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Exploring the Impact of Composite Material Fires and Associated Response Protocol on the Material Analysis During an Aircraft Accident Investigation

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Introduction

Metals, beginning in the 1930s, have been frequently used as the material of choice for aircraft construction (Hallion, 1978; Jakab, 1999). Common metals used in the aviation industry range from alloyed and heat-treated aluminum to titanium, magnesium, and superalloys, the latter used in specialized applications (Hallion, 1978; Mouritz, 2012). Nevertheless, a shift in aircraft construction – specifically in terms of the materials used – began in the 1970s, as composite materials were introduced into commercial aircraft (Mouritz, 2012). Among others, the increased use of composited materials was – and still is – propelled by the ability to manufacture comparative lightweight and aerodynamically shaped components and structures that allow for reduced fuel costs while simultaneously retaining excellent strength and performance characteristics (Gopal, 2016; Hadcock, 1998; Haresceugh et al., 1994; Kassapoglou, 2013). However, safety is a crucial factor in aviation, and as such, critically impacts material choices. Therefore, when selecting materials to use for aircraft construction, both, design parameters – such as weight and strength – as well as safety elements – including failure modes and characteristics – are to be considered (Mouritz, 2012). When applied to the shift to composite materials evidenced in the aviation industry, it is crucial to also understand how the comparatively new materials will behave in the event of a failure or when damaged, such as in an aircraft accident.

Accident Investigation Process

An aircraft accident provides compelling evidence of hazards and failures within the aviation system. A well conducted aircraft accident investigation process should identify all causal and contributing factors of a mishap as well as provide effective safety recommendations to enhance aviation safety. Thus, the aircraft accident investigation process is a pillar for the continuous development of the aviation industry. As defined by the International Civil Aviation Organization (ICAO), the primary – and only – purpose of an aircraft accident investigation process is to prevent future aircraft accidents and incidents (ICAO, 2020). To this end, the investigation process follows an organized, systematic and methodological approach, focused on the identification of the causal factors of the aircraft accident under consideration (ICAO, 2011). Specifically, the accident investigation process can be divided into the following three phases, each with a distinct focus: data collection, data analysis and presentation of findings (ICAO, 2011). As the name indicates, the first phase – data collection – is centered around the gathering of applicable information and evidence, an ongoing process throughout the investigation. The second phase – analysis of data – is conducted in tandem with the data collection phase, both complementing each other. The third phase – presentation of findings – completes the accident investigation process by outlining the information obtained and corresponding conclusions drawn based on the previous two phases (ICAO, 2011). The investigative findings obtained and the conclusion of the investigation process are ultimately used to formulate safety recommendations, such as preventive actions, with the goal of increasing safety and preventing aircraft accidents (ICAO, 2020).

Composite Materials and Aircraft Accident Investigation

With a specific focus on aircraft accidents as well as accident-related elements and investigations, certain characteristics, properties, and behaviors of composite materials may present challenges that require further consideration. For instance, depending on the specific circumstances, an aircraft accident investigation may require an in-depth analysis of the structural materials to determine failure modes. Per ICAO (2012), a so-called *Structures Group* can be formed – depending on the details of each accident – to analyze, among others, airframe structural failures. Furthermore, once the on-site/field phase of an aircraft accident investigation is completed, select structures and the respective failures may require further analysis in a laboratory setting to determine the exact causal factors and failure modes (ICAO, 2012). However, a crucial factor to consider during the post-accident, laboratory analysis of failed composite-based structures is that composite materials and the associated structures present different – more complex – failure modes than traditional, long-established aircraft metals (Stumpff, 2001a). The importance and criticality of understanding the failures of composite materials, especially in aircraft structures, are illustrated by American Airlines (AA) Flight 587, the first commercial accident involving a composite-based structural failure in flight. In the case of AA Flight 587, the added complexity of composite material failures coupled with the comparative novelty of the materials and the resulting reduced volume of literature in the field of fracture and failure analysis added a further obstacle to the accident investigation process (Fox et al., 2005).

