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The effect of initial surface roughness on water droplet erosion behaviour

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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.

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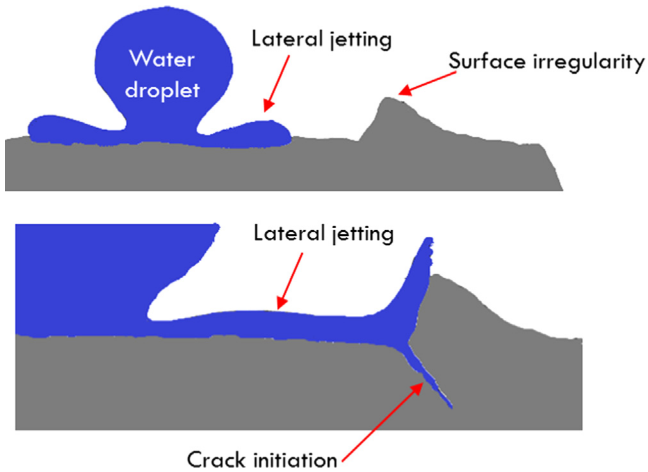

Fig. 1. Schematic reported by Heymann [15] to explain the effect of surface asperities.

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 results produced by different research groups very challenging. This was clear in the work of Elliot et al. [10], as they tried to perform comparisons for water erosion test results, for the same materials, produced using different erosion rigs. However, they neglected the fact that the starting surface conditions for samples may have a significant role in the great variation of results that they discussed. Furthermore, ASTM standard G73-10 [31] indicated that for water droplet erosion testing, the initial surface roughness of samples should be reported. Unfortunately, in many research papers [8,32–36] on the water erosion resistance of different materials, there is even no mentioning of the starting surface conditions of the samples. Other researchers [37] mentioned the initial condition of the tested surfaces without any indication of how surfaces were prepared.

Ryzhenkov et al. [12] summarised the structural materials used for blades by several steam turbine manufacturers. The main two material groups used were found to be titanium and steel alloys. The current work is mainly concerned with the effect of initial surface roughness on the erosion performance of a special martensitic stainless steel (12%Cr-steel) used in manufacturing of steam turbine blades, which will also be compared with the commonly used Ti6Al4V alloy.

Moreover, Ryzhenkov et al. [12] state that in order to have sufficiently reliable results for erosion experiments, some key parameters should be measured and maintained at a certain level of accuracy. These include impact speed, droplet size distribution and number of colliding liquid particles. In this work, these key parameters were characterised, quantified and used to represent the erosion experiments.

To summarise, the main objective of the current article is to provide experimental results produced using actual water droplets to simulate the real case of WDE of 12% Cr stainless steel, with special focus on the effect of the initial surface roughness on the WDE behaviour. Moreover, for the sake of comparison and to provide a broader prospect on the effect of initial surface roughness on the WDE behaviour of other material, additional experiments were carried out to investigate the effect of initial surface roughness on annealed Ti6Al4V.

2. Materials and experimental procedures

2.1. Materials

In this work, a special martensitic stainless steel alloy (12% Cr–steel) provided by ALSTOM Power was tested. This material is commonly used in the manufacturing of steam turbine blades. The composition and the mechanical properties of this alloy are proprietary.

Several measurements could be used to describe the surface condition. However, the R_a values are the most commonly used indication of the surface quality [13]. In the current work, only R_a values were used to evaluate the initial surface roughness. The 3D measurement of surface parameters (i.e. waviness, skewness and kurtosis) could also be used to better describe the surface condition. For surfaces with the same R_a values, these surface parameters could be different, since they mainly depend on the surface preparation method used.

In this work, two surface preparation methods were used to vary the initial surface roughness of the 12% Cr stainless steel samples. The first was to hand grind the surface of the samples using a 180 grit SiC paper on a grinding disc. The second method was to prepare the surface using a vibratomet polisher for 24 h using 1 μm diamond paste. The average linear surface roughness values (*Ra*) of 12% Cr stainless steel samples prepared using the two surface finishing methods were, 0.2 μm and 0.035 μm, for grinding and polishing, respectively. The purpose of using these two different surface preparation methods was to cause a large difference in the initial surface roughness of the samples, in order to magnify its effect.

Annealed Ti6Al4V was also tested in this work, this material is widely used in the manufacture of turbine blades [12]. Three surfaces roughness levels of Ti6Al4V samples were prepared by hand grinding and polishing. Rough samples were ground using a 180 and 600 grit SiC paper, and the smooth sample was hand ground and finally polished using 3 μm diamond paste. Average initial surface roughness values (*Ra*) of 0.3, 0.12 and 0.04 μm were recorded for the ground and polished samples, respectively.

In conclusion, the average surface roughness values used in the current work for the 12% Cr stainless steel samples are 0.2 and 0.035 μm; however, those used for the Ti64 samples are 0.3, 0.12, 0.04 μm. The 0.2 and 0.3 μm average roughness values for the 12% Cr stainless steel and Ti64 samples, respectively, are close to the surface roughness of steam turbine blades after surface finish [13]. Lower values of average roughness (i.e. 0.12, 0.04, and 0.035 μm) were studied to reveal the effect of reducing initial surface roughness on WDE performance.

2.2. Experimental procedure

2.2.1. Water droplet erosion test

Tests were conducted using the water droplet erosion rig available at Concordia University. This rig simulates the high speed rotation of turbine blades. As the schematic in Fig. 2 shows, the rig consists of a horizontally rotating disc inside a vacuum chamber, which can reach a maximum a speed of 20,000 rpm. Tests were performed under vacuum to reduce the friction between the rotating disc and air, so as to prevent temperature increase and water droplets evaporation during the test. Samples are cut in the form of rectangular coupons ($25 \times 8 \times 3\ mm^3$), and inserted in a sample holder specially designed for this purpose. In this work, two samples were tested at the same time in order to balance the disc during its rotation and to generate more data. A complete experiment requires the use of this WDE rig for at least two days. Each test cycle requires the use of the machine for at least 15–20 min, including the establishment of vacuum, acceleration of the disc, stabilizing the test speed, performing the test, and the deceleration of the disc.

During the test, water droplets fall vertically and the disc rotates horizontally; therefore, the speed of impact is considered to be the linear speed of the outer diameter of the rotating disc at the point of impact. The impact speed of this erosion rig can be set between 100 m/s and 500 m/s; however, in this work two speeds were chosen, 300 m/s and 350 m/s. The first reason for choosing these speeds is that they were not investigated before for testing the effect of initial surface roughness. The second reason, it is expected that if the severity of the test increases, represented in the impact speed, the effect of initial surface roughness on the erosion damage would decrease. Therefore, it was essential to choose speeds that allow to study surface roughness when it has a significant effect on the erosion behaviour, especially, at the initial stages of erosion.

