

Machining Characteristics of Composite Materials During Milling

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Abstract

Composite materials are widely used in aerospace, automotive, and engineering applications due to their high specific strength, corrosion resistance, and low weight. However, the heterogeneous and anisotropic structure of these materials significantly complicates the milling process. This paper analyzes the main features of composite materials milling, including the influence of fiber orientation, cutting parameters, thermal effects, chip formation mechanisms, surface defects, and tool wear. The study shows that feed rate has the greatest influence on fiber pull-out, fuzzing, and surface roughness, while cutting speed strongly affects tool wear. Due to the low thermal conductivity of composite materials, most of the generated heat is concentrated in the cutting tool, accelerating wear processes. Abrasive wear on the flank face is identified as the dominant wear mechanism during machining. The paper also reviews advanced approaches for improving machining performance, such as ultrasonic-assisted milling, variable stock removal strategies, intermittent cutting, and pre-deformation of the material layer before cutting. The obtained results provide a scientific basis for selecting rational machining conditions and developing efficient methods for increasing productivity, improving surface quality, and extending tool life during the milling of glass fiber reinforced polymer composites.

Keywords: Composite materials, milling, machining characteristics, tool wear, flank wear, cutting forces, surface roughness, fiber orientation, chip formation, abrasive wear, machining productivity, ultrasonic-assisted milling, surface defects, machining quality.

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1. Introduction

It has been shown that fiber orientation significantly affects cutting forces, surface roughness, delamination, and fuzz formation during the milling process. Ultrasonic vibration-assisted machining has been found to be more effective than conventional milling, as it reduces cutting forces, improves surface quality, and minimizes subsurface damage and edge defects [1,2,3].

Feed rate has been identified as the parameter with the greatest influence on fiber pull-out and fuzz formation. As the feed rate increases, heat generation, vibration, and tool wear intensify, resulting in poorer surface quality. Cutting speed has also been recognized as one of the primary factors affecting tool wear. Increased friction during machining along the fiber direction leads to more rapid tool deterioration [4,5,6].

Abrasive wear is the most common problem encountered during the machining of composite materials. Flank wear is the dominant wear mechanism in composite machining, and a tool is generally considered unsuitable for further use when flank wear exceeds 0.3 mm.

Materials and methods

Anisotropy, the layered structure of the material, and, in some cases, insufficient interfacial bonding strength

between the glass fibers and the epoxy matrix further influence machining performance. Increased cutting forces can induce cracks between the matrix and the reinforcement, leading to matrix degradation. Defects such as fiber fracture, delamination, fiber pull-out, and surface tearing may occur on the machined surface (Figure 1).

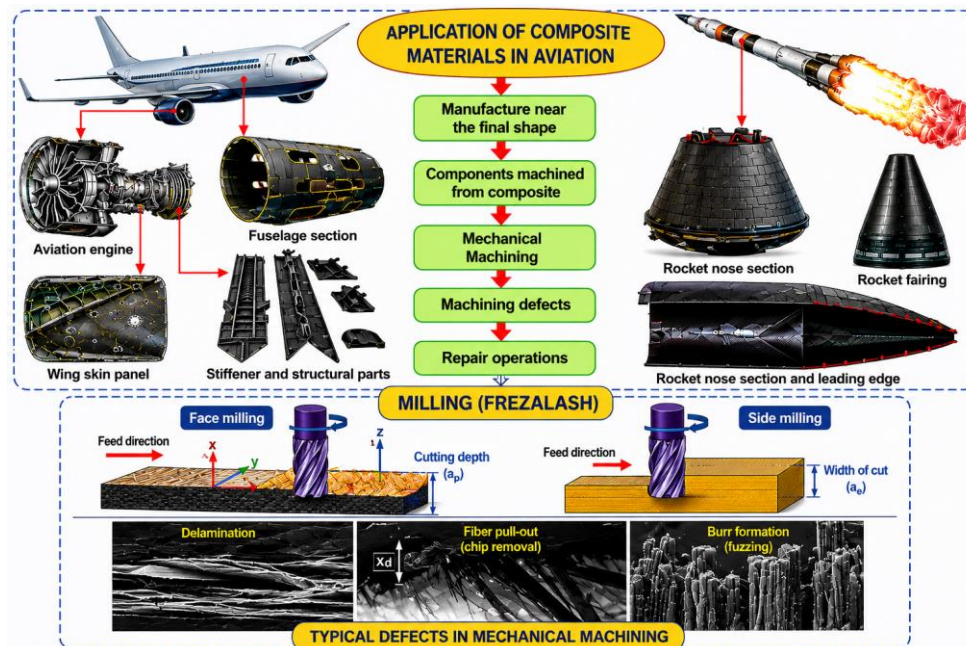


Figure 1. Application of composite-material components in aerospace engineering and typical defects occurring during milling.

