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Experimental assessment of droplet impact erosion resistance of steam turbine blade materials

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ABSTRACT

The droplet impact erosion resistance of five different but highly relevant steam turbine blade materials is investigated with the help of an erosion test rig. The rig adapts wetness and droplet impact speed conditions in the last stages of condensing steam turbines in such a way that the material degradation is greatly accelerated in order to establish monotonic saturating material loss gradients—ideally within a testing time interval of 50 h. Repeatability and reproducibility of the evaluation method is ensured to facilitate the representative ranking of materials based on droplet impact erosion resistance being a key material property for durable steam turbine blade designs.

A selection of three blade steels (X20Cr13, a steel similar to X5CrNiMoCuNb 14-5, X5CrNiCuNb 16-4) and one titanium alloy (Ti6Al4V) is tested and analysed. Additionally, X5CrNiCuNb 16-4 in a laser-hardened condition is investigated. Besides the influence of droplet impact speed and droplet impact angle on erosion, the generated surface jaggedness, the level of material degradation as well as the material loss gradients are discussed and utilised for further deductions. Among the high yield strength blade steels, the laser-hardened X5CrNiCuNb 16-4 exhibits the best erosion resistance while Ti6Al4V exhibits a higher erosion resistance than all the steel alloys tested.

Finally, a simplified but functional model is inferred from the test data to estimate the droplet impact erosion resistance of alternative steel and titanium blade materials relative to the materials discussed in this text.

1. Introduction and review

In order to enable a classification of the subsequent wear investigation, it is deemed sensible first to supply some application specific background information for the reader not involved in steam turbine erosion problems. The physical phenomenon leading to a material specific degradation process is discussed together with the motivation that triggers the scientific endeavour to remedy or at least mitigate the erosion process. A brief historical review is also given.

Water droplet impact erosion of last stage steam turbine blades has been a well-known and at times aggravating phenomenon in the steam turbine and power utility community for a century. The steam is expanded to a low pressure and temperature in order to improve the thermal efficiency of the plant and this causes the steam to expand below the saturation line leading to the formation of droplets in the flow. It is commonly agreed that this kind of droplet erosion is unavoidable when a steam turbine is operated under wet steam conditions. Only the extent of material loss over time may be positively influenced by various means being discussed later in the text. The droplet impact erosion leads to the loss of blade material and, especially in the blade tip region with high impact speed (450–600 m/s), this changes the aerodynamically optimised blade geometry and noticeably disturbs the flow around the blade profile. This in turn adversely influences the performance of the machine eventually leading to a need for turbine blade replacement. In addition, the last few decades furthered the development of highly efficient low-pressure steam turbine designs featuring significantly increased exhaust areas. These lead to high aspect ratio blades with enormous tip speeds approaching 750 m/s which may possibly result in an increased droplet impact erosion potential. Among a few other restrictions, droplet impact erosion might therefore be considered as service-life relevant for steam turbine blades. Moreover, as the extent of blade leading edge erosion is, for thermodynamic reasons, chiefly related to the actual operation of the power plant, it is deemed almost impossible to set forth a comprehensive and fool-proof blade erosion protection concept from a manufacturer's point of view. However, significant and sensible erosion mitigation measures such as properly chosen and treated blade materials have been developed.

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Having explained the motivation for the present investigation, the source of detrimental moisture leading to droplet impact erosion is now outlined. In the last stages of steam turbines, steam is expanded below the saturation line and a part of it is condensed into primary droplets with typical sizes of 0.2–2.0 μm. A fraction of these primary droplets deposits on the stationary guide vanes where it may eventually form rivulets or water films. These structures grow in size, move towards the trailing edges, become unstable due to aerodynamic forces and finally convert to a spray of coarse secondary droplets of up to 1500 μm in diameter. This spray travels in the wake downstream of the vanes' trailing edges. The large droplets eventually enter a region of higher steam velocity where they are broken further into smaller droplets, known as coarse water droplets, of the order of 100 μm. They accelerate gradually with the steam and finally hit the downstream rotating blades with an impact speed of less than, but at times close to the peripheral speed of the rotating blades. The result of this droplet impact may then be erosion, i.e., structural damage of the blade material [1–5].

Since the recognition of the phenomenon leading to blade erosion, several mitigation measures have been adopted to minimise the erosion of steam turbine blades. These include simple geometric design considerations such as an increase in the axial spacing between stator and rotor to allow the droplets to be accelerated and broken up. Thinner trailing edges of the stator vanes are thought to be advantageous as they produce smaller initial secondary droplets from the water film. Moisture extraction between the blade rows is considered to be a more sophisticated and efficient method by providing suction slots on the guide vane surface as well as by evaporating the water film and rivulets by internally heating up the stationary guide vanes. The latter is the most efficient erosion mitigation measure known to date [6]. Additionally and most importantly, attention is paid to ensure that the blade leading edges are more resistant against erosion. Laser treatments, induction or flame hardening of blade materials as well as shielding of blades with Stellite or tool steel, have been used to improve the leading edge erosion resistance [1,7,8].