Every test was divided into a set of intervals. After each interval the rotating disc was stopped and the samples were removed and weighed using an accurate balance with ± 0.2 mg accuracy. Measurement of the mass loss per cycle was performed.

2.2.2. Water droplets generation

A water droplet generation system and nozzles that produce a single streak of water droplets were used. The system follows the "Rayleigh-Plateau Instability" phenomenon. It states that if a column of water with a constant diameter is falling due to gravity, it

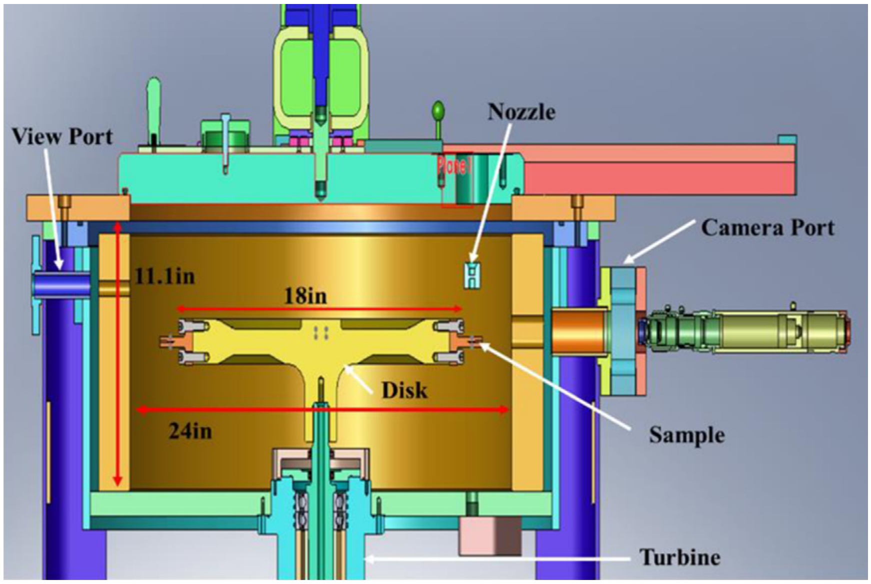

Fig. 2. Schematic of the water droplet erosion rig.

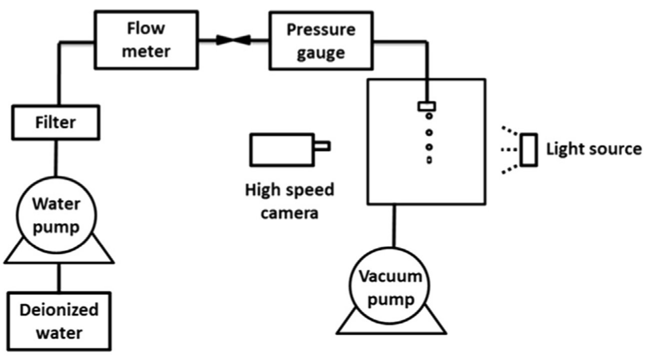

Fig. 3. Setup used to characterise the generated water droplets.

starts breaking to form droplets, when a certain ratio between length and diameter is reached [38]. The generated droplets are in a range of sizes depending on the following flow parameters: (a) water line pressure, (b) flow rate and (c) nozzle diameter. Characterisation of the size distribution of water droplets was done in a separate transparent vacuum chamber using a high speed camera, as shown in Fig. 3. This chamber achieve the same vacuum levels measured inside the erosion rig during the WDE experiments (40–45 mbar). This pressure is higher than the partial pressure of water at room temperature (26.7 mbar) to avoid boiling and excessive evaporation of water droplets.

In order to characterise the water droplets, three aspects were considered. The first was to measure the diameter of the droplets with regards to different flow parameters. The second was to find the number of droplets impinging the sample per rotation. This was done to determine the cumulative number of water droplets impacting the samples throughout the test duration. In order to verify this number, a third aspect was needed to ensure that the speed of a falling droplet is high enough to cause impacts across the whole height of the sample (i.e. 8 mm). The aim of these measurements was to find the properties of the generated water droplets at several sets of flow parameters. This helps to choose the flow parameters needed to generate the desired droplet sizes, and the number of droplets that would impact the samples during the test duration.

Table 1
Optimum sets of flow parameters used in the current study.

Set #	Nozzle diameter (μm)	Water flow (liters/min)	Water line pressure (psi)	Average droplet size (μm)
1	400	0.105	9	603
2	300	0.05	1	460

Images of the water droplets flow were taken at a high frame rate, 6000 fps, then they were used to characterise the water droplets. Measurement of the droplet diameters was performed using the images, where a set of 200 droplets was used at each set of flow parameters. It was important that flow parameters sets used in the experiments produce the least variability in the droplet diameter distribution, and the generated droplets would have a constant distance in-between. In addition, the generated water droplet diameters should be in the range found in the spectrum of different WDE applications, 50–1500 μm [12,30,35]. Table 1 describes the optimum sets of flow parameters used in this work. Sets number 1 and 2 generate average droplet diameters of 460 μm and 603 μm, respectively. Fig. 4 shows, as an example, the diameter distribution generated by set number 1.

In order to estimate the number of droplets impacting a sample per revolution, and to measure the vertical speed of droplets, 100 percent of the droplets generated in the system over a certain period of time had to be imaged. Therefore, to achieve this objective calculations were done using values of: (a) volume flow of water recorded by the flow metre in the system, and (b) imaging speed of the camera. Theoretically, it was found that if successive images were taken at a speed of 6000 frames/s and contained 3 droplets/frame, 100 percent of the water flow would be recorded in these images. All of the images taken in this study contained more than 3 droplets. Accordingly, the measurement of the speed and the number of droplets was possible to perform.

After taking the images, measurement was done to determine the number of droplets impacting a sample per rotation. Fig. 5 shows examples of images used for this purpose. For each rotation, it was estimated that when droplet diameters of 460 μm and 603 μm are used, a sample is impacted by 7 and 4 droplets, respectively.

However, as the droplets stream is interrupted by an impact, it needs time to reform as a continuous stream before the next

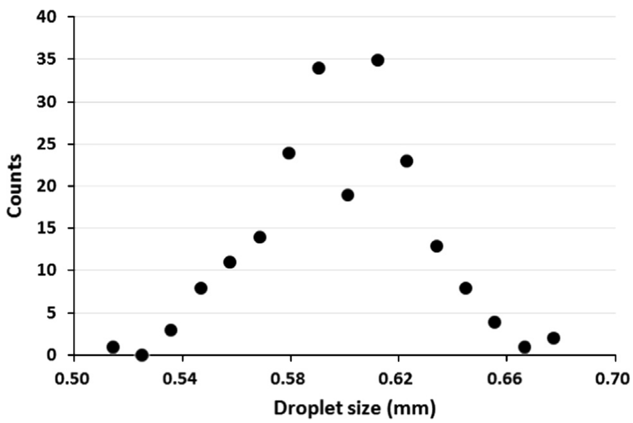

Fig. 4. Droplet size distribution produced by flow parameters of set number 1 (Table 1).

