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EFFECT OF STRESS RELIEVING ON WATER DROPLET EROSION BEHAVIOR IN X22CrMoV12-1 STEEL

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Abstract— Water Droplet Erosion (WDE) is a wear erosion phenomenon observed in compressor blades of gas turbines and the blades of low-pressure sections of steam turbines. Repeated droplet impacts cause plastic deformation and strain hardening of the surface over extended periods of time. Strain accumulation from droplet strikes onto the target metal has been a contentious issue among researchers. Some researchers mentioned that strain hardening is beneficial in prolonging the life of blade material while others argue it shortens the blade life. This study aims to better understand the mechanisms during the early stages of the WDE process. X22CrMoV12-1 stainless steel, which is a commonly used steam turbine blade material, is chosen to study the effect of strain hardening during WDE. WDE tests were performed in a rotating disc erosion rig according to ASTM G73 standard. Impact speed of 300 m/s and droplet size of 460 microns were employed. Tests were interrupted at intervals of 2 minutes or 30 seconds and the accumulated stresses in test samples were intermittently relieved at 680°C for 75 minutes. With increasing frequency of stress relieving, pitting was observed on the stress relieved sample earlier than the reference sample (not stress relieved). The SEM micrographs showed varying mechanisms of material removal in the relieved samples compared to the reference samples. For instance, a noticeable size difference in the growing erosion pits was observed in the 30 seconds relieving test compared to the reference sample. A difference in the rate of erosion was also seen as the stress relieving was changed from every 2 minutes to every 30 seconds. This work concludes that a higher frequency of relieving had an influence on the incubation period. For instance, relieving after every 30 seconds of WDE testing showed an increase in incubation period compared to relieving after every 2 minutes of WDE testing. Frequent relieving helps reduce the erosion rate in comparison with the reference sample even though it had relatively shorter incubation. The proposed concept of intermittent relieving can help remove accumulated strain due to droplet impacts. This can prolong the life of blades mainly by elongating the initial stages of erosion.

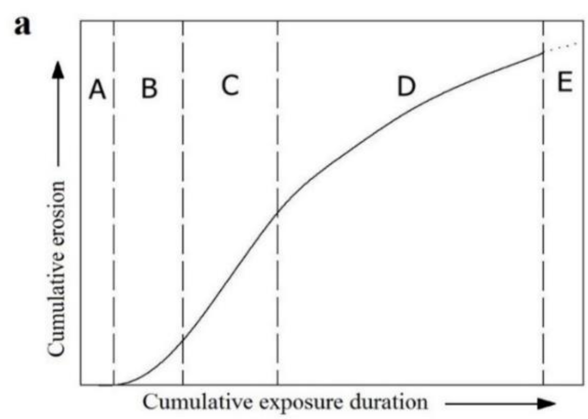
Keywords- Strain Hardening; Stress Relieving; Erosion Mechanisms; X22CrMoV 12-1 stainless steel

I. INTRODUCTION

A. Water droplet erosion phenomenon

The gas turbine efficiency can be improved by lowering inlet air temperature and increasing density and for this reason inlet fog cooling is used in gas turbines [1, 2]. This improvement in efficiency however comes at a price of leading edge erosion damage of compressor blades from coalescing droplets of water from mist and eventual reduction in turbine life span [3, 4]. The phenomenon of erosion damage from impacting water droplets at high speeds is called Water Droplet Erosion (WDE). This phenomenon is also observed in fan and compressor blades of aircraft engines due to rain and hail [5, 6], in steam turbine blades due to condensation of steam [7–9] and in wind turbine blades due to rain and hail [10, 11].

WDE is a time dependent phenomenon and is typically characterized by erosion curves, well described in ASM handbook 18 [3]. Characteristic erosion curves are plotted between cumulative mass loss or erosion rate versus the exposure duration as illustrated in Fig. 1.



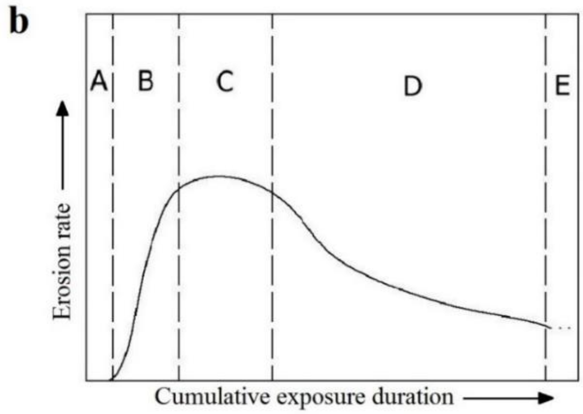


Figure 1. (a) Cumulative erosion versus cumulative exposure duration curve (b) Instantaneous erosion rate versus cumulative exposure duration curve [3].

