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Aerospace Composites, their Structural Properties, and their Impact on Future Supersonic Flight: A Review

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ABSTRACT: With new advancements and discoveries, composite materials have recently become a major option in material selection for modern aircraft. Their lightweight and durable properties make them more highly regarded in comparison to standard aerospace materials, such as alloys. However, with the renewed focus on supersonic transports (SSTs), it is important to consider whether the properties of composites are superior to those of aerospace metals under supersonic conditions. Numerous studies have been conducted on certain composites, such as those by Parveez, Bisma, *et al*. and Lakshmikanthan, Avinash, *et al*. Other works have reviewed considerations for supersonic aircraft design as well, including the work by Huda, Zainul, and Prasetyo Edi. These results have allowed composites to be widely used in the aerospace industry today. This article connects the two topics by focusing on the structural properties of composite materials and the airframe of aircraft. It reviews our current technology in composites, before analyzing these findings to determine its potential use and impact on supersonic flight. Their superior properties, such as their ability to handle higher stresses, allow them to be a viable option for future SSTs despite certain limitations regarding performance at higher speeds. It was concluded that SST operators should consider operating with stricter maintenance protocols for SSTs with current composite technology. Additionally, engineers should also research more advanced matrix and reinforcement materials as well as matrix-reinforcement combinations to enhance the structural performance of composites for this application. The results found in this paper are for future engineers working with supersonic aircraft to help advance their decisions in picking materials.

KEYWORDS: Materials Science, Composite Materials, Structural Materials, Supersonic Flight, SST.

Introduction

As the supersonic travel industry grows and the demand for lighter and more durable aerospace materials intensifies, composite materials stand out to be one of the best solutions.

For the past 80 years, the traditional material for aircraft structures has been aluminum. Its properties, such as its resistance to high temperatures and damage, have made it the material of choice. Nevertheless, with the development of high-performance composites, such as carbon-fiber-reinforced polymers (CFRPs), the use of aluminum on aircraft parts has decreased drastically.[1,2]

Composite materials are materials that combine a matrix and reinforcement material and allow properties to be tailored.[3,4] Composites are not new in the aerospace industry however, they were first introduced to fighter aircraft in the mid-60s to early-70s, such as the F-14, but their use was primarily only on certain parts of the aircraft, such as the rudders and speed brakes.[3] Soon, composites were utilized in certain parts of commercial aircraft as well, but their airframe still consisted mostly of aluminum alloys.[3] As development progressed, composites slowly took over aluminum. Modern commercial aircraft now contain up to around 80% composite materials as seen on the Boeing 787.[2]

Depending on their matrix material, composites are classified into three categories, metal-matrix composites (MMCs), ceramic-matrix composites (CMCs), and polymer-matrix composites (PMCs).[4] Each category of composites has its own advantages and is used for different parts of aircraft.

These advanced composites can strongly impact the developing supersonic transport (SST) industry and help overcome challenges faced by engineers in the past, such as economic concerns.[5,6] Extensive research has already been done on current composite technology, for example, Parveez, Bisma, *et al*. and Lakshmikanthan, Avinash, *et al*. both cover the unique properties of composite materials. Huda, Zainul, and Prasetyo Edi. Along with many others have also covered the topic of material performance in supersonic flight. Nonetheless, no direct research specifically on composite material performance on SSTs has been found. This gap could be attributed to the relatively recent resurgence of SSTs or the possibility that studies relating to this topic are classified. Without a clear and accessible connection between the two subjects, future engineers entering the SST industry may overlook the potential benefits of composite materials in supersonic applications.

The scope of this paper includes the airframe structure of aircraft as well as the structural factors one must be aware about. The paper first discusses factors one must take into consideration when selecting materials for SSTs and performs a case study on Concorde in order to explain why these factors may be more relevant in supersonic flight than subsonic flight. Then, the article reviews the current advancements made in composite materials. This paper concludes by looking at what challenges composites may still face and will face in supersonic conditions.

