Materials and Design 104 (2016) 76–86

Contents lists available at ScienceDirect

Materials and Design

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

Energy based approach for understanding water droplet erosion

H.S. Kirols [a], M.S. Mahdipoor [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, QC, Montreal H3G 1M8, Canada
[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 17 January 2016
Received in revised form 27 April 2016
Accepted 28 April 2016
Available online 29 April 2016

Keywords:
Water droplet erosion
Stainless steel
Ti6Al4V
TiAl
Energy intensity

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

---

* Corresponding author.
E-mail address: mmedraj@encs.concordia.ca (M. Medraj).

http://dx.doi.org/10.1016/j.matdes.2016.04.089
0264-1275/

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.

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

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

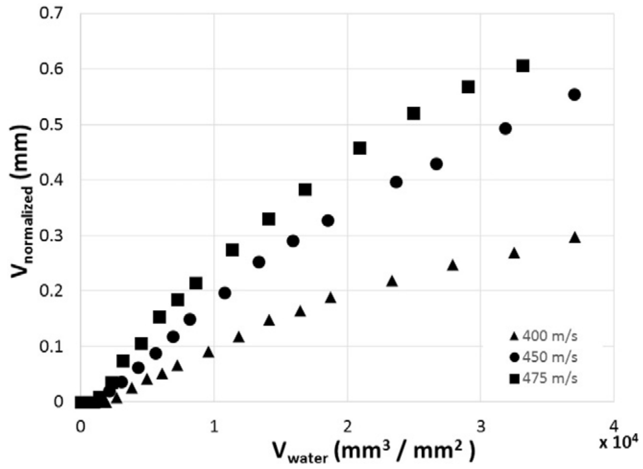

Fig. 1. Erosion curves of 12% Cr stainless steel tested at three different speeds using 220 μm droplets.

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.

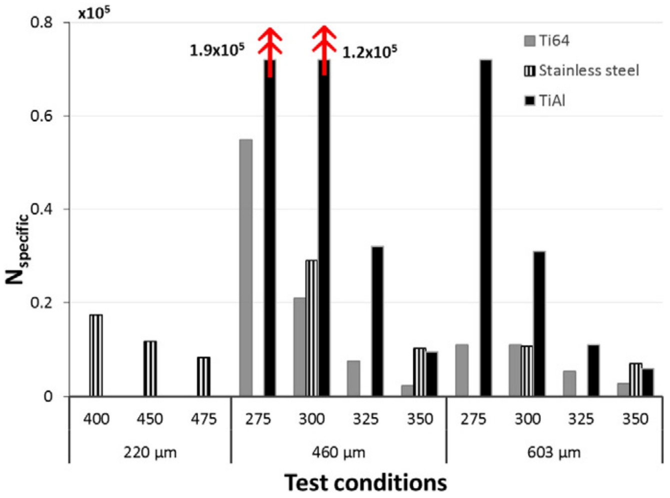

Fig. 2. Incubation period of three materials represented in terms of specific impacts.

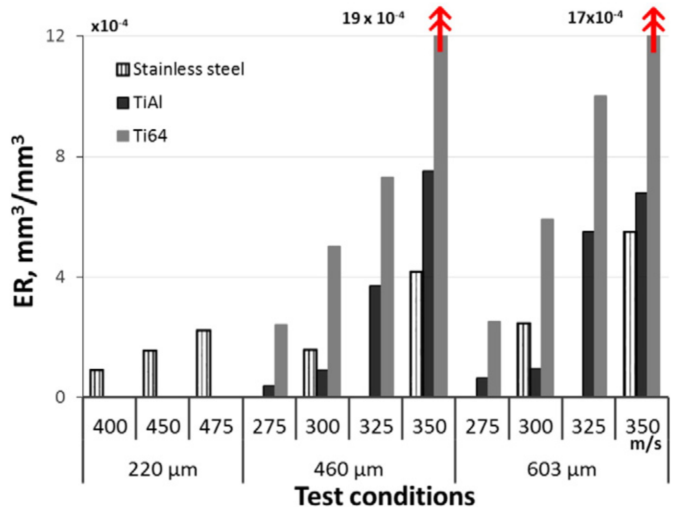

Fig. 3. Erosion rate of three materials represented in terms of volume loss per applied unit volume of water.

A is a dimensionless constant, I_c is the power intensity of impact (power applied per unit area), t_1 is the time corresponding to the maximum power absorbed per unit eroded area, r is the change in erosion depth with time, and α is a Weibull distribution shape parameter.

They developed such equation based on two assumptions. The first assumption stated that the impact is attenuated by any pre-existing liquid film on the surface of the target material [21]. Their second assumption was concerned with the material's resistance to erosion. They assumed that after impact attenuation due to any pre-existing liquid film, part of the remaining energy is absorbed by the target material and caused erosion. This part of energy is governed by the material's resistance to erosion [21]. They developed a term called the efficiency of erosion as the material's property that satisfies their second assumption ($\eta_e = \frac{I_e}{I}$, where I_e is the power absorbed by a unit area to cause erosion, and I is the remaining power intensity after attenuation). According to their definition, the term η_e is associated with the probability of failure, and they used the Weibull statistical function to represent it ($\eta_e = 1 - \exp(-(\frac{t}{t_1})^\alpha)$). Thiruvengadam et al. [12,21] believed that WDE was similar to fatigue failure, that is why the Weibull distribution was used (Weibull distribution is usually used for fatigue analysis). This method of modeling erosion [12,21] is very valuable, and the current work gained a lot from its concepts. However, erosion wear is a more complex phenomenon with several interacting parameters, not only fatigue and liquid film formation. For instance, the droplet size and surface roughness, which were not taken into account in the modeling, also influence the erosion process and may produce a totally different Weibull distribution. In addition, in their work [12,21], they did not indicate how WDE test results done using different facilities could be compared.

In conclusion, all of the discussed approaches are more than 40 years old now, none of them proved to be a general representation for what is so called the erosion strength. The reason for this might have been the lack of accurate and consistent water erosion measurements at that time.

The objective of this paper is concerned with improving WDE test results representation. The importance of this objective lies in the prominence of the affected applications by WDE. In addition, there is a need to evaluate newly developed materials and surface treatments proposed to combat WDE (tested using different facilities) by comparing their performances to each other in a quantitative way. Therefore, a novel method to report WDE test results in terms of the applied kinetic energy intensity is proposed. After reporting WDE using this new method, the variances between curves of different tests are quantified using a new term named as zeta (ξ) or the severity coefficient. (ξ) is a measure for the “variation” in the absorbed energy due to changing the test conditions. This approach should be an addition to the traditional WDE experimental data representation and analysis, it should help to: (a) further understand the physical meaning behind test results (b) compare results of tests done at different erosion test conditions, and as an ultimate goal (c) compare results of tests done using different rigs.

