Wear 342-343 (2015) 198–209

Contents lists available at ScienceDirect

Wear

journal homepage: www.elsevier.com/locate/wear

The effect of initial surface roughness on water droplet erosion behaviour

H.S. Kirols [a], D. Kevorkov [a], A. Uihlein [b], M. Medraj [a,c,*]

[a] Department of Mechanical and Industrial Engineering, Concordia University, 1455 de Maisonneuve Boulevard West, Montreal, QC, Canada H3G 1M8
[b] Thermal Power Transverse Technologies, Materials and Component Testing, ALSTOM Power, Brown Boveri Strasse 7, 5401 Baden, Switzerland
[c] Department of Mechanical and Materials Engineering, Masdar Institute, Masdar City P.O. Box 54224, Abu Dhabi, United Arab Emirates

ARTICLE INFO

Article history:
Received 18 May 2015
Received in revised form
20 August 2015
Accepted 24 August 2015
Available online 1 September 2015

Keywords:
Water droplet erosion
Surface roughness
Polishing
Incubation
Stainless steel
Ti6Al4V

ABSTRACT

Water droplet erosion (WDE) is defined as the progressive loss of original material from a solid surface due to continuous impingements of water droplets or jets. Several factors are known to influence the WDE process, such as impact speed and water droplet size. The initial surface roughness was not given enough attention in the literature as a factor that may influence the WDE behaviour of materials. In this work the effect of initial surface roughness on the WDE of a special martensitic stainless steel (12%Cr-steel) and Ti6Al4V is investigated. Experiments were done by varying three parameters: initial surface roughness, test speed, droplet size. It was concluded that the initial surface quality influences the length of the incubation stage, and may influence the maximum erosion rate. The amount of asperities and irregularities on the surface of samples was found to be the main reason for the difference in the WDE erosion behaviour. Moreover, the importance of reporting the initial surface of tested samples was emphasised, especially when comparisons between the WDE resistance of different substrate materials and/or treatments are held.

1. Introduction

To date, water droplet erosion (WDE) research has been driven by the power industry. Researchers have always tried to understand this complex phenomenon [1–8]. In steam turbines, for an example, low pressure (LP) cycles are the most affected by WDE. In these cycles, steam tends to condensate forming small liquid droplets impinging the supersonic rotating blades causing erosion [3,9–11].

In recent years, steam turbine blades' designers predominantly tend to increase the length of LP cycle blades, in an attempt to improve the output power. The increase in the blade length proportionally increases the linear speed at the leading edge of the blade's tip. In some cases it reaches 900 m/s [12] in a wet steam medium, causing severe erosion. Therefore, attention to the importance of WDE increased to a great extent.

The initial surface roughness of a steam turbine blade is defined by the manufacturing process. According to an EPRI report [13], large steam turbine blades are usually produced by forging, and their original surfaces could be improved by grinding, polishing and/or coating. Data collected from three manufacturers [13] shows that the acceptable original average surface roughness of low pressure steam turbine blades is in the range from 1 μm to 3.17 μm. It was also indicated in the EPRI report [13] that some surface finishing techniques used by manufacturers can reduce the initial surface roughness of blades to 0.3 μm.

The surface roughness effect on the water droplet erosion process was generally mentioned in the works of several researchers [3,5–7,14]. However, the attention given to the effect of initial surface roughness was not enough to quantify its importance. In his work on water-jet erosion, Honegger [7] claimed that a smooth surface is not affected by liquid impacts, as water flows off to either sides after collision. He added that upon successive impacts roughness is formed on the surface; hence, erosion starts. As soon as the roughness reaches a certain depth a protective liquid film that damps the following impacts is formed. Therefore, this protective layer causes the reduction in the erosion rate. Bowden and Brunton [14] proposed a theory explaining that the actual material removal mechanism in a rough surface is the shear failure of the asperities on the surface. This is caused by the radial outflow of droplets after impact. Heymann [3,9,15] agreed with Bowden and Brunton's [14] theory, and reported a valid analysis for the effect of surface roughness. He stated that sources of irregularities on the surface would act as stress raisers, and may help to initiate fatigue cracks due to the radial outflow of droplets.

* Corresponding author at: Department of Mechanical and Industrial Engineering, Concordia University, 1455 de Maisonneuve Boulevard West, Montreal, QC, Canada H3G 1M8. Tel.: +1 514 848 2424x3146; fax: +1 514 848 3175.
E-mail address: mmedraj@encs.concordia.ca (M. Medraj).

http://dx.doi.org/10.1016/j.wear.2015.08.019
0043-1648/

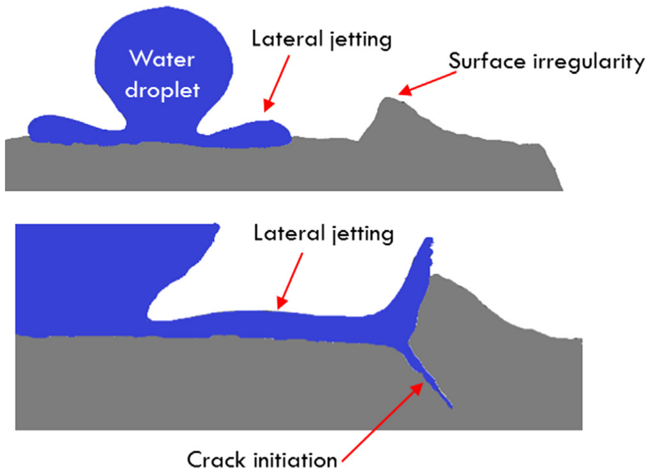

Fig. 1. Schematic reported by Heymann [15] to explain the effect of surface asperities.