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Material Considerations for Supersonic Flight:

Commercial supersonic flight is not a new concept. There have been examples of success and failures in the past, including the European Concorde as well as the Soviet Tupolev TU-144. But these projects were developed nearly 60 years ago and newer technologies, such as advanced composite materials, have been developed since then. However, before these materials can be implemented, there are numerous structural factors specific to SSTs that must be taken into consideration.

Supersonic means speeds faster than the speed of sound, more specifically, a Mach number greater than one,[5,7] while subsonic refers to speeds slower than the speed of sound.[7] A range also lies between the two, called transonic, where the Mach number is between 0.8 and 1.2.[7] Figure 1 shows the different categories of speed depending on the Mach number.

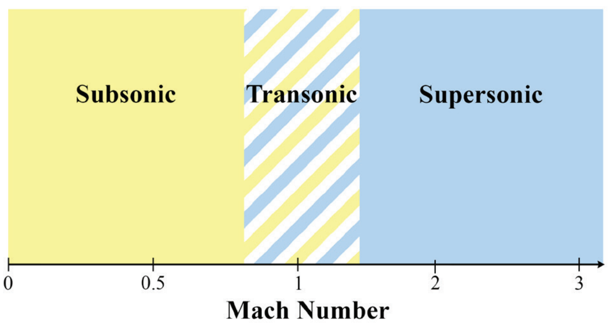

Figure 1: Mach number regime ranges: Subsonic, Transonic, and Supersonic zones. Subsonic speeds are slower than the speed of sound, while supersonic speeds exceed it. The transonic range, with Mach numbers between 0.8 and 1.2, lies between the two.

When it comes to comparing supersonic and subsonic flight, there are vast differences. The surface of the aircraft experiences more extreme conditions at supersonic speeds, as seen in the Concorde during its cruise at Mach 2.[8] For example, the surface temperature is significantly higher in supersonic flight than subsonic flight.[8] From this information, it is important that the materials selected can provide sufficient thermal performance and long-term durability while in operation for the structure. Supersonic and subsonic airflow differs greatly as well,[5] but with this paper's focus on airframe structures and materials, the aerodynamics of supersonic flight are out of scope.

Discussion

Thermal Performance:

The temperature of an aircraft's surface is significantly higher in supersonic flight than in subsonic flight due to kinetic heating.[5,9] As seen in Table 1, an aircraft traveling at Mach 2 can face temperatures of up to 100°C. When considering thermal performance, it is not only important to be aware of the immediate effects of exposure to high temperatures, but it is also important to be aware of the effects caused by long-term exposure to these temperatures.[8,9] For modern-day materials, including composites, temperatures of 100°C and up are well within their operational range,[10] but handling these temperatures for long periods can cause coatings and structural materials to degrade as well as worsen the damaging effects of flight condition exposure, such as deformation and stress accumulation.[5]

Table 1: Aircraft skin temperatures at various speeds.5 As the Mach number increases, the surface temperature of the aircraft increases at an accelerating rate, exceeding 100°C past Mach 2. These temperatures can affect a material's performance, particularly in its long-term durability and structural integrity.

Speed (Mach number)	Surface Temperature (°C)
2.0	100
2.5	150
3.0	200
3.5	300

Thermal expansion is a well-known issue related to exposure to higher temperatures in materials. Temperatures vary between parts of the aircraft, for example, more heat is generated at the nose than the main fuselage.[5,8] This variation causes different parts of the structure to expand more than others, increasing the thermal stresses on the airframe.[8] When it comes to composite materials, thermal expansion can lead to damage, such as delamination and matrix cracking.[11] Studies on a composite's performance in these conditions have been conducted and show that composite materials can present issues with degradation as well, which are covered later in the paper.[11]

A material's durability properties can also be impacted when exposed to higher temperatures for a long duration of time. Huda, Zainul, *et al*. describe two past experiments done on the hardness of aluminum alloys as they were exposed to a range of temperatures. While both presented slightly different results, one concluded that the rate of softening decreases as temperature decreases while the other concluded that the rate of softening decreases as temperature increases, both results agreed that as the alloy was exposed to high temperatures for long periods of time, their hardness values decreased.[8] Tests on composite materials have shown similar results when exposed to a heated blanket for a duration of time,[11] which will be detailed later in the paper.