2. Experimental procedure

In order to develop a method that addresses water droplet erosion data representation, several test parameters should be well identified, they are mainly: (a) impingement speed, (b) droplet size distribution, and (c) number of impinging water droplets per impact. Additionally, it is important to keep other parameters constant for comparison purposes, otherwise comparison would become very difficult. One of these parameters was studied in our previous work [18], which is the initial surface roughness of samples. It was found that initial surface roughness influences the length of the incubation period and may also affect the maximum erosion rate. The second parameter that should be kept constant is the initial impact angle. Other test parameters may also affect the erosion process but cannot be avoided or kept constant during WDE testing, examples would be: centrifugal forces [5], the time between two successive impacts especially when testing at different impact speeds [13], the pattern of water droplet impacts when different droplet sizes are used (number of droplets impacting at once), and the interaction between droplets and their subdivision after impact.

Experiments done in this work were performed using the WDE rig at Concordia University. Many of the test parameters were measured, controlled and reported in our previous works [18,20,27], which was possible due to the presence of an advanced erosion rig and imaging system. Measured parameters were mainly: (a) droplet size, (b) impact speed, and (c) number of droplets per impact, (d) number of impacts (Same as the rpm of the rotating part), and (e) impacted area (f) initial surface roughness, and (g) initial angle of impact. In our opinion, these parameters are measurable and controllable by most of the available test devices and rigs, not like other parameters that are dependent on the design of the test rig itself. For instance, the frequency of impact (the time between two successive impacts) is dependent on the test speed (in case of a rotating arm/disk) and the dimensions of the rotating part. Therefore in our opinion, to have a common understanding for the conducted experimentation by different test devices, defining

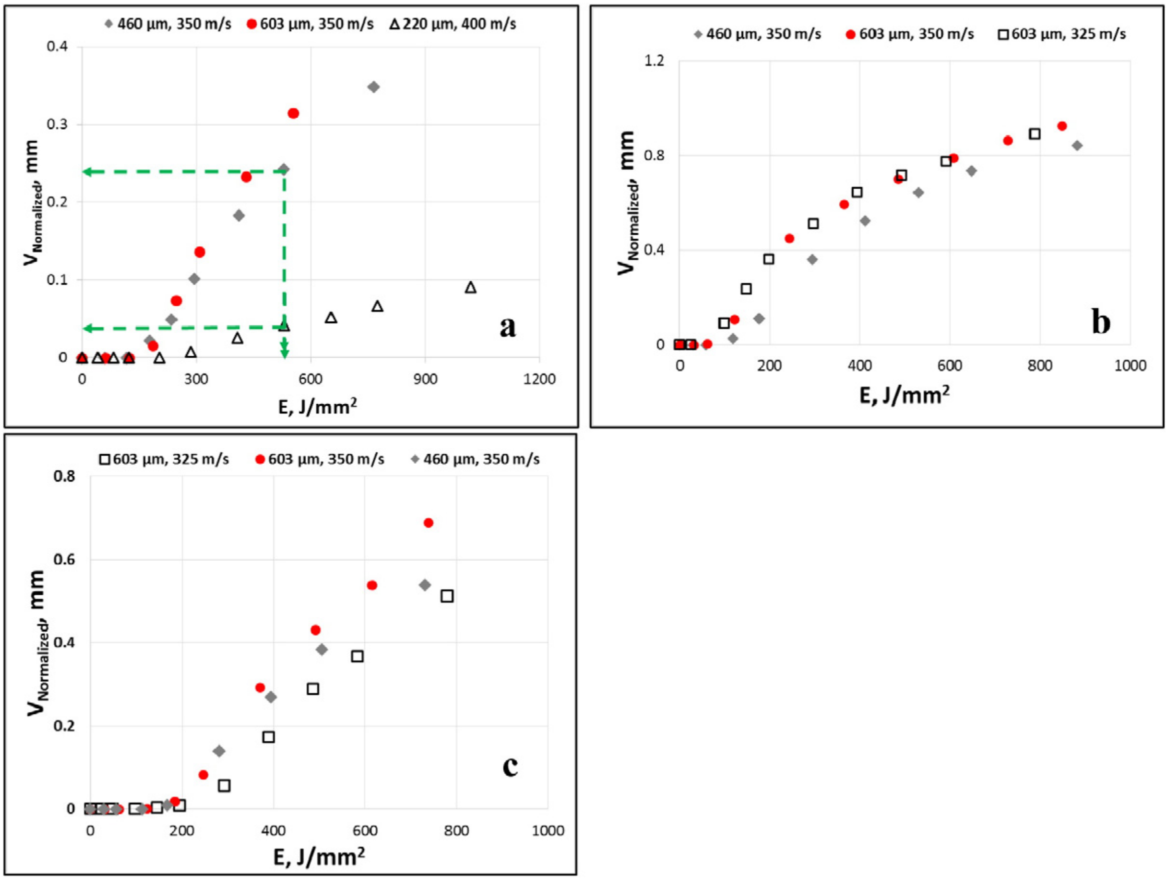

Fig. 4. Erosion curves for different materials tested at different test conditions (a) 12% Cr stainless steel, (b) Ti6Al4V, (c) TiAl.

these parameters is the minimum amount of information to describe the test. As a result, erosion results can be analyzed and presented in quantitative ways.

The erosion resistance of three different materials is compared in this work. These materials are: 12% Cr stainless steel, Ti6Al4V and TiAl. Results presented in this work come from several sources. For 12% Cr stainless steel, experimental results were mainly obtained from our previous work [18]. Moreover, for this work additional experiments were performed on 12% Cr stainless steel samples using 220 μm droplets at three impact speeds (400, 450 and 475 m/s). The number of droplets impacting an erosion line per rotation is 16, on average. The initial surface roughness of samples was set to 0.2 μm Ra. For Ti6Al4V and TiAl, experimental results were obtained from our previous work [20]. This large amount of information will help in the development of the representation method. In this paper, experimental results are analyzed and represented using the new method. Moreover, some experiments in this data set were done at similar test conditions but for different materials. Therefore, comparisons between their performances are necessary and will be presented for the first time in this paper.

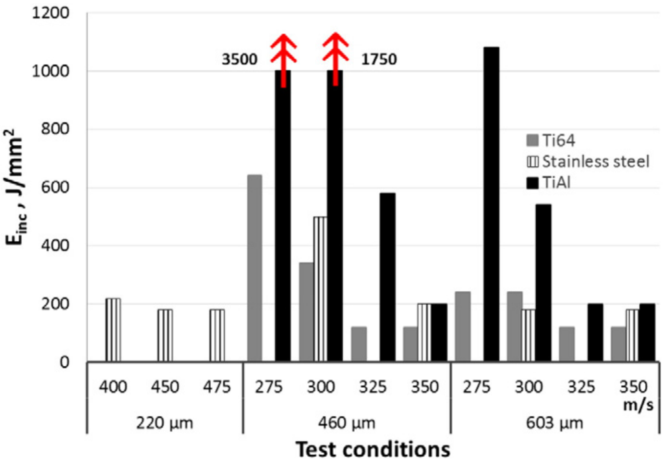

Fig. 5. Incubation energy (E_{inc}) of three materials tested at different conditions.

3. Results

As mentioned in Section 1.2, in this work three high speed tests (i.e. 400, 450, 475 m/s) were performed for the 12% Cr stainless using 220 μm droplets. Fig. 1 shows the erosion results in terms of volume loss per unit impacted area ($V_{normalized}$) versus the volume of water impacting a unit area (V_{water}). It is worth mentioning that not many tests in the literature were reported at these high speeds using actual water droplets. Usually, high speed experiments are carried out using accelerated water jets with stationary samples [28]. Exceptions for experiments carried out at similar speeds to the current work using water droplets are the works of Ahmad et al. [19] and Seleznev et al. [24].

