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Energy based approach for understanding water droplet erosion

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ABSTRACT

Water droplet erosion (WDE) is a complex wear phenomenon with many interacting parameters. For decades, many test rigs and instruments have been developed to study it, producing a vast amount of useful data pertinent to WDE resistance of different structural materials. Comparing test results produced by different test rigs has always been a challenge, since test conditions used by each rig were difficult to replicate by other test setups. In this work, a new method of representing WDE results in terms of the applied energy intensity is proposed. This method is used to report the WDE test results of three structural materials (12% Cr stainless steel, Ti6Al4V and TiAl) tested at various conditions. The new representation enables better comparison between test results. A new coefficient (ξ) is introduced as a measure of how representative the applied energy intensity is for WDE tests. The proposed severity coefficient (ξ) captures the variation in the absorbed energy by the sample's surface due to test conditions change. This is achieved by quantifying the materials response to the change in WDE test parameters. (ξ) is then used to compare the results of WDE experiments done at various erosion conditions or even on different test rigs.

1. Introduction

Water droplet erosion (WDE) is defined as the progressive material loss from a solid surface due to successive water droplets impacts [1]. The study of water droplet erosion (WDE) as a wear phenomenon started in the early 20th century by researchers and scientists who were trying to find erosion-resistant materials for steam turbine blades [2–4]. The low pressure cycle blades of steam turbines are subjected to water droplet impacts due to their rotation at supersonic speeds in a wet steam medium [2,5–9]. The main concern of researchers was to relate the erosion performance of different materials to their mechanical properties [10–13]. However, due to the complexity of this phenomenon and the lack of accurate test instruments, little success was achieved.

Throughout the years, many test rigs and instruments have been developed to study WDE [5,14–17]. They produce a great amount of useful data about the WDE resistance of different materials. Unfortunately, it has always been difficult to compare results produced by different test rigs, because the process has not been standardized and test conditions used by each rig were difficult to replicate. In addition, due to the complexity of WDE phenomenon, it has been found that even changing the erosion test conditions on the same rig, causes a great change in the erosion results produced for the same material [5,15,18–20]. Therefore, there is a serious need for discussing the reasons for such scatter in test results. In order to carry out such discussion, and since a general quantitative method suitable for representing WDE results-from different sources or even from the same rig when different erosion conditions are used could not be found in the literature, such method should be developed first. A review of the available methods in the literature for the representation of WDE test results is presented in the following two sections.

1.1. Methods used to report WDE experimental results and their drawbacks

According to the ASTM G73-10 standard [1], erosion is usually reported as a plot of cumulative erosion versus the cumulative periodic interruption of the test to weigh the samples (cumulative exposure). Exposure could be any physical quantity which is a function of the test duration. In the literature, there were not many quantities used as cumulative exposure. The most used representation of exposure so far is the cumulative time [10,12,14,19,21]. This method of representation neglects the size of water droplets used and the effective amount of water that actually causes erosion. In the works of Mann et al. [16,22,23], exposure was referred to as number of cycles, or the frequency of rotation multiplied by cumulative time. However, this method does not indicate the amount of water impacting the sample per cycle. These two methods of representing the exposure axis can be used for qualitative comparisons of the erosion resistance of different materials on a specific erosion test rig. Nonetheless, they do not permit the direct comparison between WDE test results produced by different erosion rigs. Even tests

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done on the same rig using different test conditions (i.e. droplet sizes, impact speeds) cannot be quantitatively compared.

Recently, Ryzhenkov et al. [8] claimed that for a well-defined erosion experiment the following parameters should be measured and identified: (a) impingement speed; (b) droplet size distribution; (c) number of impinging liquid droplets. In addition, as discussed in our previous work [18], the initial surface roughness should be reported and kept constant as it has a significant effect on erosion initiation (i.e. the incubation period). Some researchers reported [18,20,24,25] such details about their experiments, which enabled a better understanding of their results. Seleznev et al. [24] reported erosion results as curves between material loss (i.e. mainly volume loss per unit area) and the mass of water impacting the surface of the samples. Mahdipoor et al. [20,25] reported erosion as volume loss per unit area versus the volume of water impacting a unit area of the surface. By far, these methods are the best representations for WDE found in the literature, since they allow comparison between results of tests done using different water droplet sizes.

Moreover, several mathematical equations were proposed to represent the WDE behavior. Some of these equations were based on the similarity between fatigue damage and erosion process [13,21]. Another equation was based on correlating the essential erosion parameters with the erosion rate [6]. Other equations tried to link the erosion damage to the applied energy flux on the surface [10,11,26]. The following section presents some of the attempts to relate the WDE behavior to materials properties using the energy flux approach.

1.2. A review of attempts to relate the material's WDE to the applied kinetic energy

Due to the high plastic deformation encountered in the erosion process, it was logical that several scientists [10,11,26] attempted to balance the energy involved in it, in order to relate erosion to materials' properties. The main obstacle that confounded researchers in this endeavor, was the quantification of the amount of energy transferred to the solid surface during droplets' impingements.