For some initial duration, depending on impact conditions and target material, the material resists droplet impacts and no measurable mass loss is observed. This stage of WDE phenomenon is referred to as incubation stage (A). Erosion starts and gradually accelerates to maximum erosion rate stage (C) through acceleration stage (B). After a period of constant maximum erosion rate, deceleration stage (D) in which the erosion rate gradually falls. Terminal steady erosion rate stage (E) is reached when the erosion rate is steady and by then the severe erosion of blades renders them aerodynamically ineffective.

B. Droplet impact mechanics

Droplet impact mechanics and material response are two major aspects of erosion studies. Literature on the sequence of events in droplet impact mechanics is briefly reviewed below however the scope of this research is limited to studying the material response aspect which includes material removal mechanisms. Extensive research was done in the past to understand droplet impact mechanics. When a liquid droplet first touches the solid, compression waves are sent into the liquid. As the droplet contact periphery expands over the target surface, new wavelets are generated at each instance which constructively interfere and form a shock envelope in the impacting droplet [12, 13]. Liquid encompassed within this envelope stays compressed and exerts very high magnitudes of pressure on the target. This 'water hammer pressure' is believed to have very high magnitude. A simple water hammer pressure 'P' expression as shown in (Eqn. 1) which is a function of density of liquid 'ρ', speed of sound in liquid 'C' and impact velocity 'V' was first used by Cook [14]. However, it turns out that the shock wave velocity is higher than the acoustic velocity 'C' and properties of liquid in compressed region are different from the undisturbed one. Heymann [12] concluded that the peak pressure could be as high as three times the magnitude of water hammer pressure from his analytical model.

$$P = \rho C V \tag{1}$$

As the lateral jetting starts, the pressure on the central axis of the drop experiences Bernoulli's stagnation pressure which is much smaller than the impact pressure [15]. This also means that greater impact pressures are experienced in a region smaller than the size of the droplets. High pressures exist until the shock envelope stays attached to the target surface. As this envelope overtakes the contact periphery of the droplet, lateral jetting starts to happen and this point is labelled as a 'critical point' [9, 12, 16]. Fig. 2 shows a shock envelope at this critical point and the start of jetting as it overtakes the periphery of the droplet. Jenkins and Booker [17] observed lateral jet velocities 2 to 6 times the impact velocity in the range of 100 to 1140 m/s. Ratio of jetting to impact speeds was found to be very high at low speeds and decreases as the impact speed increases.

C. Damage mechanisms

Longitudinal stress waves, transverse shear waves and surface Rayleigh waves are generated at the site of impact and are transmitted into the material. These stress waves reflect and transmit at discontinuities in the material and their constructive interference is suspected to cause damage [15, 18]. This damage mechanism becomes predominant when the surface is either non-homogenous, like in a coating or when it has irregularities beneath the surface which act as sites of reflection of these waves [15, 18, 19]. In metals experiencing damage due to multiple impacts, various mechanisms of damage are believed to be contributing to erosion. It is a common understanding that initial droplet strikes deform the surface plastically and creates depressions and asperities [16, 18, 20, 21]. When these asperities are sufficiently large and weak, radial jetting from a nearby droplet impact can break them, thereby creating a pit [8, 16, 21, 22]. Initial surface roughness also therefore plays a crucial role in the start of erosion due to surface irregularities interacting with the jetting [23]. Surface roughness has also been found to influence the jetting behavior itself [24]. Newly created shallow pits are believed to expand by various possible mechanisms, explained throughout literature. One such damage mechanism is failure by hardening from strain accumulation and eventual embrittlement. Hardening by strain accumulation remains debatable for whether it aids or resists erosion damage. For instance, Heymann [3, 22] predicted that some prior work hardening can improve erosion performance while excess hardening can be detrimental. Among studies which used cold working to induce surface hardening, Thomas and Brunton [25] found erosion resistance of cold worked copper is reduced and attributed it to lower impacts needed for full hardening in the case of cold worked specimens. Ma et al. [26] have seen no improvement in erosion resistance of Ti-6Al-4V alloy with a Deep Rolling (DR) treatment. It was attributed to the beneficial effects of Compressive Residual Stress (CRS) from the DR treatment being cancelled by embrittlement due to work hardening, also from the DR treatment [26]. Rieger [27] relieved strain accumulated by impacts through annealing of aluminum samples and found annealed samples erode significantly earlier compared to reference samples due to removal of additional hardness gained by the strain hardening from impacts. However, the samples were reportedly tempered at 510°C which could have lowered the strength and hence the reduction in incubation time. It is therefore important to understand the effects of strain hardening induced by impacts on WDE phenomenon.