Experimental results can be analyzed and represented in several ways. For instance, the incubation period can be reported as the incubation specific impacts ($N_{specific}$) in light of the ASTM G73 standard [1,18,20]. In addition, the maximum erosion rates (ER) can be reported as the volume loss per applied unit volume of water [1,18,20]. Table 1 and Figs. 2–3 show data represented in the mentioned method [1,18,20].

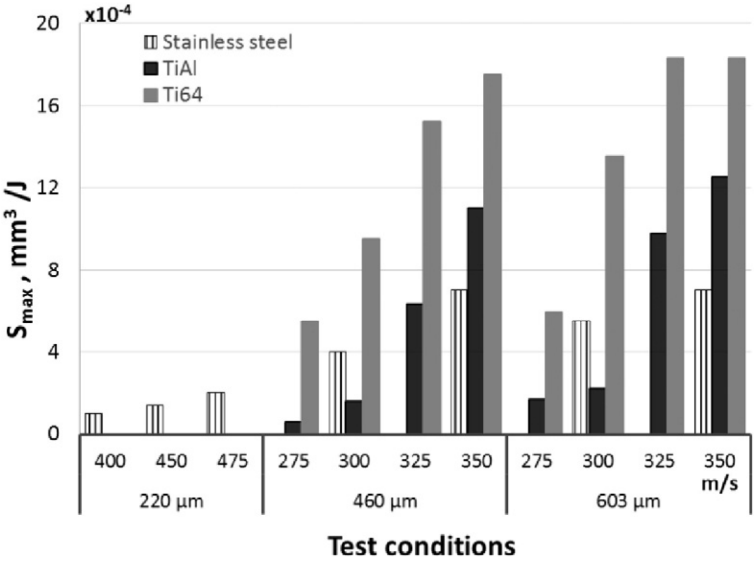

Fig. 6. Maximum erosion slope (S_{max}) of three materials tested at different conditions.

Although, this representation provides a different perspective of the data as can be seen in the Discussion section below, it still does not solve the main issue of providing a generic approach that can be used to compare test results generated using different rigs. This will be attempted here using the kinetic energy approach.

As can be seen in Fig. 2, for the same droplet size, $N_{specific}$ decreases as the impact speed increases. In Fig. 3, also for the same droplet size, ER increases with the increase in the impact speed. These results show a direct correlation between the erosion process and the impact speed. This method of results representation is suitable for such comparisons, and could enable quantifying the dependence of ER or $N_{specific}$ on the impact speed or even the droplet size. However, this way of data analysis is suitable when comparing the results of WDE tests done using the same experimental procedure, or to be more specific, using the same test rig. Other test rigs have other factors that may influence the erosion results, for instance, the pressure of the chamber where the experiments were carried out, the direction of water droplets injection, the amount of water droplets impacting the surface of the sample per cycle, etc. A new method of representation should be developed to directly link the experimental results to the impingement conditions and their physical meaning. If the underlying physical principles are uncovered, experimental results performed using different erosion rigs could be compared. To achieve this, the exposure axis (x-axis) should contain all of the important erosion test parameters (i.e. impact speed, droplet size, and number of droplets per impact). Due to the presence of a large amount of information about the erosion experiments at hand, erosion can be reported in a more rational and representative way. The physical quantity that could include all of these parameters is the kinetic energy of the water droplets and its transfer regimes upon interaction with the surface.

As discussed in Section 1.2, attempting to understand WDE with respect to the kinetic energy applied on the surface is not new, as it was debated in the literature by many researchers [10,11,13,21,29]. These efforts were of great help to the current work, which benefited immensely from the understanding of the physics of the process and continued these efforts to develop better representation of WDE results. Herein, the applied kinetic energy of impact was calculated based on the average number of droplets impacting the samples during the test, which is a new way to quantify this energy for WDE tests. After calculating the applied kinetic energy, it is used as the x-axis of the WDE curve. In the following section, the new method for estimating the applied kinetic energy to represent WDE results is discussed in details.

3.1. Erosion representation in terms of applied kinetic energy

One of the aims of this paper is to practically relate WDE to the applied energy (measurable) not the absorbed energy (difficult to actually measure or compute). The applied energy is mainly the kinetic energy, which stems from two main contributions; the mass of the impacting water droplets and the speed of impact. Hence, the total energy applied on the surface is the cumulative kinetic energy of the water droplets, which could be calculated based on the following equation:

$$E_k = \frac{1}{2} \cdot m \cdot v^2 \qquad (3)$$

where

$$m = N_{drop} \cdot \rho_{water} \cdot V_{drop}, \qquad (4)$$

v is the impingement speed, N_{drop} is the number of droplets impinging the surface, V_{drop} is the volume of one droplet assuming it to be a sphere, and ρ_{water} is the density of water. All details pertinent to measuring these parameters were reported in our previous works [18,20].

Another parameter that should be taken into account is the impacted area for the simple reason that larger droplets impact relatively larger areas and vice versa. Therefore, this area should be taken into account when calculating the applied kinetic energy of impact. The value of such area was measured from the optical macrographs at the end of the incubation periods. After normalizing the applied kinetic energy by the impacted area, it will be referred to as the applied energy intensity (E).

Volume loss is a more general method to represent the y-axis, using this term makes it possible to compare materials with different densities.

$$V_{loss} = \frac{m_{loss}}{\rho_{material}} \qquad (5)$$

Volume loss was also normalized using the impacted area. Hence, it means the amount of volume loss per unit impacted area. Another important reason for normalizing both the x and y axes using the same

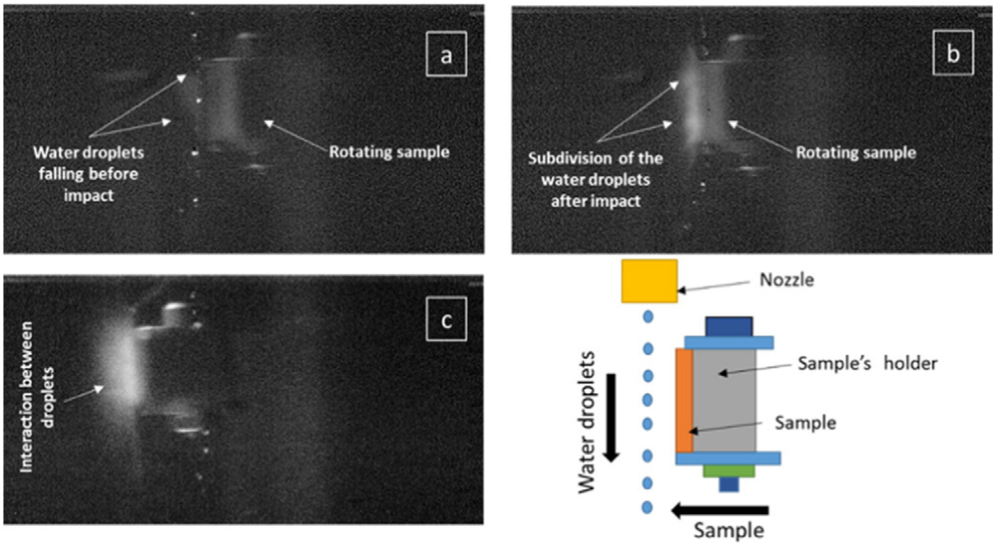

Fig. 7. Images inside the erosion rig of Concordia University at the moment of impact taken at 16,000 fps for a test done at 300 m/s using 460 μm droplets (a) the water droplets falling before impact; (b) the subdivision of water droplets just after impact; (c) the migration of small water droplets from the surface; (d) a schematic for the sample rotation direction and water droplets before impact.

area is to have an erosion rate that is not influenced by any error in measuring the impacted area.