Due to their extremely low thermal conductivity, glass fiber reinforced polymer (GFRP) composites transfer only a negligible amount of heat away from the cutting zone. As a result, most of the heat generated during machining accumulates in the cutting tool [7,8,9]. More than 90% of the thermal energy is absorbed by the tool, while only a small portion is carried away by the chips and an even smaller amount is transferred to the workpiece. Consequently, the cutting tool is subjected to severe thermal loading, leading to accelerated wear and reduced tool life.

This heat distribution differs significantly from that observed during the milling of metallic materials. In metal machining, more than 90% of the generated heat is removed with the chips, while the remaining heat is distributed between the cutting tool and the workpiece. Therefore, the thermal load acting on the cutting tool is considerably lower when machining metals.

Glass fibers possess high hardness and strong abrasive properties. Under elevated temperatures, continuous

contact between the glass fibers and the cutting edge causes wear on both the rake and flank faces of the tool. This wear increases the cutting-edge radius, resulting in reduced cutting efficiency and deterioration of machining performance.

The high temperatures generated in the cutting zone, combined with the relatively low thermal resistance of the polymer matrix, can cause the breakdown of molecular bonds within the polymer chains. This thermo-mechanical and chemical degradation leads to a reduction in the physical and mechanical properties of the material. Furthermore, the formation of chemically active molecular fragments promotes adhesion and chemical interaction between the workpiece material and the cutting tool surface, accelerating tool wear through combined chemical and mechanical mechanisms. Such wear behavior is characteristic of polymer composite machining.

Composite materials also exhibit high elastic recovery. During machining, the contact area between the flank face of the cutting tool and the workpiece becomes

significantly larger than that observed in metal cutting. Elastic recovery of the subsurface material layer causes an expansion of the contact zone, leading to a redistribution of cutting forces. In some cases, the forces

acting on the flank face may exceed those acting on the rake face, which further influences tool wear and machining accuracy.

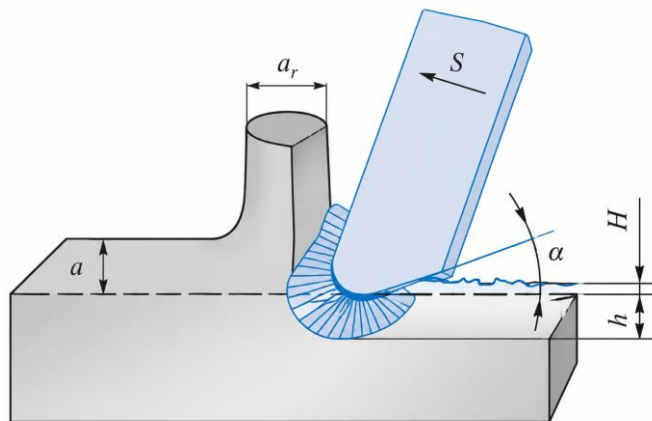


Figure 2. Contact zone between the flank face of the cutting tool and the workpiece during the machining of glass fiber reinforced composite materials.

During the machining of glass fiber reinforced composite components, the elastic recovery of the material surface is an important factor affecting machining accuracy. Cutting forces generated during the machining of composite materials are typically 10–20 times lower than those encountered in metal cutting, while the elastic properties of the material are significantly higher. Consequently, machining accuracy depends less on the rigidity of the technological system and more on the elastic behavior of the composite material itself.

2. Results And Discussion

The physical and mechanical properties of glass fiber composites must be considered when selecting criteria

for evaluating tool wear. Previous studies have shown that the predominant wear mechanisms are flank wear and cutting-edge rounding. These wear forms directly affect cutting performance and the quality of the machined surface.

The multilayer structure of glass fiber composites and the weakening of the bond between the reinforcement and matrix at elevated temperatures contribute to the formation of various surface defects during machining. Common defects include surface tearing, delamination, partially cut fibers protruding from the surface, and thermal burn marks. For this reason, the allowable wear limit for cutting tools used in machining glass fiber composites is generally lower than that applied in conventional metal machining operations.

