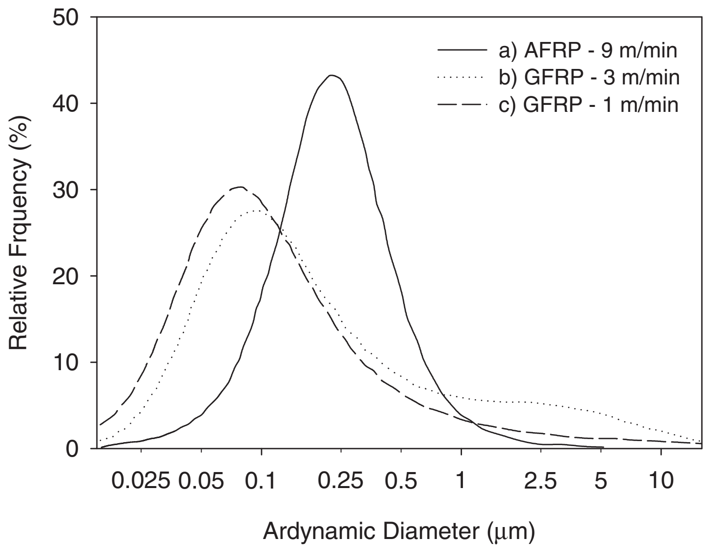

Fig. 7.2 Size distribution of dust emitted by laser beam cutting of aramid fiber epoxy and glass fiber epoxy composites with optimal cutting parameters. (**a**) AFRP: 1,000 W, 9 m/min, 50 l/min nitrogen, (**b**) GFRP: 1,000 W, 3 m/min, 50 l/min, (**c**) 1 m/min, 40 l/min [18]

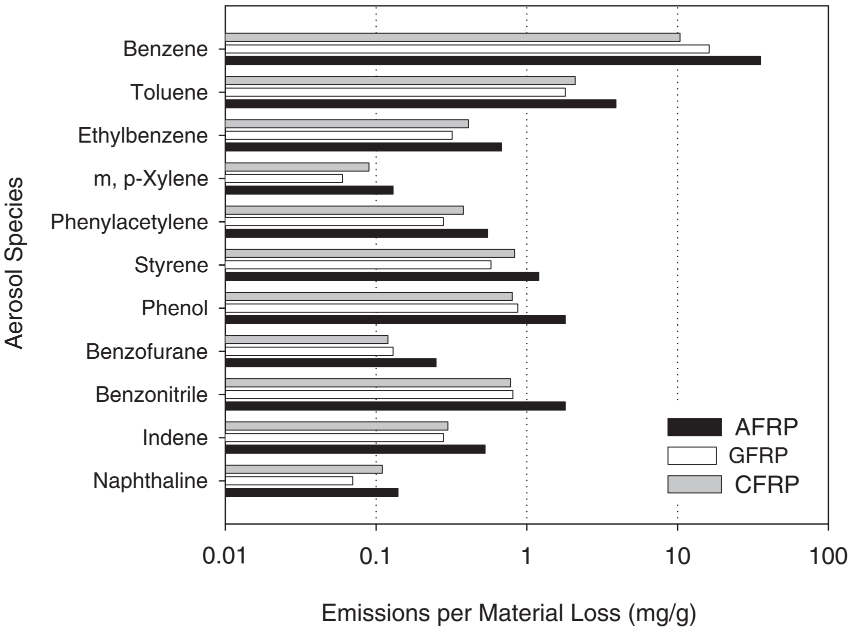

Fig. 7.3 Gaseous organic emissions during laser cutting of fiber-reinforced epoxy resins. Aramid FRP: laser power = 1,000 W, process gas = nitrogen 50 l/min, traverse speed = 8.5 m/min. Glass FRP: laser power = 1,000 W, process gas = nitrogen 50 l/min, traverse speed = 2.5 m/min. Carbon FRP: laser power = 1,250 W, process gas = nitrogen 50 l/min, traverse speed = 1.0 m/min [1]

diameter decreases and the shoulder in size distribution decreases for those cutting conditions which lead to higher temperatures.