Fig. 4 (a, b and c) show examples of WDE test results for the three materials after using the cumulative energy intensity as the x-axis and the normalized volume loss as the y-axis. Two erosion indicators could be extracted from the erosion curves. The first indicator is the incubation energy (E_{inc}), which is the amount of energy intensity exerted to end incubation. The second indicator is the maximum erosion slope (S_{max}). The values of these indicators for the three materials tested at different test conditions are presented in Figs. 5 and 6.

Theoretically, the same applied kinetic energy should cause the same level of erosion, independent of the erosion parameters used in each experiment. Hence, one may expect the values of the E_{inc} and S_{max} indicators for each material to be the same at different test conditions. This did happen in some occasions as shown in Fig. 4 which means that for these particular test conditions, the response of the material is the same, when different test conditions (i.e. impact speed and droplet size) were used. However, this did not happen for all the data sets. The dashed arrow lines in Fig. 4 (a) represent a specific amount of applied kinetic energy, and it is clear that the material response is different for each combination of test parameters. In order to understand these variations, it is important to understand the relation between the erosion parameters (droplet size and impact speed) and the applied kinetic energy. This takes us to the concept of the efficiency of energy transfer due droplet/solid surface interaction, and how this efficiency varies by changing the test conditions [11,13]. This concept and the analysis of the experimental results using this new representation method are discussed in the following section.

4. Discussion

It can be seen from Figs. 5 and 6 that for most cases, and for the same energy intensity, the volume loss is different for different erosion test conditions. This is highly attributed to the efficiency of energy transfer from the impacting water droplet through the target's surface. In addition, part of this difference can be related to the change in the materials dynamic mechanical properties due to changing the frequency of impact as a result of changing the impact speed. As reviewed in Section 1.2, it was elaborated by previous studies that quantifying the efficiency of energy transfer is very difficult. This is due to difficulties in enumerating the amount of energy dissipated and that absorbed by the target, as they depend on a wide range of interacting parameters. Some of the reasons for energy dissipation are erosion conditions dependent (i.e. impact speed, droplet size and the amount of water, angle of impact, surface roughness), some are dependent on the properties of the solid and the liquid (i.e. mechanical properties, density of the tested material, speed of sound in the solid and liquid) and others are due to the interaction between these parameters. The following subsections discuss observations during the execution of experiments, and analyses of test results.

4.1. Observations and analyses of test results after representing WDE curves in terms of energy

4.1.1. Subdivision of water droplets after impact

During the execution of experiments the subdivision of water droplets after impact was observed. A high speed imaging system was installed on the erosion rig used in this work; this system is capable of capturing the moment of impact. Images in Fig. 7 were taken at 16,000 frames per second (fps), for a test done at a speed of 300 m/s using 460 μm droplets. As can be seen from these images, after impingement, the water droplets were subdivided into smaller droplets, as they start to move away from the sample's surface. These results confirm some of Heymann's hypotheses [13], when he studied the deformation mechanism of the water droplet after impact. He assumed that part of the energy is dissipated due to the change of the droplet's flow direction, which is usually called the lateral outflow. In addition, he also claimed that another part will reflect as shock pressure waves inside the droplet itself. Then he said that since the water droplet deforms and subdivides after impact, the damage energy imposed on the surface is a function of the size and shape into which it is subdivided. It means that part of the applied kinetic energy migrates from the surface through the droplet deformation or subdivision. Heymann did not provide any experimental proof for his hypothesis. The images in Fig. 7 confirm this hypothesis, where a portion of the applied kinetic energy is dissipated through the subdivision of water droplets at the moment of impact.

It is expected that by changing the impact speed and the droplet size, the mechanism of droplet subdivision will be different. Lesser et al. [30] claimed that the response of the water droplet changes by changing the

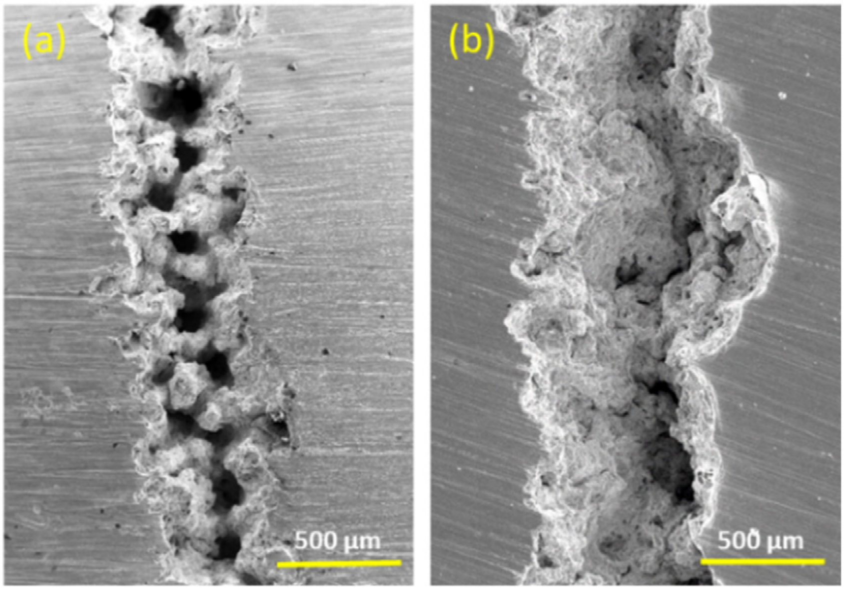

Fig. 8. Craters formed due to WDE of 12% Cr stainless steel, when tested using (a) 220 μm droplets, (b) 460 μm droplets.

impact speed, and they stated: "if the impact speed is sufficiently low for a given liquid, distinct shocks and high-speed jetting would not be expected", and vice versa.

