Investigation of rain droplet erosion of turbine blade materials in the lab

Wind turbine blades are getting longer with length, L, exceeding 100 m and generating 12 MW of power per turbine. The power generated scales with the swept area, proportional to $\mathbf{L^2}$ (Figure 1a). On the contrary, weight increase is proportional to $\mathbf{L^3}$ (Figure 1b), as a result these longer blades exert higher stress on the gears used for power transmission. Therefore, light weight advanced hollow blades with higher specific strength materials such as carbon fiber composites are being recommended. However, its erosion resistance against rain fall or water droplet is to be investigated, yet. (Figure 1c). In general, the intensity of erosion is proportional to $\mathbf{L^5}$ (Figure 1c), dependent on the tip velocity which can be as high as 150 m/s.

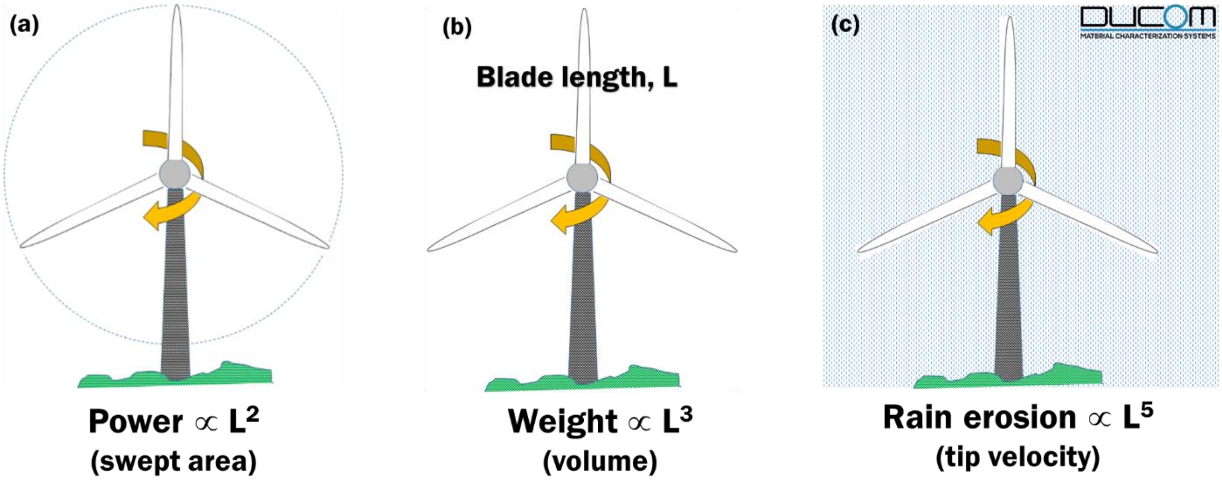

Figure 1. Scaling laws for wind rotors (a) power generated scales as L^2 (b) weight increase scales as L^3 (c) leading edge rain erosion scales as L^5.

Such aggressive erosion conditions at the leading edge are caused by repetitive impact of rain droplets and the damage progresses from isolated pits to deep gouges and delamination leading to deterioration of the aerodynamic profile. The resulting increase in drag force (50 to 400%) can reduce the AEP (annualized energy production) by 5 – 20%. Furthermore, uncontrolled erosion has the potential to rupture the underlying skin leading to imbalance and turbine failure. The mechanisms responsible for the destructive power of water drops are described and test instruments or tribometers that can simulate the field conditions (Table 1) are highlighted.

Table 1. Typical field conditions during operation of wind turbines

Rain droplet diameter	1.2 – 2 mm
Rainfall intensity	1 – 25 mm/h (drizzle to intense rain)
Blade tip speed	80 – 120 m/s

Physics of water drop impact and wear related material loss

Rain droplets can cause more damage than erosive particles due to impact mechanics (double pressure points) and resulting stress waves or Rayleigh waves. This consists of two phases (Figure 2a):
(a) Water Hammer Pressure generated by high speed impacting drop in phase I, where liquid is compressed, leading to a pressure increase given by $P = \rho_w CV$ (Figure 2a).
The impact pressure can be as high as 500 MPa lasting for < 1 µs with a characteristic profile shown in Figure 2a.

