Influence of laser peening on the water droplet erosion behaviour of gas turbine compressor blade material

Abdullahi K. Gujba [a], Lloyd Hackel [b], Mamoun Medraj [a]
[a] Concordia University, Montreal, Canada, a_gujba@encs.concordia.ca, mmedraj@encs.concordia.ca; [b] Metal Improvement Company-Curtiss Wright Corporation, California, United States, Lloyd.Hackel@cwst.com

Introduction

One of the Achilles' heels of advanced materials found in the power generation industry is the water droplet erosion (WDE) of the leading edge of compressor blades. This occurs due to the interaction between water droplets injected in to the compressor and rotating blades. WDE is defined as the progressive loss of material from a solid surface due to accumulated impacts by liquid droplets [1]. WDE encountered in gas turbines is a complex phenomenon that existed for considerable long period of time and the reason for this is the number of parameters involved during the erosion process. WDE damage is predominantly caused by two main factors; (1) the high pressure exerted by the water droplet on the exposed area of the solid surface and (2) the radial liquid flow (lateral jetting) along the surface at high speed, which occurs after the initial droplet pressure lessens [2]. Existing literature suggests that WDE is likened to fatigue-like damage due to the continuous liquid impacts in a cyclic fashion [3,4]. Also, crack initiation and propagation have been found to significantly influence WDE behaviour similar to fatigue [5]. It is known that induced compressive residual stresses from mechanical surface treatments such as shot peening (SP) or laser shock peening (LSP) retard crack initiation and propagation, improving fatigue life [6]. Hence, one would suggest that mechanical surface treatments might enhance WDE performance to a certain degree. For this reason, this work studies the effect of LSP surface treatment on WDE performance. LSP is a cold working process where the surface is subjected to pulses through high power intensity laser, generating shock waves. As the shock wave stress exceeds the dynamic yield strength of the material, plastic deformation occurs [6]. These waves deform the top surface and compressive residual stresses are extended into the material [6]. So far, the applications of LSP processing include improvement of fatigue life, stress corrosion cracking resistance, corrosion resistance, wear resistance [6]. Thus, exploring LSP in terms of WDE is worthwhile. The WDE performance is discussed based on the observed residual stresses, microhardness and microstructure. In order to understand the influence of induced compressive residual stresses, different surface conditions having variable compressive residual stress levels were employed which includes; stress relieved (SR) condition having near zero compressive residual stress, as-machined (As-M) condition having inherent compressive residual stress due to machining and laser peened (SR+LSP) sample after being stress relieved.

Objectives

The main objective of this work is to investigate the effectiveness of LSP and its attributes on the WDE performance of Ti-6Al-4V.

Methodology

For this study, Ti-6Al-4V (ASTM B265, Grade 5) alloy, used for compressor blades in gas turbines, was investigated. The starting microstructure of the Ti-6Al-4V alloy contains α- and β-phases as shown in Figure 1a. T-shaped samples shown in Figure 1b were machined in accordance to the sample's geometrical requirement of the WDE testing rig.

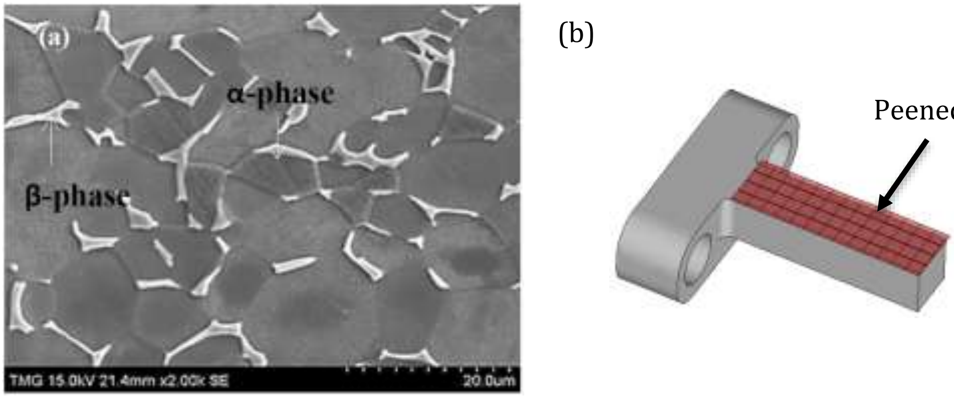

Figure 1: (a) initial Ti-6Al-4V microstructure and (b) typical T-shaped flat sample machined.