4.1.2. Relation between droplet size and the size of erosion crater

Another observed factor that may cause a difference in the erosion response of the same material when subjected to the same amount of energy using different test conditions, is the interaction between the droplet size and the morphology of the formed erosion crater. For instance, in the case of stainless steel, six tests showed incubation energy in the range of 180–220 J/mm^2. However after the end of incubation, the maximum erosion slopes showed large differences between the experiments using 460 μm droplets and 603 μm droplet sizes on one side, and the experiments using 220 μm droplets on the other. For an example, as shown in Fig. 4 (a), the maximum erosion slope of the test performed at 350 m/s using 460 μm droplets is higher than that of the test carried out using 220 μm and 400 m/s. Although, the used impact speed in this test is higher (i.e. 400 m/s), the used droplet size is smaller (i.e. 220 μm droplets). This suggests that until the end of the incubation period, the material responded similarly when subjected to these combinations of droplet sizes and speeds. As the WDE craters started to form, it seems that the droplet size started to play a larger role in the erosion process. In order to verify this argument, the fracture surfaces resulted from two tests, performed using different droplet sizes, 220 μm and 460 μm, were studied using the SEM, as shown in Fig. 8. It is important to mention that both samples are in their terminal erosion stages. Fig. 8 (a) shows the formation of pits in a size range of 100–300 μm on the eroded surface of stainless steel samples, when tested using 220 μm droplets. It can be seen that the formed pits are abundant on the surface, and that the size of these pits are close to the droplet size used in the test (220 μm). It was not the case in Fig. 8 (b), when the sample was tested using 460 μm droplets, since the surface does not show any special pattern in the erosion crater. These images suggest that there is a relation between: (a) the maximum erosion slope, (b) water droplet size, and (c) any morphological pattern of the crater.

This argument can also be supported by Heymann [13], as he claimed that when the damage on the surface 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. To conclude, the amount of energy transferred to the surface, not only depends on the test parameters, but also on the morphology of the eroded surface (the formed erosion crater in the advanced stages).

4.1.3. Similarity and coincidence of erosion curves for the same material tested at different erosion conditions

Several curves coincided when x-axis was represented in terms of energy intensity for the three materials. For 12% Cr stainless steel, tests done at 350 m/s using 460 μm droplets and 603 μm droplets coincided as shown in Fig. 4. Three experiments showed close results for Ti6Al4V, the first two curves are for tests done at 350 m/s using 460 μm droplets and 603 μm droplets, the third test was done at 325 m/s using 603 μm droplets, these curves are shown in Fig. 4 (b). In the case of TiAl, also three tests showed close results similar to the case of Ti6Al4V, as shown in Fig. 6. This means that for these tests the different test conditions did not change the materials volume loss at the same energy intensity level. In our previous work [18], it was claimed that there is a threshold speed after which the droplet size ceases to have an effect on the extent of damage when the same amount of water is used. This claim was based on the explanation of DeCorso [9]. In addition, the overlap of curves for the 12% Cr stainless steel was justified using this claim when curves were represented in terms of mass loss versus amount of water impacting the surface [18]. In this work and due to expressing the exposure axis in terms of the energy intensity, coincidence of curves found for the three materials (i.e. 12% Cr stainless steel, Ti6Al4V, and TiAl) can be explained in terms of the applied energy. It could be claimed that the energy intensity applied on samples in experiments producing coinciding curves is the same.

In the case of Ti6Al4V and TiAl, tests done for both materials using 460 μm droplets at 350 m/s showed the same erosion as tests performed using 603 μm droplets at 325 m/s. Although both the droplet sizes and speeds are different, similar erosion is produced. These results suggest that there are two opposing and competing parameters (i.e. increase in droplet size and decrease in speed) that are playing roles in the erosion process, and these experiments are showing the break-even point for their effects. Therefore, the effect of the increase in droplet size (i.e. from 460 μm to 603 μm) was compensated by the decrease in impact speed (i.e. from 350 to 325 m/s), for these two materials.

These results suggest that although the erosion mechanism is different, experiments done at low speeds and large droplet sizes may be used to simulate water erosion at conditions desired for practical

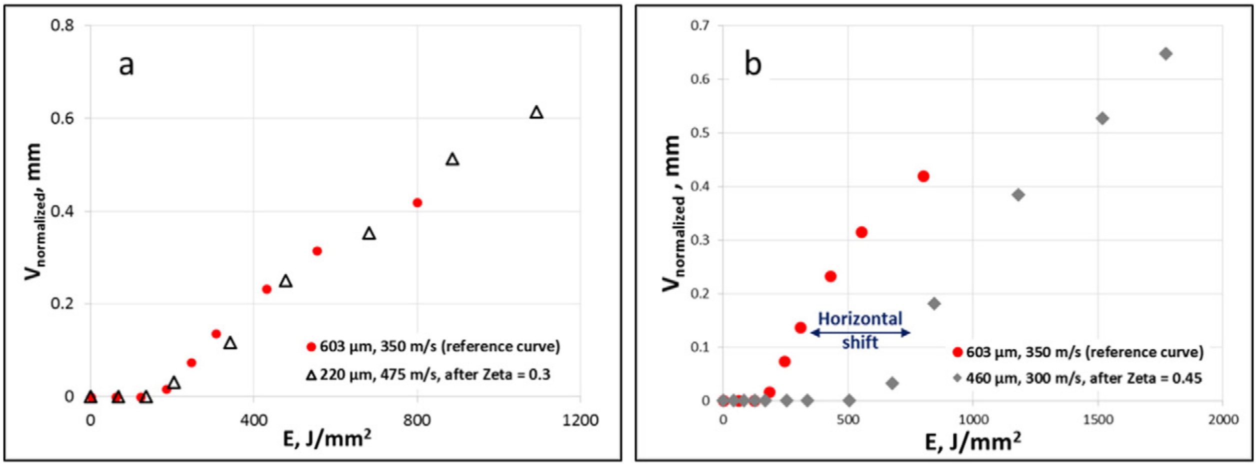

Fig. 9. Erosion curves for 12% Cr stainless after the application of (ξ) (a) for curves having the same incubation energy than the reference curve (i.e. 350 m/s and 603 μm), (b) for curves having different incubation energy than the reference curve (i.e. 350 m/s and 603 μm).

reasons such as higher speeds and smaller droplet sizes. In other words, simulating the very high speed (>500 m/s) erosion conditions taking place in steam or gas turbines, can be achieved through testing with lower impact speeds and larger droplet sizes as long as the erosion curves can be comparable. This approximation should be done for two main reasons. Firstly, some speeds encountered in steam turbines are unattainable in laboratory test setups. Secondly, the cost of constructing test rigs that could reach higher speed is expected to be very high.

4.2. The erosion severity coefficient (ξ)

Water droplet erosion process is complex, where several factors play roles in determining the amount of energy transferred between the solid and water droplets and the response of the material to such exerted energy. Besides, as discussed earlier quantifying this amount of energy is very difficult. Therefore, a new method was developed to study the “variation” in the absorbed energy with changing the test

