Ultrasonic vibration cutting of advanced aerospace materials: a critical review of in-service functional performance

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Abstract

Purpose – Unconventional machining processes, particularly ultrasonic vibration cutting (UVC), can overcome such technical bottlenecks. However, the precise mechanism through which UVC affects the in-service functional performance of advanced aerospace materials remains obscure. This limits their industrial application and requires a deeper understanding.

Design/methodology/approach – The surface integrity and in-service functional performance of advanced aerospace materials are important guarantees for safety and stability in the aerospace industry. For advanced aerospace materials, which are difficult-to-machine, conventional machining processes cannot meet the requirements of high in-service functional performance owing to rapid tool wear, low processing efficiency and high cutting forces and temperatures in the cutting area during machining.

Findings – To address this literature gap, this study is focused on the quantitative evaluation of the in-service functional performance (fatigue performance, wear resistance and corrosion resistance) of advanced aerospace materials. First, the characteristics and usage background of advanced aerospace materials are elaborated in detail. Second, the improved effect of UVC on in-service functional performance is summarized. We have also explored the unique advantages of UVC during the processing of advanced aerospace materials. Finally, in response to some of the limitations of UVC, future development directions are proposed, including improvements in ultrasound systems, upgrades in ultrasound processing objects and theoretical breakthroughs in in-service functional performance.

Originality/value – This study provides insights into the optimization of machining processes to improve the in-service functional performance of advanced aviation materials, particularly the use of UVC and its unique process advantages.

Keywords Ultrasonic vibration cutting, Advanced aerospace materials, In-service functional performance, Unique advantages

Paper type Literature review

1. Introduction

In recent years, with the increasing demand for high-performance aerospace equipment and rapid developments in the manufacturing industry, advanced aerospace materials (such as superalloys, titanium alloys, ultrahigh-strength steels, carbon-fiber composites, metal matrix composites (MMC) and ceramic matrix composites (CMC)] with good physical properties have been widely used in aerospace applications (Alami *et al.*, 2023; Soni *et al.*, 2023; Sreenu *et al.*, 2020).

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However, owing to the high strength, high hardness and low thermal conductivity of these advanced aerospace materials (difficult-to-machine materials), they suffer from problems such as the need for excessive cutting force, prevalence of high cutting temperature, severe tool wear and poor surface quality during traditional mechanical processing (turning, milling, grinding, drilling, etc.) (Arrazola *et al.*, 2009; Babitsky *et al.*, 2003; Babitsky *et al.*, 2004; Zhang *et al.*, 2023b).

As is well known, poor surface integrity is not conducive to the in-service functional performance of components (including fatigue performance, corrosion resistance and wear resistance). As advanced aerospace materials are widely used in various key high-performance aerospace components that are related to the safety and stability of aircraft, it is particularly important to process these materials in the best possible manner (Morioka *et al.*, 2001; Onawumi *et al.*, 2018; Sharma *et al.*, 2023). In popular commercial aircraft such as the Boeing 787 and Airbus 350, the main frame, fuselage and related longitudinal beams are primarily manufactured using carbon-fiber-reinforced plastics (CFRP). Nowadays, in drones, the weight of the related structures can reach 60–90% (Borchardt, 2004). Superalloys are widely used in various components of aircraft engines and account for approximately 50% of their weight (Ulutan and Ozel, 2011). However, owing to the difficulty in processing these advanced aerospace materials, machining defects are inevitable at both the macro and microscales (Liu *et al.*, 2020). Changes in the surface morphology, metallurgical state and mechanical properties strongly affect the in-service functional performance (fatigue performance, corrosion resistance and wear resistance) of aviation parts (Gavalda Diaz *et al.*, 2019; Liao *et al.*, 2019). Hence, it is critical to understand these aspects to ensure the safety and reliability of key aerospace components. For example, in the aerospace engine industry, safety standards are formulated based on performance measures such as fatigue resistance.

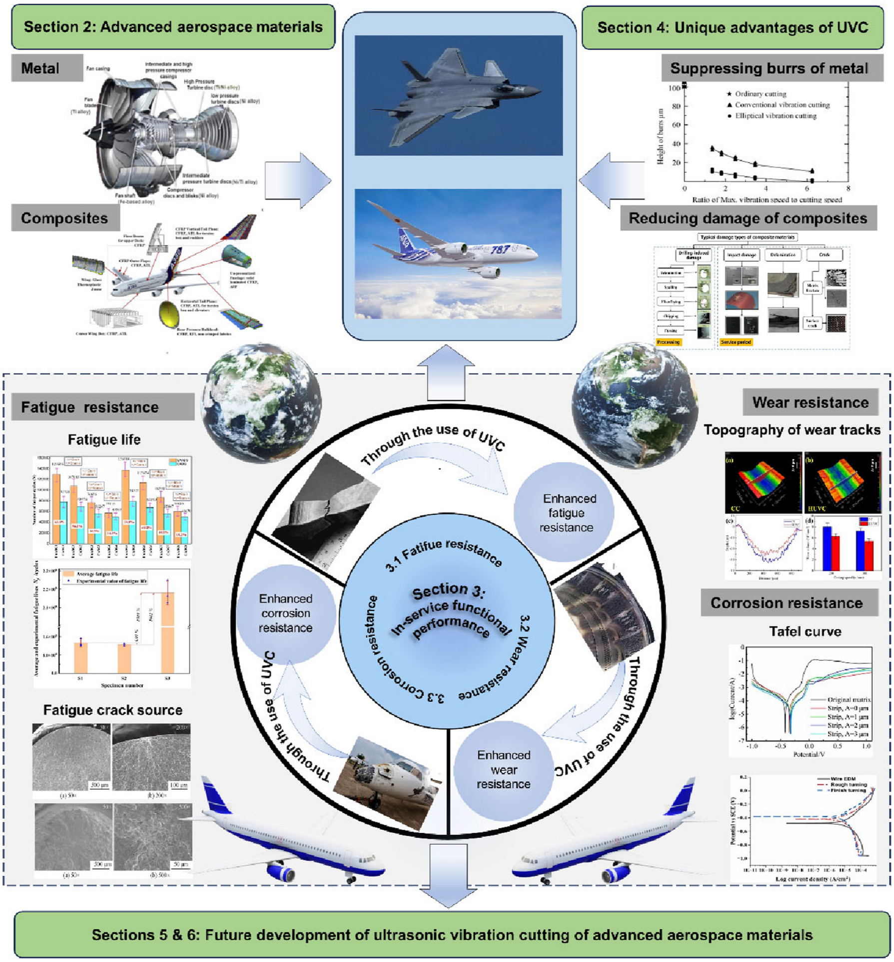
In recent years, with the increasing demand for high-performance aerospace equipment, both academia and industry have made tremendous efforts to elucidate defects in the processing of advanced aviation materials and their impact on the in-service functional performance of components and improvement measures have been explored. Generally, these defects are influenced to a certain extent by the machining conditions, including the machining parameters, tool selection and wear and the application of cooling methods (cutting fluid cooling, atomization cooling, gas-shielded cooling, etc.) (Jia *et al.*, 2019; Yang *et al.*, 2023a). A "mild" machining method (with reduced cutting speed and feed rate) can achieve better surface integrity and in-service functional performance, but this can lead to increased production costs and reduced machining efficiency. In addition, adopting advanced machining methods such as ultrasonic vibration cutting (UVC), laser-assisted machining and water-jet machining can improve the service performance of parts (He *et al.*, 2023; Nath and Rahman, 2008; Siva Prasad and Chaitanya, 2023). UVC, as a high-precision machining process, is suitable for many difficult-to-machine materials such as superalloys, titanium alloys, ultrahigh-strength steels and composites. UVC generates high-frequency ultrasonic vibrations in cutting tools or workpieces to achieve intermittent machining, which has advantages such as reduced cutting force, reduced cutting heat, improved tool life, suppressed chatter, suppressed adhesion and improved machining surface quality (Liu *et al.*, 2019; Namlu *et al.*, 2022). In addition, UVC has unique advantages in the processing of advanced aerospace materials, such as suppressing burrs in metallic materials, reducing delamination in CFRPs and reducing damage in CMC and MMC (Ma *et al.*, 2005; Xu *et al.*, 2021). In current industrial production processes, enterprises generally have their own standards to quantify processing defects, optimize production costs and achieve maximum production efficiency. However, establishing causative performance standards across all processing conditions and operating ranges requires a significant allocation of resources (Thakur and Gangopadhyay, 2016).

Although existing reviews have mainly focused on the surface characterization of special materials processed using specific methods to improve the surface integrity of aerospace equipment, the relationship between the UVC process of advanced aerospace materials and their in-service functional performance has not been explored. Many researchers have studied the machining performance of different advanced aviation materials using UVC.

However, few studies have comprehensively analyzed and summarized the characteristics and in-service functional performance of UVC from the perspective of advanced aerospace materials. Therefore, as shown in Figure 1, this study first provides a detailed introduction to the characteristics and usage background of advanced aerospace materials in Section 2 and summarizes the current research status of the impact of UVC on in-service functional performance in Section 3. In Section 4, the unique advantages of UVC during the machining of metallic and composite materials are highlighted to remove, reduce and eliminate certain processing defects to support their further application. The conclusions and possible future directions are presented in Sections 5 and 6, respectively.

2. Advanced aerospace materials

With the continuous upgradation of aviation equipment, the demand for improved core performance of key components is also constantly increasing, driving the iterative



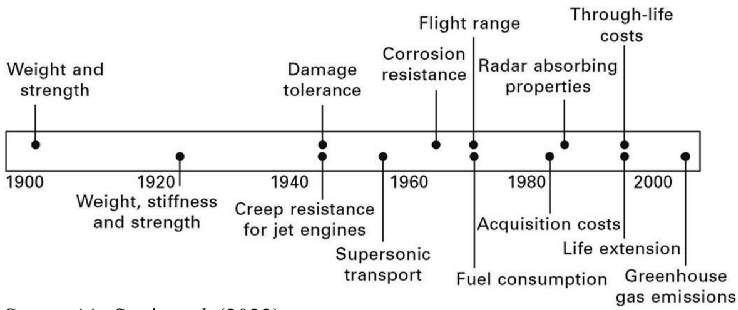
Source(s): Authors' own work

Figure 1.
Structure of this study

development of advanced materials (Figure 2). Owing to the developmental needs of the aerospace industry, the selection of advanced aviation materials has gradually shifted from aluminum alloys and steels to superalloys, titanium alloys, ultrahigh-strength steels and various composite materials. Currently, the main advanced aviation materials are classified as metallic and composite materials (Soni *et al.*, 2023).