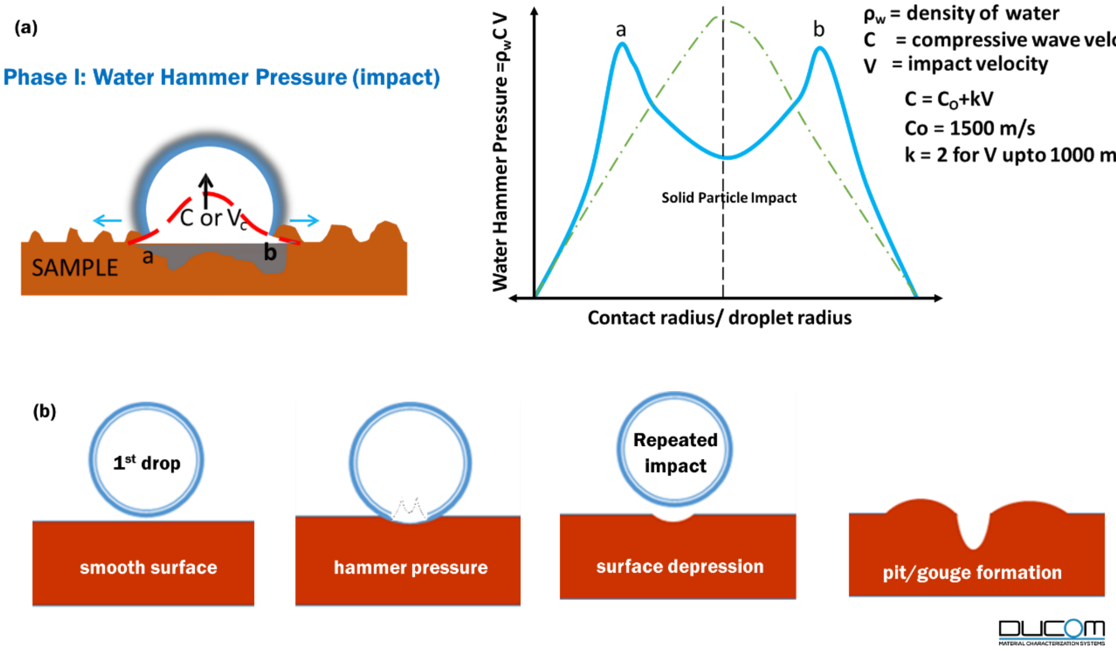

Figure 2. (a) In Phase I, shock waves within compressed water drop result in impact pulse. Characteristic impact pressure profile for water droplet erosion (stress peaks at periphery) compared to solid particle erosion (central stress peak at contact) is shown. (b) Damage accumulation from water hammer pressure starting from surface depression to deepening and pit formation in case of ductile materials.

Repeated impact of droplets leads to initial depression and deepening resulting in pit/gouge formation as seen in early operational life of leading edges of the turbines. Rayleigh waves (lateral jetting) emanate in phase II, where the compressed liquid drop spreads laterally outward with formation of Rayleigh and shear waves (Figure 3a). High velocity shear waves rip through surface undulations caused by water hammer pressure and remove surface undulations to widen the wear scar (Figure 3b). Shear waves also lead to subsurface microcracking at pre-existing flaws, which coalesce over time leading to delamination failure, as observed in the advanced stages of blade leading edge erosion.

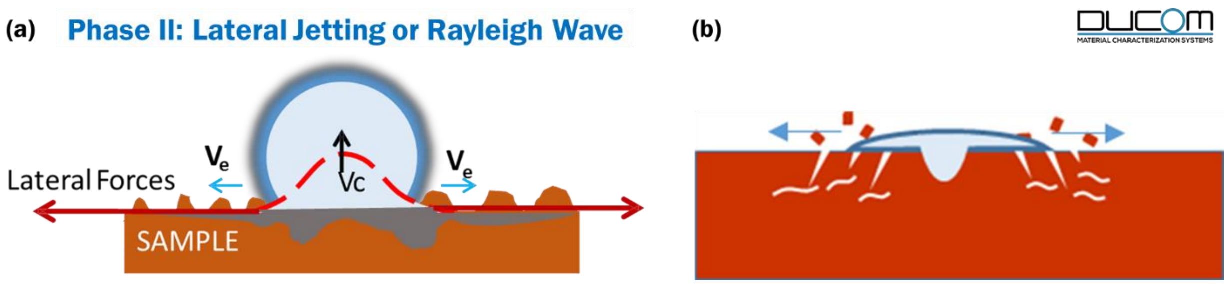

Figure 3. (a) In Phase II lateral jetting where water drop spreads outward with velocity 10 times greater than impact with generation of both shear and Rayleigh waves. (b) Rayleigh waves lead to shear damage or microcracking followed by water drop lateral spreading which removes surface asperities.