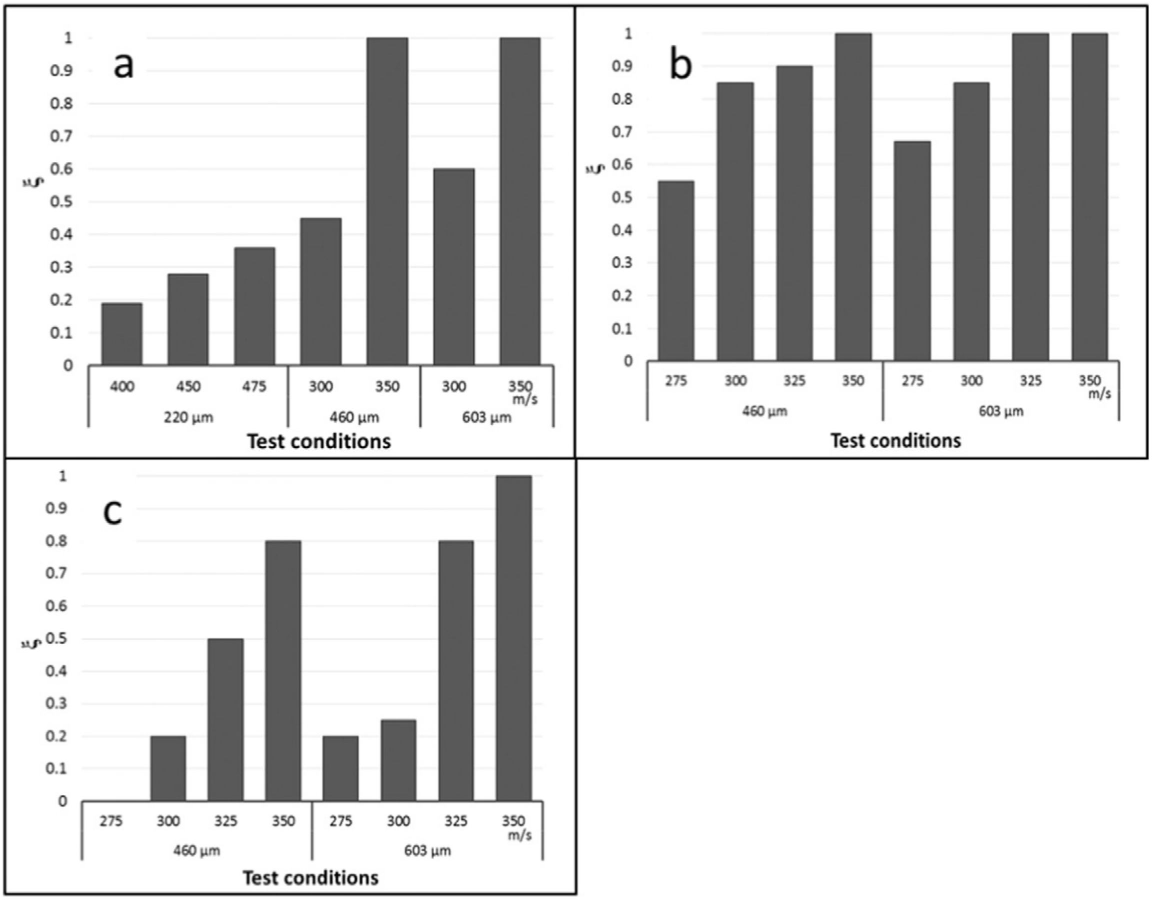

Fig. 10. Values of (ξ) at different testing conditions (a) 12% Cr Stainless steel, (b) Ti6Al4V, (c) TiAl.

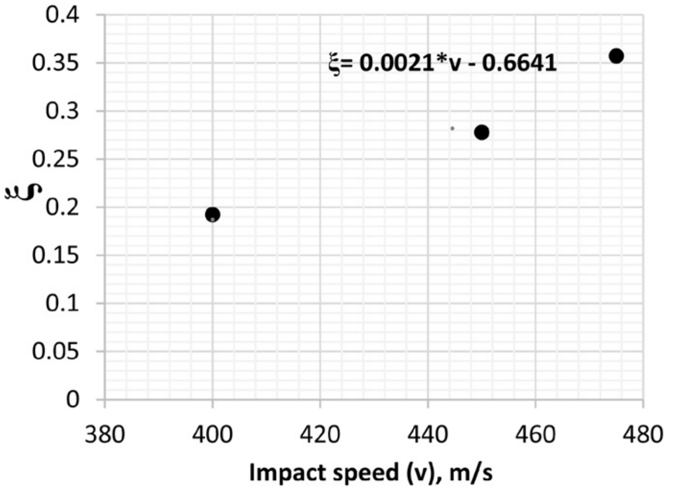

Fig. 11. Graph showing the trend of (ξ) of change for tests done using 220 μm droplets in the speed range 400–475 m/s.

conditions. This method will not attempt to measure the amount of energy absorbed by the surface, but monitor how it is varying due to changing the test conditions.

In this method, comparisons between different WDE test results performed using different erosion conditions can be held. A reference of comparison was set and all test conditions were scaled to it. In this work, the WDE curves of tests done at 350 m/s using 603 μm droplets were set as reference. The reason for choosing tests done at this condition as reference conditions is that these tests have the highest "maximum erosion slope" for all the materials tested here. All curves produced from other tests were scaled to overlap with the reference curve, by dividing the material loss axis data only (cumulative volume loss per unit impacted area) by a certain variable, which is named as (ξ) or the "erosion severity coefficient". The value of (ξ) is different for each test condition and each material.

Tests having the same incubation energy as the reference condition will totally coincide with the reference curve after the application of (ξ) as shown in Fig. 9 (a); however, tests having different incubation energy than the reference curve will become parallel to the reference curve, when (ξ) is applied, as shown in Fig. 9 (b). It is interesting to note that there is only a horizontal shift in the curves in Fig. 9 (b). This shift indicates that after the application of (ξ), although incubation period is different, the slopes of the curve become similar to that of the reference curve. The value of (ξ) is still very useful, since it could predict the trend of erosion after the material loss initiation. The main reason that (ξ) did not capture the incubation period is that only the y-axis was divided by (ξ); therefore, when the y-axis value is zero (i.e. during incubation) (ξ) does not affect it. This happens with tests having long incubation, usually, low speed tests.

The value (ξ) can be considered as an index for the change in the amount of material loss due to the variation in the amount of the absorbed energy at each test condition. The novelty of this analysis approach is that by a single value (ξ), the variation in results of different erosion test conditions can be quantified. For instance in Fig. 9 (a), the material loss at any point on the WDE curve of the test performed at 475 m/s using 220 μm droplets needs to be divided by ($\xi = 0.3$) to be similar to that of the corresponding point on the reference curve. This means that when the same energy intensity was applied on both samples in the form of impacting water droplets, the reference sample lost 81% more material than the test performed at 475 m/s and 220 μm droplets. These results suggest that more energy was absorbed by the reference, which led to more material loss. Therefore, (ξ) expresses such variation in the absorbed energy by quantifying the difference in the material loss between the two samples. This kind of information is useful for further understanding of the WDE behavior of materials. Fig. 10 shows graphs for the values of (ξ) of three different materials tested at various WDE conditions. The current results suggest that changing the impact speed has a more significant effect than changing the droplet size, in the range of 460 μm and 603 μm, in the case of the 12% Cr stainless steel and Ti6Al4V. However, TiAl is more sensitive to this droplet size change. In addition, the large difference in the value of (ξ) between tests performed on 12% Cr stainless steel using 220 μm droplets and those done using larger droplets (460 μm and 603 μm) captures the effect of the erosion crater morphology discussed in Section 4.1.3.