Composite Aircraft Fires

In addition to presenting further complications during the material analysis steps of an accident investigation process, composite materials also introduce health hazards to aircraft accident investigators and first responders. Similar to other materials under combustion, composite materials release smoke to, and reduce the content of oxygen in, the atmosphere, subsequently worsening the surrounding air quality (Vajdová et al., 2019). Furthermore, ICAO (2012) lists composite materials alongside with other potential hazards present at an accident investigation site such as oxygen system components, batteries, and fuels. Specifically, common materials and chemicals used for composite aircraft construction – including carbon, aramid fibers, fiberglass, and epoxies – may release noxious gases or small fragments, presenting respiratory hazards when damaged or upon burning (Australian Transport Safety Bureau [ATSB], 2008). A range of organizations, institutions, and authors have recommended and enumerated guidelines and protective steps to control and reduce the hazards presented by composite fire byproducts, respectively. Common examples include, among others, wearing specific personal protective equipment (PPE) together with filtering respirators and biohazard suits (ATSB, 2008; ATSB & Directorate of Defence Aviation and Air Force Safety [DDAAFS], 2017), and containing the release of dangerous substances by extinguishing the fire and through the application of hold-down or fixant solutions (Olson, 1994; United States Army Combat Readiness Center [USACRC], 1996).

A specific area to focus on, in terms of fires in composite-based aircraft components and structures, include aircraft engines, as they commonly employ composite-based structures for the construction of engine blades, cowlings, nacelles, and pylons (ATSB, 2008). Furthermore, aircraft engines are classified fire zones, defined by the Federal Aviation Administration (FAA) as “a flammable fluid leakage zone that contains a nominal ignition source” (2009, p. 11). Therefore, the risk for fires coupled with the abundance of composite materials used, make aircraft engines critical health hazard areas after an aircraft accident and the subsequent investigation.

Focus Statement

This project, thus, focuses on how engine composite structures during powerplant fires may affect first respondents, search and rescue efforts, as well as the accident investigation process. The health hazards and consequences presented by burning composites will be explored in relation to their impact on the subsequent materials analysis. Specifically, how the hazardous materials handling protocols for composite materials aforementioned affect the damaged materials and the associated fractographic evidence will be evaluated. In this research, consequences of specific hazardous, burning composite material handling protocols will be assessed from the material analysis perspective, with the purpose of identifying the effect thereof on the material fractographic study, highlighting potential detrimental impacts on the surfaces studied that may reduce the investigative analysis depth. Within the specific scope of the present study, the first two phases of an accident analysis process – data collection and data analysis – as highlighted by ICAO (2011), are of interest. The data collection phase applies to the collection of materials-related evidence at the accident site, while the data analysis phase relates to the examination of the collected material evidence in the laboratory environment. If issues arise that impact these two first phases, i.e., through the application of hazardous/burning composite material protocols to burning composite-based aircraft structures, the findings obtained can be affected, potentially derailing the original intent of the investigation: developing effective safety-enhancing recommendations.

Aircraft Engines, Composite Materials, and Fires

As afore-indicated, composite structures are frequently employed for the construction of engine blades, cowlings, nacelles, and pylons (ATSB, 2008). Even though the hot-section of a turbine engine, comprising the combustion chamber, turbine blades, and exhaust, is primarily reliant on metallic- and ceramic-based materials due to the extreme temperatures, the cold-section offers prime conditions for the implementation of polymer composites (Marsh, 2012). Specifically, sandwich-based composite structures are used to line engine cowlings and nacelles due to the ability of sandwich cores to act as a sound-absorbents/suppressors while allowing for reduced weight (Anoshkin et al., 2018). The liners used include materials such as fiberglass, epoxy, and aramid-honeycomb sandwich cores (Marsh, 2012). Furthermore, carbon/epoxy-based composite material is used to manufacture larger, but lighter, complex-shaped engine fan blades and fan containment cases (Corman et al., 2016; Ma et al., 2017; Marsh, 2012). Engine pylons, due to their structural significance, rely on aramid/Kevlar fibers for damage protection (Mrazova, 2013). In addition to epoxy thermosetting resin, thermoplastic resins including polyether ether ketone (PEEK) and polyphenylene sulfide (PPS) are also used in aircraft engine applications as matrix materials (Berry, 2002; Soutis, 2005; Vieille et al., 2011).