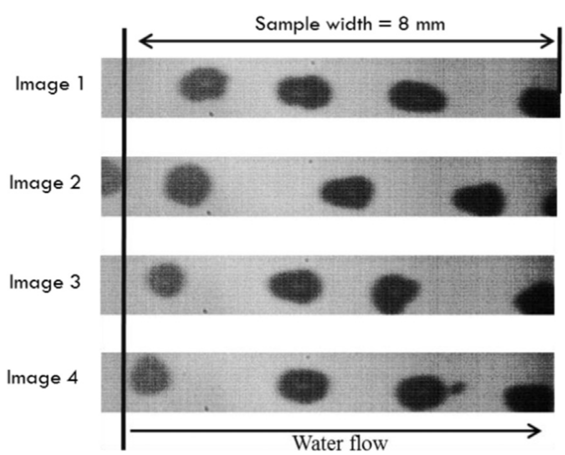

Fig. 5. An example of images used to find the number of droplets impinging each sample in each rotation for flow parameters set number 1 (Table 1).

impact. If the time needed by a falling droplet to pass the height of the sample (8 mm) was more than that needed by the rotating sample to return to the point of impact, the sample's surface would be partially impacted on its upper part only, and erosion would not be uniform. Therefore, an additional measurement was performed to find out the speed of the falling droplets for each set of flow parameters. The displacements per frame done by the tracked droplets were measured, and their speed was calculated. It was found that the average speeds of 603 μm and 460 μm droplets were 8.7 m/s and 13.5 m/s, respectively. As mentioned earlier, the rotating disc carry two opposite test samples. Calculations for the time taken by the rotating disc to complete half a rotation indicate that in the case of test speeds of 300 m/s and 350 m/s time values are 2.5 ms and 2.1 ms, respectively. In these time durations, a 603 μm droplet would pass 22 mm and 18 mm, when the test is performed at 300 m/s and 350 m/s, respectively. In addition, a 460 μm droplet would pass 34 mm and 28 mm, respectively. Since the width of the sample is only 8 mm, therefore, in all cases the speed of the falling droplets is fast enough to cause full erosion line across the width of the sample.

Based on these measurements the erosion results can be represented in terms of the amount of water droplets impinging the surface of samples during the test.

2.2.3. WDE test data representation

According to the ATSM standard G73-10 [31], an erosion curve is usually divided into five sections: (a) incubation stage, (b) acceleration stage, (c) maximum erosion rate stage, (d) deceleration stage, and (e) terminal steady state stage. Moreover, erosion curves are drawn as cumulative material loss versus exposure. The cumulative material loss can be described as mass loss or volume loss. If the aim is the comparison between different materials, the volume loss is considered a more appropriate method of representation. However, if the comparison is done for the effect of test parameters on the erosion behaviour of one material, any material loss expression would be sufficient. Therefore, mass loss was chosen to represent the material loss in this work. Exposure can be represented as time, impact cycles, volume of impinging water droplets, number of effective droplets impacting the surface, and cumulative kinetic energy of impact. In this work, the average number of droplets impacting the sample over a defined period of time is considered as exposure. Therefore, the observed damage would be quantified and correlated to the actual number of water droplets causing erosion. Such representation would help for comparison purposes between different test results performed on different WDE rigs, and helps toward further standardisation of the WDE experiments. The number of droplets can be calculated by multiplying the average number of droplets impacting the sample per rotation by the number of rotations in a test interval:

$$\text{Number of droplets } (N_{drop}) = N_{drop/rotation} * \text{RPM} * \text{time} \quad (1)$$

It should be noted that the number of droplets (N_{drop}) is an approximation of the actual number of droplets impacting the sample, since measurements were done without the rotation of the rig's disc. However, to improve the accuracy of the experiment a wind shield was added to the nozzle's jig to protect the water droplet stream from deflection till it reaches the sample during the test. The result of this shield can be observed in the straightness and the continuity of the erosion line on the sample's surface, as shown in Fig. 6.

Furthermore, a term to describe the duration of the incubation period can be represented as shown in the following equation [31]:

$$\text{Incubation specific impact } (N_0) = \frac{N_{inc} * A_p}{A_e} \quad (2)$$

where N_{inc} is the number of impacts during incubation, A_p is the projected area of an impacting liquid body, and A_e is the area exposed to erosion. The projected area of the impacting liquid body is considered as the projected area of one water droplet, $\frac{\pi}{4}D_{drop}^2$. However, the total surface area exposed to erosion is considered as the average impacted flat area measured using optical macrographs at the end of the incubation stage. During incubation, the impacted area is clearly noticeable on the surface of the sample by a colour difference that distinguishes it from unimpacted areas, as shown in the optical macrograph in Fig. 6. This area is the projection of the impacting water droplet stream on the surface of the sample.

The incubation specific impact (N_0) is defined as the number of impacts needed to end the incubation stage of a unit impacted surface area (1 mm^2). In other words, it is the portion of the total

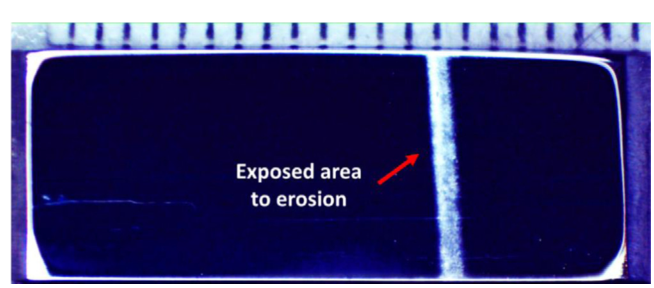

Fig. 6. Optical macrograph of the impacted area on the surface of a polished 12% Cr stainless steel sample.

number of droplets used in the experiment that ends the incubation stage of a unit impacted surface area. The values of the “total number of droplets needed to end the incubation stage” for the whole impacted area can be acquired from the erosion curves. According to the ASTM G73-10 standard [31] the incubation period is measured by extending the maximum erosion rate till it intersects with the x-axis, at this intersection the length of the incubation period is evaluated. If the x-axis is represented as number of droplets, the length of the incubation stage will also have the same measure.

Another method of representation was used by Seleznev et al. [39] who reported erosion curves as material's volume loss per unit area versus the mass of applied test water per unit area. In the representation method they used, the incubation period can be described by mass of the applied water droplets, and it could be calculated using the following equation:

$$m_{inc} = \frac{N_{inc} * \rho * V_{drop}}{A_e} \quad (3)$$

Where m_{inc} is the mass of applied water droplets per unit area to end incubation, ρ is the density of water, and V_{drop} is the volume of one droplet. This representation of the incubation period is useful for test results analysis, since it allows the direct comparison between test results performed using different sizes of water droplets.

