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Effect of impact angle and testing time on erosion of stainless steel at higher velocities

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ABSTRACT

Erosion is vitally important in aerospace and petrochemical industries, especially when the targets such as flight engines, gas control valves etc are subjected to high speed in an environment containing sand particles. A new erosion test rig, with a capability of producing a velocity greater than Mach 3, was built up to cater to this purpose. Results obtained from stainless steel testing showed that erosion rate was saturated at 120 s and reduced subsequently. In addition, the results of erosion rates at different impact angles indicated that severe erosion maximizes at an impact angle of 40°. Further, erosion profiles showed different erosion effects on the sample surface. Surface roughness increased with respect to time and peaked at 45°. Investigation into surface microstructure revealed different erosion mechanisms associated with different impact angles. The erosion mechanism transition from micro-plowing to indentation induced plastic deformation took place from low to high impact angles. Further, computational fluid dynamic model was used to compare with experimental results.

1. Introduction

Erosion caused by sand particles is a big challenge in aerospace and petrochemical and power industries [1–6]. Researchers are trying situation based problems, such as when a flight passes though an erupting volcano releasing the fine particle containing ash or a flight passes though a sand storm in a desert. A catastrophic flight accident happened in the past when a British airplane flew through an erupting volcano in Indonesia. All engines stopped working due to flying ash containing erosive particles [1]. Another example is in the oil and gas industry when gas is pulled up through a tube consisting of control valves. The gas contains complex compositions where fine sand particles are unavoidable. The fine sand particles accelerated to high velocity, eg. supersonic (greater than Mach 1) or hypersonic, may impinge on the control valves and damage it [7,8]. The cost of repair can be up to millions of dollars. Thus, understanding erosion mechanisms and getting a solution for each case is vitally important.

The literature search shows that there has been a number of research works conducted on sand erosion. Wood et al., Lemistre et al., and Huttenen et al., fabricated test facilities to study erosion characteristics and mechanisms of different types of materials and coatings [6,8–10]. Different ceramics (WC, Si_3N_4, ZiO_2 etc), steel, polymers, composites were tested and they showed different erosion behaviors [11–15]. Attempts to apply coatings on target materials have also been done and the results revealed significant erosion resistance [16,17]. Further, numerical modeling was proposed to predict erosion behaviors of materials [18–20]. The erosion is not only dependent on the test materials but also on sand properties such as its hardness, density, size and shape.

So far limited research has been conducted to study erosion of stainless steel with deep analysis on its microstructure to reveal erosion characteristics and mechanisms. Thus, in this study, a new erosion test facility with capability of providing a high speed of air—sand mixture was built to cater to this purpose. Powerful analysis tools such as 3D surface profilometer, SEM equipped with EBSD and EDX, and AFM were used to study insight into microstructure to reveal erosion characteristics and erosion behaviors of stainless steel samples. Additionally, computational fluid dynamics (CFD) modeling was used to support this study.

2. Experimental procedure

2.1. Air–sand erosion test

The air–sand erosion tester, equipped with a high capacity air compressor, was designed and built up at National University of

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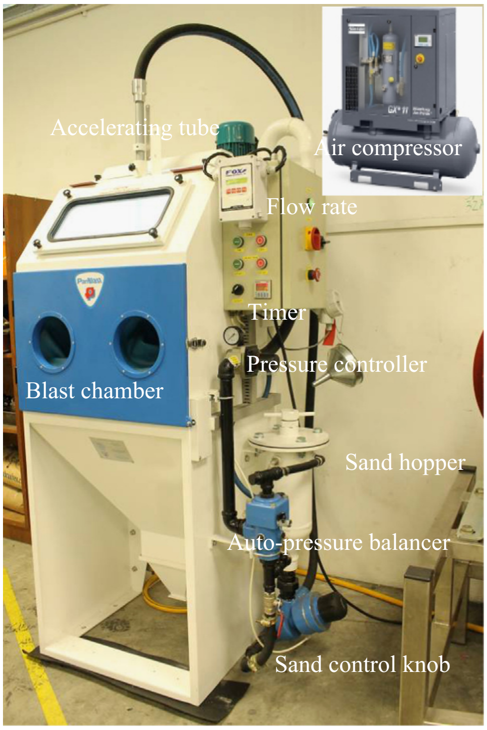

Fig. 1. Photograph of dry erosion test rig.