In addition to the inherent failures from an accident, composite structures exposed to a fire may be damaged from the combustion process itself. Common failure modes observed in composite material samples when subjected to fires and high temperatures are delamination and matrix cracking (Dodds et al., 2000; Mouritz & Gibson, 2006). Similarly, char formations are found on burnt composites. These charred regions, however, can presents benefits related to fire propagation, as char can act as a thermal insulator and oxygen blocker (Mouritz & Gibson, 2006). These elements are further to be considered during the material analysis steps.

As briefly previously introduced, the combustion byproducts of composite materials used for the construction of engine structures present a line of hazards for first respondents to the accident scenes, ranging from toxic smoke and combustion gases to potentially respirable fiber fragments.

Hazards Presented by Fiber Dispersion

Small-sized fibers released during the combustion of fiber-reinforced composite materials present a number of health effects, ranging from the irritation of skin and eyes to respiratory difficulties resulting from the inhalation of said fibers (Mouritz & Gibson, 2006). Specifically, fibers between 0.7 μm and 7 μm in diameter present risks to the human respiratory system (Mouritz & Gibson, 2006). Each material, however, presents differing health hazards dependent on the materials' intrinsic virgin fiber size and combustion characteristics.

Carbon Fiber Combustion: Virgin carbon fibers, with an approximate diameter of 7 μm, are on the upper limit of the respirable particle size. However, through combustion, the diameter of said fibers is decreased through chemical processes to dangerously small sizes (Brown, 2014; Mouritz & Gibson, 2006; Gandhi et al., 1999). Various elements impact the decomposition of the carbon fibers in a fire, thus influencing the volume of dangerous respirable carbon fiber released (Eibl, 2016). On one hand, fires with comparatively low temperatures – i.e. average temperatures below 600°C (~1,110°F) – are generally not expected to yield a critical quantity of carbon fiber fragments. On the other hand, presence of fuels (i.e. aircraft fuel) as well as oxygen (i.e. through large exposed surfaces) result in further carbon fiber decomposition and a greater chance of critical fiber fragment formation. The intrinsic – initial – fiber size, moreover, is an influential factor in the formation of fiber fragments of respirable size (Eibl, 2016).

Fiberglass Combustion: While, as aforementioned, the diameter of carbon fibers can decrease in a fire, glass fibers do not present the same behavior. Specifically, glass fibers are observed to melt at temperatures above 600°C (~1,110°F), thus not decomposing into smaller fiberglass fragments (Mouritz & Gibson, 2006). Furthermore, the diameter of virgin glass fibers (~12 µm) is above the upper limit of respirable particle size, thus not presenting an inhalation hazard per se. Nevertheless, fiberglass dust or pulverized fibers – which could potentially present an inhalation hazard – can be a result of impact- or collision-type events (Mouritz & Gibson, 2006), such as aircraft accidents.

Aramid Fiber Combustion: Aramid fibers are a form of high-performing organic fibers (Yang et al., 2019). At temperatures ranging from 500C° (~930°F) to 550C° (~1020°F), aramid fibers commence charring and decomposing, resulting in potential respirable particles (Bourbigot et al., 2001; Mouritz & Gibson, 2006).

It is important to note, however, that even though potentially respirable, neither virgin carbon fiber, virgin glass fibers, nor virgin aramid fibers present short-term toxicological hazards upon inhalation (Mouritz & Gibson, 2006). Nevertheless, health risks resulting from inhaling post-combustion fibers cannot be ruled out, as fibers involved in the combustion process of composite materials may be contaminated with potentially hazardous materials and chemicals. Post-combustion fibers have been reported to present char, matrix residuals, phenols, aromatic compounds, and polycyclic aromatic hydrocarbons (PAHs) on their surfaces, adding further health concerns (Lipscomb et al., 1997; Mouritz & Gibson, 2006).