3. Results

Three test parameters were varied in the experiments involving the 12% Cr stainless steel: (a) initial surface roughness, (b) test speed and (c) water droplet diameter. In this investigation eight WDE tests were conducted by varying each parameter using two levels. An additional test was carried out to confirm the repeatability of the experiments.

Fig. 7 presents the results of two samples tested with the same: (a) surface quality, (b) test speed and (c) droplet size. Each sample was tested separately on a different day, in order to test the repeatability of the results. The two curves almost coincide for most of the testing points, indicating an acceptable level of repeatability.

Erosion test results are shown in Figs. 8–11. Analysis of the curves showed that there is an enhancement in the erosion resistance of the 12% Cr stainless steel alloy, by just improving the surface quality. The main improvement is in the incubation stage,

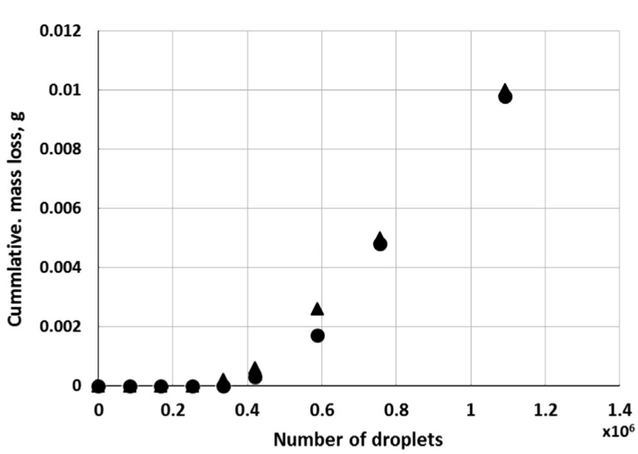

Fig. 7. Repeatability of the water droplet erosion measurements at impact speed of 350 m/s and droplet diameter of 460 μm for two tests using the same surface condition.

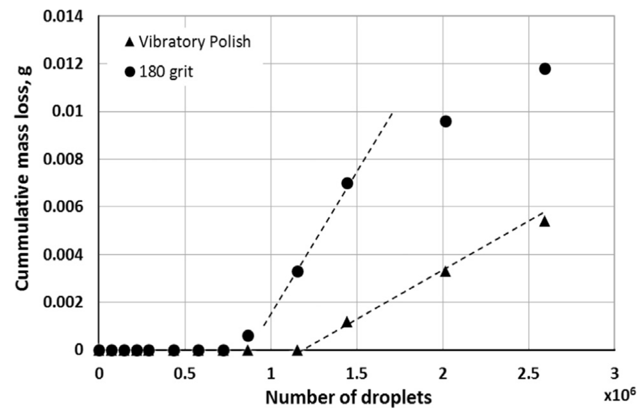

Fig. 8. Water droplet erosion of 12% Cr stainless steel at impact speed of 300 m/s and droplet diameter of 460 μm for the two surface conditions.

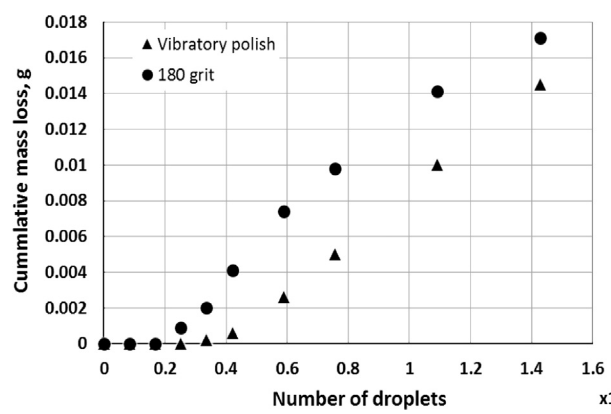

Fig. 9. Water droplet erosion of 12% Cr stainless steel at impact speed of 350 m/s and droplet diameter of 460 μm for the two surface conditions.

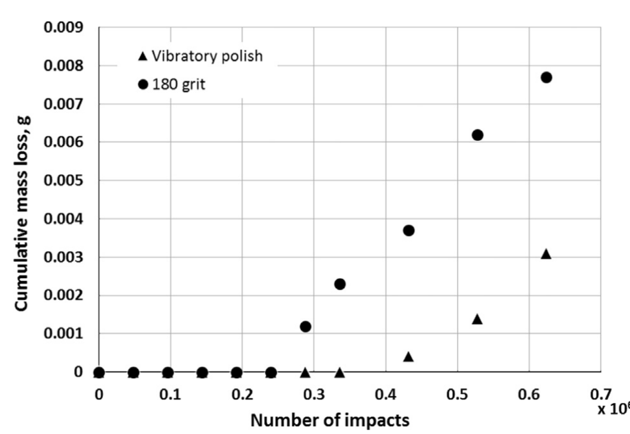

Fig. 10. Water droplet erosion of 12% Cr stainless steel at impact speed of 300 m/s and droplet diameter of 603 μm for the two surface conditions.

as it is clear that improving the surface quality increases the incubation period. As erosion progressed, roughness of the tested surfaces increased, and samples with better initial surface quality started to lose their superiority. Tests were terminated as soon as the erosion curves showed similar behaviour.

Table 2 and Figs. 12 and 13 show the difference between the lengths of the incubation periods of tests done at different erosion conditions. It was found that the test done at impact speed of 300 m/s and both droplet sizes 460 μm and 603 μm droplets, shown in Figs. 8 and 10, present the highest improvement. As the impact speed increased, the improvement decreased. In most of the cases, as the incubation stage ended, samples with different initial surface roughness started to act similarly. In each graph, the slopes of the maximum erosion stage are almost equal. Except for the graph in Fig. 8, where the maximum erosion rates showed some difference, represented by the dashed lines.

An interesting observation could be seen in Fig. 13. For the same initial surface roughness, the incubation periods of samples tested at 350 m/s (i.e. experiments # 2 and 4 in Table 2) are close in value regardless to the droplet size used. This suggests that the difference in the droplet size (i.e. 460 μm and 603 μm) has a minimal effect on the erosion process at this speed (i.e. 350 m/s). This behaviour is in accordance with DeCorso [6] who stated: "*given an equal amount of impinging fluid, at velocities well above the damage threshold, droplet size does not affect the extent of damage, but that at velocities near the threshold, damage increases with droplet size*". In order for DeCorso's statement to be true for the presented results in this work, samples tested with different droplet sizes and showing similar response should be subjected to the same amount of water. This condition is satisfied for experiments done at 350 m/s as shown in Fig. 13. Therefore, for the same amount of applied water droplets, the speed at which the droplet size ceases to have an effect on the erosion damage for the tested 12% Cr stainless steel is close to 350 m/s. However, to further proof this claim more experimental results are needed, which maybe a topic for a future investigation.