An Nd:Glass laser at Metal Improvement Company (MIC), Livermore Laser Peening Division, California, USA, was used for the LSP processing. Ablative layer of Aluminum, intensity of $10GW/cm^2$, pulse time of 18ns and a square spot geometry (3 x 3mm spot size) were used. Two peening layers were used and in the first layer during peening, a 3% spot overlay was used, whereas 50% spot overlay was used for subsequent layer. For the SR condition, As-M sample was heat treated in an oven (Thermolyne Oven model FD1535M) at 1100°F (590°C) for 2hrs. This approach relieved the compressive residual stresses induced during machining.
Top surface compressive residual stresses before and after LSP were measured using the XRD $\sin^2\phi$ technique at Proto Manufacturing Inc., USA. Microhardness measurements were carried out. Surface and in-depth microstructures were acquired using SEM.
The WDE performances of treated and untreated Ti-6Al-4V was conducted in a rotating disc rig in accordance with the ASTM G73 standard [7]. Figure 2 shows a schematic illustration of the rig used in the present work. More information about the rig has been detailed by the same authors in [5]. Influence of impact speed (between 150 and 350m/s) on WDE performance was explored. Average droplet size of 463μm was used. The setup enabled the droplets to impact the samples at 90° in a repetitive fashion. Number of droplets is the number of droplets impinging the sample at particular time which has been determined in [5]. During the WDE tests, experiments were halted at certain intervals and eroded samples were weighed using a balance having ±0.2mg accuracy. Finally, typical erosion curves were plotted and analysed.

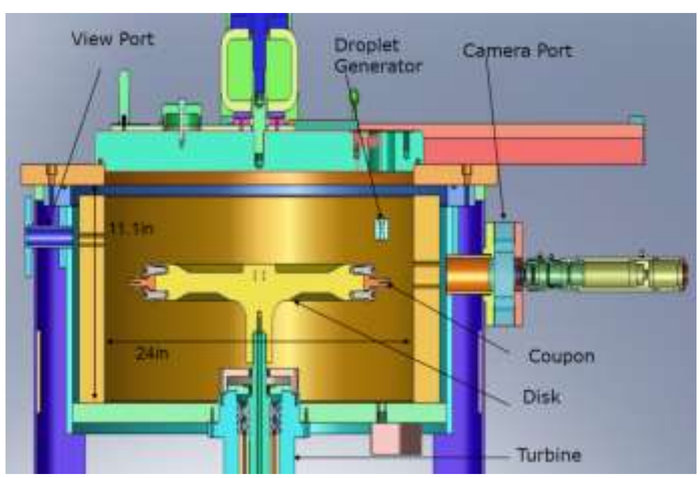

Figure 2: Schematic illustration of the water erosion rig used in the present work.

Results and Analysis

The influences of LSP and its associated attributes on the surface and in-depth characteristics of Ti-6Al-4V alloy have been studied and discussed in this section. This section highlights the effect of LSP process on the observed compressive residual stress, microstructure and microhardness. Also, the WDE performances of untreated and treated conditions are presented.