High specific strength blade materials should offer high resilience and fracture toughness to absorb the impact energy and dampen stress waves to mitigate erosion wear. Such materials and coatings can be quickly screened in Ducom water droplet erosion tester which can reproduce the rain erosion conditions (Table 1) and damage mechanisms (Figure 2b and 3b).

Ducom water droplet erosion (Figure 4) operates on the principle of repeated high velocity impact of droplets on an erosion resistant material. A high velocity water jet (up to 250 m/s) is chopped into water droplets by a rotating disk with two holes. The speed of rotating disk is used to control the impact frequency of water droplets (upto 100 Hz). Multiple impact testing at the same location under high velocity offers accelerated erosion testing of materials, reproducing years of field leading edge damage within reasonable time frames in the lab.

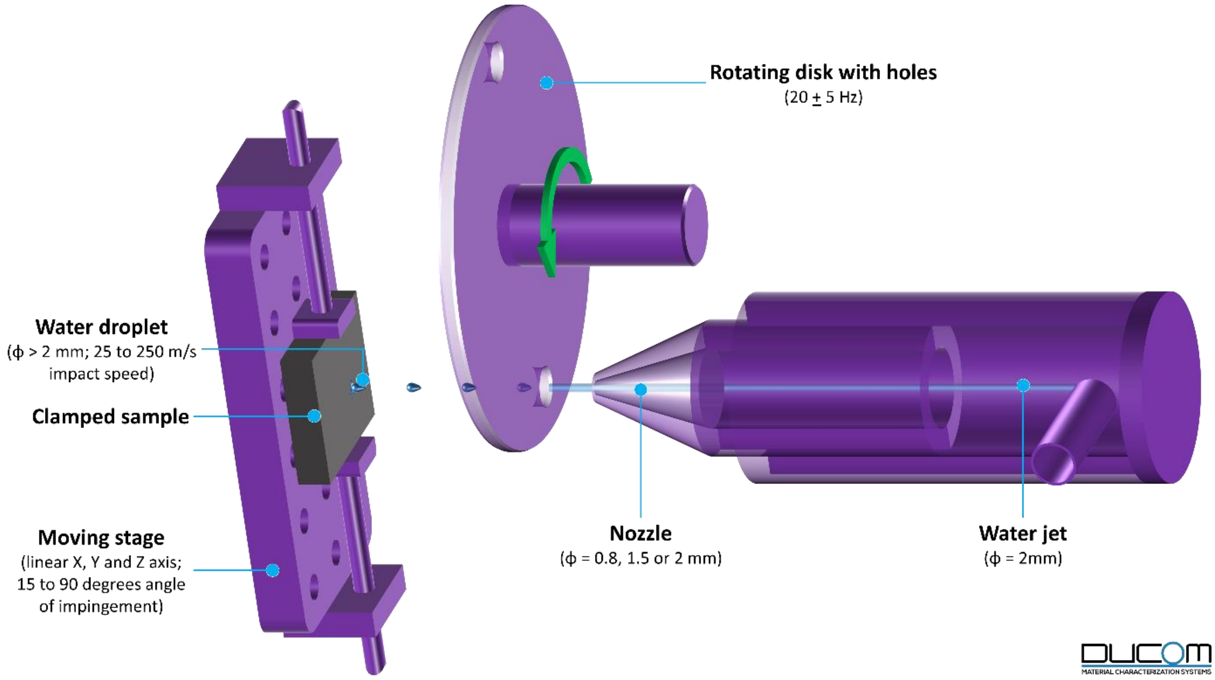

Figure 4. Schematic of Ducom water droplet erosion tester.

Unique features include:

- High velocity water drop impact up to 250 m/s
- Water drop diameters up to 2 mm
- Controllable drop impact frequency (up to 100 Hz) at same location
- Movable X-Y-θ stage for conducting multiple tests at different angles
- Pressurized air blade to remove residual water films and eliminate ‘water cushioning’ effect
- High speed camera port for imaging droplet size and quantifying velocity

Please contact us for a personalized technical presentation.

Ducom water droplet erosion tester (WDE)