Fig. 14 represents the relationship between the lengths of the incubation period for both of the surface preparation methods at different test conditions. The graph shows the percentage of increase in the length of incubation period for both starting surfaces, plotted at different test conditions

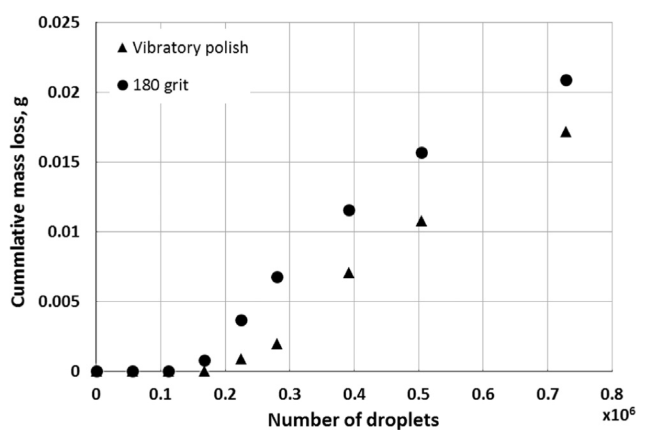

Fig. 11. Water droplet erosion of 12% Cr stainless steel at impact speed of 350 m/s and droplet diameter of 603 μm for the two surface conditions.

% increase in the length of the incubation period

$$= 1 - \frac{H_p}{H_g} \times 100 \tag{4}$$

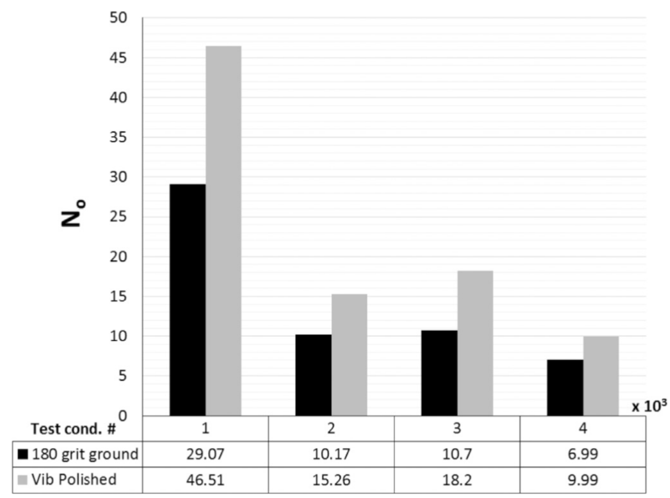

Fig. 12. Bar chart for the incubation specific impacts for 12% Cr stainless steel at different test conditions for the two different surface conditions. The details of test conditions are given in Table 2.

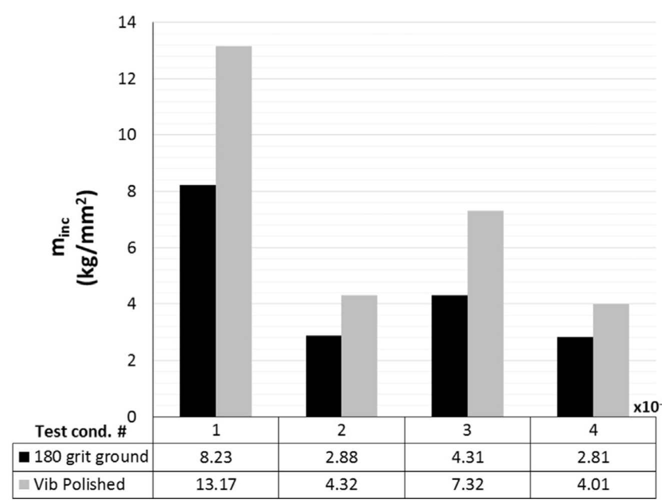

Fig. 13. Bar chart for the mass of applied water per unit area to end the incubation of 12% Cr stainless steel at different test conditions for the two different surface conditions. The details of test conditions are given in Table 2.

Table 2
Erosion test results of 12% Cr stainless steel samples.

Test cond. #	Test conditions	Surface conditions	Incubation time (min)	No. of impacts to end incubation (N_{inc}) (x10^5)	Incubation specific impacts (N_0)(x10^3)	Mass of water to end inc. (m_{inc}) (kg/mm) ($\times 10^{-3}$)
1	Speed: 300 m/s	180 grit	10	8.4	29.07	8.23
	Droplet size: 460 μm	Polished	16	13.4	46.51	13.17
2	Speed: 350 m/s	180 grit	3	2.94	10.17	2.88
	Droplet size: 460 μm	polished	4.5	4.41	15.26	4.32
3	Speed: 300 m/s	180 grit	5	2.4	10.7	4.31
	Droplet size: 603 μm	polished	8.5	4.04	18.2	7.32
4	Speed: 350 m/s	180 grit	2.8	1.568	6.99	2.81
	Droplet size: 603 μm	polished	4	2.24	9.99	4.01

where H_p is the length of the incubation period of the polished samples, and H_g is the length of the incubation period for the ground samples. From the graph, it could be deduced that the effect of initial surface roughness when both droplet sizes were used is more significant at the low speed (i.e. 300 m/s) than at the higher speed (i.e. 350 m/s).

In order to have a broader prospect, additional materials need to be tested, therefore, additional tests were carried out for annealed Ti6Al4V samples. The reason for choosing Ti6Al4V is that it is widely used in manufacturing steam and gas turbine blades [12,30]. As mentioned in the experimental procedure section, the surface of Ti6Al4V samples was prepared to have 3 different initial surface roughness levels. Erosion tests were carried out at an impact speeds of 300 and 350 m/s using 460 μm droplets. Figs. 14 and 15 show the results of these tests.

It is clear from the graphs that the length of the incubation Ti6Al4V samples increased by improving the surface quality. In addition, polishing influenced the maximum erosion rate of Ti6Al4V, as illustrated by the arrows in Figs. 15 and 16. The differences between the maximum erosion rates of the polished and ground samples are significant; however, there is smaller difference between the two ground samples. The same influence of initial surface roughness on the maximum erosion rate was observed for the 12% Cr stainless steel, when tested at 300 m/s using the 460 μm droplets.

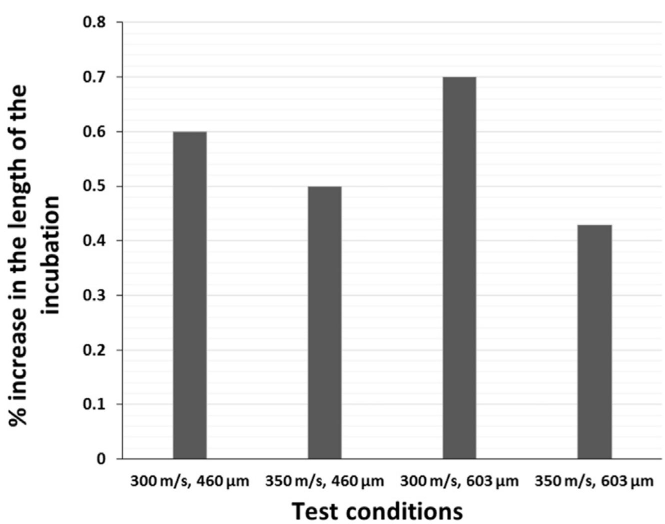

Fig. 14. Bar chart showing the ratio between the lengths of incubation period of vibromet polished and hand ground samples at different test conditions.

