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Water droplet erosion behaviour of Ti–6Al–4V and mechanisms of material damage at the early and advanced stages

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ABSTRACT

In this study, the water droplet erosion (WDE) behaviour of Ti–6Al–4V and mechanisms of material damage were investigated. The WDE test was conducted in an advanced rig in accordance with the ASTM G73 standard. The influence of impact speed between 150 and 350 m/s on the WDE behaviour was explored and the cumulative mass losses *versus* the exposure time/number of impingements were plotted. It was observed that the higher the impact speed the faster the erosion initiation time and greater the maximum erosion rate (ER_{max}). ER_{max} was also found to be related to the impact speed with an exponent of 9.9 in a log–log scale. SEM images showed that the early stages of erosion damage were mainly limited to the formation of microcracks, asperities and isolated pits of irregular shapes. It was found that the most profound mode of material removal during the advanced stage of water droplet erosion was hydraulic penetration. Sub-surface, side wall cracking and material folding/upheaving were also features observed.

1. Introduction

In the electric power generation industry the gas turbine efficiency is an important issue and is directly affected by the ambient temperature. Meher-Homji and Mee [1] reported that a rise of 1 °F results in a 0.3–0.5% in turbine efficiency decrease. This adverse temperature effect is obviously a season-dependent phenomenon. For instance, in the United States, a 9% loss of gas turbine output power was recorded in summer *versus* winter periods [2]. The lower turbine efficiency is attributed to a decrease in air density leading to a decrease in the intake air mass [3]. The lower efficiency results in high electricity cost [4] and high CO_2 emissions [3]. To keep the ambient temperature as low as possible, the inlet air fog cooling technique is used [1]. In this technique, water droplets are sprayed into the inlet of the gas turbine compressor to cool down the intake air thereby increasing the intake mass. The water droplets reduce the temperature leading to an increase in the output power [5]. However, an overspray can occur when all droplets are not evaporated [5,6]. Despite the cost effectiveness of this fogging method, droplets cause a severe erosion damage problem for the leading edge of the compressor blades and consequently a significant fatigue cracking issue for the full blades, especially at high speeds. Khan [6] stated that the erosion damage phenomenon was featured as the synergy of the impacting water droplets and the rotating blade. This is usually termed as the "water erosion by impingement or water droplet erosion (WDE)".

Water erosion by impingement is a special form of erosion produced by repetitive impingement of high velocity liquid droplets on a solid surface [7]. The mechanism of the erosion process is complex because of the many parameters involved, including: impact velocity, impact angle, droplet size, droplet density, frequency of impacts, liquid film formation and mechanical properties and conditions of the target material. However, this erosion phenomenon has also been found in several industrial applications including cooling pipes of nuclear plants [8], sewage plants and sea water systems [9], aerodynamic surfaces of aircrafts and missiles [10] flying through rainstorm at subsonic and supersonic speeds [11]. The WDE damage is predominantly caused by two main factors: (1) the high pressure exerted by the water droplet on the exposed area of the solid surface and (2) the radial liquid flow along the surface at high-speed, which occurs after the initial droplet pressure lessens [11]. Moreover, this erosion damage reduces the efficiency of mechanical components due to aerodynamic losses [12]. Despite the efforts to combat or mitigate the erosion damage, it has not been possible to identify or quantify an absolute parameter for WDE resistance [10]. This is due to the fact that erosion rate is not constant with time and therefore, no single

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value can quantify the erosion test. Significant attempts have been made to attribute the hardness [11], toughness [11], work hardening [13], and ultimate resilience [14] to the WDE resistance. More so, a synergistic effect of these parameters would be a more appropriate term. For this reason, the material (rating) ranking system which is somewhat semi-quantitative has been developed by Heymann [15]. He [15] proposed sets of comparative studies in order to evaluate erosion resistance under different sets of conditions. In this system, the normalized erosion resistance, which is the maximum rate of volume loss of a reference material divided by the maximum rate of volume loss of material being evaluated, is calculated. However, the major setback here is the lack of precision in projecting the erosion damage. ASTM standard [10] mentioned that for bulk materials, the incubation period and the maximum erosion rate determined from empirical relationships could be used for the material rating; provided, the principal liquid impingement parameters such as droplet size, impact velocity are known. Also, due to the variation of erosion rate with exposure time and synergy of different interacting WDE parameters such as impact speed and droplet size, different WDE behaviours and damage mechanisms will prevail. Thus, predicting or projecting the erosion damage becomes difficult. In this case, the experimental investigations become paramount. The mechanism by which a material is removed or chipped out is an important aspect of the WDE damage. However, the challenge lies in defining the hydrodynamic conditions that cause particular erosion and material detachment effects [11]. Nevertheless, it is paramount to fully understand the WDE behaviour of materials and the mechanism by which a material is removed when exposed to an erosive medium. To understand this, the concept of water hammer pressure, stress wave propagation, liquid outflow and hydraulic penetration as well as material response must be comprehended.