Hazards Presented by Thermal Decomposition

As the combustion of fibers is accompanied by airborne, and potentially respirable, fiber particles and fragments, the decomposition of polymeric matrix materials and the afore-described fibers introduces a volume of toxic chemicals which are released upon combustion (Mouritz & Gibson, 2006). From experimental studies conducted over the last three decades, byproducts formed and released during the thermal decomposition of fibers and matrix materials have been identified. Even though the exact composition of byproducts obtained as well as the relative proportion thereof is dependent on the combusted material, general trends can be recognized from literature. Lipscomb et al. (1997), Mouritz & Gibson (2006) and Vogt (1985) reference carbon monoxide (CO), carbon dioxide (CO_2), nitrogen dioxide (NO_2), hydrogen cyanide (HCN), alkylated phenols and aromatic ethers as byproducts resulting from epoxy resin matrix material combustion. During the thermal decomposition of the thermoplastic matrix PEEK, phenol is the primary observed gas together with a combination of further organic gases. PPS thermoplastic matrix, on the other hand, yields benzene, benzenethiol, and a range of dimers, trimers, and tetramers (Mouritz & Gibson, 2006). Furthermore, both types of thermoplastic resins described herein – PEEK and PPS – are observed to yield comparatively large volumes of char (Mouritz & Gibson, 2006). In composite materials reinforced by carbon fibers, aromatic compounds, phenols, as well as PAHs, including quinoline and toluidine, were observed (Courson et al., 1996; Mouritz & Gibson, 2006). Byproduct yields from thermally decomposing aramid fibers include nitrogen oxides (NO_x), CO, CO_2, HCN, and aromatic compounds, such as toluene and benzene (Mouritz & Gibson, 2006; Tewarson & Macaione, 1993). Similar byproducts – including hydrochloric acid (HCl), CO, CO_2, acetone, propylene, styrene, toluene, benzene, and further aromatic compounds – are observed in experiment including glass fiber-reinforced composites (Mouritz & Gibson, 2006; Tewarson & Macaione, 1993). The chemical compounds listed herein, as well as the compounds contaminating burnt fibers previously introduced, can present short- and long-term negative health effects, including – but not limited to – harm to the eyes, skin, kidneys, thyroids, and to the liver, as well as the respiratory, blood, nervous, and cardiovascular systems (National Institute for Occupational Safety and Health [NIOSH], 2007). Furthermore, it is important to note that certain substances are carcinogenic (NIOSH, 2007). The exact health impacts and respective hazards, however, are dependent on the particular concentration and mixture of materials, and are thus unique to each scenario (Mouritz & Gibson, 2006).

The previous paragraph outlined a range of chemicals and the corresponding health effects that are produced as a result of the thermal decomposition of fibers and matrix materials that are commonly employed for the manufacture of aircraft engine components. While the byproducts introduced above are separated in terms of the specific composite materials, it is important to note that matrix materials and fibers interact with one another in a real composite system. Therefore, the combustion byproducts produced by the fibers and matrix materials – and especially the health effects thereof – are to be considered in conjunction, as the combined toxicity may be increased (Gandhi & Lyon, 1998; Mouritz & Gibson, 2006). Furthermore, to reduce the flammability or to improve flame retardant properties, composite materials are frequently modified through the use of coatings, addition of compounds into the matrix, or by chemically modifying the matrix, among others. However, even though these methods may delay the onset of fires or improve flammability properties, in some cases, they may result in more toxic emissions, thus worsening health effects (Black et al., 2015; Mouritz & Gibson, 2006).

Adjusted Processes for Composite Fire Handling

In light of the health hazards presented by burning composites during an aircraft accident involving a fire, the corresponding response protocol has been adjusted by the according aircraft accident investigation authorities. Specifically, the procedures impact personnel that is involved in the handling of the composite material, such as first responders and aircraft accident investigators, during and/or post- combustion. For the protection of individuals requiring to handle composite materials, personal protective equipment (PPE) is used as the first defense mechanism. A general, overarching list of PPE to be worn includes (ATSB, 2008; Black et al., 2015; Olson, 1994; USACRC, 1996):

- Respiratory protection: Respirators (full- or half-face) to protect from the inhalation of fiber fragments/particulates, vapors, and fumes.
- Eye protection: If half-face respirators are worn, additional eye protection – in the form of fitting safety glasses or goggles – are required to reduce and prevent the exposure of eyes to fiber fragments/particulates.