Durability:

Thermal stresses already play a large role in affecting a material's durability properties. On top of that, materials on SSTs will also face other operating stresses, including environmental stresses caused by weather, such as hail, ice, sand, etc., and aerodynamic stresses.[5,6] Similar to a material's resistance to heat, mentioned above, most aerospace materials are already capable of handling these conditions, thus, engineers focus their selection of materials based on the duration they can handle within these environments.[9]

Generally, the probability of a structural failure is higher among supersonic aircraft than subsonic aircraft.[6] Some factors that played a role in this investigation include mean stress level and load spectrum.[6] The most common stresses that aircraft structures tend to face include tension, compression, bending, and torsion.[5]

Three variables that can be used to compare materials to predict their performance under these stresses include the ultimate tensile strength (UTS), the elongation at break percentage, and Young's modulus.[5] These variables were picked as they can be used to describe the strength, ductility, and ability to handle deformation. The UTS, which is the maximum stress a material can handle before breaking while being stretched or pulled,[12] of common aluminum alloys, such as the 2000 and 7000 series alloys, range from approximately 465 MPa to 575 MPa, while the UTS of a standard modulus CFRP ranges from 3,450 MPa to 4,830 MPa.[5]

However, CFRPs have an elongation at break percentage, which describes a material's ability to handle deformation without damage,[13] in the range of 1.5-2.2%,5 while aluminum alloys have a percentage in the range of 6-12.3%.[5] The combination of a high UTS and low elongation at break percentage means CFRPs are more brittle and rigid.[3] For this reason, composite materials are more prone to significant damage when it comes to debris impact.[3] The higher speeds of supersonic flight causes the debris to collide with the surface at a higher velocity with a greater extent when compared to subsonic flight. A method to test the effect of this is the high-velocity impact test.[3] The procedures and results of this test on composite materials are described later in the paper. But a more brittle material may be necessary for faster travel. A trend has been discovered that a higher Young's modulus (E), or elastic modulus, which represents the stiffness of a material,[14] indicates that a material is more suitable for higher Mach speeds.[5] A stiffer material can prevent fatigue by resisting dynamic stresses, such as compression.[6]

Despite CFRPs being a more suitable option due to its rigidity, the possibility of damages can lead to more frequent maintenance checks and higher costs, a significant factor when it comes to selecting materials. However, this paper focuses on the technical and structural aspects of aerospace materials and does not address the economic considerations.

Past Example: Concorde:

Concorde was an SST developed by Britain and France that could cruise up to Mach 2.[8,9] Due to its fast cruise speed, the main material selected for the airframe was the Hiduminium-RR58 aluminum alloy developed by High Duty Alloys.[9,15] This alloy consisted of mainly aluminum, but also had copper, magnesium, iron, and nickel in small quantities.[9] For materials to be applicable on Concorde, it was decided that the material had to handle 20,000-30,000 hours of service at temperatures of 120-150°C.[9] Previous work with the RR58 in the Whittle jet engine of the Gloster Meteor aircraft has shown that the alloy is capable of providing sufficient creep resistance, which refers to a material's ability to withstand continuous deformation under load, in temperatures of up to 250°C in short durations.[14] One solution to improve its long-term temperature resistance was to have a 0.18-0.25% silicon content.[9,15] Another issue with the RR58 alloy was its relatively poor corrosion resistance. To protect the material, an aluminum 1% zinc alloy cladding was used.[9,15] Homogenization in the manufacturing process also slightly improved the creep resistance of the RR58.[9]