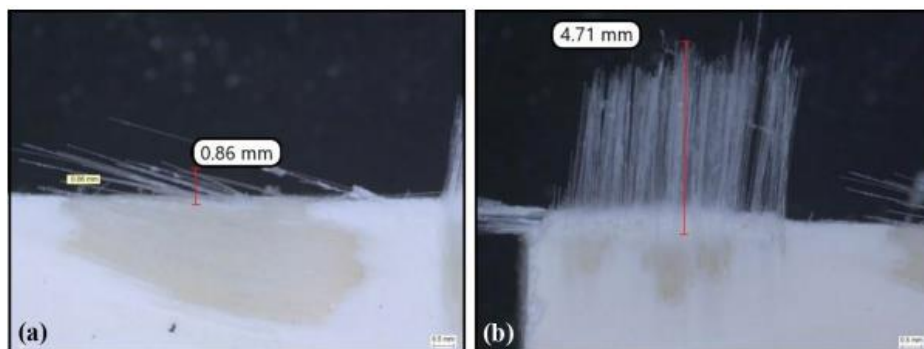


Figure 3 Microscopic view of fiber fuzzing and delamination after milling of glass fiber reinforced composites: (a) Type I fuzzing; (b) Type II fuzzing.

Although glass fiber reinforced composites possess high strength characteristics, their thermal resistance is

relatively low. Depending on the type of polymer matrix used, the thermal stability of these materials generally ranges from 160 to 300 °C. When the temperature in the cutting zone exceeds this range, thermal degradation of the matrix occurs, which may result in burn marks and surface damage. Unlike metal machining, the use of conventional cutting fluids is generally not recommended for glass fiber composites because these materials can absorb moisture, which may adversely affect their properties.



Figure 4. Types of chips formed during the machining of glass fiber reinforced composites: (a) fragmented chips, (b) powder-like chips, and (c) continuous chips.

The unique characteristics observed during the machining of glass fiber reinforced composites indicate that conventional machining recommendations developed for metals and their alloys cannot be directly applied to these materials. Therefore, a comprehensive understanding of the cutting process is required to ensure efficient and high-quality machining of composite materials.

Particular attention should be given to the study of chip formation mechanisms, the influence of cutting parameters on cutting forces, and the evaluation of surface roughness and dimensional accuracy. A thorough analysis of these factors makes it possible to improve machining productivity while maintaining high surface quality.

Research findings provide a scientific basis for selecting optimal machining parameters and developing practical recommendations for manufacturing components made of composite materials. Such recommendations can reduce technological preparation time and improve production efficiency.

At present, many existing guidelines for milling, turning, and drilling composite materials are either inconsistent or insufficiently developed. Consequently, additional experimental investigations and validation tests are

The chip formation mechanism in glass fiber composites differs significantly from that observed in metals and metallic alloys [10]. Due to the high elasticity of the polymer matrix and the high strength of the glass fibers, the material tends to fracture rapidly under mechanical loading with minimal plastic deformation. This behavior gives composite machining its distinctive chip formation characteristics. As a result, chips are typically generated simultaneously in the form of fragmented, powder-like, and continuous chips, as illustrated in Figure 4.

required. Some technical sources recommend the use of VK3M, VK2, and VK8 cemented carbide tools for machining glass fiber composites and provide corresponding tool geometries and cutting conditions. However, these recommendations are not always optimal for modern composite materials, as frequent tool regrinding reduces productivity. Although diamond tools enable high-speed machining and superior wear resistance, their application significantly increases production costs.

Numerous studies have demonstrated that machining productivity can be enhanced through effective control of the milling process. However, there is still a lack of well-established methodologies for selecting and applying these techniques under specific machining conditions.

Several advanced approaches have been proposed to improve milling performance. For example, when machining workpieces with variable stock allowance, adjusting the cutter inclination angle according to the stock variation helps maintain a constant contact area between the cutting tool and the workpiece, thereby stabilizing cutting forces. Tool life can also be extended by employing curved tool-entry trajectories, which reduce tool wear and improve machining accuracy.

Similar benefits can be achieved through intermittent cutting techniques, where vibrations are introduced into the cutting zone to lower cutting temperatures and reduce thermal loading. These methods can prevent dimensional errors and eliminate defects that may have formed during previous manufacturing stages.

Another promising approach involves the pre-deformation of the material layer before cutting. This technique creates more favorable cutting conditions, improves tool life, and enhances process stability. Surface plastic deformation methods, which deform only the surface layer without removing material, can also be applied to improve surface integrity and the performance of composite components.

3. Conclusion

Composite materials have unique machining characteristics due to their anisotropic structure, low thermal conductivity, and high abrasiveness. Fiber orientation, feed rate, and cutting speed significantly affect surface quality and tool wear. Abrasive flank wear is the dominant wear mechanism, while defects such as delamination, fiber pull-out, and fuzzing commonly occur during milling. Advanced techniques, including ultrasonic-assisted and intermittent milling, can improve machining performance, reduce tool wear, and enhance surface quality. Therefore, selecting appropriate cutting parameters is essential for achieving efficient and high-quality machining of composites.

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