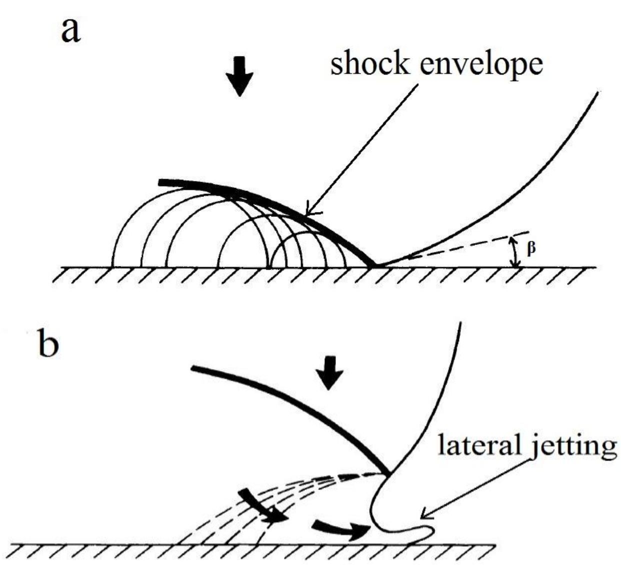


Figure 2. (a) Shock envelope in the initial compression stage of droplet impact (b) Start of lateral jetting after reaching critical point [20].

Various erosion test parameters such as droplet size [28, 29], impact speed [7, 9, 30], impact angle [31], initial surface roughness [23, 24] and target mechanical properties [9, 32–35] are known to influence the erosion performance and are studied in the literature. In this work, all parameters known to influence the erosion behavior are kept constant and only the effect of relieving strain accumulation is studied.

II. Experimental procedure

A. Sample material and preparation

The samples are prepared out of 3 mm thick X22CrMoV 12-1 stainless steel strips. This stainless steel is a commonly used blade material in steam turbines. Samples are ground to a shape which fits into the sample holder. Each sample is 8 mm in height. The rectangular test surface of each sample is ground to 1200 grit finish using SiC paper to maintain uniform surface finish.

B. Strain relieving treatment

Strain relieving was carried out in a Barnstead-Thermolyne FD1535M benchtop furnace at 685°C for 75 minutes followed by air cooling. X22CrMoV 12-1 stainless steel has a well-established relieving temperature range of 660-690°C for at least an hour. Both the test piece and the reference sample were initially relieved before the start of the test and only the test pieces are relieved after every cycle. Tests were either at 2 min or 30 s intervals and are referred to as SR-1 and SR-2, respectively.

C. WDE testing and characterization

Water droplet erosion tests were carried out on a rotating disc erosion rig that can reach 20,000 RPM which translates to a linear speed of 500 m/s at the impingement site. The Water droplet erosion rig as shown by a schematic in Fig. 4 is controlled using a computer program which allows erosion testing by constantly monitoring various operating parameters like test chamber pressure, temperature, rotational speed, etc. along with control of various solenoid valves in the system. The test chamber can be evacuated to 30-50 mbar vacuum pressure to minimize air friction and eventual rise in temperature during tests. The test and reference samples are fixed in their respective sample holders mounted diametrically opposite to each other on the rotating disc which is driven by a compressed air turbine. An exploded view of sample holder assembly is shown in Fig 3.

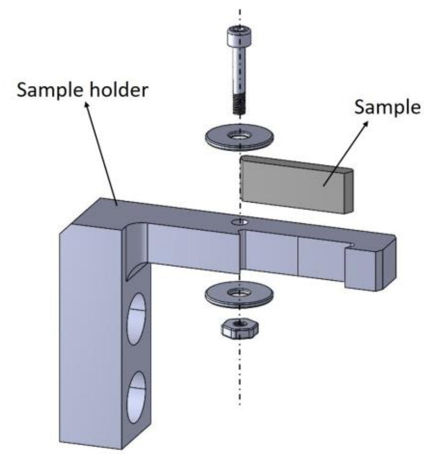


Figure 3. Sample holder assembly.

