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Case study

In situ remote hot erosion scar measurement

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ABSTRACT

When particles of grit, oxide or other contaminants get entrained in high speed gas or steam sections of power or aero turbines they can damage components through repeated impact of particles with the surface. This erosion in turn produces additional debris which can damage other surfaces further downstream. An instrument to evaluate and quantify high temperature solid particulate erosion (HTSPE) is being designed and built at the National Physical Laboratory (UK). In order to speed up the measurement of the erosion scars, a system is required that can measure the shape and depth of scars on test coupons of materials without the need to remove them from the HTSPE system to perform the measurement. This paper deals with the optical technique that has been developed and validates its performance against a specially prepared test artefact containing 'erosion pits' of several different depths as well as on actual erosion scars produced with a particulate erosion system.

1. Introduction

Shortened service life of mechanical components and other complications due to wear are a considerable industrial burden for industry. Guides have been published to help engineers assess the damage and manage the consequent degradation of plant and equipment [1]. Erosion differs from wear in that it does not involve the interaction of two separate surfaces, however the resulting mechanical and financial consequences may be similar.

Erosion is defined as a "progressive loss of original material from a solid surface due to mechanical interaction between that surface and a fluid, a multi-component fluid, or impinging liquid or solid particles" [2]. Pressure vessels containing gas flowing at high speeds can erode internally, losing metal thickness (and consequently operational strength). This internal erosion can be caused by particulate contamination which becomes entrained in the flow. Its source may be environmental dust, oxides from the power plant itself, or other debris present in the system [3]. The effect can be exacerbated when the vessels are held at elevated temperatures, as is the case in turbines for the aero and power industries. Even before or after the turbines high pressure steam or hot combustion gases may flow through high pressure tubes which can become degraded by this hot erosion.

Work on the study of hot erosion testing and measurement intercomparisons between other systems have been reported by others [4]. In their paper they show some typical erosion damage, describe particle erosion mechanisms describe the equipment that was used in a round-robin erosion measurement intercomparison between 9 different partners. They later report [5] on the technical details of the instruments and erodent used. However none of the instruments used by the partners were capable of measuring the wear in situ, so required cooling and extraction of the test coupons before any measurements could be made using mass loss, contact and optical profilometry. ASTM G211 [6] dealing with the determination of material loss by entrained solid particles in a gas jet does not include the facility for the measurement of the wear scar of mass loss in situ. In order to facilitate and expedite the study of the effect of hot erosion on different materials, a purpose designed system is being built at the National Physical Laboratory (UK). Its goal is to measure and quantify erosion damage on test materials. To make accurate measurements it is important to quantify the damage at periodic intervals during a test so that reliable information on the progression of damage can be obtained. To do this efficiently it is necessary to be able to measure wear scars while the samples are still at temperature in the test system. Interrupting the test and allowing the specimen to cool in between measurements would be simpler, but with the cooling and heating times for the test system is time consuming, and the temperature regime that this imposes on the samples is not representative of the operating regimes that prevail in power plants.

To fit the NPL HTSPE test system, the requirement is for the volume of erosion scars to be measured remotely from a distance of some 450 mm while the specimen is at elevated temperatures (200 – 700 °C). The system must also be able to acquire its measurements

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without having access to a plan view of the specimen (as this is the direction from which the erodent will be injected). The double solution pursued in this work includes in-situ weighing – with a balance that can be locked off (to protect it from the large forces experienced during the erosion blasts), and an optical triangulation technique described below. These two methods were chosen because they were non-invasive and had the potential to give complimentary information – mass loss as well as shape of the erosion pit.

2. Measurement principle

The technique used in this work uses a line laser (projecting a straight line instead of a spot) and a conventional digital SLR camera, using the principle of laser triangulation [7,8]. Commercial systems are available for these measurements [9], but none of the available systems had the combination of violet light (to enable measurements to be made eventually at high temperature) and large measurement stand-off distance.

For this application, it is important that surface is optically rough so that it does not produce a specular reflection but a diffuse one. Although this may give rise to speckle – with its associated limitations [7] - it makes it possible for the camera to image the position of the projected line on the surface without being saturated by an intense specular reflection. What matters is the position where the line laser illuminates the surface, not the direction in which the combination of blue light subsequently reflects.

When a line laser is projected perpendicularly on to a surface, the line will appear like a straight line when viewed from the same direction as the line laser source. This will be true whether the surface is flat or curved. However, if the line laser is made to shine on a surface at an angle that is significantly different from the observation angle, the line will only appear straight if the surface is perfectly flat. If the surface of the specimen has bumps or dents the laser line will appear distorted. The sensitivity of the projected line deflection to the height or depth of the surface feature is higher if the glancing angle of the laser illumination (A) is made smaller, see Fig. 1. Although a smaller illumination angle would increase the sensitivity, it would make it impossible to illuminate erosion scars with steep edges.