Residual stresses

The top surface compressive stresses were measured for the SR, As-M and LSP conditions in the 0°, scanning, and 90°, transverse, directions. The SR condition showed close to zero compressive residual stress (-29.14±5.80 and -22.2±17.83MPa in the 0° and 90° directions, respectively). This approach relieved the compressive residual stresses induced during machining. The As-M condition showed -490±19 and -607±90MPa, respectively in the 0° and 90° directions due to the machining process. LSP condition showed residual stresses of -770±13.50 and -768±14.82MPa in the 0° and 90° directions, respectively, which are higher than those observed for the As-M condition. This is due to the effectiveness of LSP in inducing compressive residual stress. The LSP induced stresses are in the range of 600-750MPa and about 60-80% of the materials' yield strength. This is in accord with the current observation. Detailed studies on the variation of compressive residual stress with depth after the LSP process have been reported by the same authors in [6]. For this reason, the in-depth residual stresses are not reported in this paper.

Microstructure

The top surface and cross-sectional views of the untreated and LSP conditions were observed using SEM. Despite the level of compressive residual stresses induced during LSP, no microstructural changes were observed after LSP. This is mainly attributed to the small amount of cold working induced during LSP process [6]. This observation is in accord with other reports [8–10]. For instance, Graham *et al.* [8] stated that LSP processing does not cause macroscopic deformation in the treated region. This was supported by the works of Shepard *et al.* [9] and Zhao [10]. These observations could be due to the laser shock interaction times which are very short (in nanoseconds) compared to other conventional peening techniques such as shot peening [6]. Thus, the short interaction times and very limited impacts per unit area might not significantly change the microstructure.

Microhardness

A 50gf load was used to measure the top surface and in-depth microhardness. Microhardness at 7-8 locations were obtained across the depth of untreated and treated conditions. The top surface microhardness values were 331±5.3HV, 330±4.2HV and 333±6.2HV for As-M, SR and LSP conditions, respectively. Microhardness across the depth shows that only a mild or no appreciable increase after the LSP treatment. These observations are in accord with the work of Chávez *et al.* [11] where it was shown that LSP had no apparent effect on the microhardness of Ti-6Al-4V. Similar microhardness trend after LSP has been reported on 2205 duplex stainless steel [12] and several aluminum alloys [13]. This can be attributed to the low level of cold working associated with the LSP processing. Other reports [14,15] have shown that LSP induces about 5% cold working. It is well known that cold working improves the mechanical properties such as hardness and tensile strength of materials such as Ti alloys[16-18]. Based on the 5% cold working from laser peening, no appreciable hardness is expected. For this reason, the present work also showed that LSP had no significant effect on hardness. This accompanied with the unchanged microstructure could have led to the observed unchanged microhardness. It is known that refinement of microstructure or reduction in grain size is associated with enhanced microhardness [3]. This is not the case in this work.

WDE Performance

During WDE tests, two coupons (untreated *versus* LSP treated) were tested at the same time in order to investigate their WDE performances. To understand the effects of LSP and its attributes on WDE performance, a wide range of impact speed was used. Here, impact speeds of 150, 200, 250, 300, 325 and 350m/s and droplet size of 463μm were selected. Figures 3a and b show the graphs of cumulative mass loss *versus* number of impingements for LSP and As-M conditions at impact speeds ranging from 150 to 350m/s.

Figure 3b shows typical well-behaved erosion curves with an S-shape. With this curve shape, distinct erosion stages such as incubation (initiation) period with negligible mass loss; acceleration stage up to a maximum erosion rate (ER_{max}) stage; deceleration (attenuation) stage with declining ER and terminal erosion state with constant ER can be observed [1]. From Figure 3, it can be seen generally that increasing the impact speed from 150 to 350m/s showed faster erosion evolutions and progressions in both As-M and LSP conditions. This is due to the increase in test severity with increase in impact speed. However, at impact speed of 150m/s (Figure 3a), no erosion was observed on both As-M and LSP conditions after 840 minutes of exposure which corresponds to approximately 30 million impingements. Here, only a shiny erosion line trace was observed under the optical macrograph and no visible damage was detected. This is as shown in the insert macrograph in Figure 3a. This reveals that the threshold speed for both As-M and LSP conditions is greater than or equal to 150m/s but less than 200m/s (i.e. 150 m/s $\leq V_{threshold} <$ 200m/s) under this test condition. The threshold speed is the speed below which no apparent damage is seen. Moreover, the definition of this speed is somehow subjective and depends on the testing conditions such as impact speed, droplet size and number of impingements. This is an important observation that has not been captured in previous studies on WDE of Ti-6Al-4V [19–21]. Based on Figures 3a and b, it can be seen that at all tested speeds, similar WDE performance was observed for both As-M and LSP conditions. In other words, both conditions showed similar WDE behaviour at all stages of the erosion. The little difference observed at each speed is considered within the experimental errors.