However, the size of these irregularities matters. If they are small compared to the droplet diameter, there will be a great opportunity for lateral outflow attack, as shown in Fig. 1 [15]. When the damage is large enough exceeding the size of the droplet, the effect of impact is attenuated. He attributed this attenuation effect to two factors. Firstly, the impact itself may often occur on a sloping surface. Secondly, the lateral outflow will be disrupted and contained. Heymann [9] also added that for a given roughness, smaller droplets would have less potential to cause damage than larger droplets. During damage initiation, Huang et al. [16] also emphasised that surface discontinuities act as stress raisers and interact with lateral jetting, and as the amount of these irregularities increases, more surface damage is expected.

Field et al. [17] and Haag [18] elaborated the steps of water droplet erosion initiation. They explained that the hydraulic pressure caused by the droplet impacts produce what is called surface depressions, and upon repetitive impacts the depth of these depressions increases. In addition, after every impact a radial overflow of the droplets extrudes a surface feature called asperities. These asperities are considered as stress raisers and potential locations for fatigue crack propagation. Their analysis mirrors what was discussed by other researchers [3,9,14–16], regarding the effect of surface asperities and irregularities on erosion. The similarity between the analyses is that they all considered the presence or occurrence of asperities and irregularities on the surface as the main reason for the initiation of erosion. Mednikov et al. [19] and Foldyna et al. [20] presented micrographs to confirm the incremental increase of the surface roughness and the formation of surface irregularities on tested samples during the erosion initiation process. However, such irregularities and asperities can be also pre-existing due to surface preparation. Hence, if the surface initially had depressions and asperities, in case of high surface roughness, one can expect to have an accelerated erosion and vice versa. This suggests that surface original condition plays a significant role in the initiation of erosion pitting on the surface, which in turn affects the length of the incubation period. This is the subject of the current paper.

Many researchers [21–28] studied the effect of surface roughness on cavitation erosion. There are similarities in the damage progression of cavitation and water droplet erosion, in addition, they both exhibit time dependant erosion curves [3]. In the work of Wheeler [21], he showed that by periodic polishing of the surface, erosion can be kept indefinitely in the incubation stage. Karunamurthy et al. [22] and Litzow and Johannes [23] claimed that cavitation erosion is directly proportional to surface roughness. Dulias and Zum Gahr [24] indicated that the wear loss during reciprocating sliding and cavitation erosion decreases by decreasing the initial surface roughness. Tomlinson and Talks [25] discussed the effect of increasing surface roughness by electrochemical salt water corrosion of cast iron, and found that it reduces the cavitation erosion resistance, especially, decreasing the length of the incubation stage. In addition, Espitia and Toro [26] recorded the increase of surface roughness of stainless steel during the incubation stage of cavitation erosion through topographical measurement. The work of Espitia and Toro [26] is similar to what was presented by Tobin et al. [29] on water droplet erosion. Tobin et al. [29] recorded the increase of surface roughness during their experiments using topographical measurement as well. According to the reported results [21–26,29], and due to the similarity in the erosion progression of both wear problems, it should be expected that the initial surface roughness would affect resistance to water droplet erosion as it affects that of cavitation erosion.

Two experimental works were reported in the literature that held direct comparisons between the effect of different initial surface qualities on the water droplet erosion behaviour [5,6]; however, these experiments were mainly done using water-jets not actual water droplets. Firstly, Hancox and Brunton [5] used a jet of 1.3 mm diameter and impact speeds of 60 m/s and 90 m/s to study the effect of the initial surface roughness on the erosion behaviour for two different materials, poly methyl methacrylate and 18/8 stainless steel. A range of abrasive particle sizes, 1–37 μm, were used to prepare the surfaces of the samples. It has been claimed that coarse polishing of the samples increases the erosion rate. One drawback of their work is the low impact speed used for eroding the stainless steel samples, 90 m/s, which is considered unpractical, if compared to the actual in-service conditions of most WDE applications [12,30]. Secondly, DeCorso [6] studied the erosion behaviour of two stellite alloys, 6% and 12% Cr. The surfaces of the studied samples were prepared by two methods: mechanical-polishing and electro-polishing. The aim of this study [6] was not to determine the effect of initial surface roughness of samples on the erosion damage, but to study the effect of surface working due to mechanical-polishing on the damage. It was implied from the text that the initial surface roughness of the samples was less than 0.5 μm on average. Samples were tested using the single shot technique at water-jet velocities up to 1060 m/s and jet diameters up to 1.5 mm. The reported results were based on the measurement of dimensions of the erosion crater at the end of each experiment. It was concluded that changing the polishing technique did not have a significant effect on the erosion damage of both of the tested alloys. It is worth mentioning that DeCorso [6] did not explicitly study the effect of using different polishing techniques on WDE; however, it was only an issue he briefly raised.

Most of the reported experimental work was done using water jets [5–7,14,17], therefore, there is a strong need for quantitative experimental results produced using actual water droplets to simulate the real case of WDE. In addition, the work done so far in the literature is not enough to have a decisive conclusion about the level of importance of this factor, because only few researchers such as Hancox and Brunton [5] reported a parametric study to investigate the effect of initial surface roughness on the erosion process. However, effect of roughness was presented [5] as an additional investigation in their work, and tests were done at relatively low speeds. They also claimed that the slight change in initial surface roughness below an average scratch depth of 10 μm, significantly influenced the length of the incubation stage of their experiments. It is important to further verify such claim for more-practical (higher) test speeds and different droplet sizes. This is especially important because the difference in initial surface roughness may be one of the factors that make the comparison of