In order to enhance the sensitivity of the arrangement, the camera is placed on the opposite side of the sample from the laser. Ideally the camera would be placed perpendicularly above the plane of the surface, but this position is not available as it is needed for the erodent injection system. A compromise was reached whereby both the line laser and the camera are mounted at 45 degrees to the surface of the specimen (A = B = 45 degrees in Fig. 1. The angles A and B are also shown in Fig. 2, and in Fig. 5 the angle A is also referred to as the "Illumination Angle").

It should be noted that the technique is not reliant on specular reflection of the laser line; the line laser is simply illuminating a section of the surface of the specimen and some of the light scattered at the surface (in all directions) is collected by the camera. A change in surface height affects where the scattered light is seen to be coming from. See Fig. 2. It should be noted that of all the light scattered from the surface of the scar, only the light scattered in the direction of the camera (marked with arrows towards the camera) will be collected to form the image.

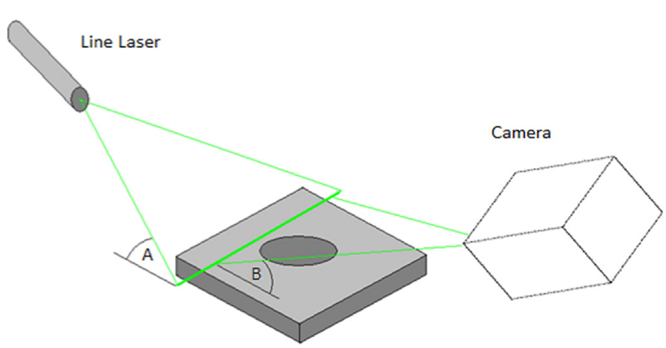

Fig. 1. Principle of the wear scar measurement technique.

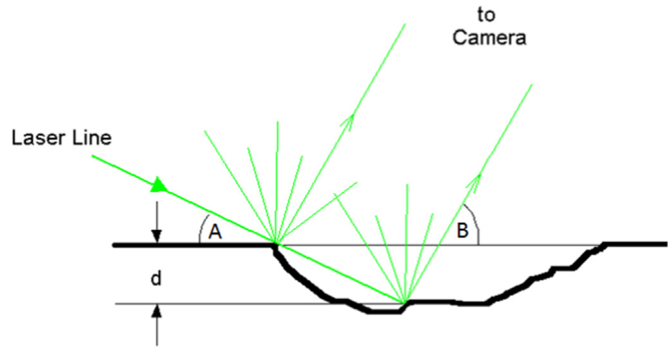

Fig. 2. Detail of how a change in vertical surface height affects the position at which the line laser will strike the surface, and hence where the scattered light will originate from.

3. Theory

Fig. 3 shows the left hand side of the erosion scar shown in Fig. 2. The laser line illumination comes towards the surface originating at the top left hand side making an angle A with the flat surface of the sample. The ray that grazes the undamaged surface proceeds to strike inside the erosion scar at a depth d below the original surface and there the light is scattered towards the camera, making an angle C between the incident ray and the scattered ray as shown in Fig. 3. L is the lateral displacement along the original surface of the sample between where the incident ray first strikes the still undamaged surface and the place from which the scattered ray goes past that surface line on the way towards the camera. Further clarification on the meaning of the symbols in the following theory are given in Figs. 2 and 3.

Using basic trigonometry we find the following relationships:

$$A + B + C = 180^\circ\ (\text{true for all triangles}),\ \text{therefore}$$
$$C = 180^\circ - A - B \quad (1)$$

$$(\text{Sin}\ C)/L = (\text{Sin}\ B)/X\ (\text{Sine rule}),\ \text{therefore}$$
$$X = L\,(\text{Sin}\ B)/(\text{Sin}\ C) \quad (2)$$

$$\text{Sin}\ A = d/X,\ \text{therefore}\quad d = X\ \text{Sin}\ A \quad (3)$$

Combining Eqs. (1)–(3),

$$d = L\left[\text{Sin}\ A\ \text{Sin}\ B\right]/\left[\text{Sin}\,(180 - A - B)\right] \quad (4)$$

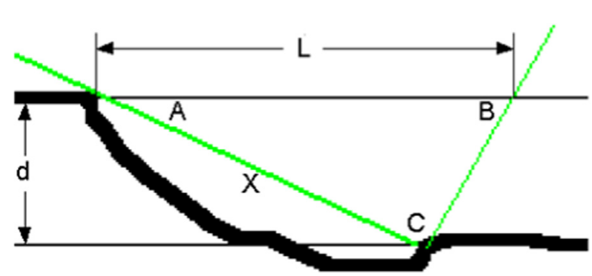

Fig. 3. Schematic diagram used to derive the theory.