As the disc reaches the set speed, the water droplet generation system then introduces water droplets over the samples to simulate erosion conditions in accordance with ASTM G73 standard [36]. Water droplets are introduced for the cycle duration through a nozzle positioned over the samples thereby creating impacts at 90° with the sample surface. An impact speed of 300 m/s was used for both the tests. Water accumulated from the droplets during the erosion test in the chamber is constantly drained to a scavenge tank attached to the rig. The rotating disc is gradually brought to rest and the test chamber is re-pressurized to remove samples from their holders. This completes a single cycle of erosion testing on a pair of samples. Samples are weighed on a sensitive balance, which is accurate to ±0.2 mg, after every cycle of testing to calculate the cumulative erosion mass loss. This information is used to plot an exposure time versus cumulative mass loss graph for each of the samples. Multiple cycles constitute a single erosion test. Cycle times of 2 minutes or 30 seconds each were used as intervals between the relieving experiments. The test samples were relieved keeping the reference sample unchanged at the end of each cycle. Pictures of the samples were also taken after each cycle, compilation of which is shown in Fig. 5, to trace the development of pits in each sample.

The droplet size and number of droplets were characterized using a glass box and high speed camera as reported in the earlier works [23, 26]. At 30-50 mbar vacuum pressure and a vertical standoff distance of 50 mm between the nozzle and the sample, an average droplet size of 464 µm and 6 droplets over 8 mm sample width were observed.

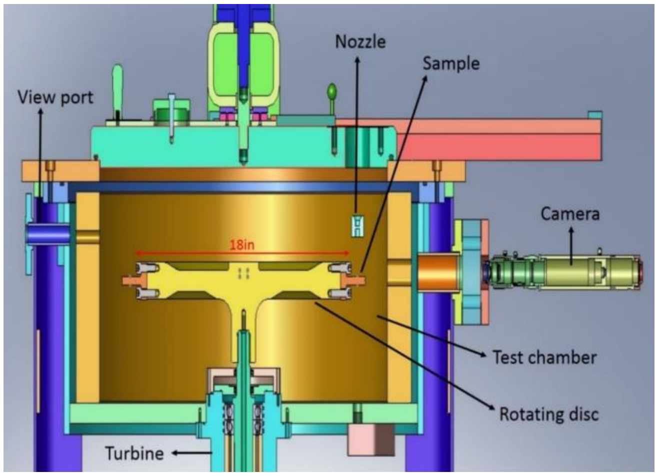


Figure 4. Schematic of water droplet erosion rig.

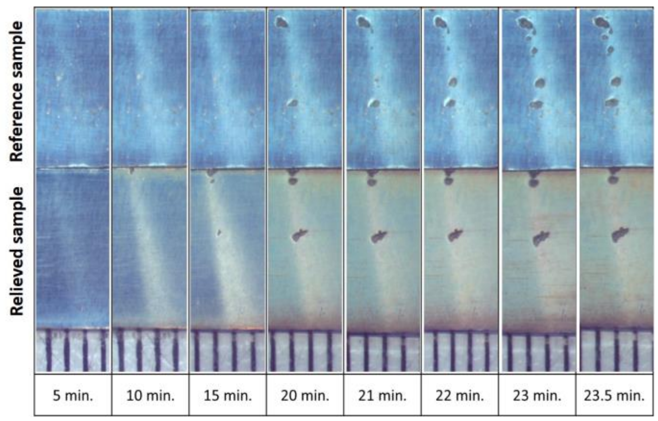


Figure 5. Macrographs showing the progression of erosion during SR-2 test.

D. Scanning Electron Microscopy

A Hitachi S-3400N Scanning Electron Microscope (SEM) was used to examine pits developed at the end of the incubation stage and to study the evolution of pit growth. Surfaces were imaged using Secondary Electron Imaging (SEI). Samples were only cleaned, and no additional surface preparation was done during erosion tests. Pits and their surroundings were imaged to study the difference in mechanisms of pit growth between the relieved and reference samples.