- Skin protection: Coveralls, gloves and boots to reduce and prevent dermal exposure to fiber fragments/particulates. The coveralls shall be fastened with duct tape around potential opening points (i.e., wrists and ankles) to intercept penetration of fiber fragments/particulates. The gloves shall be made out of puncture-resistant materials (i.e. leather) and be complemented by nitrile/rubber gloves to prevent further exposure to chemical hazards such as fluids. Footwear guidelines include steel-toe, hard-soled boots

The above-listed PPE guidelines are highly dependent on each individual scenario, and are impacted by factors such as environmental conditions, condition of the hazardous material, as well as distance to the hazardous area. The United States Army Combat Readiness Center (USACRC, 1996) defines a 25-foot (~ 7.5 meter) boundary around burning composites as the high-risk of exposure area in which the PPE requirements outlined above are to be stringently followed. However, the exact size of the high-risk of exposure area is not fixed, but rather dependent on environmental factors. For instance, on one hand, high-winds may aid the dispersion of fibers and other hazardous materials, resulting in an increased high-risk exposure zone. On the other hand, rainy conditions may reduce the dispersion of hazardous materials, narrowing the high-risk exposure zone (Black et al., 2015; USACRC, 1996). Outside the high-risk exposure zone – in the so-called peripheral area – Olson (1994) and the USACRC (1996) recommend less restrictive PPE protocols. Similarly, the exact condition of the damaged and burned composite materials in question influences the choice of PPE. Specifically, composites that are burning or smoldering require more protective respiratory protection and clothing, while not permitting the use of nitrile/rubber gloves. Protective equipment for the handling of composite materials that are broken or present splintering, such as after a fire, oppositely, includes rubber/nitrile gloves as well as respirators instead of self-contained breathing apparatuses (Olson, 1994; USACRC, 1996). A summary of the specific PPE requirements for each scenario, per Olson (1994) and the USACRC (1996), is outlined in Table 1.

Table 1.

Specific PPE Requirements at a Burning Composite Material Accident Site.

	Respiratory Protection	Eye Protection	Skin Protection
Burning/ Smoldering Composites	Self-contained breathing apparatus (SCBA)	Self-contained breathing apparatus (SCBA)	NFPA 1971 standard: Full-body suit, gloves, and boots *No rubber/nitrile gloves*
Broken/ Splintered Composites	Full- or half-face respirators with dual cartridge filters: Dust/mist protection and high efficiency particulate air (HEPA)	Goggles (if a half-faced respirator is worn)	Tyvek®-type full-body suits Leather and rubber/nitrile gloves Hard-soled, steel-toe boots
Peripheral Area	High efficiency particulate air (HEPA) disposable or reusable respirators	Safety glasses or goggles	Long-sleeve clothing Leather and rubber/nitrile gloves Hard-soled, steel-toe boots

In addition to adjusted PPE guidelines, burning composite handling protocols include procedures to mitigate further fiber dispersion. Specifically, so-called fixant solutions are suggested to be applied over burning and smoldering composite fires to secure loose fibers and particulates stemming from a composite fire (ATSB, 2008; Black et al., 2015; Olson, 1994; USACRC, 1996). Fixant solutions currently in-place include acrylic floor wax (mixed with water) and polyacrylic acid (PAA) (USACRC, 1996). Application of fixant solutions can be conducted through backpack sprayers, hoses, and spraying guns, and is to be directed to thoroughly cover all surfaces (aircraft structures and others) that may contain fiber particulates, regardless of whether the composite structure in question is burning. After application, the fixant is to be allowed to dry (ATSB, 2008; Black et al., 2015; Olson, 1994; USACRC, 1996). When the fixant is dry, the respectively coated parts may be further protected through wrapping in plastic films or sheets. The wrapped parts may, in turn, be placed in plastic bags of at least 0.006 inches (0.15 millimeters) in thickness (Black et al., 2015; Olson, 1994; USACRC, 1996).