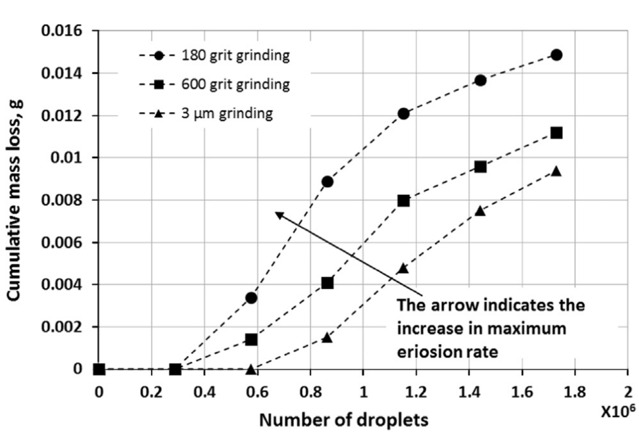

Fig. 15. Water droplet erosion of annealed Ti6Al4V at impact speed of 300 m/s and droplet diameter of 460 μm for the three surface conditions.

4. Discussion

In order to understand the relation between the current results and the existing theories discussing the effect of the surface conditions on WDE, one should first discuss the reasons for observing such differences in WDE behaviour by changing the initial surface roughness. To achieve this, two aspects should be addressed. The first is to understand the behaviour of the water droplet after impact, as it is the dominant source of the applied load on the surface. The second is to investigate the difference of the impacted surface response caused by the altering the surface roughness.

4.1. The response of different surface qualities to water droplet impact

According to several researchers [3,4,9,14–17,40,41] after impact a water droplet induces stresses on the surface through an impact pressure, known as the hammer pressure. Afterwards, the water droplet deforms over the surface producing a lateral outflow, which slides on the solid surface at a very high speed.

Haag [18] generally described the surface response of a ductile material during the incubation period. He assumed that damage progresses in the following sequence: (a) roughening of the surface; (b) formation of micro-cracks and their propagation; (c) the detachment of material and the formation of pits. However, what happens if the surface is rough before the erosion process starts? This will be discussed in the following parts of this section.

Hammitt et al. [42] described the factors that determine the level of influence of a liquid droplet impact on a solid surface. He claimed that they are: (a) material and liquid properties; (b) geometrical aspects (angle of impact, surface roughness, shape and size of droplets); (c) speed of impact. Hence, in this work all possible combinations between water droplet conditions and surface conditions are tested. Accordingly, for a given test condition, the response of the two different surface conditions to water droplet impacts would mainly depend on two aspects: (a) material's mechanical properties; and (b) geometry of surfaces.

Although, the same material was used, one can assume that due to the difference in the surface preparation methods, different levels of residual stresses are obtained [43,44]. This implies that these different levels of residual stresses may cause a difference in the erosion behaviour. However, it was recently reported that compressive residual stresses induced by a deep rolling process did not improve or deteriorate the water droplet erosion resistance of Ti6Al4V[30]. Deep rolling is a surface treatment technique usually used to deliberately induce compressive residual stresses on the surface of samples. In this manner, the effect of the residual

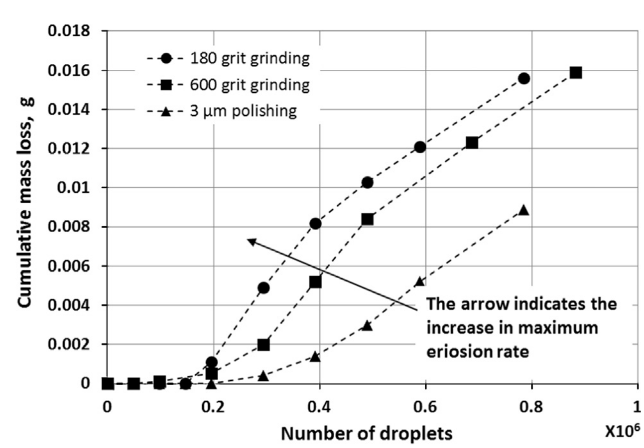

Fig. 16. Water droplet erosion of annealed Ti6Al4V at impact speed of 350 m/s and droplet diameter of 460 μm for the three surface conditions.

stresses due to different surface preparation methods was assumed insignificant in this study. Hence, the major affecting parameter for the difference in the surface response, would be more related to its geometry, in this case the initial surface roughness.

A possible physical explanation for such observation is that the change in the surface roughness causes the change in the water droplet loading conditions. In other words, if the surface roughness is changed, the degree at which the surface is being influenced by the lateral outflow, for instance, would change too. From a tribological prospect, if the surface was (theoretically) perfectly flat, with no irregularities, the lateral outflow of the water droplets will smoothly slide on it. However, as the amount of irregularities is more abundant, in the case of rougher surfaces, they will tend to entrap the lateral outflow of the water droplet, hence, more damage occurs.

This explanation is in accordance with Bowden and Brunton's theory [14], that the actual damage mechanism for a surface with pre-existing miniscule steps is the shear stresses induced by the lateral outflow. In addition, it also fits with Heyamann's [3,15] description of erosion as a fatigue-like phenomenon. Since, the surface irregularities would be very important in initiating fatigue cracks, as they may act as raisers for the lateral outflow induced shear stresses. In addition, these irregularities may also act as raisers for stresses induced due to the impact itself [3]. Therefore, it could be comprehended that reducing the amount of these surface irregularities would delay cracks formation; hence, delay erosion itself. The current experimental results confirm this theory. As delays in the initiation of erosion of the samples were observed by reducing the initial surface roughness.

SEM micrographs were taken to analyse the difference between the damage mechanisms of both surface conditions. Fig. 17 shows the surface of the vibratory polished sample and it is divided into two parts: (a) presents the surface before testing, and (b) shows the same surface during the incubation period after being subjected to water droplet impacts. Although, the sample did not lose any measurable mass in Fig. 17b, the water droplet impacts plastically deformed the surface and changed its topography. It is clear that even at this high magnification there is no significant micro-pits formation. Fig. 18 shows the initial surface of another sample which was manually ground with 180 grit SiC paper, before testing. It is clear that the surface after manual grinding contains many defects such as scratches, asperities and pits.