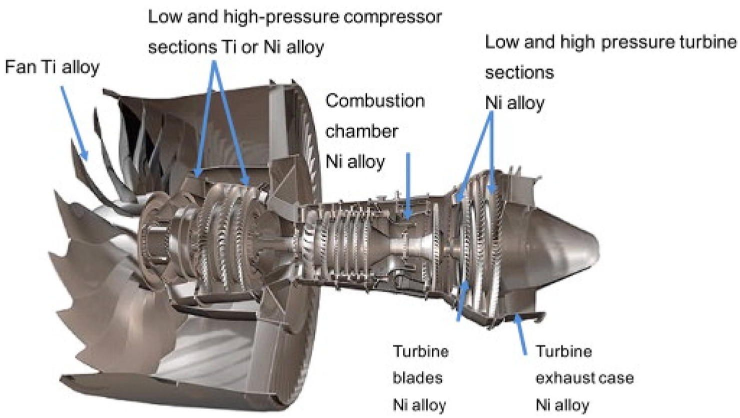
2.1 Metallic materials

2.1.1 Superalloys. Superalloys (i.e. high-temperature alloys) can be divided into iron, cobalt and nickel-based superalloys based on the composition of the matrix elements. With the progress in processing and material synthesis technologies, iron-based, cobalt-based, iron-nickel-based and iron-nickel chromium-based alloys are mostly being replaced by nickel-based high-temperature alloys (Choudhury and El-Baradie, 1998). High-temperature alloys are widely used in aircraft engines owing to their excellent high-temperature strength, thermal fatigue performance, corrosion resistance and creep resistance. They generally account for approximately 50% of the weight of aircraft engines (Rathi *et al.*, 2023). Figures 3 and 4 illustrates the application of superalloys in turbine engines. With the increasing complexity of modern aircraft engines and increased operating temperatures, the development of high-temperature alloys has evolved from simple nickel–chromium matrices to multi-element and multiphase systems that meet stricter operating conditions (Shahwaz *et al.*, 2022).



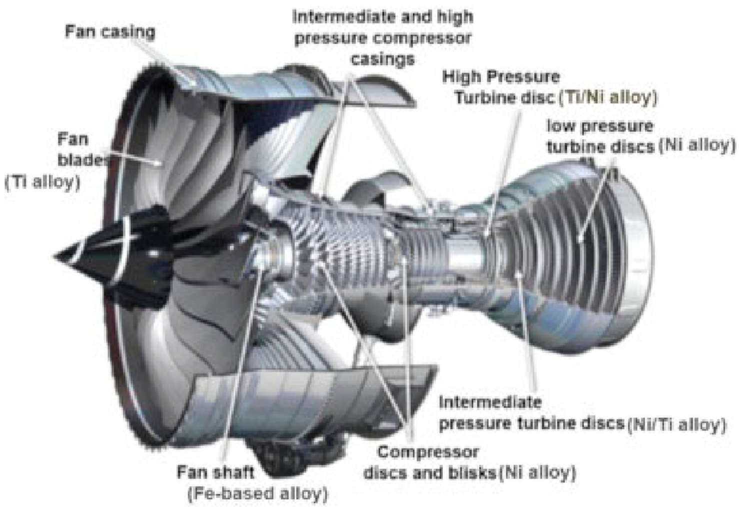
Source(s): Soni *et al*. (2023)

Figure 2. Historical timeline demonstrating the introduction of important material selection factors in airplane design



Source(s): Ulutan and Ozel (2011)

Figure 3. Cross-section of an aerospace jet engine



Source(s): M'Saoubi *et al*. (2015)

Figure 4.
Schematic of
Rolls-Royce XWB
Turbofan engine

Inconel 718 is the most widely used Ni-based superalloy. Owing to its excellent heat resistance, good plasticity, resistance to high-temperature oxidation and corrosion and long-term structural stability, it is widely used in turbine engine blades and discs (Toubhans *et al.*, 2020). FGH95, ME-16, RR1000 and Udimet 720LI have also been used in the aviation industry (Dong *et al.*, 2021; Du *et al.*, 2014; Soo *et al.*, 2011). In addition, Nimonic C-263, Nimonic-75 and Nimonic-105 are primarily used in hot combustion chamber gas turbines (Ezugwu *et al.*, 1999). IN-713LC cast high-temperature alloys are primarily used for rotor blades in gas turbines, aircraft turbines and rotor impellers (Kunz *et al.*, 2010; Kunz *et al.*, 2012).

Although nickel-based superalloys are widely used in the aviation industry owing to their excellent high-temperature performance and rapid work-hardening during processing, they exhibit extremely poor mechanical processing performance in actual production. High cutting force and high cutting temperature lead to severe tool wear and surface changes during the machining process that reduce the mechanical and corrosion resistance of the workpiece. Additionally, burrs are formed during the machining process (Jangali Satish *et al.*, 2021; M'Saoubi *et al.*, 2015).

2.1.2 Titanium alloys. Titanium alloys are suitable for aircraft engines and fuselage manufacturing because of their excellent mechanical properties and processability (Plate 1) (Nyamekye *et al.*, 2023). The main advantages of titanium alloys are their low density (half of the density of nickel-based superalloys), good high-temperature performance, high specific strength, corrosion resistance, creep resistance and good compatibility (Pushp *et al.*, 2022). In aircraft engines, titanium and its alloys are commonly used in low- and high-pressure compressors, components that withstand high centrifugal loads (such as discs and blades with reduced flow diameters) and components that operate under severe fatigue conditions (Williams and Starke, 2003). However, owing to the special properties of titanium alloys that are superior to conventional materials, challenges arise in production and processing. These problems include their high resistance to elastic-plastic deformation when torn by cutting teeth, severe work hardening and high cutting heat. Additionally, severe wear and tear can cause chips to easily adhere to the tool under high-temperature conditions, leading to the formation of chip lumps and difficulty in controlling chips (Che-Haron and Jawaid, 2005).

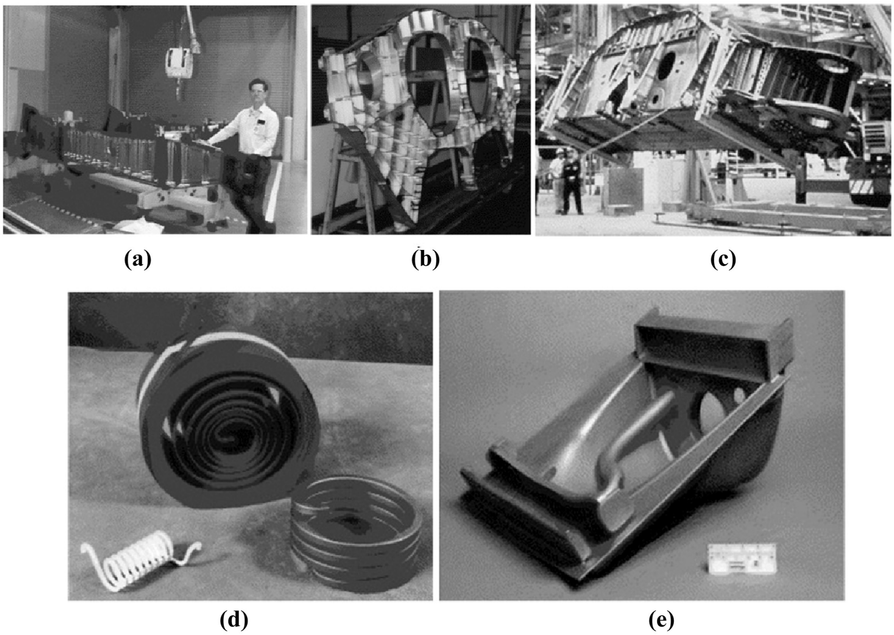


Plate 1.
Components made from Ti-based alloys: (a) landing gear beam for Boeing 747; (b) bulkhead for a fighter aircraft; (c) wing box of the B1-B bomber aircraft; (d) springs used in Boeing aircraft; (e) a casting used in a military transport aircraft

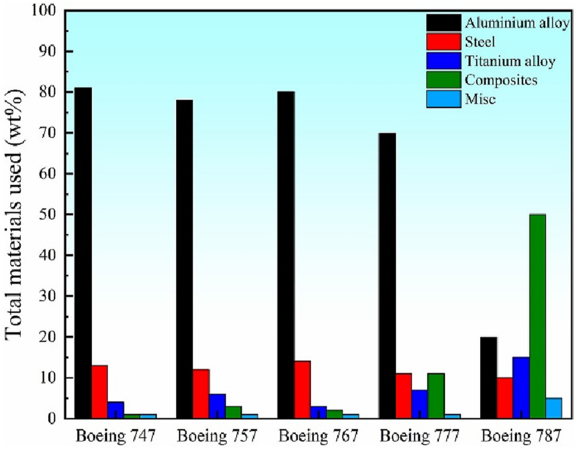
Source(s): Williams and Starke (2003)

The most commonly used titanium alloys are α, β and $\alpha-\beta$ titanium alloys. Among α titanium alloys, near α titanium alloys have good creep resistance at high temperatures and are commonly used in high-temperature environments, with operating temperatures up to 400–520 °C(W. Jia *et al.*, 2011). Ti-6Al-2Sn-4Zr-2Mo is commonly used in turbine engine blades, discs and rotors and can also be applied in high-pressure compressors (Sefer *et al.*, 2016).

β titanium alloys have high hardenability and stress corrosion resistance and can be heat treated to high strength α compared to titanium alloys. Additionally, β titanium and near β titanium alloys have higher tensile and fatigue strength and are commonly used in aircraft landing gear and aircraft springs (Boyer and Briggs, 2005). Research has shown that Ti-10V-2Fe-3Al (Ti-10-2-3) and Ti-5Al-5Mo-5V-3Cr (Ti-5553) are superior to mature alloys such as Ti-6Al-4V (Ti-6-4) for use in landing gear and load-bearing fuselage applications (Filho *et al.*, 2023; Wu *et al.*, 2018). $\alpha-\beta$ alloys have higher strength and a good combination of properties to ensure stable operation at 315–400 °C. Ti-6-4 is the most commonly used alloy, accounting for 60% of the total titanium production and is primarily used in fasteners in compressor discs and static and rotating components in turbine engines (Chen *et al.*, 2022).

2.1.3 Ultrahigh-strength steels. Since the launch of the first aircraft, steel has played an important role in the aviation industry, particularly in aircraft gears, bearings and fasteners. However, with developments in the aviation industry, the performance requirements of key aviation equipment are constantly increasing. The composition of steel has changed from carbon- and iron-based to complex alloys containing Fe and a large number of alloying elements. In recent years, advanced aerospace materials with good mechanical properties have been widely used, and the use of steel has rapidly decreased (Zhang *et al.*, 2018). Figure 5 shows the steel materials used in the Boeing 7E7 aircraft series.