As mentioned, other surface conditions have been employed during the current research. For instance, stress relieved (SR) and stress relieved plus laser shock peening (SR+LSP) surface conditions were also explored. Figure 4a shows the WDE performance of SR *versus* LSP conditions at 275 and 350m/s. Despite having high level of compressive residual stresses after LSP, similar WDE performance was observed for SR condition which had close to zero compressive residual stress. Also, Figure 4b shows similar WDE behaviour for the SR+LSP and As-M conditions at 250 and 300m/s. Based on the graphs presented in Figures 3 and 4, the As-M, LSP, SR and SR+LSP conditions have similar WDE performance at each test condition.

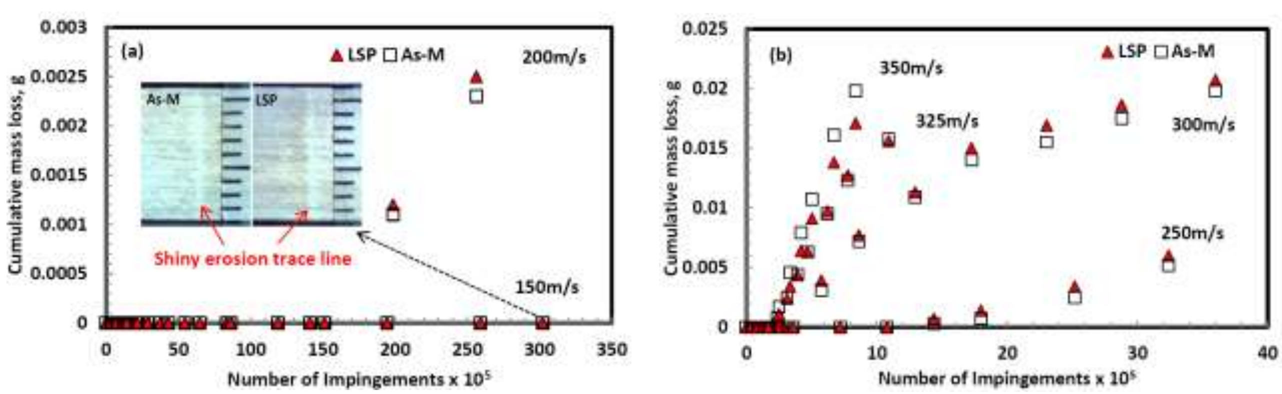

Figure 3. WDE curves for As-M versus LSP at (a) 150-200m/s and (b) 250-350m/s.