Figure 7.3 shows the emission rate of gaseous compounds relative to the weight loss of the material (i.e., in mg/g) in laser cutting of fiber-reinforced epoxy. The gaseous emissions were also recorded when cutting glass-reinforced polyester and glass-reinforced polyamide resins in the same study [1]. These findings reveal that, independent of type of composite, the same gaseous compounds are emitted during the laser cutting process. This suggests that formation of these gaseous compounds is determined by their thermodynamical stability, rather than by the chemical structure of the polymer. A variety of aromatic hydrocarbons are observed in high concentrations dominated by benzene (more than 15 mg/g) and toluene (more than 1 mg/g). Moreover, several alkylbenzenes, phenyl-acetylene, styrene, indene, and naphthalene are formed in substantial amounts. Higher emissions are observed for aramid-reinforced polymer as compared to glass and carbon-fiber-reinforced polymers, which is likely due to the contribution of the fiber decomposition to the overall emissions. The cutting speed was shown to affect the emissions of organic compounds when machining aramid fiber composites, but has no significant influence when machining glass fiber composites. An increase in the emissions by roughly a factor of two occurs when the cutting speed is increased by a factor of three in the case of aramid FRP. Furthermore, substantial amounts of hydrocyanic acid (HCN) were emitted during laser cutting of aramid-fiber-reinforced epoxy (1.5 mg/g), glass-fiber-reinforced epoxy (0.7 mg/g), carbon-fiber-reinforced epoxy (9.9 mg/g), and aramid-fiber-reinforced phenol (22.2 mg/g). The formation of HCN is believed to be the results of further combustion or break up to smaller units of the organic compounds initially formed by the laser cutting process. The high emissions of HCN for aramid composites is due to the decomposition of the aramid fibers which contain nitrogen. The remarkably high emissions for carbon fiber composites is perhaps due to the reaction of nitrogen in the process gas at the high temperatures required for cutting the carbon fibers. It is noted that for many compounds shown in Fig. 7.3 as well as for HCN there exist PEL and TLV values that must be consulted and compared in order to take the necessary precautions for minimizing exposure.

7.4 Workplace Controls

The health hazards brought about by composite machining are mainly due to inhalation of dust particles that are generally insoluble and gaseous compounds that may be allergic, toxic, or carcinogenic. Skin contact with condensation particles from these emissions may also present dermal hazard. Good work place controls are essential for eliminating possible exposure to these hazards or reducing exposure levels below regulatory limits and as low as reasonably achievable. The various types of workplace controls are generally divided into administrative and engineering controls. These measures aim at reducing overall emissions, containing remaining emissions, and minimizing operator exposure. In addition, personal protective equipment (PPE) may be used in cases when engineering controls are too expensive, impractical, or incapable of reducing and containing emissions.

7.4.1 Administrative Controls

Administrative controls consist of various policies and requirements that are established at an administrative level to promote safety in the workplace. Exposure to work hazards is minimized this way by properly managing the workers interaction with the source of hazard, isolating the hazard, following specific safe handling procedures and proper personal and industrial hygiene. Since this form of control is largely dependent on individual users acting with knowledge and responsibility, it is less satisfactory than engineering controls.Therefore, this form of control should only be used under well-documented conditions and after engineering controls have first been considered or used.