In order to further analyse the presented SEM micrographs, they should be related to the theories discussing erosion initiation. According to the discussed literature [3,14,15,17,18], pits usually initiate due to the shearing of asperities and irregularities on the surface by the lateral outflow. Irregularities and asperities can be formed by the erosion process itself, or they can be pre-existing due to surface preparation. For ductile materials, Field et al. and Haag explained how surface irregularities are formed by the WDE itself. They stated that in the initial stages of erosion, water droplets tend to roughen the surface by the formation of depressions and other surface irregularities. Later on, the surface becomes more influenced by the lateral outflow. However, another factor should be added, which is the friction between the material's surface and the water outflow sliding on it, as it should be important at these high speeds. In general, friction is highly influenced by the topography of the surfaces in contact [45]. A recent finite element model was presented by Li et al. [46] indicating that the spreading process of a water droplet on a solid surface is influenced by the friction between the moving liquid and the texture of the surface. Fig. 17 shows the formation of surface irregularities by the water droplet erosion itself. In Fig. 17a, the surface initially had a minimum amount of irregularities and pits did not exist. As the surface roughness of the target increased, shown in Fig. 17b, it is expected that the lateral outflow started to play a greater role on the damage. Both the hammer pressure and friction may cause such deformation to the surface. However, Fig. 18 presents the second form of surface irregularities, pre-existing irregularities due to surface preparation. This surface condition shortens the incubation stage, because it decreases or eliminates what is called the “roughening stage”, putting the sample one step ahead in the damage process. Since, the ground surface has defects due to the direction of grinding, and it also has some initial pitting due to grinding itself. Similarity could be found between Figs. 17b and 18, as they both share the presence of irregularities on their surfaces, indicating that the polished surface needs more time for such irregularities to be created before the beginning of the mass loss. In conclusion, polishing increases the

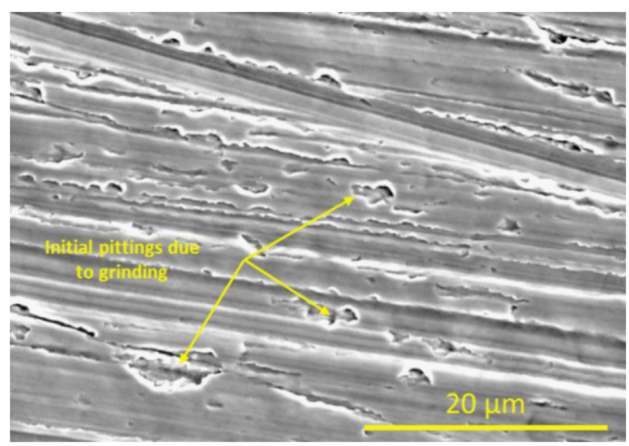

Fig. 18. Manually ground 12% Cr stainless steel sample before the WDE test.

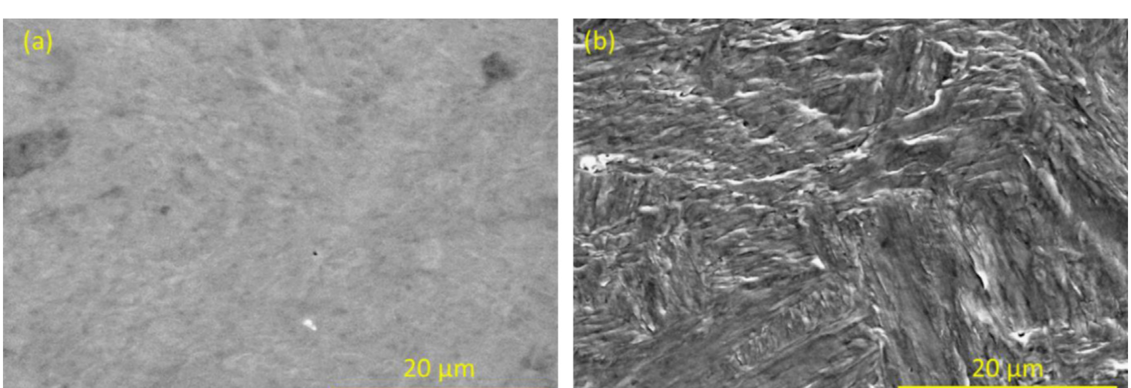

Fig. 17. Vibratory polished 12% Cr stainless steel sample (a) before the WDE test and (b) during the incubation stage.

length of the incubation stage, as the water droplets needs more time to roughen the surface and initiate erosion pits.

It is expected that by changing the surface preparation method the response of the material would also change, this point was not studied in the current work but may be a subject for future investigations.

4.2. The effect of initial surface roughness on the progression of WDE

The general water droplet erosion progression mechanism of a similar (12% Cr) stainless steel alloy was extensively studied by Haag [18]. The erosion progression observed in his study is in accord with the current work. However, Haag [18] did not study the effect of initial surface roughness on the water droplet erosion behaviour. Erosion progression as seen in Fig. 19 is different for both roughness levels. Pits formed on the polished samples tend to be isolated at the beginning, where some locations on the erosion line are more resistant than others. However, the formed pits tend to slowly increase in size as erosion continues. Later on, large pits tend to merge and form a complete erosion crater. In the case of rough surfaces, pits nuclei were abundant as shown in Fig. 18. Pits start rapidly spreading over the erosion line, then they start to merge quickly forming a rougher surface or crater.

This difference in the erosion progression mechanism of both surface conditions may be the reason for the difference in the maximum erosion rate shown in Fig. 9. Whereas discussed for polished samples, pits initiation is gradual and non-uniform. In other words, if a pit on the erosion line is still in the initiation stage others pits may have reached advanced stages as can be seen in Fig. 19. This results in a lower overall mass loss and tends to reduce the erosion rate. However, for rougher surfaces, erosion does not progress in the same manner, where pits initiate and merge rapidly on the surface causing a large amount of mass loss over a short period of time, which is represented in the higher maximum erosion rate.

For more severe erosion conditions, there is a reduction in the effect of initial surface roughness, on both the incubation period and the maximum erosion rate. It could be attributed to the higher level of exerted energy, caused by the increase in the droplet size and speed. Because, as the amount of energy exerted increases, the stresses applied on the surface also increase, which accelerates the erosion process in general. It is also expected that by increasing the impact speed, there should be an increase in the amount of energy transferred to the surface of the sample for the same droplet size. This increase can be attributed to the change in water properties due to the change in speed of impact. Lesser et al. [47] claimed that the response of the water droplet changes by changing the 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. In the case of an initially smooth surface, high levels of stresses due to the increase

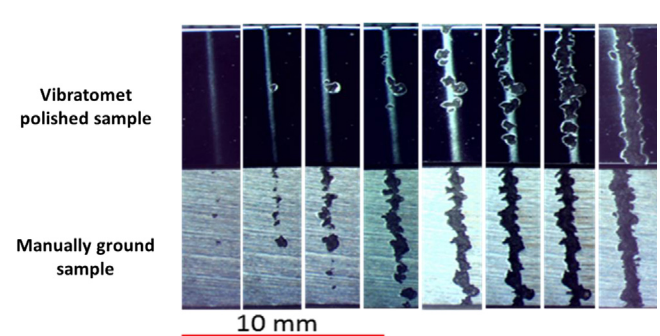

Fig. 19. Optical macrographs for erosion progression of two 12%Cr stainless steel samples.

in the amount of transferred energy to the surface are expected to decrease the length of the roughening stage significantly.