Singapore and is shown in Fig. 1. The GXe22 Atlas Copco air compressor is equipped with a 500 l tank can operate at high working pressure of 13 bar. It is integrated with a dryer and air filter so that the air supplies to the sand erosion tester is clean and dry. This erosion tester is able to provide an air velocity of greater than Mach 3 with high accuracy through a digital pressure regulator and a FOX flow rate meter. The sand hopper was designed to contain up to 10 kg of sand and with auto-pressure feed back function to make sure that sand flow rate is released constantly. The sand flow rate is adjusted through a fine control knob. Air and sand is accelerated though a one meter long downstream stainless steel tube to a 8 mm orifice and 43.5 mm long boron carbide nozzle before hitting the sample surface. The sample holder was designed to rotate from 0–90^o and the distance from the sample surface to the blasting nozzle is adjustable and fixed at 24 mm in this study. In the present study, a constant velocity of 200 m/s, a constant sand flow rate of 1 g/s, an interval of 10° impact angles and different testing time were set up.

2.2. Sample preparation

The $25 \times 25 \times 5$ mm^3 stainless steel SUS304 samples with an experimental density of 7929 kg/m^3 were cut from a $500 \times 500 \times 5$ mm^3 sheet using a precision laser-cutting machine. Prior to laser cut, the stainless steel sheet was auto-polished to a mirror level with an average surface roughness of 25 nm. All the furs at the sides of sample were removed and the samples were alcohol washed in an ultrasonic bath and then hot dried and kept inside the digital dry cabinet prior to the tests. An EBSD image of stainless steel sample before the test is shown in Fig. 2. The chemical composition of the stainless steel SUS-304 is: C$\sim$0.024%, Si$\sim$0.55%, Mn$\sim$1.8%, P$\sim$0.03%, S$<$0.001%, Cr$\sim$18.2%, Ni$\sim$8.2%, N$\sim$0.049% and Fe balance. Its mechanical properties are as 0.2% proof strength $\sim$296 MPa, 1% proof strength $\sim$327 MPa, Tensile strength $\sim$616 MPa, Elongation at 5 mm $\sim$56%, elongation at 50 mm $\sim$55% and Brinell hardness$\sim$187 HB.

2.3. Sand material

The sand material contains mainly aluminum oxide with an average size of 90 mesh with chemical composition of Al_2O_3 $\sim$95%, TiO_2 $\sim$3%, SiO_2 $\sim$1.3%, F_2O_3 $\sim$0.16%, CaO $\sim$0.5%. The sand has a density of 2400 kg/m^3 and a hardness of 9 Moh. The microstructural morphology and size distribution of sand particle was reported earlier [21]. Selected sand flow rate of 1 g/s was used in this study.

2.4. Weight loss

Prior to the test, the samples were taken out from the dry cabinet and their weight was measured immediately to avoid the humidity effect, using a microelectronic balance with an accuracy of 0.00001 g. The samples after test were first water washed, air-blown and then alcohol washed in the ultrasonic bath, hot dried and kept inside the dry cabinet for at least 2 h before measuring its weight to ensure that all sand particles are ultrasonically removed and there was no effect of differential humidity. The weight loss and then erosion rate were then calculated accordingly.

2.5. Surface characterization

Powerful surface characterization techniques were used, such as 3D surface profilometer, scanning electron microscopy and atomic force microscopy, to reveal insight into surface erosion characteristics, e.g. erosion profile, erosion shape, surface roughness, as well as erosion mechanisms.

3. Results and discussion

3.1. Erosion rate

Tables 1 and 2 show the erosion rates of stainless steel sample at different testing times and impact angles. As seen in Table 1, erosion rate increased in the beginning and peaked at 120 s and then gradually reduced [22,23]. In the beginning, the sample surface was considered as free stress stage and hard particles were accelerated at high speed which resulted in high impact energy. This impact energy includes kinetic energy and potential energy and is expressed in the following equation [24]:

$$E = E_k + E_p = 1/2mv^2 + mgh \tag{1}$$

Where, E is the impact energy, E_k is the kinetic energy, E_p is the potential energy, m is the weight of a sand particle ($m = 4/3\pi r^3 \rho$), r is the particle radius, ρ is the particle density, v is the particle velocity, g is the acceleration of sand particle due to gravity ($=9.8$ m/s^2) and h is the height of acceleration tube.

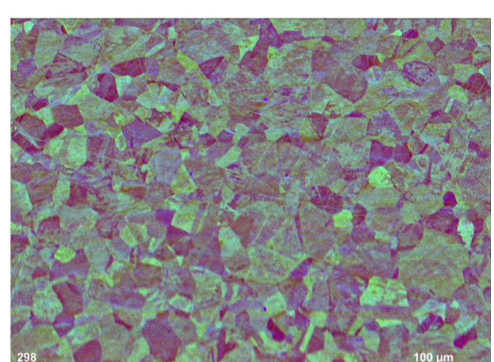

Fig. 2. EBSD image of stainless steel sample before the test.