One of the early attempts to explain the energy balance was the work done by Hoff et al. [10,26]. In their work on the rain erosion problem, they developed a formula for a term called erosion strength, *f*, defined as a ratio between the applied energy flux and the volumetric material loss. Hoff et al. [10,26] made several assumptions to derive an equation for *f*. They claimed that energy absorption by a solid surface is governed by a factor (λ), which can be divided into two parts. The first part monotonically depends on the applied impact pressure, and the second part depends on the sound impedances of both the target material and water. The final formula for *f* is a combination of several functions that satisfied their assumptions. Heymann [13] disputed their final formula, since it was more concerned with the response of the material, and totally neglected the issue of what portion of impact energy (E) was actually transferred to the surface of the target material due to the impact. In addition, the formula neglected the fact that part of the impact energy dissipates, through the subdivision of the water droplet into smaller ones during impact, for instance, and may not affect the target material's surface.

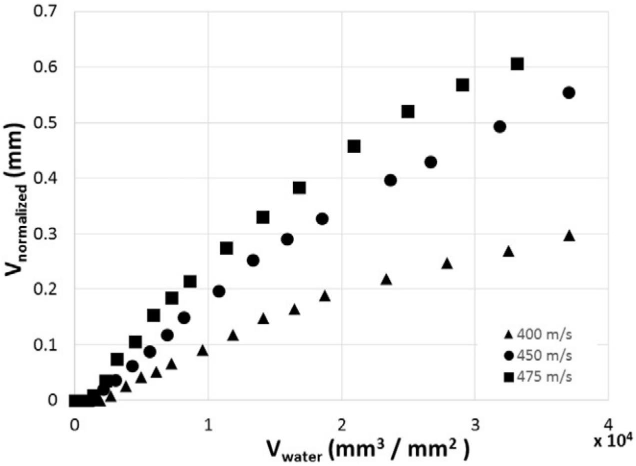

Fig. 1. Erosion curves of 12% Cr stainless steel tested at three different speeds using 220 μm droplets.

Later on, Hammitt et al. [11] worked more on Hoff's basic energy flux model. They developed an equation based on the relation between the mean depth of erosion penetration (*MDPR*) and the applied kinetic energy. Moreover, they named a factor, η, that they defined as the efficiency of energy transfer between the impinging droplet and the solid surface. It was mentioned in their work that this efficiency should be a function of several factors, including: (a) liquid and solid material properties, mainly: (a) the acoustic impedance, (b) the geometric aspects of both the surface and the impinging droplets (droplet shape, impingement angle, surface roughness), and (c) the velocity of impingement. However, they did not develop a formula that mathematically describes this term.

Similar analysis was done by Heymann [13], he admitted that the liquid/solid energy balance was very complex. He elaborated on the distribution of the droplet's kinetic energy after impingement, and claimed that: (a) part of the energy will remain as kinetic energy of the lateral outflow after the impingement; (b) another part will be dissipated in the form of pressure waves reflected inside the droplet itself; (c) the last part will be absorbed by the target material. Heymann [13] also added that the amount of energy transferred to the solid surface is a function not only of the mass and speed of the impinging droplets, but also of the behavior of the droplet after impingement. The water droplet behavior after impingement means the change in size and shape of the liquid droplet after impingement, and its possible subdivision into smaller droplets.

Thiruvengadam et al. [12,21] attempted to find a formula that describes what they called the erosion strength (S_e). The final form of their reported formula is shown in Eq. (1).

$$S_e = \frac{A^2\, I_c\, M^2}{t_1^2\, (r\cdot)^3_{max}} \tag{1}$$

where

$$M = \frac{\alpha}{\left[e^1 (e^1 - 1)\right]^2}, \tag{2}$$

Table 1
WDE test represented by $N_{specific}$ and the maximum erosion rate (ER).

	Speed (m/s)	$N_{specific}$ (droplets)			ER (mm^3/mm^3)		
		Ti64[a]	TiAl[a]	12% Cr SSt.[b]	Ti64[a]	TiAl[a]	12% Cr SSt.[b]
220 μm droplets	400	–	–	17,377	–	–	0.91
	450	–	–	11,730	–	–	1.55
	475	–	–	8254	–	–	2.22
460 μm droplets	275	55,000	72,000	–	2.4	0.36	–
	300	21,000	72,000	29,083	5	0.87	1.59
	325	7600	32,000	–	7.3	3.7	–
	350	2300	9400	10,179	19	7.5	4.16
603 μm droplets	275	11,000	72,000	–	2.5	0.63	–
	300	11,000	31,000	10,709	5.9	0.93	2.44
	325	5300	11,000	–	10	5.5	–
	350	2800	5900	6997	17	6.8	5.48

[a] All Ti6Al4V and TiAl data are from the authors' previous work [20].

[b] All the 12% Cr Stainless steel data are from authors' previous work [18], points highlighted in grey are reported for the first time in this work.