Historically, the erosion of steam turbine blades became the topic of scientific interest and research in the beginning of the 20th century when the tip velocities of the rotating blades of steam turbines became sufficient to cause erosion. The material degradation of steam turbine blades had been explained by every possible phenomenon including chemical attack, oxidation, solid particles carried by the steam except liquid droplet impact (Coles, 1904). However in the 1920s, experiments had been carried out to correlate erosion of steam turbine blades with droplet impact [9,10]. In 1928, Cook presented his famous water-hammer equation in which he estimated the pressure generated when a liquid column of water impacted on a solid surface. In his theory, he showed that the pressure generated at liquid solid impact is sufficient to cause erosion of steam turbine blades [10,11]. According to Heymann [12], Cook's water–hammer relation may be extended as follows:

$$p_{\text{impact}} = \rho_l c_l v_{\text{impact}} \cdot \left(1 + \frac{k \cdot v_{\text{impact}}}{c_l}\right) \quad (1)$$

where the droplet impact pressure p_{impact} depends on the droplet impact speed v_{impact}, the liquid density ρ_l and the liquid acoustic speed c_l which, with some limitations, represents the shock speed in the compressed liquid. Here k is a constant depending on impacting liquid properties and according to Heymann's experiments, its value approaches to 2 for water. The first term denotes the "classical" water hammer pressure derived from momentum considerations while the second term reflects the variant nature of the shock speed. It is important to note that the magnitude of impact pressure is independent of droplet size, its duration, however, is dependent on droplet size and geometry [13].

In the period from the 1960s to the 1990s, a lot of scientific research was undertaken in the field of droplet impact erosion, see e.g. [4,10] and [14–20]. The basic finding was that, as the droplet impacts on a solid surface, a pressure wave is generated within the droplet at the point of contact which travels back inside the droplet with the speed of sound. This shock wave remains in contact with the solid surface as long as the contact velocity is higher than the shock velocity and the liquid remains compressed within this shock envelope. Later on, shock speed overtakes the contact edge velocity and the shock wave detaches from the contact surface. At this point, a lateral jetting is observed with velocities many times higher than the impact velocity. The impact pressure then reaches its maximum value (about three times the water hammer pressure). Shock speed, jetting time and impact pressure remain the topic of interest during all these investigations.

A variety of dedicated erosion test rigs have been constructed in the past where erosion caused by repeated droplet or jet impact has been studied. Generally, these experiments show that droplet impact erosion depends on the impact count and hence is a time dependent process. It starts with a so-called incubation period with no or very minor material damage, followed by an acceleration period where the rate of erosion increases rapidly to a maximum value, followed by a deceleration period where the erosion rate decreases to some fraction of maximum erosion rate (1/2 to 1/4) and finally a steady terminal erosion condition where the erosion rate remains almost constant. The erosion rate is found to be sensitive to impact velocity preferably described by a power law equation $R_e \sim V^n$ where the value of n is reported to be 4–5 for ductile materials and 6–9 for brittle materials. In accordance with theory, bigger droplets produce more erosion while the impact angle is found to be most significant in terms of erosion damage at perpendicular impact to the target surface. Moreover, dependencies of the liquid properties on erosion are observed as erosion rate varies at 2nd to 2.5th power with liquid density and 1/2 to 3/4 power with the inverse of the liquid viscosity. An increase in temperature of the impacting liquid generally increases the erosion slightly. This effect is attributed to the increased shear damage of the surface caused by the evolving lateral jet flow [1,17,18,21].

Extending the definition of erosion test rigs to real steam turbines, the impact count is chiefly related to the local wetness value. The droplet size may be related to the trailing edge diameter of the stationary vane and the local density of the steam, which is proportional to the local steam pressure. Besides the axial spacing between stator and rotor, the relative droplet impact speed may be related to the steam density as well. However, more significant is the rotor blade tip speed [6,22]. As in the past, the rotor blade materials have not been varied to a great extent, the described multi-variable system is often condensed to a set of semi-empirical characteristic numbers that determine the amount and strength of necessary countermeasures. This pure phenomenological approach essentially requires a large fleet experience as a key factor to success.

From the stressed blade material's perspective, it seems desirable to correlate the erosion resistance of a specific material to a well-defined set of macroscopic mechanical properties. It is found that hardness, resilience, toughness, tensile strength, ductility and strain energy can significantly affect the ability of a material to withstand droplet impact erosion. However, none of them proves to be a single material parameter to whom erosion resistance can be related uniquely [1,13,17]. Hardness proves to be the most reliable material property to assess the erosion resistance. It is found that erosion generally varies with the 2nd to 2.5th power of Vickers hardness number. However, for materials of different categories or metallurgic structures, this simple relation may not hold [9].