Building trends for how (ξ) is changing by altering the test conditions is important for understanding more about its physical meaning, and would help to predict WDE behavior of materials at untested erosion conditions. An example of such trend is illustrated in Fig. 11. The graph shows the (ξ) values of tests done on the 12% Cr stainless steel at 400, 450 and 475 m/s using 220 μm droplets plotted against the impact speed. This linear trend expresses the increase in (ξ) values as the impact speed increases. The regression equation in Fig. 11 can be used to predict the erosion curves of untested erosion conditions in this speed range. These results indicate that the value of the severity coefficient (ξ) increases with the increase in the impact speed. Similar graphs for the dependence of ξ on impact speed at other droplet sizes or vice versa can be obtained from the data in Fig. 11.

4.3. An example of comparison between WDE results obtained using different rigs

The ultimate goal of improving the representation of WDE results is to be able to compare experimental results acquired using different rigs. Representation in terms of energy opens the door for such comparison. We urge researchers and authors to report complete information about their erosion experiments, for instance: impact speed, droplet size

Table 2
Evaluation of applied energy intensity and the corresponding normalized volume loss based on this work for two different titanium alloys tested at different WDE conditions.

Seleznev et al. (TS-5) [24]				Mahdipoor et al. (Ti6Al4V) [20][a]			
436 m/s		524 m/s		275 m/s		325 m/s	
E (J/mm^2)	$V_{normalized}$ (mm)	E (J/mm^2)	$V_{normalized}$ (mm)	E (J/mm^2)	$V_{normalized}$ (mm)	E (J/mm^2)	$V_{normalized}$ (mm)
0	0	0	0	0	0	0	0
136.7	0	78.2	0.01	96.3	0	115.2	0.02
297.6	0.08	133.7	0.04	192.5	0	230.4	0.09
499.8	0.25	306.5	0.3	288.8	0.05	345.6	0.24
777.5	0.37	473.1	0.46	385	0.12	460.8	0.44
907	0.41	641.7	0.6	577.5	0.26	720	0.67
1117.8	0.45	1020.1	0.89	770	0.37	979.2	0.89
–	–	–	–	962.5	0.47	1267.3	1.01
–	–	–	–	1283.4	0.61	–	–

[a] Authors previous work.

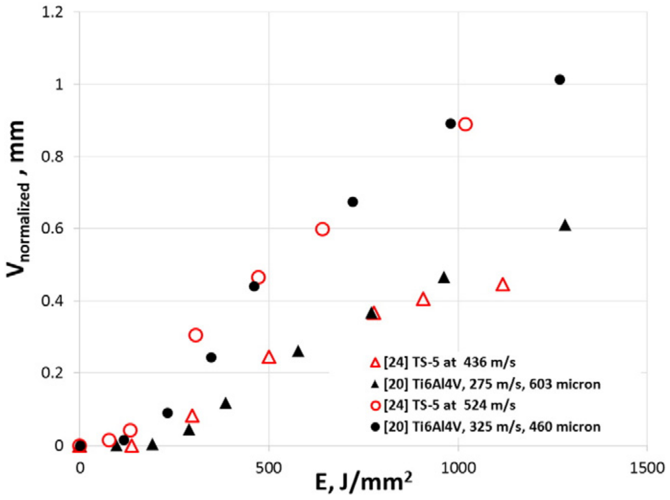

Fig. 12. Comparison between erosion curves of tests performed on two different WDE for Ti6Al4V and TS-5 tested at different erosion conditions.

distributions, number of droplets impacting samples during test cycles, number of cycles, initial surface roughness of sample, impact angle, and the impacted area. If this is done, comparison between tests can be done and the reported information would be more beneficial. An example for such comparison is presented in this section.

Seleznev et al. [24] reported the WDE curves for TS-5 titanium alloy at different test speeds. They reported graphs between amount of water impacting the samples and the cumulative mass loss. They also reported the impact speed, however, they neither reported the droplet size nor the initial surface roughness of the samples. TS-5 is an α-phase titanium alloy with the following chemical composition (wt.%): Al, 4.5–5.5; Zr, 1.0–3.0; Sn, 2.0–4.0; V, 4.5–5.5 [31]. In this paper, the x and y axes of their results are recalculated using Eqs. (3)–(5), and presented in Table 2 and Fig. 12. In addition, two WDE results from our previous work [20] for Ti6Al4V were also represented using the same equations and presented in Table 2 and Fig. 12. The graph shows a coincidence of overlapping curves for two different titanium alloys tested using different rigs at different test conditions without using the severity coefficient (ξ). In other words, Fig. 12 indicates that tests done by Seleznev et al. [24] at high speeds, 436 m/s and 524 m/s for TS-5, produced similar results as our experiments done for Ti6Al4V at lower speeds, 275 and 325 m/s, respectively. The overlapping of curves from these different sources when the energy intensity approach is used shows that the WDE conditions used in these tests resulted in the same amount of applied impact energy for both alloys causing similar amount of material loss. This example indicates the potential of this comparison approach. However, for this approach to be applied, a complete data set along with a complete description of the test parameters for the performed experiments has to be provided.

Finally, the presented energy based approach is very practical in correlating results produced using different erosion rigs. The first step of performing this correlation is to have the full definition of test parameters used in WDE experiments, and to report these parameters. The second step is to determine the difference (e.g. disk diameter, vacuum levels, temperature during the experiment, initial impact angle) between test rigs, by performing tests at the same test conditions (as much as possible) for the same material. Differences could be expressed in terms of severity coefficients similar to (ξ). The last step is to actually compare experimental results for different materials after applying these coefficients. If this kind of approach is realised, it might be a great step towards further standardizing WDE representation and correlating experimental results to actual in service water droplet erosion.

5. Conclusions

In this work a new method to represent WDE was developed and used to analyze test results. This method opens the door for studying WDE from another perspective through further parametric investigations. Important points could be summarized as following:

1- WDE was reported as normalized volume loss versus the applied kinetic energy intensity. The importance of the term “applied kinetic energy intensity” is that it includes all measurable and controllable parameters of the WDE experiment.

2- In order to represent WDE in terms of the applied kinetic energy, several parameters should be quantified and controlled: (a) droplet size, (b) impact speed, and (c) number of droplets per impact, (d) number of impacts, and (e) impacted area. It is important to keep other parameters constant for comparison purposes, otherwise comparison would become very difficult. These parameters are: (a) initial surface roughness, (b) initial impact angle.

3- Sub-division of water droplets into smaller ones upon impact was observed experimentally, which proves the claim of Heymann [13]. This may have contributed to the energy dissipation and the fact that not the entire impact energy is transferred to the solid material.

4- Experimental results suggest that there is a possibility to simulate erosion tests at desired conditions such as higher speeds (unattainable in laboratory experimental setups) and smaller droplet sizes using larger droplet sizes and lower speeds. However, attention should be given to the differences in the erosion mechanisms.

5- A novel method was developed in this work to help analyzing WDE test results in a more practical way. The “variation” in the amount of energy absorbed by the solid surface due to the water droplet impact was estimated. The advantage of this method is that the variation in results of different erosion test conditions can be quantified by a single value (ξ). The erosion severity coefficient (ξ) can be considered as an index for the change in the amount of material loss due to the variation in the amount of the absorbed energy at each test condition. Building trends to describe the change in (ξ) with test conditions is very important for further understanding of its physical meaning.