Table 2, which shows the UTS of the alloy decrease as it is exposed to higher temperatures, along with the other solutions that engineers have developed, shows the significance of the factors mentioned before when it comes to designing SSTs. Additionally, Table 2 shows that the strength of the RR58 alloy is similar to more modern aluminum alloys, mentioned above, due to their similar UTS. Given how the alloy performed at supersonic speeds, the higher UTS of CFRPs can provide benefits, such as improved long-term fatigue resistance, while also being a lighter material in general, which can improve the fuel efficiency of the aircraft.[16]

Table 2: Ultimate tensile strength (UTS) of RR58 in various forms exposed to temperature for 1,000 hours.[9] Prolonged exposure at high temperatures results in a lower UTS for RR58 and modern aluminum alloys. The higher UTS of CFRPs can offer longer lifespans in high-temperature environments.

Temperature (°C)	Ultimate tensile strength of Forged Bar (MPa)	Ultimate tensile strength of Extruded Bar (MPa)
20	400	411
150	342	364
200	223	243

Composite Materials:

Newer aircraft, such as the Boeing 787, are beginning to use composite materials in their structures. Their superior properties, such as their high strength-to-weight ratio, make them stand out from the traditional metals used on aircraft.[5]

Composites have two fundamental parts, the matrix and the reinforcement. The matrix material is continuous and provides rigidity and resistance to its surroundings. The matrix covers the reinforcement material, which is discontinuous and provides the strength and stiffness properties of the composite.[3,17] Figure 2 summarizes the relationship between the two using resin as the matrix and fibers as the reinforcement. One of the advantages of using composite materials is that they can tailor properties or produce new properties that neither material has.[3] Some of the properties that can be improved in composites include strength, weight, thermal conductivity, wear resistance, and fatigue life.[3]

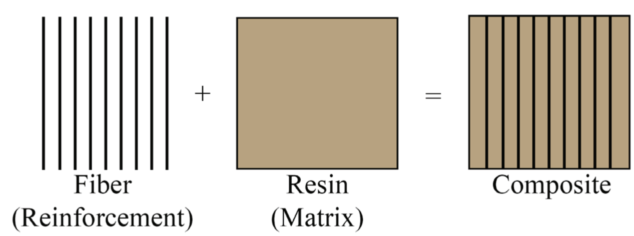

Figure 2: Formation of a composite material (e.g. CFRP) by combining reinforcing fibers (eg. carbon fiber) and a resin matrix (e.g. epoxy). The interaction between the reinforcement and matrix material allows for tailoring of properties, such as the strength and weight of the final composite.

Depending on the matrix material, composites are organized into three categories, metal-matrix composites (MMCs), ceramic-matrix composites (CMCs), and polymer-matrix composites (PMCs).[4] The reinforcement material also helps organize these composites based on their chemical nature, which includes oxides, carbides, and nitrates, and their shape, including continuous fibers, short fibers, whiskers, and particulates.[17]

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MMCs have a metal as its matrix material and are well known for their high wear resistance.[4] Common metals used for its matrix include aluminum, magnesium, titanium, copper, nickel, and steel.[4] CMCs, on the other hand, utilize ceramics as their matrix material, including $ZrBr_2$, HfB_2, and oxides.[1] CMCs are recognized to be able to handle extremely high operating temperatures with low thermal expansion and have high compressive strength, chemical inertness, and hardness as well as relatively low weight.[1,4] Lastly, PMCs feature polymers as their matrix material and are known for their high specific strength shown in Figure 3.[1]

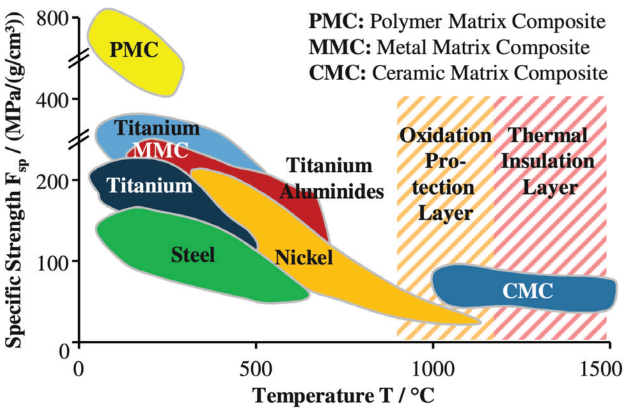

Figure 3: Specific strength of materials as a function of temperature.[10] PMCs exhibit a higher specific strength than MMCs and CMCs, which results in stronger and lighter material. PMCs are desirable in applications where strength and weight are critical.