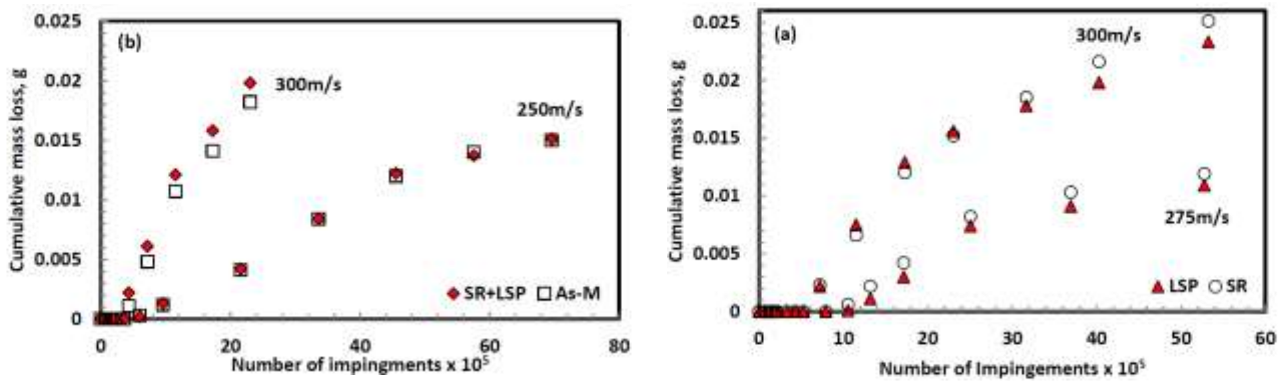

Figure 4: WDE curves for (a) SR *versus* LSP and (b) SR+LSP *versus* As-M.

The influence of the impact speed on the erosion behaviors presented in Figures 3 and 4 could be addressed in terms of erosion initiation and maximum erosion rates (ER_{max}). Generally, the higher the impact speed, the shorter the incubation period and the greater the ER_{max}. This was attributed to the increased kinetic energy with increase in impact speed.

In summary, all surface conditions employed here showed similar erosion initiation and progression. Two main reasons for the observed WDE performance are the lack of noticeable microstructural changes and only small increase in microhardness after the LSP treatment. Even though WDE is likened to fatigue damage, induced compressive residual stresses had no influence on the erosion performance. This is because of the water hammering pressure resulting from the high impacts of the droplet. Here, the continuous droplet impacts produce stress waves that are transmitted and reflected. As the transmitted wave travels and encounters a discontinuity, the compressive residual stress layer in this case, significant portion of the waves is reflected. The continuous interaction between the transmitted and reflected stress waves result tensile stress waves that a high in magnitude especially at high impact speed. This renders the induced compressive residual stresses ineffective in combating the erosion damage. Comparing LSP with other mechanical surface treatments such as ultrasonic nanocrystalline surface modification (UNSM) [3] and low plasticity burnishing (LPB) [4] in combating WDE, a general conclusion can be drawn. These three processes (LSP, UNSM and LPB) cause different levels of residual stresses, microstructural changes and hardening. Based on these works, it was concluded that for mechanical treatment to be effective in improving the WDE performance, it has to cause surface hardening and grain refinement along with deep and high compressive residual stresses. In this work, only the level of compressive residual stress was achieved without noticeable changes in the microstructure and microhardness. Finally, since mechanical surface treatments such as LSP, LPB and UNSM have proven to improve fatigue behaviour of Ti-6Al-4V alloy, this indicates that the fatigue-like mechanism is not dominating in WDE of this alloy.

References

[1] ASTM G40-15: Standard terminology relating to wear and erosion, ASTM International, West Conshohocken, PA, 2015. Available online: www.astm.org.

[2] F. G. Hammitt, F.J. Heymann: Liquid-erosion failures, failure analysis and prevention, ASM Handbook, ASM International, Vol. 11, 1986, pp. 163–171.

[3] A. K. Gujba, Z. Ren, Y. Dong, C. Ye, M. Medraj: Effect of ultrasonic nanocrystalline surface modification on the water droplet erosion performance of Ti-6Al-4V. Surf. Coat. Tech., Vol. 307, 2016, pp. 157-170.

[4] D. Ma, A. Mostafa, D. Kevorkov, P. Jedrzejowski, M. Pugh, M. Medraj: Water impingement erosion of deep-rolled Ti64. Metals, Vol. 5, No. 3, 2015, pp. 1462–1486.

[5] A. K. Gujba, L. Hackel, D. Kevorkov, M. Medraj: Water droplet erosion behaviour of Ti-6Al-4V and

mechanisms of material removal at the early and advanced stages. Wear, Vol. 358-359, 2016, pp. 109-122.