III. RESULTS AND DISCUSSION

A. WDE behaviour

Erosion tests were conducted at normal of 300 m/s impact speed and 464 µm droplet size. Each sample experiences impact from 6 droplets over their 8 mm height per revolution. Two tests with variation only in cycle time were conducted. The SR-1 test showed the relieved test sample having a shorter incubation time of 8 minutes compared to 10 minutes for the reference sample. The difference is insignificant as it could have been shorter than 2 minutes but has not been captured due to the larger cycle duration of 2 minutes. The SR-2 test however showed qualitatively larger difference in the incubation times and also slower erosion rate. In the maximum erosion rate region, erosion rates, represented by the slope of the dotted lines in Fig. 6, were clearly different and this was not the case for SR-1 test which had less frequent strain relieving. At longer times, the SR-2 relieved sample shows lower mass loss even though its incubation period was shorter than the reference sample. A clear difference in the rate at which pits grew was observed during the SR-2 test which is reflected as the difference in the erosion rate. Fig. 7 shows the evolution of a pit in both a relieved and in a reference sample over time. As a pit in the reference sample grew rapidly, the one in the relieved sample barely grew in its overall size. Even though the pits in the stress relieved samples appeared much earlier, their growth rate was slower thereby resulting in lower erosion mass loss compared to that of the reference samples at the end of SR-2 test.

This proves that removal of accumulated strain can help decelerate erosion loss. A probable explanation for this is that the relieved strain leaves some room for accumulation, from subsequent impacts, before cracks start to form and propagate. When stress relieving is done again, only the accumulated strain is removed but not the cracks which have formed. This additional impact energy that can be absorbed helps in lowering the erosion rate. This result is in contrast to the stress relieving experiment by Rieger [27] on aluminum which showed no change in erosion rate but reduced the incubation period. This can probably be due to the higher relieving temperature used in that work causing a decrease in strength which eventually led to significant reduction in the incubation time.

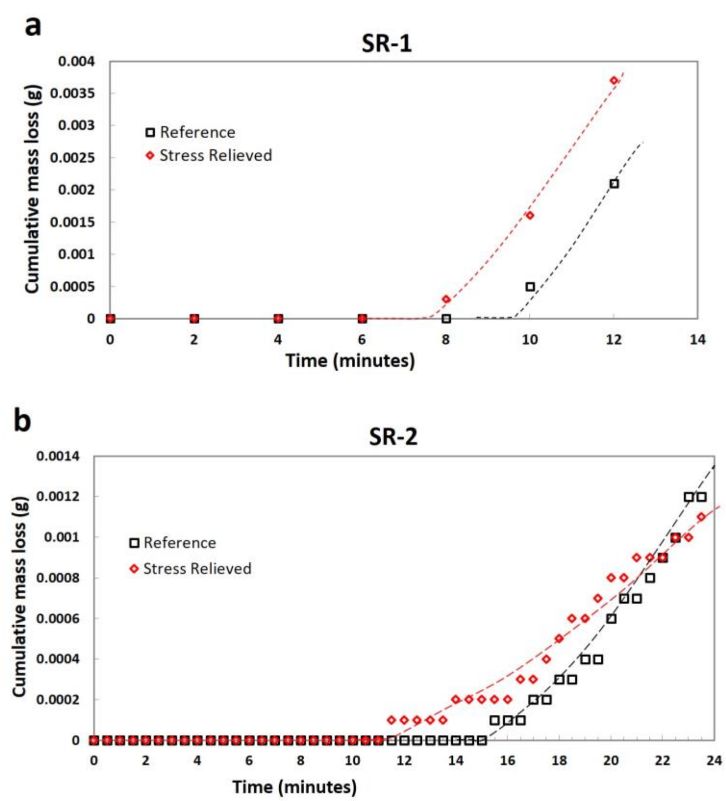


Figure 6. Erosion curves of a) SR-1 and b) SR-2 at 300 m/s.

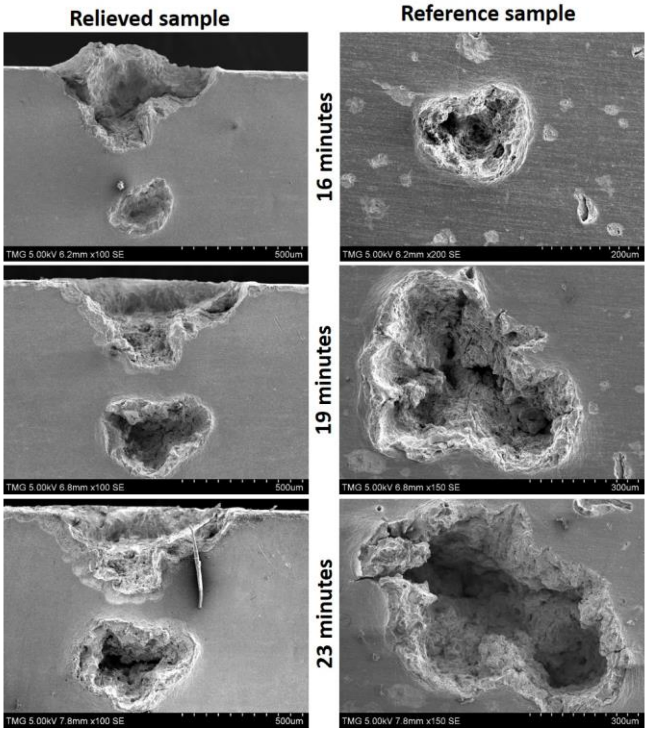


Figure 7. Evolution of pits in relieved and reference samples during SR-2 test.