While both MMCs and CMCs possess desirable properties, CMCs suffer from poor fracture toughness and both MMCs and CMCs have inferior specific strength when compared to PMCs, despite having a much higher temperature resistance seen in Figure 3. MMCs are mainly found on aircraft wings, landing gears, and engines while CMCs are mainly found on aircraft brakes, turbine blades, and other high temperature areas.[1] Considering the use of CMCs and MMCs, additional exploration outside of this research is necessary for these categories.

Polymer Matrix Composites (PMCs):

PMCs are the main composite materials found on the airframe of aircraft.[1] They are also known as fiber-reinforced polymers (FRPs) and resin-based polymers (RBCs).[3] Along with the extremely high specific strength that PMCs have displayed in Figure 3, their low cost and simple manufacturing processes make them stand out from other options.[1]

Common PMC matrix materials are resins, such as polymers, polypropylene, polylactic acid (PLA), epoxy, and silicone.[1] They are reinforced by fibers, including carbon fibers, glass fibers, and ramie fibers, as well as nanoparticles.[1,4] The most common combination of matrix and reinforcement materials found on the airframe of aircraft is epoxy as the matrix and carbon fiber as the reinforcement. This combination is also known as CFRP.[1]

The 787 Dreamliner is a good example of CFRPs in use on commercial aircraft. 80% of it is composed of composite materials, and the most abundant composite found on its airframe are CFRPs, with glass-fiber-reinforced polymers (GFRPs) being used on impact-sensitive areas, such as the nose.[3] The properties of CFRPs and GFRPs on the 787 made the aircraft lighter and simpler, allowing for more efficiency by reducing fuel consumption and weight-based maintenance and fees. When compared to traditional metallic materials, the higher resistance toward corrosion and fatigue on CFRPs has decreased maintenance times and increased aircraft flight time.[11]

There are several simple manufacturing methods of PMCs. When deciding which method to proceed with, one must take into consideration the final shape of the composite, the reinforcement material, the geometry and proportions of the reinforcement, as well as the nature of the interface between the reinforcement and matrix to ensure that the final product's structural properties will match the requirements of its intended use.[1]

The laying prepreg process is when a prepreg, a material where a fiber, such as carbon fiber, is pre-impregnated with an uncured thermosetting or thermoplastic resin, is cut into an appropriate size and placed into an open mold. Activation from temperature is then required to cure the resin.[1] This process has been used for aerospace applications in the past, including producing CFRP parts for the Boeing 757, 767, and Airbus A310.[16]

Resin transfer molding (RTM) is a closed mold method. RTM is capable of producing large and complex 3D parts with improved properties, small dimensional tolerances, and a high surface finish. In this process, a mold made of two halves is used, and the cavity between the two halves defines the shape of the part. The thickness of the part is determined by the space between the halves. First, the lamination sequence, which acts as the reinforcement, is placed on one half of the mold. The mold is then closed and resin, the matrix material, is injected through a gate under pressure until the resin reaches the vent, impregnating the reinforcement. The gate is then closed for the resin to cure. Finally, the part is removed from the mold. RTM is a method useful in multiple aerospace applications due to its high quality and low cost.[1,16]

Injection molding involves fiber composites in particle form being fed through a hooper before being transported by a screw with a heated barrel. Once complete, the screw injects the material into a mold before cooling. This procedure produces high-quality parts with a low cycle time, but there are numerous defects that the final product may have, such as flow marks and weld marks.[1]