Administrative control of exposure to workplace hazards may include, but not limited to practices such as:

- Ensuring that all workers have been provided with adequate training to enable them to conduct their duties safely
- Properly reviewing MSDS by trained personnel prior to handling materials in question
- Rotation of workers to minimize the length of time a worker is exposed to a certain chemical
- Restricting access to areas in which particularly hazardous chemicals are used
- Posting appropriate signs to identify specific hazards within an area
- Requiring that various standard practices for chemical safety and good housekeeping be observed at all times in the laboratory
- Following adequate personal hygiene program

7.4.2 Engineering Controls

Machining fiber-reinforced composites generates significant amounts of airborne dust and fumes that must be effectively cleared from the workplace in order to reduce exposure. Particles and gases must be removed from the worker's breathing zone, transported by the ventilation system and properly removed by an air cleaning device before venting air to the atmosphere. The most effective engineering control measure is the use of on-tool extraction systems that are attached to a high-vacuum dust collection system. Using this method, aerosols are captured at the generation point, preventing the contaminant from escaping into the air. On-tool extractions systems come in a variety of designs and include shrouds, hoods, suction nozzles (for laser cutting), and sometimes total tool enclosures. The high-vacuum dust collection system creates a negative pressure at the extraction point that is capable of capturing most machining by-products. Due to this powerful vacuum, ventilation efficiency is extremely good and no respiratory protection is therefore necessary. The on-tool extraction system must provide minimum interference with the worker and be easy to use. High-vacuum systems allow the use of smaller diameters extraction hoses that do not restrict the workspace and are lighter and less bulky to handle by the worker.

In a study on the use of shrouded hand tools in grinding and sanding of composites it was shown that the total dust exposure at the worker's breathing zone was significantly reduced to levels below the detection level of the sampling instrument [19]. For laser cutting most of the aerosol emissions occur at the bottom of the workpiece. Applying exhaust air just below the workpiece was shown to capture most of the cutting fumes in machining glass FRP [20]. The captured air was filtered to remove organic gases and then released to the workplace. The average respirable dust concentration was about $0.15\,\mathrm{mg/m^3}$ and the concentration of organic gaseous compounds was below their respective detection limits and far below the threshold level values.

7.4.3 Personal Protective Equipment

Gloves, protective clothing, and eye protection may frequently be required, especially when the engineering controls are not capable of protecting the worker from exposure to hazards. PPE should be used as last resort or temporary solution. The correct approach to safety in the workplace is to reduce or preferably completely eliminate the inherent need for PPE through administrative and engineering control. Nevertheless, when PPE are required, it is necessary that proper equipment is selected according to health authority regulations whenever such regulations are available. The requirements for a respirator program, for example, are described in the OSHA regulation 29 CFR 1910.134 [6]. Similarly, requirements may be described for eye, hearing, and skin protection.

7.4.4 Machine Tool Health

Dust generated from machining FRPs is also harmful to the machine tool. Glass and carbon fibers and particles are highly abrasive. Carbon fibrils are also electrically conductive. Due to the small size of the dust particles and the fibrils, and their ability to become airborne, it is very likely that these particles will penetrate into tight spaces between machine components and into the machine control box. The prolonged contact of the abrasive dust with the moving machine elements such as slideways, ball screws, and bearings may lead to wear. Deposition of the carbon fibrils on printed circuit boards on the machine control will cause short circuits and very expensive damage to the machine tool. It is therefore essential to encapsulate the machine slides with dust covers. Machine enclosure will also help to extract the dust removed and to filter it to protect the operator from dust emissions. The electrical components should be isolated from the machine tool and air-conditioned separately. Figure 7.4 below shows a schematic of a machine tool for machining FRPs with proper components and features installed to meet the demand of this task [16].

7.5 Summary

Traditional machining processes produce dust-like chips that may become airborne. Some of this dust might be small enough to make its way to the lower respiratory tract and hence poses a health hazard. The upper limit to the size of respirable dust particles is 10 μm aerodynamic diameter and only 1% of the particle distribution below this size can make its way into the alveolar region of the lungs. Larger particles that are not respirable, deposit in the head and tracheobronchial airways and can pose a serious nuisance to the eyes, skin, and upper respiratory tract. Laser cutting