To meet current needs, ultrahigh-strength steels (UHSSs) have experienced rapid development. These steels are developed by adding various alloying elements to traditional alloy steels to



Source(s): Li *et al*. (2023c)

Figure 5.
Steel materials used in Boeing 7E7 series aircraft

enhance their mechanical properties. According to the composition of the alloy elements, UHSSs are divided into low-alloy ultrahigh-strength steels (LUHSSs), medium-alloy ultrahigh-strength steels (MUHSSs) and high-alloy ultrahigh-strength steels (HUHSSs) (Li *et al.*, 2023b). The yield strength of UHSSs is generally greater than 1,380 MPa (Niu *et al.*, 2021). Compared with traditional steel, UHSSs have significant advantages in terms of hardenability, tempering and softening ability, wear resistance and corrosion resistance and are commonly used in aviation engine bearings, landing gear and other key components (Li *et al.*, 2023c). Plate 2 shows a photograph of the landing gear assembly for a Boeing 777 aircraft. Some common UHSSs in the aviation industry include 4130, 4140, 4340, 6150, 9260, 300M and D6ac (Li *et al.*, 2023c).

However, hydrogen easily degrades UHSSs because hydrogen atoms at the crack tip weaken the interatomic bonds and promote crack propagation through slips and micropores. Under applied stress, the distribution of hydrogen is highly uneven, leading to local deformation and damage, which seriously affects the in-service functional performance (Herbsleb *et al.*, 1981).

2.2 Composite materials

2.2.1 Carbon-fiber-reinforced plastics (CFRPs). CFRPs have excellent mechanical properties such as high specific strength, high specific stiffness and fatigue resistance and were initially used in secondary structures such as ailerons, trim plates and rudders in aircraft (Deshmukh *et al.*, 2022; Singh *et al.*, 2023). With advancements in synthesis technology and usage, new fiber and matrix materials have significantly improved the performance of laminated boards (Fleischer *et al.*, 2018; Geier *et al.*, 2023). CFRPs have replaced traditional alloys (such as aluminum and titanium alloys) and are widely used in major aircraft structures, such as fuselages and wings (Angelone *et al.*, 2021).

They are widely used in civil aircraft developed by organizations such as Boeing and Airbus. Figure 6 shows the percentage of the total structural weight attributed to composites and the use of composites in Airbus A380 aircraft. From Boeing the 737 to the Boeing 757, CFRPs are still mainly used for auxiliary structures. At present, composite materials account for over 25% of Airbus A380 and over 50% of Boeing 787 aircraft. Composite materials not only have enormous development potential in structural applications but are also widely used in aircraft main frames and the skin of fuselage/wings. Hence, CFRPs have strong

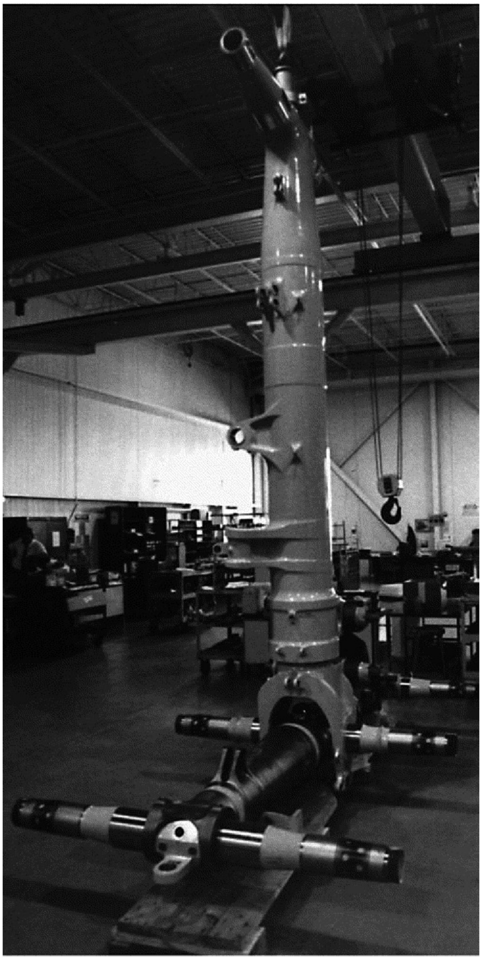


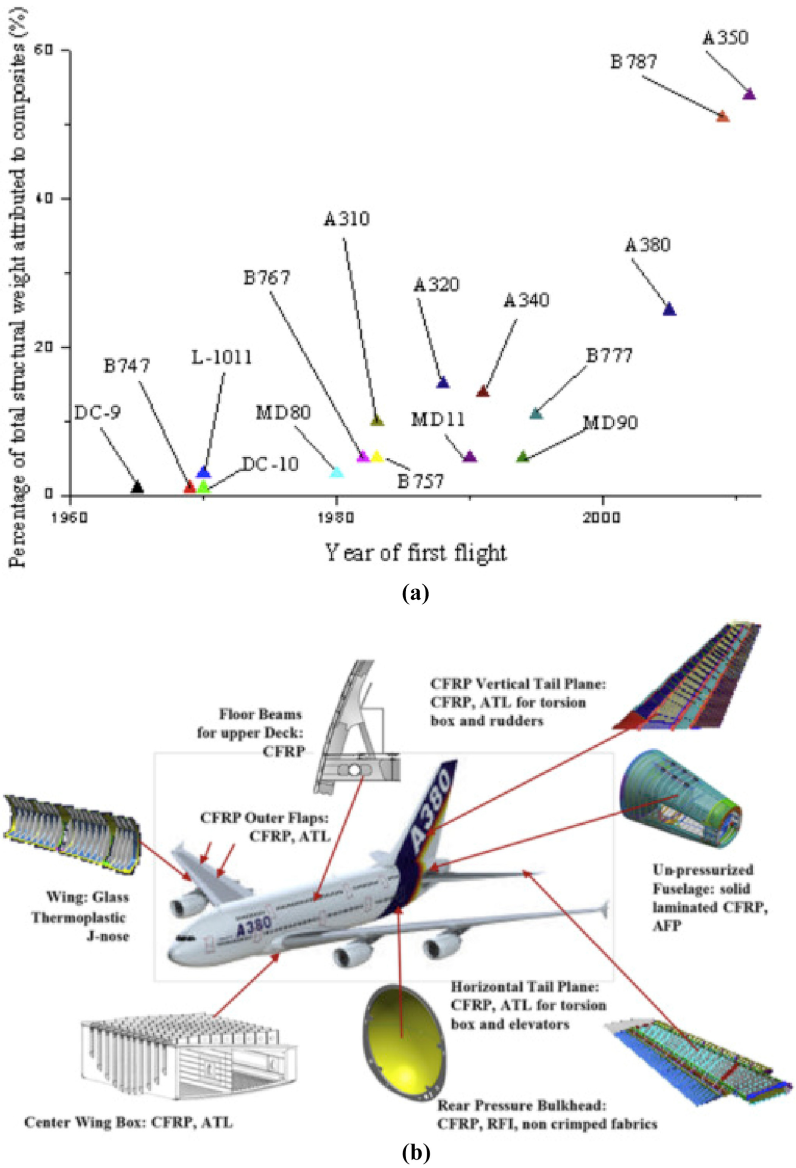
Plate 2.
Photograph of the landing gear assembly for a Boeing 777 aircraft

Source(s): Williams and Starke (2003)

development prospects in aircraft engines as well (Zhang *et al.*, 2023c). One of the driving forces behind the application of CFRPs in aircraft is the strong focus of the aerospace industry on enhancing ecological efficiency by reducing fuel consumption, greenhouse gas emissions and costs (M'Saoubi *et al.*, 2015).

However, owing to the nonuniformity and anisotropy of CFRPs, the application of conventional processing techniques can lead to poor material integrity as well as damage phenomena such as burrs and delamination (Geier *et al.*, 2019). The milling process can cause burrs and delamination of uncut fiber yarns (Hou *et al.*, 2021). Turning and drilling processes can lead to severe tool wear and poor surface integrity (Lin and Chen, 1996). Therefore, suppressing burrs and delamination, improving surface integrity and improving processing efficiency have become key to the widespread application of CFRPs.

2.2.2 Metal matrix composites (MMCs). MMCs are composite materials based on metals and their alloys, artificially synthesized with metals, nonmetal reinforcing phases, or organic



Source(s): Zhang *et al*. (2018)

Figure 6.
(a) Percentage of total structural weight attributed to composites and (b) use of composites in Airbus A380

compounds. MMCs for advanced aerospace applications have a low thermal expansion coefficient, high strength, high stiffness, high creep resistance, a long fatigue life and good corrosion/oxidation resistance (Liu *et al.*, 2014). Based on the type of matrix, MMCs are primarily divided into Al, Mg, Zn, Cu, Ti, Ni and intermetallic compound matrices (Dorri Moghadam *et al.*, 2015). Most reinforcing materials are inorganic nonmetals such as ceramics, carbon, graphite and boron. The most commonly used MMCs in the aerospace industry are aluminum, magnesium and titanium-based composites. The applications of aluminum-based MMCs include aircraft fuselage, wings, fan guide blades and hydraulic system bypass valve boxes, whereas titanium-based MMCs are used in the relay pistons of gas turbine engines (Garg *et al.*, 2019; Li *et al.*, 2013).

By using ceramic particles such as SiC, Al_2O_3, C, B, B_4C, AlN and SiO_2 as reinforcing materials, the hardness, strength, corrosion resistance and wear resistance of MMCs can be improved (Kaczmar *et al.*, 2000; Wang and Monetta, 2023). For example, using SiC can help achieve higher tensile strength and better hardness, density and wear resistance. The use of Al_2O_3 has a significant effect on improving compressive strength and wear resistance (Haque *et al.*, 2022; Prater, 2014). In addition, fibers play a crucial role in MMCs (Watanabe *et al.*, 2018).

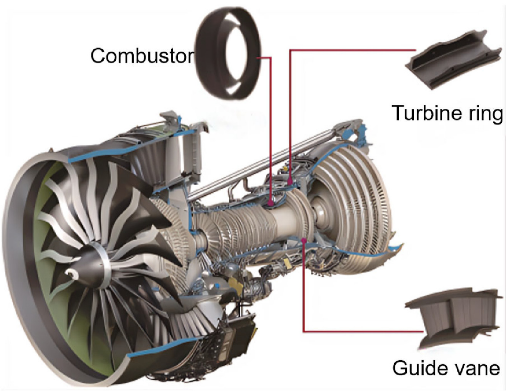
MMCs have been used in various applications (including the aerospace, automotive and military industries) to meet the requirements of light weight, high strength, high stiffness and high performance in aviation equipment, and their proportion is constantly increasing.