Compression molding has similar benefits. A backing made of prepreg is placed between two molds and is compressed into its desired shape. However, this method is mostly used in the automobile industry.[1]

Pultrusion is often used for fast-curing resins. Resin-impregnated fibers are passed through a mold continuously at a certain speed to mold and cure the composite.[1] If the final composite part can be directly obtained from the resin matrix and reinforcement, pultrusion is another cost-effective method.[16]

All of these methods have their benefits along with their disadvantages. Some have a longer production time but results in higher quality while some may be quicker and cheaper but require lower standards. It is important to consider what the final product and the budget are before deciding the specific manufacturing process.

Challenges:

While composites possess many benefits, a couple of their properties can present issues while in service, especially in supersonic flight. These properties include their durability and thermal performance.

The strength properties of composite materials can pose issues in operation and maintenance. Zimmermann, Natalie, and Peng Hao Wang describe that in a previous experiment conducted by Maolli, the three main causes for failures in composites are the same as those in metallic structures, including improper design, improper manufacturing, and improper use of the product.[18] Brittleness in composite materials can pose an issue in their resistance toward debris and stress. Metals can absorb energy in the elastic and plastic region, but composites mainly only absorb energy in the elastic region.[3] While metals can be plastically deformed, composites would become damaged at that point.

Low and high-velocity impact tests can simulate how these materials can react to projectiles and debris at different speeds. Low-velocity impact tests are meant to simulate events that occur within the 1-10 m/s range, such as dropped tools during maintenance or collisions with service cars or cargo. Tools used to simulate these conditions can include pendulums, drop towers, and drop weights.[3] High-velocity impact tests simulate events that may include runway debris impact during takeoff, hail, and even bird strikes. In this test, a powder gun or a single-stage light-gas gun is used to fire a projectile.[3]

The three main modes of failure shown in these tests are matrix cracking, delamination, and fiber failure.[3] Both matrix cracking and delamination are not visible to the naked eye.[3,18] Matrix cracking is, as the name suggests, when the matrix material of a composite experiences cracking. These cracks occur parallel to the fibers and do not have any immediate impact on the material, though issues such as decreased shear and compression strength can arise if the cracks are left undetected and untreated.[3,18] Delamination forms between layers of laminates and is one of the most damaging forms of failure.[3,18] Delamination and other internal damage modes reduce the affected area. It can pose significant issues in performance if the area is not further looked into.[18] Multiple methods of detecting these damages have been proposed, including an X-ray CT scan, which is said to be the most accurate way of detecting the distribution of delamination and matrix cracks.[11] On the other hand, composites that have experienced matrix cracking, along with other external damage modes, such as dents, do not require immediate attention as they do not have any immediate effect on the material.[18] The last mode of failure for composite fiber failures. Fiber failure refers to the failure of the reinforcement material and can include multiple different types, such as fiber pull-out and breaking of the fiber.[18]

Traditionally, methods used to repair composites that have suffered damage from debris included resin patches, resin injections, and heat plates.[1] However, these methods require continuous damage monitoring and are only used if the damage is detected, meaning they are not effective for repairing less visible modes of damage, such as matrix cracks. A more advanced solution is self-healing composites. These composites incorporate hollow glass fibers (HGFs) infused with uncured resin. Upon impact, such as when debris strikes the surface, these fibers burst, releasing the resin to fill and repair the damage. After testing, it was determined that this solution would be able to repair and restore the material to 97% of its original undamaged performance.[1]

Thermal performance can pose challenges as well as it can cause materials to degrade. For matrix materials, when temperatures exceed the glass transition temperature (T_g), about 100°C for resins, it can soften the epoxy even when temperatures decrease and also create a higher risk of thermal decomposition at high temperatures in the future.[11] For the reinforcement material, carbon fiber in this case, the oxidative effect produced by a heated resin causes the fibers to decompose faster.[11] A solution for this can be to use fibers with a higher graphite degree since they can provide more oxidative resistance.[11]