6- Representing WDE in terms of energy is a valuable tool to compare experimental results carried out using different erosion rigs. This could be done by performing experiments at the same test conditions on different rigs, and evaluating ξ coefficients between these experiments. The value of ξ, in this case, will account for the differences in the experimental procedures used in each test rig.

Acknowledgments

Authors of this work would like to acknowledge the support of ALSTOM Power, Switzerland for funding this work (Grant no. TTT PR 2014-1285). In addition, they would also like to thank colleagues at the Thermodynamics of Materials Group (TMG) of Concordia University for their help in carrying out the experiments.

References

[1] ASTM Standard G73, Standard test method for liquid impingement erosion using rotating apparatus, ASTM Int., West Conshohocken, PA (2010), http://dx.doi.org/10.1520/G0073-10 www.astm.org.
[2] E. Honegger, Tests on erosion caused by jets, Brown Boveri Rev. 14 (4) (1927) 95–104.
[3] S.S. Cook, Water-hammer erosion in turbines, Proc. Univ. Durham Phil. Soc. 8 (1929) 88–100.
[4] T.F. Hengstenberg, Erosion-resisting metals. Accelerated tests, Power 76 (1932) 118–120.
[5] D.E. Elliott, J.B. Marriott, A. Smith, Comparison of erosion resistance of standard steam turbine blade and shield materials on four test rigs, Characterization and Determination of Erosion Resistance (ASTM International) 1970, pp. 127–161 STP 474.
[6] B.E. Lee, K.J. Riu, S.H. Shin, S.B. Kwon, Development of a water droplet erosion model for large steam turbine blades, KSME Int. J. 17 (1) (2003) 114–121.

[7] J.A. Hesketh, P.J. Walker, Effects of wetness in steam turbines, Proc. Inst. Mech. Eng. C J. Mech. Eng. Sci. 219 (12) (2005) 1301–1314.

[8] V.A. Ryzhenkov, A.I. Lebedeva, A.F. Mednikov, Erosion wear of the blades of wet-steam turbine stages: present state of the problem and methods for solving it, Therm. Eng. 58 (9) (2011) 713–718.

[9] S.M. DeCorso, Erosion tests of steam turbine blade materials, Am. Soc. Test. Mater. – Proc. 64 (1964) 782–796.

[10] G. Hoff, G. Langbein, H. Rieger, Material destruction due to liquid impact, American Society for Testing and Materials. Committee G-2 on Erosion by Cavitation or Impingement, 408 1966, pp. 42–69 ASTM STP.

[11] F.G. Hammitt, Y.C. Huang, C.L. Kling, T.M. Mitchell Jr., L. Solomon, A statistically verified model for correlating volume loss due to cavitation or liquid impingement, Characterization and Determination of Erosion Resistance (ASTM International) 1970, pp. 288–322 STP 474.

[12] A. Thirwvengadam, S.L. Rudy, M. Gunasekaran, Experimental and analytical investigations on liquid impact erosion, ASTM Spec. Tech. Publ. (1970) 249–287.

[13] F.J. Heymann, A survey of clues to the relationship betweenerosion rate and impact parameters, Proceedings of the Second Meersburg Conference on Rain Erosion and Allied Phenomena Held on the Bondensee, Fedreal German Republic, 16th–18th August 1967 1967, pp. 683–760.

[14] M. Ahmad, M. Casey, M. Sürken, Experimental assessment of droplet impact erosion resistance of steam turbine blade materials, Wear 267 (9–10) (2009) 1605–1618.

[15] Y.I. Oka, S. Mihara, H. Miyata, Effective parameters for erosion caused by water droplet impingement and applications to surface treatment technology, Wear 263 (1–6) (2007) 386–394.

[16] B.S. Mann, V. Arya, B.K. Pant, Cavitation erosion behavior of HPDL-treated TWAS-coated Ti6Al4V alloy and its similarity with water droplet erosion, J. Mater. Eng. Perform. 21 (6) (2012) 849–853.

[17] A.F. Mednikov, et al., Studying the variation of parameters characterizing the material surface during the droplet erosion incubation period, Therm. Eng. 59 (5) (2012) 414–420.

[18] H.S. Kirols, D. Kevorkov, A. Uihlein, M. Medraj, The effect of surface roughness on the initiation of water droplet erosion, Wear (342–343) (2015) 198–209.

[19] M. Ahmad, M. Schatz, M.V. Casey, Experimental investigation of droplet size influence on low pressure steam turbine blade erosion, Wear 303 (1–2) (2013) 83–86.

[20] M.S. Mahdipoor, H.S. Kirols, D. Kevorkov, P. Jedrzejowski, M. Medraj, Influence of impact speed on water droplet erosion of TiAl compared to Ti6Al4V, Science Reports 5:14182 (2015).

[21] A. Thiruvengadam, S.L.R., Experimental and analytical investigations on multiple liquid impact erosion, Hydronautics Inc., National Aeronautics and Space Administration, 1969 NASA CR-1288.

[22] B.S. Mann, V. Arya, HVOF coating and surface treatment for enhancing droplet erosion resistance of steam turbine blades, Wear 254 (7–8) (2003) 652–667.

[23] B.S. Mann, water droplet erosion behavior of high-power diode laser treated 17Cr4Ni PH stainless steel, J. Mater. Eng. Perform. 23 (5) (2014) 1861–1869.

[24] L.I. Seleznev, V.A. Ryzhenkov, A.F. Mednikov, Phenomenology of erosion wear of constructional steels and alloys by liquid particles, Therm. Eng. 57 (9) (2010) 741–745.

[25] M.S. Mahdipoor, F. Tarasi, C. Moreau, A. Dolatabadi, M. Medraj, HVOF sprayed coatings of nano-agglomerated tungsten-carbide/cobalt powders for water droplet erosion application, Wear (330–331) (2015) 338–347.

[26] H. Busch, G. Hoff, G. Langbein, G. Taylor, D.C. Jenkins, M.A. Taunton, A.A. Fyall, R.F. Jones, T.W. Harper, Rain erosion properties of materials [and discussion], Philos. Trans. R. Soc. London, Ser. A, Math. Phys. Sci. 260 (1110) (1966) 168–181.

[27] H.S. Kirols, Water Droplet Erosion: Influencing Parameters, Representation, and ComparisonsMaster's Thesis Concordia University, Montreal, Canada, 2015.

[28] L. Huang, J. Folkes, P. Kinnell, P.H. Shipway, Mechanisms of damage initiation in a titanium alloy subjected to water droplet impact during ultra-high pressure plain waterjet erosion, J. Mater. Process. Technol. 212 (9) (2012) 1906–1915.

[29] N.L. Hancox, J.H. Brunton, The erosion of solids by the repeated impact of liquid drops, Philos. Trans. R. Soc. London, Ser. A, Math. Phys. Sci. 260 (1110) (1966) 121–139.

[30] M.B. Lesser, J.E. Field, The impact of compressible liquids, Annu. Rev. Fluid Mech. 15 (1) (1983) 97–122.

[31] V.N. Moiseyev, in: J.N. Fridlyander, D.G. Eskin (Eds.), Titanium Alloys: Russian Aircraft and Aerospace Applications, Advances in Metallic AlloysCRC Press, 2006.