2.2.3 Ceramic matrix composites (CMCs). CMCs are composite materials composed of a ceramic serving as the matrix and various fibers. CMCs can be divided into oxide- and non-oxide-based composite materials based on their matrix composition. Oxide-based composite materials include glass, glass ceramics, oxides and composite oxides. Non-oxide-based composite materials are primarily composed of SiC, Si_3N_4 and MoS_2 (Duan *et al.*, 2021; Gavalda Diaz *et al.*, 2019).

CMCs have high temperature resistance (working temperature up to 1,400°C), high hardness, low density and good corrosion resistance (Sommers *et al.*, 2010). They are widely used in the high-temperature parts of aviation equipment, such as turbine blades, tail nozzle control fins, combustion chamber substrates and flame stabilizers (Krenkel and Berndt, 2005). Figure 7 shows the application of SiCf/SiC composites in the thermal structural components of aeroengines.

More than 20 years ago, general electric company (GE) began developing and researching ceramic-based composite materials for combustion chamber linings in civilian transport aircraft. The leading edge aviation propulsion (LEAP) aircraft engine developed by CFM has become the most widely used ceramic-based composite material product. Currently, the secondary sealing plate of F414 tail nozzles is composed of a CMC material.

CMCs exhibit excellent performance and are expected to replace high-temperature alloys in thermal components in aviation engines. By increasing the working temperature by 400–500 °C and reducing the structural weight by 50–70% on the basis of high-temperature alloys,



Source(s): Authors' own work

Figure 7.
Application of SiCf/SiC composites in thermal structure components of aeroengines

CMCs have become a key thermal structural material in aircraft engines (Wang *et al.*, 2021). However, owing to the complexity of CMCs, including their heterostructure, anisotropic thermal and mechanical behavior and the hardness of at least one component (such as fibers or matrix), processing becomes extremely challenging. In addition, the orthogonality, brittleness and heterogeneity of CMCs lead to different material removal mechanisms, resulting in unique surface defects (Gavalda Diaz *et al.*, 2019).

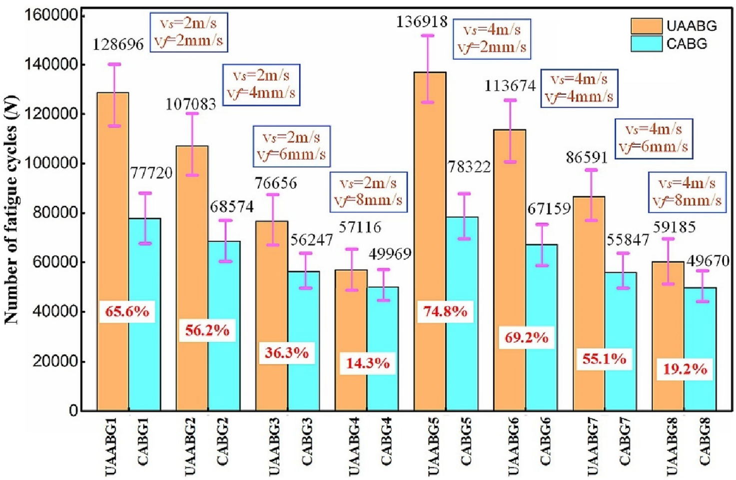
3. In-service functional performance

3.1 Fatigue resistance

The fatigue resistance of advanced materials is closely related to their chemical composition, microstructure and mechanical properties. The integrity of machined surfaces affects their fatigue performance through the crack initiation location and propagation rate (Doremus *et al.*, 2015). Several engineering practices have shown that fatigue fracture is the main mode of mechanical component fracture failure. Statistically, most major accidents caused by mechanical component fractures are related to fatigue fractures, and over 70% of fracture failures in aviation equipment are fatigue fractures (Suárez *et al.*, 2019; Sun *et al.*, 2018). Therefore, extensive research has been conducted to demonstrate the impact of surface integrity on the fatigue performance of components. Regarding the indicators of surface integrity, reducing surface processing defects, increasing surface residual compressive stress and moderately increasing the surface hardness can suppress crack initiation and prolong the fatigue life of specimens (Doremus *et al.*, 2015; Han *et al.*, 2022; Madariaga *et al.*, 2022; Novovic *et al.*, 2004).

Li *et al.* (2023a) noted that ultrasonic-assisted abrasive belt-ground (UAABG) optimized the surface texture, reduced surface roughness, increased residual compressive stress and microhardness and promoted the formation of surface deformation layers in Inconel 718. Compared with conventional abrasive belt-ground (CABG), UAABG improved fatigue performance by 14.3–74.8% (Figure 8).

Research has shown that when processing titanium-alloy fatigue specimens, high-speed ultrasonic vibration cutting (HUVC) can achieve higher surface microhardness, residual



Source(s): Error bars denote the standard deviation
Li *et al.* (2023a)

Figure 8.
Fatigue life of grinding samples

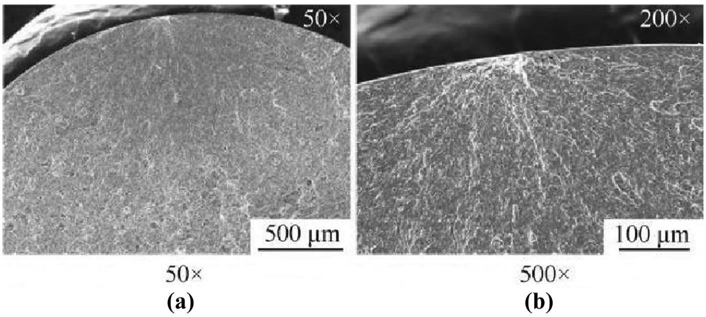
compressive stress and a thicker microstructure deformation layer than conventional cutting (CC). According to tensile fatigue tests, compared to CC, the fatigue life of specimens obtained by HUVC can be increased by 10.4 times. After fatigue fracture analysis, it is evident that the fatigue crack source in CC is on the surface of the specimen, whereas the fatigue crack source in HUVC is on the subsurface of the specimen (as shown in Figures 9 and 10) (Li *et al.*, 2020).

Xue *et al.* (2021) found that rotated ultrasonic milling improved the surface quality of C/SiC composite materials, reduced defects such as fiber cracks and pits and suppressed the growth of fatigue fiber cracks in room-temperature environments. The accumulation of damage, first stress redistribution and fiber reinforcement stage were all delayed, and the damage rate decreased by approximately 31–80%. Figure 11 shows the fatigue test results. After the fatigue test, the residual tensile strength of the sample improved, reaching 95.8% of the original tensile strength.

Yin *et al.* (2023) conducted fatigue tests on nickel-based superalloys using ultrasonic peening milling (UPM) and conventional milling (CM) and found that UPM significantly extended the fatigue life of the specimens. Compared with CM, the average life of the UPM milled specimens increased by 16.12 times (Figure 12). After fatigue fracture analysis, it was observed that unlike CM, the fatigue crack source was present at a depth of 640 μm from the machined surface, and the stress concentration and surface defects reduced after processing.

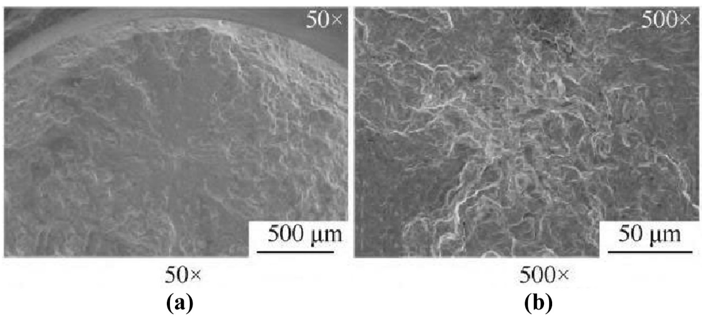
3.2 Wear resistance

Wear is an extremely important failure process. In industrial production, approximately 23% of the energy is wasted on overcoming friction (Perry and Tysoe, 2005). Statistically, by



Source(s): Li *et al.* (2020)

Figure 9.
Fatigue crack source in conventionally machined samples

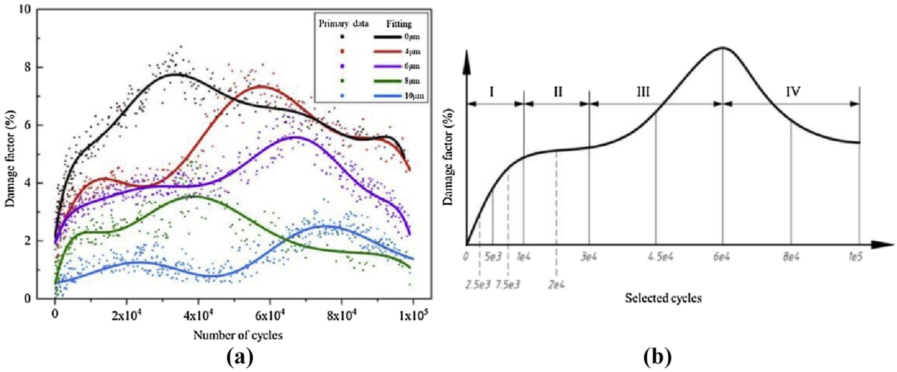


Source(s): Li *et al.* (2020)

Figure 10.
Fatigue crack source in high-speed ultrasonic vibration machined samples

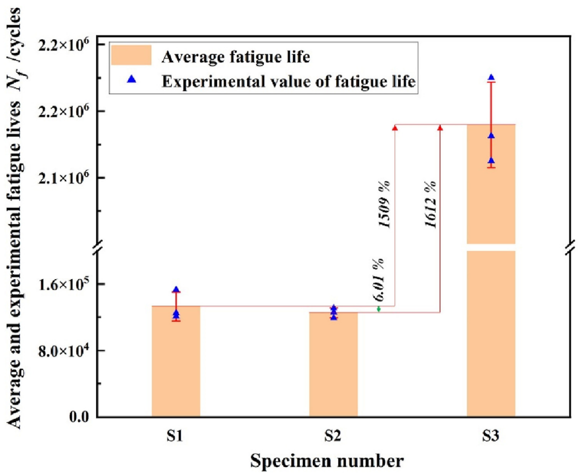
improving new technologies to reduce wear and friction in various industrial processes, economic benefits equivalent to 1.4% of the global gross domestic product (GDP) can be achieved (Yi *et al.*, 2021). Therefore, understanding and improving the wear resistance of key components is particularly important to enhance safety, energy savings and economic benefits in the aviation industry. During the machining process, the microstructure of the material undergoes certain changes and the contact surface of the metal undergoes plastic deformation. In addition, the surface integrity of the material affects its wear resistance Peng *et al.* (2023a). In recent years, researchers and engineering technicians have started studying the wear mechanism and material characteristics, continuously optimizing and improving processing methods and parameters to enhance the wear resistance of advanced aerospace materials.