Furthermore, exposure to higher temperatures can impact the performance and durability of these composite materials. Juon, Pang Hee, *et al*. mention that in a research conducted by Armstrong-Carroll *et al.*, the flexural strength, which describes a material's ability to resist deformation under load,[12] of a CFRP component dropped by 304 MPa and the Rockwell hardness value, which represents how well a material can resist penetration, dropped by 24 after 5 and a half minutes of being exposed to a heated blanket, which was heated to 370°C, displayed in Table 3.[11] While these temperatures are not relevant in today's commercial aircraft, since they typically have surface temperatures in the negatives in Celsius,[11] the surfaces of SSTs and supersonic aircraft can increase to above 100°C,5 where these numbers can become more relevant, despite not being to the same extent depending on the selected cruise speed.

Table 3: CFRP mechanical properties after exposure to a 370°C heated blanket.[11] As time exposure increases, flexural strength, and Rockwell hardness values decrease, increasing the risk of deformation and penetration. A similar trend can be expected at lower temperatures, such as those experienced in supersonic flight.

Time (s)	Flexural Strength (MPa)	Rockwell Hardness
0	435	73
80	453	84
140	450	82
200	434	73
260	414	69
280	373	68
295	414	82
315	182	54
335	131	49

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Conclusion

This paper demonstrates that the properties of composite materials can benefit the designs of future SSTs, albeit with certain limitations. Due to the differences between supersonic and subsonic flight, it was first determined that thermal performance and durability were two large factors that would affect the performance of a supersonic aircraft's structure. After reviewing current composite material technology, including PMCs and their specific manufacturing processes, potential issues that may arise during operation were discovered among composite materials. These included significant damage modes due to their rigid nature that would be difficult to identify during maintenance and degradation from thermal exposure.[11,18] However, it was acknowledged that the rigidity of composite materials does make composites more suitable for higher operational speeds.[5] Given the current composite technology discussed in this paper, CFRPs remain a strong candidate for SST design. Nonetheless, to address the issues mentioned before, future SST operators should consider using current CFRP technology with stricter maintenance protocols to detect damage modes, such as matrix cracking and delamination, to ensure that SSTs operate safely and efficiently. Alternatively, SST design could also benefit from further research on advanced resin matrices, fiber reinforcements, as well as optimized matrix-reinforcement combinations that could enhance the structural performance of PMCs. Additionally, further research done on different properties of composite materials can allow SSTs to benefit from the well-known advantages of composites such as their lightweight, which can lower fuel consumption and weight-based maintenance time and cost.[11] Using a similar approach as this paper, future research on materials for different parts of SSTs, such as the wings and engines, and different perspectives, including the economic and aerodynamic considerations, can further aid development in the industry.