Discussion: Impact of Adjusted Handling Procedures on the Material Analysis

As part of the second phase of the aircraft accident investigation, the data analysis phase, material evidence may be subject to a series of laboratory tests to determine – as applicable and necessary – failure modes and causes of aircraft components and their effect on the accident causal factors and sequence (ICAO, 2011). Among others, tests and tools used for the fractographic examination of composite failures include stereomicroscopes (optical microscopes), scanning electron microscopes (SEM), transmission electron microscopes (TEM), X-ray, X-ray computer tomography (CT), ultrasound, infrared spectroscopy (IR), thermomechanical analysis (TMA), dynamic mechanical analysis (DMA), differential scanning calorimetry (DSC), and electron spectroscopy for chemical analysis (ESCA) (Fox et al, 2005; ICAO, 2011; Stumpff, 2001b; Sultan et al., 2009). However, in order to use the techniques above-mentioned, the specimens under examination may require special preparation (ICAO, 2011; Purslow, 1984). Consequently, in light of the requirements, needs, purpose, technology, and limitations of the specific material analysis techniques that may be used, it is crucial to consider how the methods employed to handle the hazards presented by burning composites at an aircraft accident site interact with the subsequent material analysis process. Previously introduced and discussed literature presents and highlights potential detrimental impacts of the afore-mentioned hazardous material handling procedures on the material analysis steps. In an overarching sense, as introduced by Black et al. (2015) – "in certain circumstances, spraying fixant may interfere with the analysis of evidence" (p. 10).

To analyze the material evidence in a laboratory, the parts and components in question need to be moved from their accident location to the adequate analysis facility. Furthermore, as previously introduced, the analysis of material evidence requires, in certain instances, specific preparation of the specimens. However, both of these steps may result in disrupting the fixant coating applied, detrimentally impacting the original intent of the fixant – preventing fiber dispersion (Black et al., 2015). To prevent further dispersion of fibers, the Australian Transport Safety Bureau (ATSB, 2008) recommends not handling or moving composite structures that may have been involved in a fire.

Moreover, certain analyses require the fixant application to be completely removed. In said cases, so-called stripping solutions, frequently based on ammonia or trisodium phosphate, can be used to remove the fixant solution from the surfaces to be studied (Olson, 1994). However, stripping solutions, similar to the fixant solutions themselves, present dangers to the material analysis process. As introduced by Olson (1994), the stripping solutions can interact with the material evidence on which it is applied on, potentially damaging the part, and thus removing evidence during the accident investigation process.

Studies such as Ferreri (2010) have focused on analyzing the effectiveness of different fixant solutions at reducing the fraction of dangerous respirable fibers. However, literature related to the interaction between fixant and stripping solutions with the materials evidence is scarce. Therefore, as indicated by the USACRC (1996), research in the area of fixant and stripping solution compatibility specifically with burning modern composite materials is required to minimize the trade-off between minimizing health hazards while ensuring critical evidence is not removed or destroyed. If material evidence is damaged or destroyed, the depth and detail gathered during the material analysis process may be detrimentally impacted, potentially compromising the overall accident investigative effort. Moreover, as aforementioned and also an area of interest of Ferreri (2010), fiber release during the material analysis steps, specifically as fixant solutions are disturbed and specimens are cut, is to be considered, specifically as it relates to the hazards presented to the specialists conducting the material analysis steps. The health hazards presented during the study of the material evidence drive the PPE requirements to be followed in the corresponding laboratories. Nevertheless, it is crucial to ensure that the mandated PPE does not interfere with the ability of specialists to conduct the required analyses.

Conclusion, Practical Implications, and Future Work

Composite materials, when involved in an aircraft accident fire, can present a range of health hazards to first responders and aircraft accident investigators. In response to the dangers presented, authorities have developed novel protocols and procedures that aid in mitigating the aforementioned hazards. However, these procedures – especially the application of fixant/hold-down and stripping solutions to reduce the dispersion of respirable fibers – have the potential of detrimentally impacting the fractographic analysis of the involved composite structures. Consequently, the investigative depth of the accident investigation process may be reduced.

Therefore, as is suggested in literature (Black et al., 2015), the application of fixant and stripping solutions needs to be carefully considered against the potential impact on the subsequent steps of the accident investigation. Furthermore, specific factors that may impact the interaction between fixant/stripping solutions and the material evidence can be explored to aid in the decision-making process. Examples include specific composite materials used, intrinsic health hazards of each of the materials employed, importance and criticality of the structures in question on the accident investigation process, and combustion characteristics such as temperature, length of exposure, and chemicals involved in the fire. Understanding these factors is critical considering the development of composite materials in the aeronautical realm, as they are increasingly used for primary structures and the materials used are continuously evolving. Similarly, by evaluating potential impacts of the factors outlined, accident investigation authorities may better balance the minimization of health hazards while maximizing critical composite-based evidence.

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