Peng *et al.* (2023b) studied the effect of HUVC conditions on the surface integrity and wear behavior of titanium alloys. Compared with CC, HUVC achieved a thicker plastic deformation layer, higher surface residual compressive stress and microhardness and lower surface



Source(s): Xue *et al.* (2021)

Figure 11. Fatigue test results: (a) damage parameters of the 1st test; (b) damage stages of the C/SiC composite fatigue process and node selection



Source(s): Yin *et al.* (2023)

Figure 12. Average and experimental fatigue life results for different nickel superalloy specimens

roughness. In addition, experiments found that HUVC reduced the friction coefficient and wear volume loss by 20.98–25.59%, effectively improving the wear resistance of titanium alloys (Figure 13).

When processing superalloys, compared with conventional side milling (CSM), longitudinal-torsional ultrasonic vibration side milling (LTUVSM) has been found to result in better surface quality, a maximum reduction of 23.4% in surface roughness and higher microhardness and residual compressive stress (Chang *et al.*, 2024). In addition, after LTUVSM, the superalloy exhibited enhanced dislocation accumulation and grain boundary fracture, resulting in complete grain refinement and a 7.3% decrease in the average grain diameter. The refinement of the internal grains improved the mechanical properties of the material surface, thereby enhancing its wear resistance. Figure 14 shows the sliding-wear friction coefficient waveform and its variation.

To improve the service and processing performance of parts, Chang *et al.* (2023) systematically studied the surface quality and wear resistance of a GH4169 superalloy under CSM and LTUVSM conditions. LTUVSM significantly reduced tool wear and improved surface machining quality. Meanwhile, the regular ultrasonic vibration texture suppressed the friction and growth of the contact nodes in the contact area, reducing the degree of surface wear. The maximum reductions in the friction coefficient and extent of wear were 18.2 and 15.8%, respectively (Figure 15).

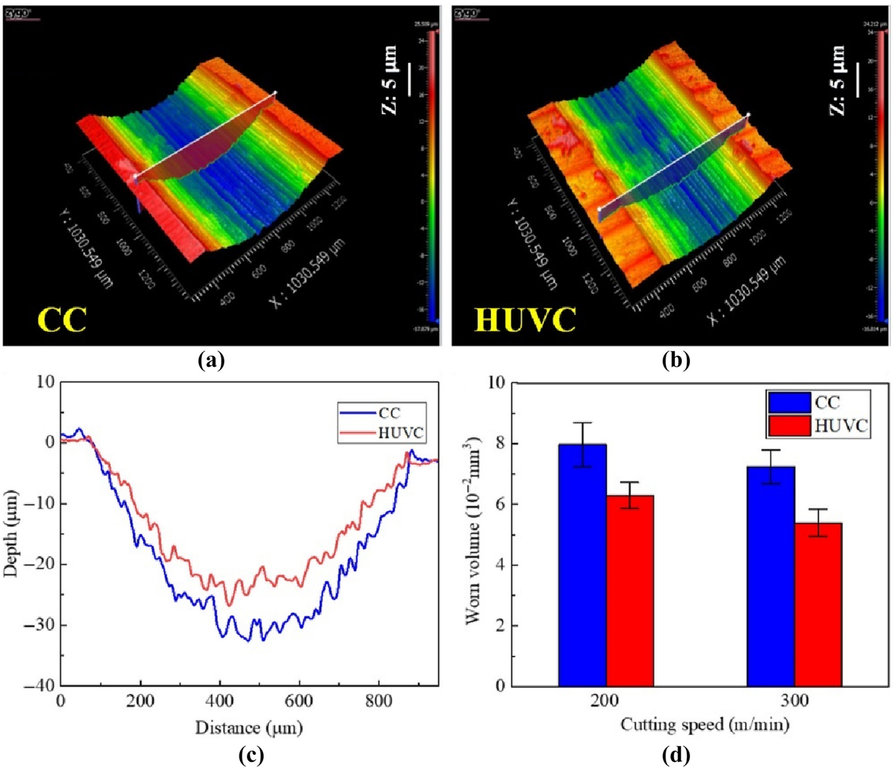


Figure 13.
3-D topography of wear tracks in (a) CC and (b) HUVC-machined samples; (c) cross-sectional profile curves at a cutting speed of 200 m/min; (d) variation of the worn volume with cutting speed for the two machining processes

Source(s): Peng *et al.* (2023a)

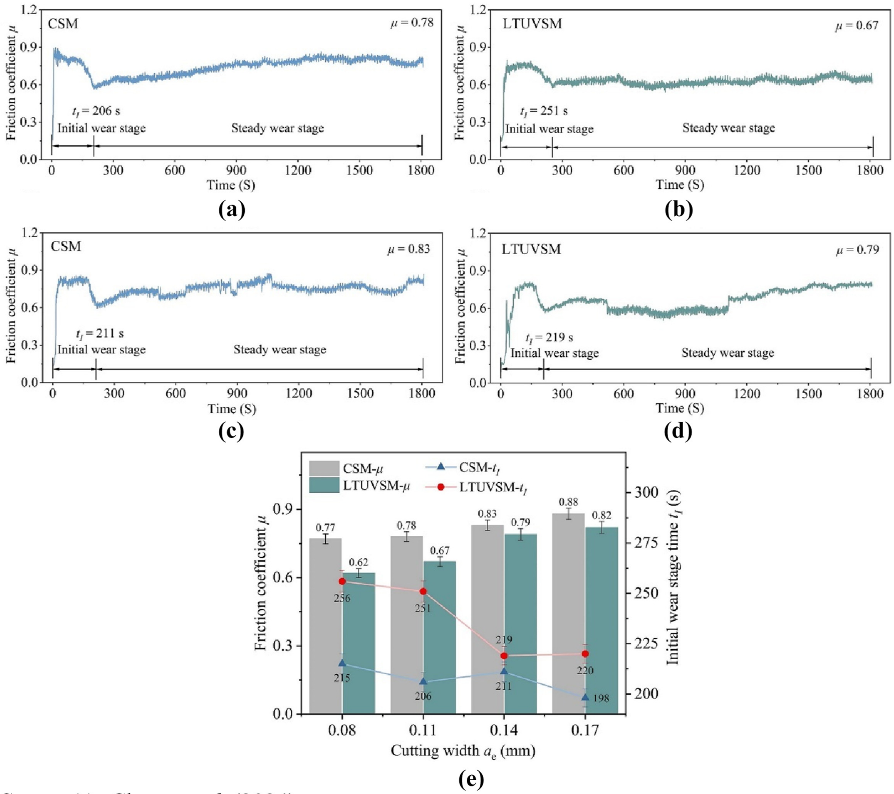


Figure 14. Sliding-wear friction coefficient waveform and variation: (a) a_e = 0.11 mm, CSM; (b) a_e = 0.11 mm, LTUVSM; (c) a_e = 0.14 mm, CSM; (d) a_e = 0.14 mm, LTUVSM

Source(s): Chang *et al*. (2024)

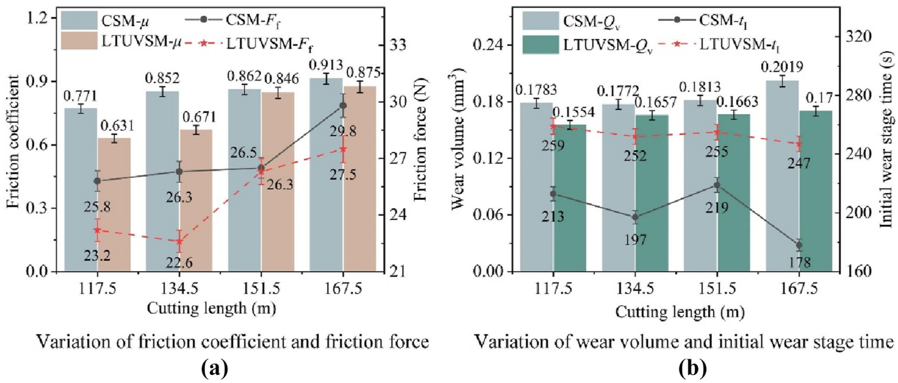


Figure 15. Variation of wear resistance characterization parameters

Source(s): Chang *et al*. (2023)

Wang *et al.* (2024) conducted multidimensional ultrasonic vibration-assisted machining (MDUVM) of titanium alloys. They noted that, compared to conventional machining (CM), MDUVM introduced more impact energy, achieving deep grain refinement and a 10.9%

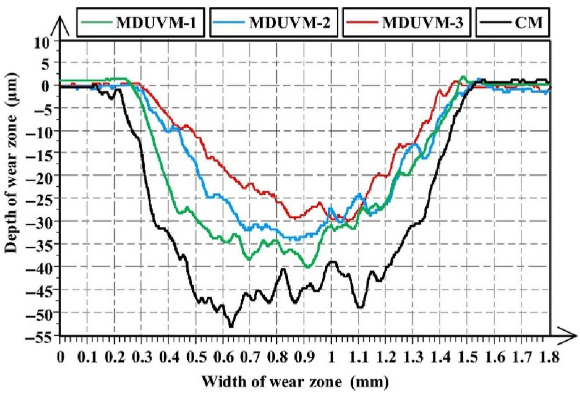
increase in surface hardness. After friction and wear testing, the average friction force on the surface of the MDUVM specimens decreased by 15.6%, and the average friction coefficient decreased by 23.4%. Smooth wear contours and reduced oxidation of wear fragments helped reduce the wear depth. Figure 16 shows the profile of the wear zone on the MDUVM and CM surfaces. In addition, after MDUVM processing, the uniformly distributed microstructure on the surface of the titanium alloy was conducive to the uniform distribution of surface pressure, improving the surface hardness and reducing material peeling.

3.3 Corrosion resistance

Corrosion is a phenomenon in which the properties of a metal change through chemical or electrochemical interactions with its environment, resulting in damage or deterioration. During the machining process, local changes may occur on the material surface that can adversely affect its functional use (Mishurova *et al.*, 2021). Surface defects caused by machining can promote corrosion. Therefore, poor surface integrity combined with corrosive environments can lead to the premature failure of components (Okorokov *et al.*, 2018; Zhang *et al.*, 2023a). Furthermore, in certain situations (such as in the aviation industry), the failure of critical components may lead to catastrophic consequences. Therefore, exploring the relationship between surface integrity and corrosion resistance of workpieces is particularly important for improving the performance, safety and reliability of aviation equipment.

In recent years, corrosion-resistant coatings on the surfaces of metallic materials have been widely used in practical industrial environments. Although this is a practical solution, it cannot be applied to professional applications, and its high cost makes it unaffordable in certain situations. In such cases, the surfaces of metallic materials are directly exposed to corrosive environments, exacerbating their functional failure (Turnbull *et al.*, 2011). Therefore, ensuring high corrosion resistance of metallic materials is particularly important, and it is necessary to improve the processing methods and parameters to enhance the corrosion resistance of the workpiece.