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References

1. Parveez, B.; Kittur, M. I.; Badruddin, I. A.; Kamangar, S.; Hussien, M.; Umarfarooq, M. A. Scientific Advancements in Composite Materials for Aircraft Applications: A Review. *Polymers* **2022**, *14* (22), 5007. https://doi.org/10.3390/polym14225007.
2. Boyer, R. R.; Cotton, J. D.; Mohaghegh, M.; Schafrik, R. E. Materials Considerations for Aerospace Applications. *MRS Bulletin* **2015**, *40* (12), 1055–1066. https://doi.org/10.1557/mrs.2015.278.
3. Safri, S. N. A.; Sultan, M. T. H.; Yidris, N.; Mustapha, F. Low Velocity and High Velocity Impact Test on Composite Materials – A Review.
4. Lakshmikanthan, A.; Angadi, S.; Malik, V.; Saxena, K. K.; Prakash, C.; Dixit, S.; Mohammed, K. A. Mechanical and Tribological Properties of Aluminum-Based Metal-Matrix Composites. *Materials* **2022**, *15* (17), 6111. https://doi.org/10.3390/ma15176111.
5. Huda, Z.; Edi, P. Materials Selection in Design of Structures and Engines of Supersonic Aircrafts: A Review. *Materials & Design (1980-2015)* **2013**, *46*, 552–560. https://doi.org/10.1016/j.matdes.2012.10.001.
6. Fischler, J. E. Design Considerations for a Supersonic Transport. *SAE Transactions* **1964**, *72*, 659–665.
7. Chapter 15 - Compressible Flow. In *Fluid Mechanics (Fifth Edition)*; Kundu, P. K., Cohen, I. M., Dowling, D. R., Eds.; Academic Press: Boston, 2012; pp 729–778. https://doi.org/10.1016/B978-0-12-382100-3.10015-0.
8. Huda, Z.; Zaharinie, T.; Min, G. J. Temperature Effects on Material Behavior of Aerospace Aluminum Alloys for Subsonic and Supersonic Aircraft. *Journal of Aerospace Engineering* **2010**, *23* (2), 124–128. https://doi.org/10.1061/(ASCE)AS.1943-5525.0000015.
9. Doyle, W. M. The Development of Hiduminium-RR.58 Aluminium Alloy: The Background to the Choice of the Main Structural Material for Concorde. *Aircraft Engineering and Aerospace Technology* **1969**, *41* (11), 11–14. https://doi.org/10.1108/eb034573.
10. Klocke, F.; Zeis, M.; Klink, A.; Veselovac, D. Experimental Research on the Electrochemical Machining of Modern Titanium- and Nickel-Based Alloys for Aero Engine Components. *Procedia CIRP* **2013**, *6*, 368–372. https://doi.org/10.1016/j.procir.2013.03.040.
11. Juon, P. H.; Saeedipour, H.; Goh, K. L. Chapter 12 - Thermal Damage in Carbon-Fiber-Reinforced Polymer Composites: A Critical Review. In *Composite Materials*; Low, I.-M., Dong, Y., Eds.; Elsevier, 2021; pp 285–305. https://doi.org/10.1016/B978-0-12-820512-9.00021-6.
12. Pal, T.; Pramanik, S.; Verma, K. D.; Naqvi, S. Z.; Manna, P. K.; Kar, K. K. 6 - Fly Ash-Reinforced Polypropylene Composites. In *Handbook of Fly Ash*; Kar, K. K., Ed.; Butterworth-Heinemann, 2022; pp 243–270. https://doi.org/10.1016/B978-0-12-817686-3.00021-9.
13. Djafari Petroudy, S. R. 3 - Physical and Mechanical Properties of Natural Fibers. In *Advanced High Strength Natural Fibre Composites in Construction*; Fan, M., Fu, F., Eds.; Woodhead Publishing, 2017; pp 59–83. https://doi.org/10.1016/B978-0-08-100411-1.00003-0.
14. Budynas, R. G.; Nisbett, J. K. *Shigley's Mechanical Engineering Design*, 9th ed.; McGraw-Hill series in mechanical engineering; McGraw-Hill: New York, 2011.
15. Buttler, T. Forging For Excellence The Story of High Duty Alloys, 1928 to 2000.
16. Matsui, J. Polymer Matrix Composites (PMC) in Aerospace. *Advanced Composite Materials* **1995**, *4* (3), 197–208. https://doi.org/10.1163/156855195X00014.
17. Garg, P.; Jamwal, A.; Kumar, D.; Sadasivuni, K. K.; Hussain, C. M.; Gupta, P. Advance Research Progresses in Aluminium Matrix Composites: Manufacturing & Applications. *Journal of Materials Research and Technology* **2019**, *8* (5), 4924–4939. https://doi.org/10.1016/j.jmrt.2019.06.028.
18. Zimmermann, N.; Wang, P. H. A Review of Failure Modes and Fracture Analysis of Aircraft Composite Materials. *Engineering Failure Analysis* **2020**, *115*, 104692. https://doi.org/10.1016/j.engfailanal.2020.104692.

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