As presented earlier in Fig. 12, the level of superiority for the polished surface dropped from 60% for the least severe test condition to 42% for the most severe test conditions. However, this level of superiority is still recognisable. Later on, due to the high levels of applied stresses, the surface starts to lose a large amount of material over a short period of time. Therefore, this leads to the increase in the maximum erosion rate, consequently, it becomes similar to that of the initially rough surface. For rough surfaces, the increase in energy flux (rate of energy transfer to a surface) may eliminate the roughening stage, and increases the maximum erosion rate.

4.3. The effect of initial surface roughness on the WDE of Ti6Al4V

It has been proven by experimental results in this work that reporting the initial surface conditions of tested samples, before reporting the water droplet erosion behaviour is important. The results produced for Ti6Al4V strengthen the claim that in some cases initial surface roughness may influence both the incubation period and the maximum erosion rate. Moreover, they indicate that the effect of initial surface roughness on the erosion behaviour is dependant on both the material and erosion conditions. Since, the initial surface roughness affected the maximum erosion rate of Ti6Al4V at the two tested impact speeds (300, 350 m/s), which was not the case for the 12% Cr stainless steel, where its maximum erosion rate was influenced at only one speed (i.e. 300 m/s).

The relation between the length of the incubation period and the maximum erosion rate was also discussed by Seleznev et al. [39]. They claimed that the maximum erosion rate is inversely proportional to the length of the incubation period, of the same material, when tested at different erosion test conditions (i.e. droplet sizes and impact speeds). However, Seleznev et al. [39] did not discuss the effect of the initial surface roughness on this relation between the length incubation period and the maximum erosion rate. The current results suggest that this relation is valid, in some cases, for samples tested using the same droplet size and test speeds but different initial surface roughness.

4.4. Initial surface roughness and comparisons between WDE resistant coatings and surface treatments

According to the ASTM G73-10 standard [31], the incubation period is the most significant test result for coatings and surface treatments, as their useful service life may be terminated by the initial surface damage. According to the results of the current work, reporting the surface conditions of the coating or the treated surface and the reference material is important. In addition, the effect of this treatment or coating on the roughness of the resulting surface should be addressed, especially, when a surface treatment is claimed to prolong the length of incubation stage. It was found that simple polishing could cause a considerable delay in erosion progression, and reduce the significance of any further treatment to the surface. For example, it is noticed in this work that polishing alone increases the incubation period of stainless steel by around 80% for the case of 300 m/s impact speed and 460 μm droplet diameter. In addition, the incubation period of Ti6Al4V increases by almost 100% for the case of testing at 350 m/s using 460 μm droplet diameter, by polishing only.

Several articles are presented in the literature claiming treatments and coatings to combat the WDE wear [36,48–51]. In his work, Mann et al. [36] presented a surface treatment (high-power diode laser) paired with a coating (Twin Arc Wire Spraying) for water droplet erosion applications. They claimed that the erosion resistance of the treated substrate improved by their treatment, however, they did not mention to which roughness level of the substrate's surface the treatment was compared. In another work by Mann et al. [48], they compared the erosion resistances of 10 surface treatments and substrate materials; however, the starting surface roughness of samples was mentioned in three cases only, these roughness values had a wide range from 0.47 μm to 3.27 μm. Such considerable variation in the initial surface roughness should be taken into account while comparing the erosion resistance of the substrate to that of the proposed treatments. In general, as a recommendation it would be a good practise to have similar starting surface quality, by using similar surface preparation techniques, for water droplet erosion resistance comparison purposes.

Moreover, the improvement achieved by polishing only is comparable to that reported in the literature for certain surface treatments, as for example in the work of Mann et al. [48]. They claimed that the incubation period of an HVOF coated 12% Cr stainless steel with WC–10Co–4C was two times higher than the uncoated substrate, when tested at 147 m/s and a water-jet diameter of 3.77 mm. These results are close to what was presented in this work by simple polishing of a similar 12% Cr stainless steel alloy, when it was tested at even a higher speed of 300 m/s and droplet size of 460 μm. However, it would be expected that if the surface roughness of the coated sample (3.27 μm Ra) was reduced, the coating would have shown better results. This claim is supported by what was discussed by Mahdipoor et al. [52] concerning the effect of the surface roughness on the water droplet behaviour of HVOF coatings for water droplet erosion applications. Therefore, as a recommendation, improving the final surface quality by reducing the surface roughness of treated or untreated material surfaces used in WDE applications is a viable tool to delay erosion.

5. Conclusions

This work provides a quantitative evaluation of the effect of the initial surface roughness on the incubation period, especially, for 12% Cr stainless steel. The following conclusions could be drawn from the current work:

1. This study revealed that the initial surface roughness has a significant impact on the water droplet erosion behaviour.
2. The amount of surface asperities and irregularities was found to be the main reason for the difference in the WDE behaviour of the same material with different initial surface roughness, since, the presence of these features accelerates the erosion damage.
3. The length of the incubation period for the 12% Cr stainless steel increased by 70% after polishing of the surface, when tested at 300 m/s using 603 μm droplets. In addition, it increased by 100% for Ti6Al4V, when the polished sample (0.06 Ra) is compared to the roughest sample (0.3 Ra), tested at 350 m/s using 460 μm droplets.
4. The maximum erosion rate may also be influenced by the initial surface quality. But this effect is material and erosion conditions dependant. For instance, the initial surface roughness influenced the maximum erosion rate of 12% Cr stainless steel, when tested at speed of 300 m/s and droplet size of 460 μm. It also influenced that of Ti6Al4V tested at 300 and 350 m/s and 460 μm droplets. This effect could be attributed to differences in the erosion progression mechanisms of smooth surfaces and rough surfaces.
5. In the case of 12% Cr stainless steel, the effect of initial surface roughness is more significant for both droplet sizes when tested at 300 m/s than at 350 m/s. It should be considered that this study was done with two droplet sizes and two impact speeds only, it is expected to have a less effect of initial surface roughness as the severity of the erosion conditions increases (higher impact speeds and/or larger droplet sizes).
6. The quality of the surface should be taken into consideration while comparing the erosion resistance of different materials and/or surface treatments. Generally, it would be a good practise to use similar initial surface roughness, as much as possible, by using the same method of surface preparation.
7. The improvement in the erosion resistance achieved by polishing could be compared to what could be obtained by surface treatments. In general, improving the final surface quality by reducing the initial surface roughness of components subjected to WDE is a practical tool to delay erosion.

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