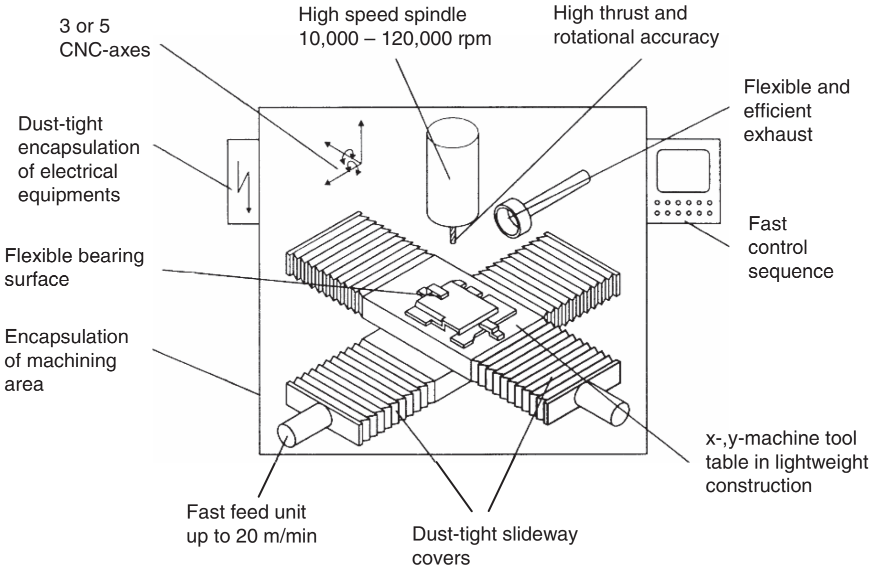

Fig. 7.4 Recommended configuration of milling machine for machining FRPs [16]

on the other hand produces re-solidified particles and gaseous emission that might be toxic, allergic, or carcinogenic.

The common sources of machining aerosols are the mechanical breakage of reinforcement fibers and the chemical breakdown of the polymer matrix and aramid organic fibers due to excessive heating. Carbon fibers are the major source of respirable dust because they may splinter lengthwise during machining producing fibrils of diameters less than 6 μm. Aramid fibers are also capable of splintering, but their emission of respirable fibrils is typically low. Glass fibers on the other hand do not possess the cleavage mechanism that causes splintering and they break perpendicular to the fiber axis into particles of the same order of the fiber diameter. Chemical breakdown of the polymer matrix and aramid fibers occurs in laser machining because of the high temperatures involved. The aerosols generated by vaporization and condensation process contain gaseous organic compounds and solid particles that are generally in the respirable range. A variety of aromatic hydrocarbons are generated in high concentrations, but are dominated by benzene and toluene. Most of these gasses have adverse effects on health after prolonged exposures. Therefore, RELs in the workplace have to be adhered to during machining.

The size distribution of aerosol particles is influenced by machining process parameters. Lower concentrations of respirable dust can be obtained in trimming applications by increasing the chip per tooth (which can be achieved by increasing the feed rate while keeping the spindle speed fixed, by reducing the spindle speed, and by using tools with less cutting teeth). In laser cutting, a decrease in the median aerodynamic diameter is achieved by increasing laser beam power and reducing the traverse speed. Both conditions are responsible for generating higher temperatures at the cutting front.

There are two main approaches for eliminating exposure to health hazards: administrative and engineering controls. Administrative controls pertain to establishing proper work scheduling, worker training, and policies that will result in minimum workers exposure to hazards. Engineering solutions are those equipments or systems installed at the work place in order to contain and remove hazards. The most effective engineering control of machining dust and fumes is ventilation. In addition, PPE may be used but only as a last resort because priorities should be set on eliminating health hazards or their exposures.

Another key concern in machining FRPs is protecting the machine tool against damage caused by machining byproducts. Two main areas of machine tool system must be properly guarded. One area is the machine electric and electronic control boxes, which have to be isolated and be ventilated separately in order to prevent deposition of the electrically conductive carbon dust on the circuit boards. The second area is the accurate machine slides and ball screws, which have to be protected against abrasive wear of the dust particles.

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