Rui *et al.* (2015) studied the influence of surface roughness on the corrosion resistance of titanium alloy and inferred that an increase in surface roughness not only increased the activity of dislocations, but also made the material more susceptible to corrosion. However, when the surface roughness was high, the micro-surface area involved in the corrosion reaction increased, leading to accelerated corrosion. Moreover, as the surface roughness increased, the probability of forming microcracks was greater, and the potential difference between peaks and valleys increased, which amplified the possibility of pitting corrosion.



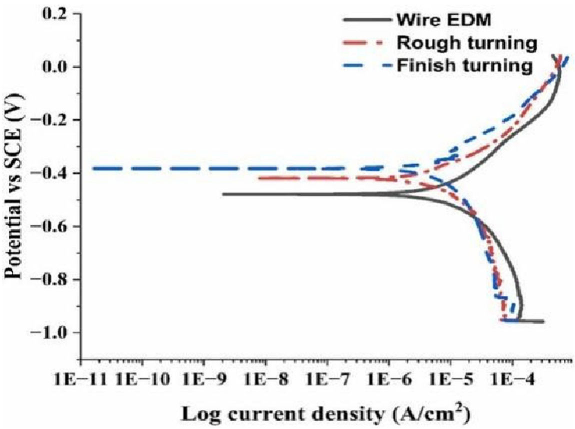
Source(s): Wang *et al*. (2024)

Figure 16.
Profile of the wear zone on the MDUVM and CM surfaces

Okorokov *et al.* (2018) investigated the effect of residual stress on the corrosion resistance of machined surfaces and found that residual compressive stress helped to close surface defects and increased electron escape work, thereby improving the corrosion resistance, whereas residual tensile stress had the opposite effect.

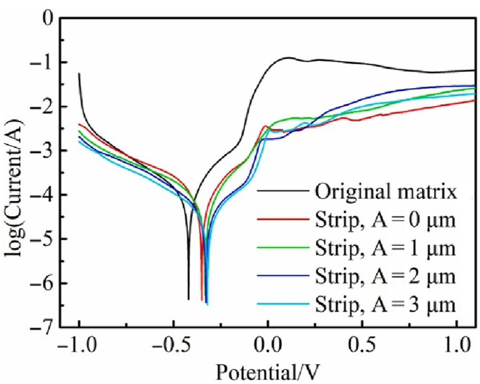
Sreejith *et al.* (2023) investigated the effect of machining operations on the corrosion performance of tungsten heavy alloys (Figure 17). They studied the effects of three different machining operations (wire electrical discharge machining (EDM), rough turning and finish turning) on the corrosion performance. It was found that the corrosion current on the rough turning surface was the highest, followed by wire EDM; and the finish-turning surface. A higher corrosion current led to a higher corrosion rate. Compared to finish-turning surfaces, more machining defects and higher surface roughness increased the corrosion rate of the surface after rough turning and wire EDM.

Wang and Niu (2023) investigated the effects of ultrasonic vibration extrusion cutting (UVEC) on the corrosion performance of materials at different amplitudes. As the amplitude increased, the equivalent strain, equivalent strain rate and degree of grain refinement of the material gradually increased. Figure 18 shows the Tafel curves of the original matrix and



Source(s): Sreejith *et al.* (2023)

Figure 17. Potentiodynamic polarization curves of the surfaces



Source(s): Wang and Niu (2023)

Figure 18. Tafel curve of the original matrix and strip in 5% NaCl solution

strip in a 5% NaCl solution. The electrochemical corrosion test showed that with an increase in ultrasonic amplitude, the electrochemical parameters were improved. Additionally, the corrosion resistance of the samples prepared by UVEC was significantly improved compared to the original matrix.

4. Unique advantages of UVC during machining of advanced aerospace materials

4.1 Suppressing burrs when machining metallic materials

Advanced metallic materials (superalloys, titanium alloys and ultrahigh-strength steels) are widely used in the aviation industry because of their superior properties compared to conventional materials. However, their unique characteristics also seriously affect their processing performance. With advancements in technology, the precision requirements for aviation microparts are becoming increasingly high. Advanced metallic materials may encounter problems that affect the surface accuracy and processing efficiency during the machining process, such as surface burrs and residual tensile stress (Gao *et al.*, 2021). In industry, measures such as changing cutting tools, selecting appropriate machining parameters and using appropriate cooling methods are commonly used to improve machining quality and efficiency. However, their implementation is difficult (Lin and Shyu, 2000; Ma *et al.*, 2005; Ni *et al.*, 2019; Zhang *et al.*, 2023d). UVC, as a special machining technology, has significant advantages in the processing of advanced metallic materials that are difficult to machine. Multiple studies have shown that UVC can significantly reduce the cutting force and cutting temperature, extend the tool life, remove or reduce machining defects and improve the machining surface quality (Chang and Bone, 2005; Fang *et al.*, 2021; Takeyama and Kato, 1991).

Fang *et al.* (2021) found that the ratio of feed rate per tooth to the cutting edge radius is a key factor affecting burr thickness in ultrasonic vibration-assisted micro-milling (UVAMM) of nickel-based superalloys. Within the range of size effects, compared with traditional micro-milling (TMM), UVAMM suppressed burrs and chip deposits, thereby significantly improving the machining quality and milling process (as shown in Figure 19).

Gao *et al.* (2021)investigated the effect of longitudinal torsional ultrasound-assisted vibration drilling (LTUAVD) on microhole drilling. They found that reducing the spindle speed and amplitude reduced the height of the burrs when drilling titanium alloys. In addition, compared to conventional microdrilling (CD), LTUAVD reduced the burr height by 33.4–44.9%. Figure 20 shows the burr morphologies of the microholes in CD and LTUAVD.

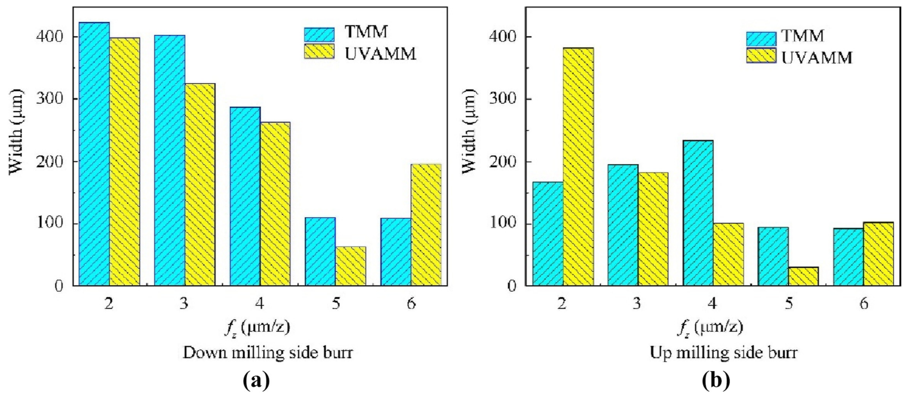
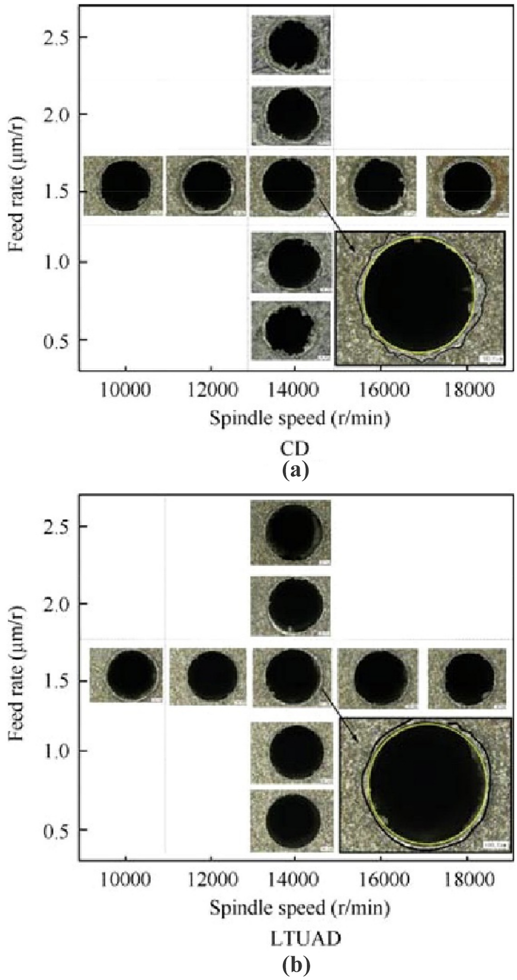


Figure 19. Change in burr size with TMM and UVAMM

Source(s): Fang *et al.* (2021)

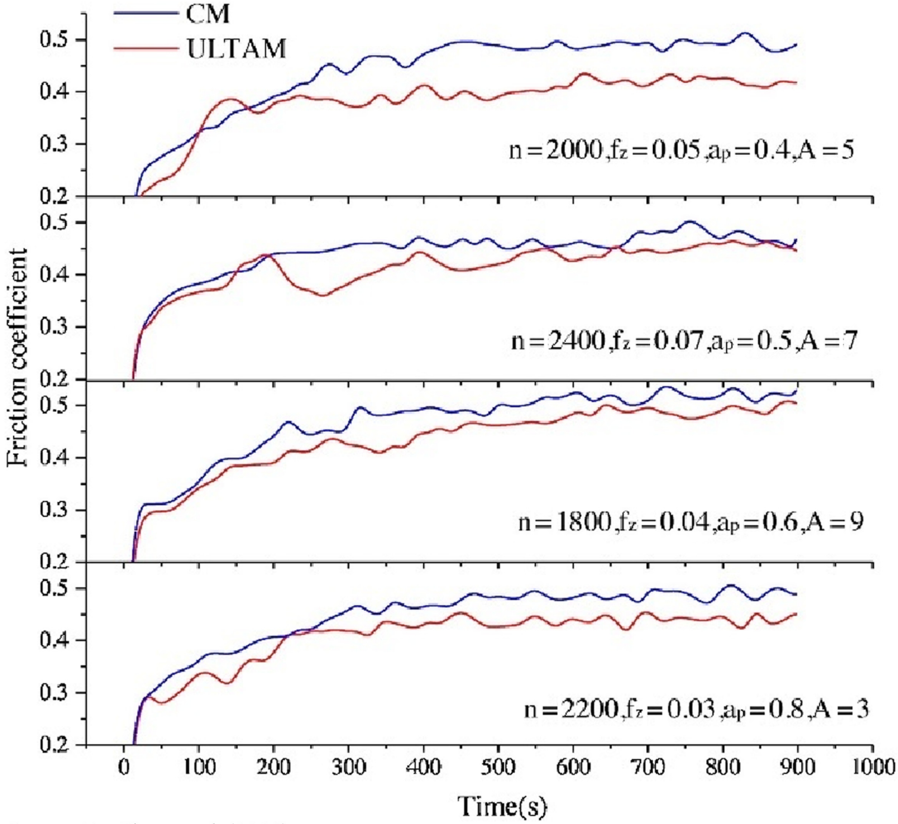


Source(s): Gao *et al*. (2021)

