Chapter 4

Erosion resistance

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Abstract

Repeated impacts of liquid droplets, solid particles or cavitation can cause significant damage to composite materials removing both matrix and fiber material. The addition of fillers and nanoscale constituents can improve the erosion resistance and service life. Droplet erosion mechanisms differ from those of solid particle erosion which leads to a trade-off for the desired material properties. Impact angle and velocity of erodent are parameters which will affect the damage mechanisms. The following sections outline the historical and current norms of *liquid droplet erosion* (LDE) and *solid particle erosion* (SPE) testing. Results and data from test campaigns on composite materials are also presented.

4.1 Liquid droplet erosion

Liquid droplet erosion describes the damage and material removal caused by repeated high velocity impacts of liquid droplets on a solid surface. This phenomenon is referred to by different names within different industries. The differentiating aspect is generally in relation to whether the damage is caused by rain or by impact with droplets created internally within a system. In the aerospace industry it is known as *rain erosion* as the damage occurs to the exterior of an aircraft during high-speed flight through rain [1]. This term is also used to describe the damage caused to propeller and helicopter blades and also to wind turbine blades when operating in rain or situated offshore. The terms *water droplet impact* or *water droplet impingement erosion* are used in the energy industry for turbine blade erosion in steam turbines [2–4]. Within academia and the research world, it can also be known as liquid droplet erosion or high-speed droplet impact/impingement. In this case, the terminology is used to indicate that the research is far reaching and encompassing both regimes. The medium generally used for testing is water; however, other liquids can be used. Tests at the Cavendish laboratory in Cambridge, UK in the 1980's used liquids of different densities to investigate different mechanisms of high velocity droplet impacts [5]. The significant physical difference between testing regimes can be described by the droplet size and impact velocity. Rain erosion generally occurs on a macro scale with droplets 1 to 6 mm in diameter and at velocities ranging from 100 m/s for commercial aircraft to 1000 m/s in the case of missiles and hypersonic aircraft. Within the steam turbine industry water droplet erosion occurs usually with droplets from 100 μm to 500 μm at velocities above 300 m/s. Below this velocity, droplets of this scale tend not to cause damage to the turbine materials used.

Resistance of aircraft leading edges to high velocity water droplet erosion during flight has, once again, become of keen interest to the aeronautics community. The subject was extensively investigated from the early 1950's to the 1970's, with the main focus of the research directed at supersonic military applications [6, 7]. Radomes, in particular, were seen to be vulnerable to this form of erosion [6]. At subsonic speeds, structural materials, such as aircraft-grade aluminum, titanium alloys and steels, provided adequate resistance to the repeated effects of water droplet impact, although paints and other surface finishes could still be damaged. The widespread interest in the use of carbon fiber reinforced composites (CFRP) for commercial aircraft primary structures, including wing and empennage leading edges, has brought the topic to the fore once again. A second driver has come from a renewed interest in drag reducing laminar flow technologies. Laminar flow can be lost over a section of the wing/empennage if the roughness of the leading edge increases and causes a laminarturbulent transition of the boundary layer [8]. Both these drivers come from the constant need to produce more efficient aircraft in terms of reduced weight and fuel consumption. The need to develop new methods for protecting aircraft leading edges from rain erosion follows directly from these emerging trends.

Another industry where rain erosion of composite materials is a significant issue is the wind energy industry. The development of large wind turbines with glass fiber composite material blades over the past few decades especially for off-shore applications has highlighted very similar erosion concerns. Blade tip velocities in the region of 100 m/s or greater will experience erosion damage due to water droplet impact, in both on-shore and off-shore applications. Leading edge erosion damage to wind turbine blades has been identified as a major research area in the wind turbine industry, with new test standards currently being developed to qualify coatings for rain erosion protection. Serveral reviews covering various aspects of rain erosion have been written; for example, Field et al. [9] in 1994 and Gohardani [10] in 2011 published reviews on rain erosion in the aerospace domain.

4.1.1 Erosion mechanism

When a droplet hits a surface, a number of mechanisms of damage are initiated. The droplet firstly begins to be compressed at the point of contact between the surfaces. Also at the same moment shockwaves are sent out through the surface in which

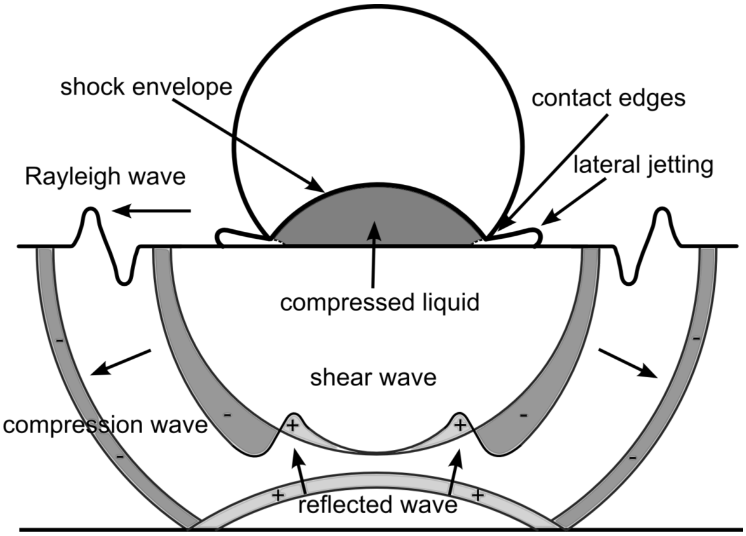

Figure 4.1: Liquid droplet impact.

it is now in contact. These waves come in the form of compression waves, shear waves, and Rayleigh waves [11–13]. This creates an increase in the pressure within the droplet. As the droplet tries to release pressure through expansion outwards at the contact edges, the contact edges are seen to move at a velocity faster than that of the shockwave moving from the center of impact. This causes the pressure to continue to increase as the droplet volume is compressed further. This effect is called the water hammer pressure [14]. Theoretical methods describing this were produced by Lesser [15] and Springer and Baxi [16].

As the shockwaves reach the contact edges, the droplets are seen to produce lateral jets of water as the pressure build-up is released (Figure 4.1). The jetting effect is unique to low viscosity liquids impacting at moderate to high velocities [17]. These lateral jets, which in the case of an impact normal to the surface will be equal in all directions, cause further damage and erosion to the surface. Any imperfections on the surface will begin to be eroded by the shear stresses between the surfaces and the water. The velocity of the jets is seen to be higher than that of the impact velocity. A particular situation which is of interest in terms of damage caused by these lateral jets is the off-normal impact angle case. In this case a supersonic edge (for small angles) moves away from the impact site, in the direction the droplet is tending towards, leading to different erosion patterns [18, 19].

Natural rainfall intensity

There are a number of parameters that are significant when attempting to simulate natural rain erosion effects; rainfall intensity is one such key parameter. As weather conditions vary widely around the world, rainfall conditions that are prevalent and possible can range considerably. The conditions in temperate climates will be less extreme than those of the tropical regions. Rainfall rates of below 2 mm/hr are