[6] A. K. Gujba, M. Medraj: Laser peening process and its impact on materials properties in comparison with shot peening and ultrasonic impact peening. Materials, Vol. 7, No. 12, 2014, pp. 7925–7974.

[7] ASTM G73-10: Standard test method for liquid impingement erosion using rotating apparatus. ASTM International, West Conshohocken, PA, 2010. Available online: www.astm.org.

[8] G. Hammersley, L. A. Hackel, F. Harris: Surface prestressing to improve fatigue strength of components by laser shot peening. Opt. Lasers Eng., Vol. 34, No. 4–6, 2000, pp. 327–337.

[9] M. J. Shepard, P. R. Smith, M.S. Amer: Introduction of compressive residual stresses in Ti-6Al-4V simulated airfoils via laser shock processing. J. Mater. Eng. Perform., Vol. 10, No. 6, 2001, pp. 670–678.

[10] Y. Zhao: Effects of laser shock peening on residual stress, texture and deformation microstructure of Ti-6Al-4V Alloy. PhD Dissertation, University of Cincinnati, 2012.

[11] J. Chávez, E. Rodríguez, M. Flores, J. Ibarra-Montalvo, O. Jiménez, G. Gómez-Rosas: On the properties and resistance to abrasive wear of surface-modified Ti-6Al-4V alloy by laser shock processing. Superficies y Vacio, Vol. 27, No. 2, 2014, pp. 54–60.

[12] C. Rubio-González, C. Felix-Martinez, G. Gomez-Rosas, J.L. Ocaña, M. Morales, J. A. Porro: Effect of laser shock processing on fatigue crack growth of duplex stainless steel. Mater. Sci. Eng. A, Vol. 528, No. 3, 2011, pp. 914–919.

[13] A. H. Clauer, B. P. Fairand: Interaction of laser-induced stress waves with metals. Proc. ASM Conference Applications of Lasers in Materials Processing; Washington DC, 1979.

[14] F. Baoxiang, Y. Guanjun, M. Xiaonan, Y. Lanlan, W. Xiaodong: Research development of shot peening strenthening of titanium alloys. Titanium Industry Progress, No. 03, 2008, pp. 1–5.

[15] P. R. Smith, M. J. Shepard, P. S. Prevey, A. H. Clauer: Effect of power density and pulse repetition on laser shock peening of Ti-6AI-4V. J. Mater. Eng. Perform. Vol. 9, No. 1, 2000, pp. 33–37.

[16] S. Nagarjuna, K. Balasubramanian, D. S. Sarma: Effect of prior cold work on mechanical properties and structure of an age-hardened Cu-1.5wt % Ti alloy. J. Mat. Sci., Vol. 2, No. 32, 1997, pp. 3375–3385.

[17] E. V. Petunlna, V. L. Poplayskaya: Strength increase of titanium-base alloys by cold working. Met. Sci. Heat Treat., Vol. 1, No. 10, 1959, pp. 24–27.

[18] R. K. Gupta, V. A. Kumar, C. Mathew, G. S. Rao: Strain hardening of Titanium alloy Ti-6Al-4V sheets with prior heat treatment and cold working. Mater. Sci. Eng. A, Vol. 662, 2016, pp. 537–550.

[19] N. Kamkar: Water droplet erosion mechanisms of Ti-6Al-4V. PhD Dissertation, École de Technologie Supérieure (ÉTS), Montreal, QC, Canada, 2014.

[20] H. S. Kirols, D. Kevorkov, A. Uihlein, M. Medraj: The effect of initial surface roughness on water droplet erosion behaviour. Wear, Vol. 342-343, 2015, pp. 198-209.

[21] C. Gerdes, A. Karimi, H. Bieler: Water droplet erosion and microstructure of laser nitrided Ti-6A1-4V. Wear, Vol. 186–187, Part 2, 1995, pp. 368–374.