Figure 20. Burr morphology of microholes

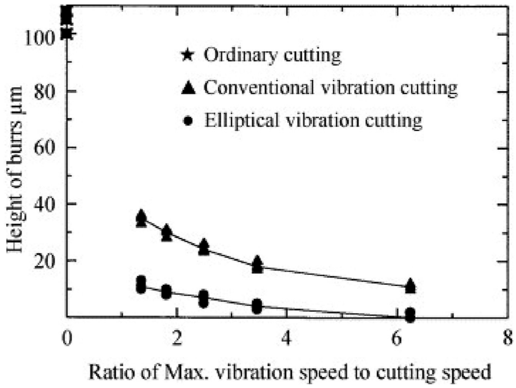
Research has shown that during ultrasonic longitudinal-torsional assisted milling (ULTAM) of titanium alloys, the longitudinal amplitude produces surface ironing and trimming effects, whereas the torsional amplitude transforms continuous cutting into intermittent cutting. During the process of contact and separation between the tool and workpiece, the ultrasonic longitudinal and torsional amplitudes act simultaneously, reducing the formation of scratches and burrs and thereby improving the surface quality after machining (Figure 21). Simultaneously, the characteristics of intermittent cutting in ULTAM improve the machining environment, effectively reduce the cutting force and tool wear and thereby suppress the generation of scratches and burrs (Chen *et al.*, 2020).

Ma *et al.* (2005)compared the effects of three cutting methods (ordinary cutting, conventional vibration cutting (CVC) and elliptical vibration cutting (EVC)) on the formation of burrs (Figure 22). The height of the burrs generated in CVC and EVC was reduced compared to ordinary cutting. As the ratio of the maximum vibration speed to the cutting



Source(s): Chen *et al*. (2020)

Figure 21.
Surface friction and wear test of CM and ULTAM machined surfaces



Source(s): Ma *et al*. (2005)

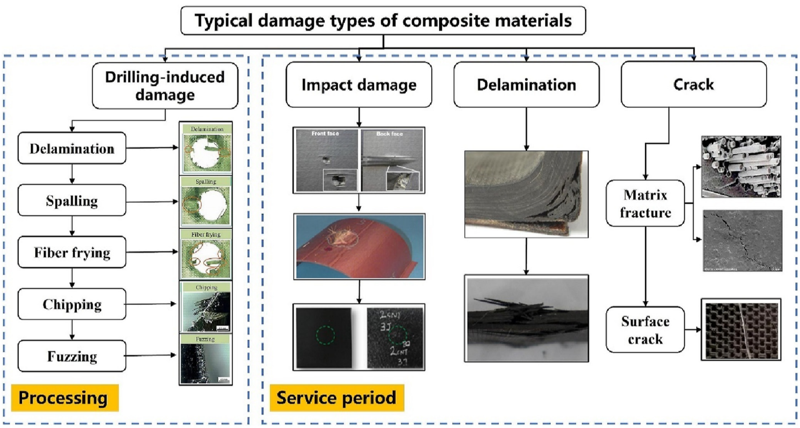
Figure 22.
Height of burrs resulting from three cutting methods

speed increased, the height of the burrs decreased. In addition, compared to CVC, EVC had the lowest average thrust stress and average bending stress in the deformation zone of the workpiece edge when burrs were formed, which effectively suppressed burrs.

4.2 Reducing damage when machining composites

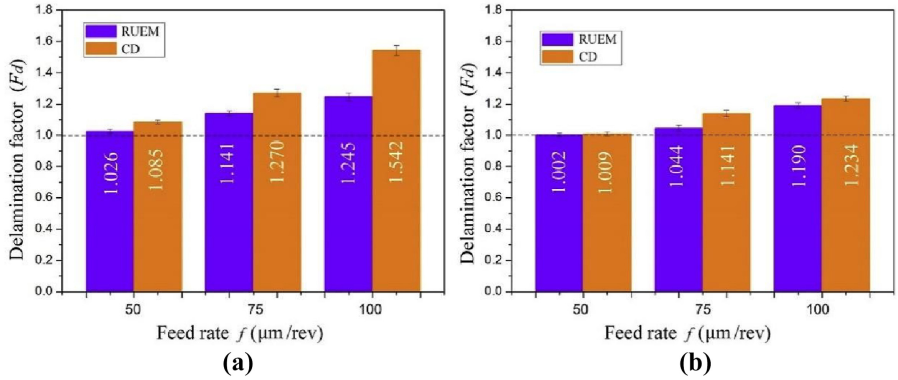
With the increasing usage of composite materials in aviation equipment manufacturing, it is crucial to consider and study their behavior and failure during aircraft structural damage. Damage to advanced composite materials is likely to occur during manufacturing and processing (Yang *et al.*, 2023b). As shown in Figure 23, the typical types of damage include drilling-induced damage, impact damage, delamination and cracking. Owing to the heterogeneity, anisotropy and hardness of composite materials, the common damage morphologies caused by drilling include delamination, spalling, fuzzing, fiber frying and chipping (Feito *et al.*, 2014). Surface failures can seriously threaten the safety and stability of aviation equipment, which has prompted researchers to conduct studies continuously to eliminate or mitigate them. For example, when using traditional machining tools to process CFRPs, typical issues related to precision machining and surface integrity are often encountered. The occurrence of various types of faults, such as delamination, spalling, fuzzing and fiber-frying chipping, ultimately leads to the abandonment of numerous workpieces (Geng *et al.*, 2020; Liu *et al.*, 2021; Xie *et al.*, 2022). According to previous reports, the scrap rate of aircraft components due to layering-related failures in the aircraft industry is as high as approximately 60%. Therefore, adopting reasonable processing methods and techniques to improve processing quality has become the key to the widespread application of composite materials.

Geng *et al.* (2020) found that the main factors that inhibited delamination in rotating ultrasonic elliptical machining (RUEM) of CFRPs were as follows: (1) the thrust force was significantly reduced, (2) the tearing shear effect caused by chip removal was significantly reduced, effectively alleviating delamination propagation and (3) the sharpening of the cutting edge and the increase in cutting speed accelerated the occurrence of fiber fracture during the drilling process. As shown in Figures 24 and 25, compared with conventional drilling effects, the delamination coefficient of the 1/2 layer in RUEM was reduced by 5.4–19.3%. The layering coefficient of the 2/3 layer decreased by 0.7–8.4%, achieving lower layering damage and higher processing efficiency.



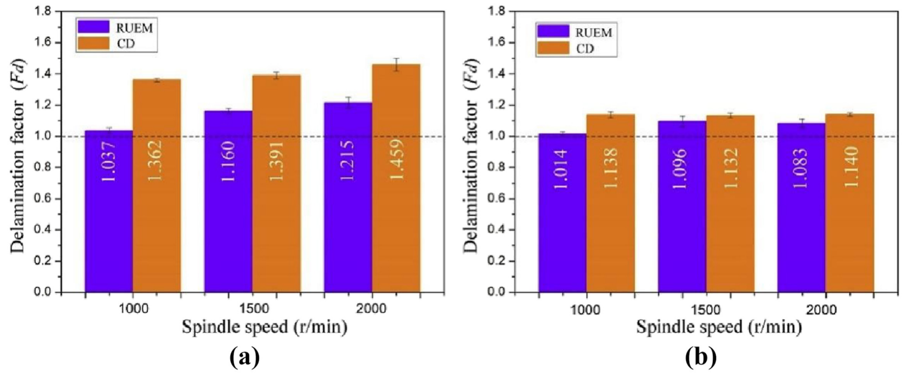
Source(s): Yang *et al.* (2023b)

Figure 23. Typical damage types of composite materials



Source(s): Geng *et al*. (2020)

Figure 24. Delamination factor at the hole exit between the (a) 1/2 plies and (b) 2/3 plies with respect to the feed rate



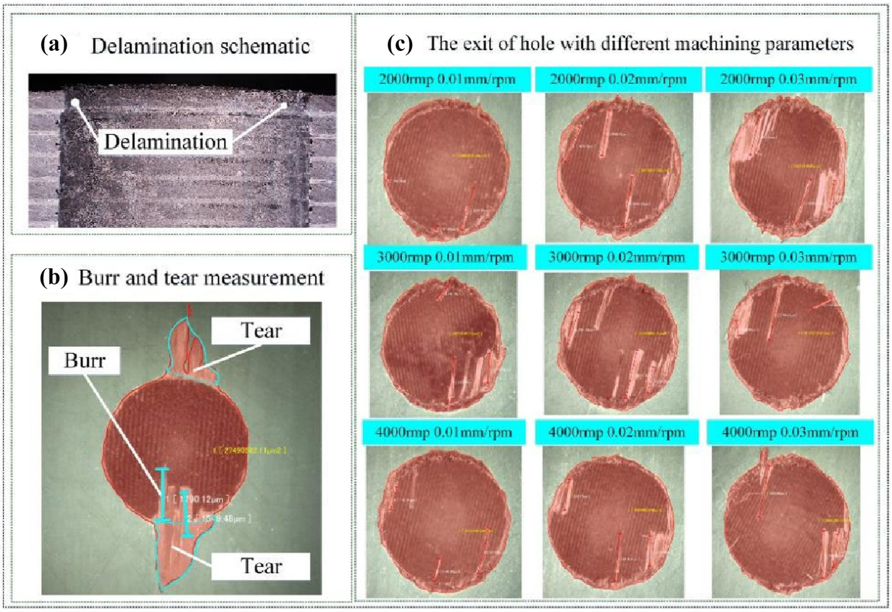
Source(s): Geng *et al*. (2020)

Figure 25. Delamination factor at the hole exit between the (a) 1/2 plies and (b) 2/3 plies with respect to the spindle speed

Liu *et al.* (2021) examined longitudinal torsion-coupled-rotation ultrasonic-assisted drilling (LTC-RUAD) of CFRPs. Compared with conventional drilling (CD), when the spindle feed rate Sf was 0.01 mm/rev, the spindle speed Sr was 4,000 rpm, the minimum burr coefficient, tear coefficient and delamination coefficient were 0.021, 0.011 and 0.054, respectively. The damage factors decreased by 62.56, 76.6 and 69.67%, respectively. The comprehensive coefficient decreased by approximately 66.77%. Figures 26 and 27 show the damage defects using CD and LTC-RUAD, respectively.