B. *Water droplet erosion mechanism*

Erosion mechanisms were investigated using SEM imaging through the acceleration stage as it reaches the maximum erosion rate stage in samples from the SR-2 test. Pit growth by notably larger size chunks was observed in the reference sample, as shown in Fig. 8, and was clearly absent in the case of stress relieved samples. This micrograph in Fig. 8 was taken at 16 minutes of cumulative erosion time and the highlighted chunks eroded away during the next cycle. Fig. 5 also provides a general idea of quicker pit growth in the reference sample compared to that in the stress relieved sample.

Subsurface cracks were also seen around larger pits in the reference sample. A network of subsurface cracks expands with successive impacts and when large enough, the material beneath deforms and breaks away as chunks, often in the range of 100-200 µm. These observations suggest that if strain accumulated from droplet impacts is removed frequently enough, before formation of micro-cracks and their subsequent growth, erosion can be decelerated in blade materials. However, some similarities were found during SEM examination of reference and relieved samples. A mostly intergranular fracture surface, freshly exposed by erosion of overlying material, undergoes plastic deformation from successive impacts as demonstrated in Fig. 9. Although this was predominantly observed in the reference sample, it was also seen in the relieved sample closer to the deep crevice cracks when opened up. Identical upheaval, due to plastic deformation from lateral jetting, in the periphery of existing pits was observed in both samples alike. This upheaval or material folding can be seen around pits in Fig. 7 and 8.

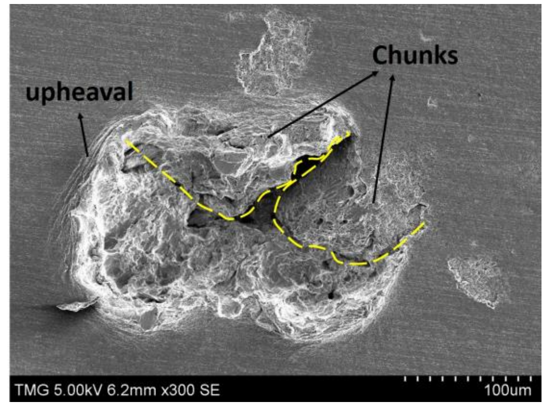


Figure 8. Pit growth by chunks breaking away in reference sample of SR-2 test.

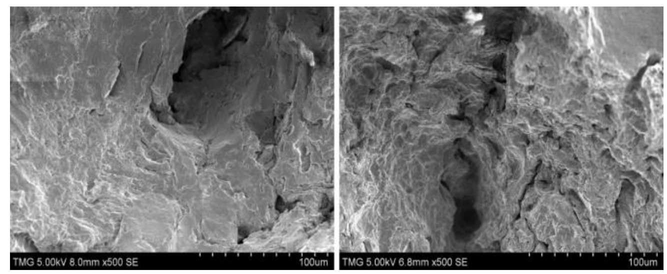


Figure 9. A typical freshly exposed surface (left) and a typical eroded surface exposed to subsequent droplet impacts (right).

IV. CONCLUSIONS

Strain relieving every 2 minutes (SR-1) or every 30 seconds (SR-2) were conducted on X22CrMoV 12-1 stainless steel. The relieved samples from both tests showed shorter incubation period compared to the unrelieved reference samples. A qualitative difference in erosion behavior was observed between the two cases. A clear difference in the erosion rates between the test and reference samples was observed in the SR-2 test but no difference was seen in the case of the less frequently relieved SR-1 test samples. Differences in erosion mechanisms between the stress relieved (SR-2) and unrelieved samples were evident. Larger chunks were removed during erosion and the presence of subsurface cracks around pits was observed in the case of the reference sample. This was absent in the case of the stress relieved sample. Similar mechanisms like plastic deformation over freshly exposed intergranular fracture surface from subsequent impacts and surface upheaval around growing pits were seen in both cases.

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