In this study, the WDE behaviour of Ti–6Al–4V and the mechanism of material removal during the early and advanced stages of erosion damage were investigated. Special attention was given to the influence of impact speed of the erosion behaviour. Cumulative mass loss, number of impingements, erosion initiation time and maximum erosion rate (ER_{max}) with respect to the impact speed were derived. Study on the mechanism of material removal was conducted with the aid of a scanning electron microscope (SEM). Here, the as-eroded surface and polished cross-sectional views were investigated.

2. Experimental procedure

2.1. Material and geometry

For the present study, the Ti–6Al–4V (ASTM B265, Grade 5) alloy, used for compressor blades in gas turbine, was investigated. Typical room temperature physical and mechanical properties are: elastic modulus (113 GPa), Poisson's ratio (0.342), melting point temperature range (1604–1660 °C) and tensile strength (880 MPa). T-shaped coupons, as shown in Fig. 1, were machined using a CNC Haas machine under flood coolant in accordance to the WDE testing rig geometry. Fig. 2 shows the starting microstructure of the Ti–6Al–4V alloy which contains α and β phases.

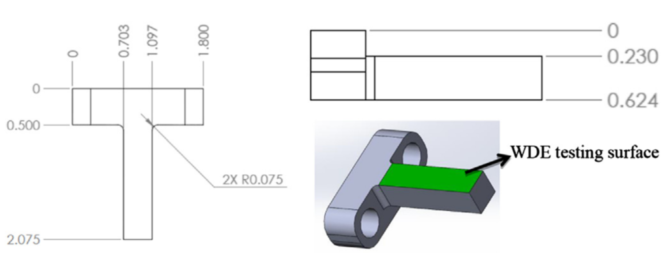

Fig. 1. Typical T-shaped Ti–6Al–4V sample (dimensions are in inches).

2.2. WDE testing, mass loss measurement and characterization of eroded coupons

A state-of-the-art rotating disc rig at Concordia University, shown in Fig. 3, was used for studying the WDE behaviour of the Ti–6Al–4V alloy. The test was carried out in accordance with ASTM G73 standard [10]. This is a unique testing rig that reaches up to 500 m/s linear speed (equivalent to 20,000 rpm rotational speed). It has a working chamber coupled with a vacuum system, a compressed air driven turbine and a water droplet generating system. The rig has a user friendly control system allowing monitoring of the vibration level, vacuum level, chamber temperature, turbine bearing temperature as well as the rotational speed. Coupons are fixed at the opposite ends of the rotating disc as depicted in Fig. 3.

To avoid friction between the rotating disc and air, which causes significant temperature rise, a 30–50 mbar vacuum is maintained during the experiment. Thus, favourable working temperature was maintained and water evaporation was avoided. This vacuuming approach further allows for WDE testing at very high impact speeds. It is worth mentioning that a separate setup using a transparent chamber was used to simulate the water droplets behaviour inside the rig. The droplet size distribution was monitored using a high-speed camera (9000 frames per second) with the aid of this setup. Furthermore, the number of droplets was counted which was essential for computing other parameters such as the volume of impinging water. Similar water droplet generation and size distribution determination has been reported in [16–18]. Typical WDE testing parameters are summarized in Table 1. Once a desired rotational speed was attained, the water droplets (de-ionized water) were introduced while controlling the flow rate. The setup enabled the droplets to impact the coupons at 90° in a repetitive fashion. The impact angle of 90° causes the most severe water erosion damage. The erosion exposure time depended on the impact speed used. However, timings at 30 s intervals were used in order to capture the first stage of the erosion process (incubation period). Also, longer times (1, 2, 3 up to 840 min) were employed as the test progressed to the advanced stage of the erosion process.

Coupons were weighed using a balance and pictures were taken with a standard stereo optical microscope, at each interval. Typical erosion curves such as cumulative mass loss *versus* exposure time/number of impingement and ER_{max} *versus* impact speed were plotted. For accurate determination of the incubation period and maximum erosion rate, a three line representation method was used as demonstrated in Fig. 4 [19]. The mechanism of material removal during the incubation and advanced stages was monitored and the damages were characterized using SEM. Here, the as-eroded surface and polished cross-sectional views were investigated. Microcracks, stress wave propagation, crack initiation sites, formation of pits and removal of cavity were primarily investigated. Results and discussion are presented in the next section.

3. Results and discussion

3.1. Droplets generation and size distribution

Prior to the WDE tests, several experiments were performed with an impact angle of 90° in order to establish and calibrate the erosion test conditions, such as initial pressure, flow rate and droplet size distribution. Droplet generating system and a nozzle