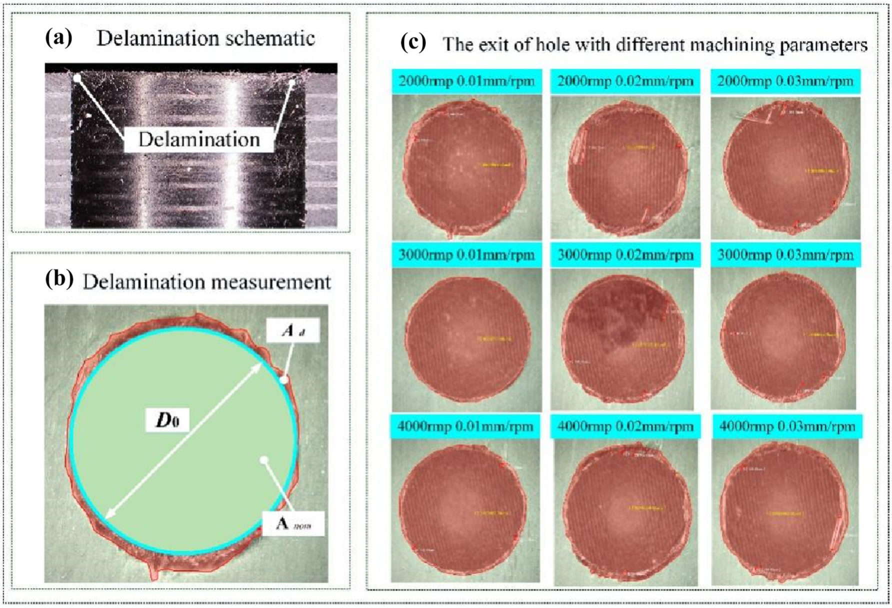
Research has shown that longitudinal-torsional ultrasonic vibration milling (LTUVM) can significantly improve the processing quality of aramid fiber-reinforced plastics and reduce the length of burrs and subsurface damage. Compared with CM, after LTUVM, the burr length of aramid fiber-reinforced plastic was observed to reduce by 23–38%, fiber compression deformation was reduced and crack propagation was suppressed (Figure 28) (Xu *et al.*, 2021).

To alleviate the limitations of using C/SiC composites in industrial applications, Xie *et al.* (2022) improved the machining quality of C/SiC composites using longitudinal ultrasonic vibration-assisted side milling (LUVASM). Figure 29 shows the fiber debonding depth under various amplitudes. The shear stress of carbon fiber increased with the friction reflection angle



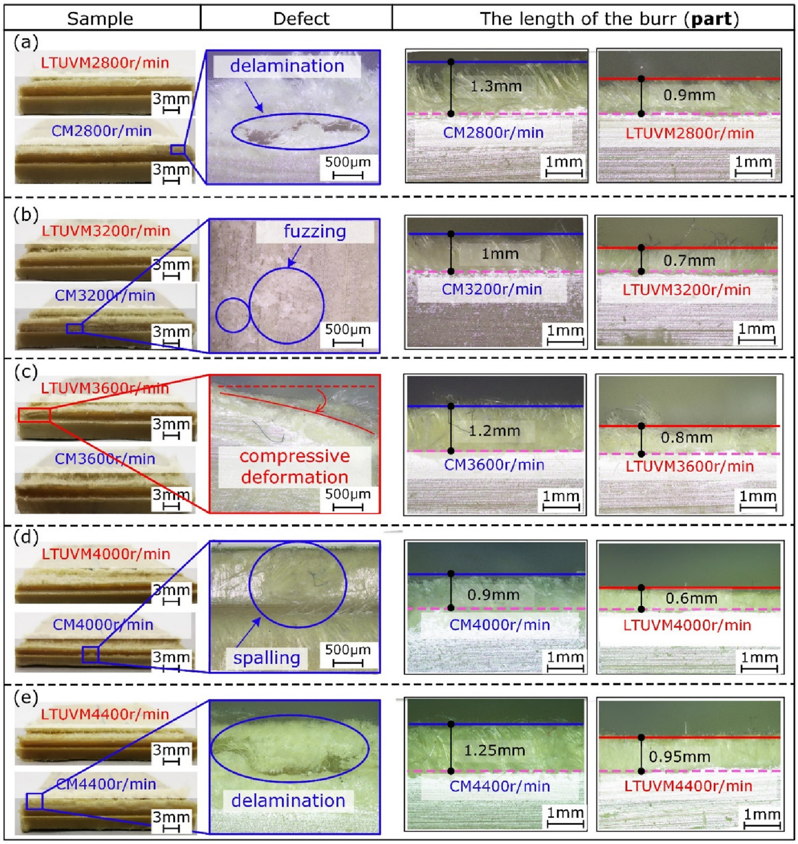
Source(s): Liu *et al*. (2021)

Figure 26.
Damage defects using CD



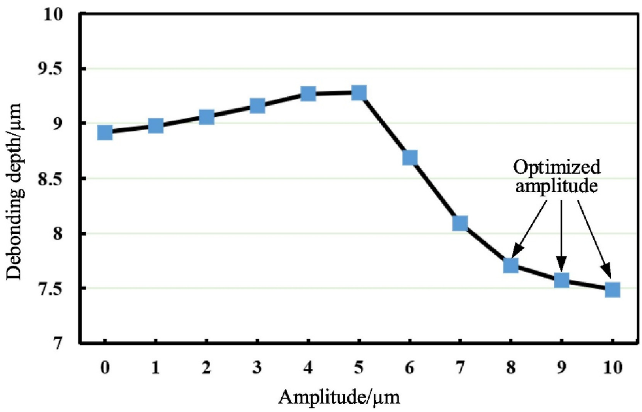
Source(s): Liu *et al*. (2021)

Figure 27.
Damage defects using LTC-RUAD



Source(s): Xu *et al*. (2021)

Figure 28.
Comparison of machining quality after CM and LTUVM for spindle speeds (a) 2,800 r/min, (b) 3,200 r/min, (c) 3,600 r/min, (d) 4,000 r/min and (e) 4,400 r/min



Source(s): Xie *et al*. (2022)

Figure 29.
Fiber debonding depth under various amplitudes

or matrix dynamic modulus due to longitudinal ultrasonic vibration, further inhibiting the debonding damage of carbon fiber. In addition, after LUVASM, the surface roughness of the C/SiC composite materials was reduced by up to 40%, effectively suppressing debonding damage to the carbon fibers and significantly reducing the number of voids on the processed surface.

5. Conclusions

In this review, we elaborated on the characteristics and applications of advanced aerospace materials, highlighted current research on the effect of UVC on the in-service functional performance of advanced aerospace materials and described developments related to its unique processing advantages. The main findings are as follows.

(1) Advanced metal aerospace materials are widely used owing to their unique mechanical properties. For example, nickel-based superalloys have good heat resistance, plasticity, high-temperature oxidation resistance and corrosion resistance and are widely used in turbine blades and discs of turbine engines. The primary advantages of titanium alloys are their low density, good high-temperature performance, high specific strength, high corrosion resistance, creep resistance and good compatibility. They are typically used in low- and high-pressure compressors. Ultrahigh-strength steels have significant advantages in terms of hardenability, tempering and softening ability, wear resistance and corrosion resistance and are commonly used in aviation engine bearings, landing gear and other key components.

(2) Composite materials exhibit characteristics such as high specific strength, high specific stiffness and fatigue resistance. Their application and development are important for significantly improving the efficiency, comfort and environmental friendliness of aircraft structures. With the advancement of synthesis technology and usage experience, the use of composite materials such as CFRPs, MMCs and CMCs has been increasing annually. CFRPs are widely used in the skin of aircraft main frames and fuselage/wings. MMCs are commonly used in the relay pistons of gas turbine engines, aircraft fuselage, wings and fan guide blades. CMCs are widely used in high-temperature parts of aviation equipment and are expected to replace high-temperature alloys in thermal components in aviation engines in the future.

(3) Improving the in-service functional performance (fatigue resistance, wear resistance and corrosion resistance) of aircraft components is crucial to ensuring their stability and safety. Numerous studies have demonstrated that UVC can effectively improve the service performance of parts.

UVC can significantly increase the microhardness and residual compressive stress on the surface of the workpiece, promote the formation of subsurface deformation layers and help improve the fatigue life. Through fatigue testing, the fatigue life has been found to be significantly improved and fatigue cracks are distributed on the subsurface of the specimen. When processing composite materials, UVC can significantly improve the surface quality, reduce defects such as fiber cracks and pits and suppress the growth of fatigue fiber cracks.

In terms of wear resistance, UVC can improve the surface microhardness, residual compressive stress and surface deformation layer of the workpiece. At the same time, it helps to refine the internal grains, improve the surface mechanical properties and enhance wear resistance. In addition, after ultrasonic processing, the regular ultrasonic vibration texture on the surface also helps to improve wear resistance.

Excellent machining surface quality contributes to improved corrosion resistance. Corrosion tests have shown that UVC can improve the corrosion resistance of workpieces, which increases with increasing amplitude.

(4) Ultrasonic vibration machining can effectively remove and suppress defects such as burrs, scratches and chip deposits in metallic materials after processing. When processing composite materials, various types of damage such as delamination, spalling, fuzzing, fiber frying and chipping often occur. UVC effectively improves the processing quality of composite materials by removing or reducing the occurrence of processing defects such as delamination, palling, fuzzing, fiber frying and burrs.

6. Possible future directions

(1) Advanced UVC devices

With recent breakthroughs in UVC theory and devices, the application of UVC to advanced aerospace materials has become increasingly widespread. However, owing to the difficulties in material processing and the limitations of ultrasonic devices, problems still arise in controlling the ultrasonic system during processing. For example, the conditions for improving the electromechanical conversion efficiency of ultrasonic systems and the methods for stabilizing the working frequency near the resonant frequency during machining remain unresolved. In the future, transducers with high electromechanical conversion efficiency and high-power output and generators with self-tracking resonant frequencies should be incorporated into ultrasonic systems to improve processing quality and efficiency.

(2) Complex UVC objects

Ultrasonic machining is widely used for machining advanced aerospace materials. With the development of the materials industry, UVC has broad application prospects for advanced materials that are extremely difficult-to-machine (such as powder superalloys, intermetallic compounds and nickel-based single-crystal alloys).

(3) UVC theory

Breakthroughs have been achieved regarding the cutting method and cutting characteristic theory of ultrasonic machining. However, the effects of ultrasonic machining on the surface integrity of the workpiece and the mechanism of crystal phase transformation of the subsurface layer have not been fully elucidated. Therefore, in the future, researchers should continue to explore the strengthening mechanism of ultrasonic machining on the serviceability of components so that production practices can be guided to achieve excellent in-service functional performance.

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