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A review on the application of peening processes for surface treatment

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Abstract. In today's practice, mechanical surface treatments have been widely applied particularly in the automotive and aerospace industries. It was realized that the failure due to fatigue depends on many factors, and very often it develops from particular surface areas of engineering parts. So, it seems possible to improve the fatigue strength of metallic components by the application of suitable mechanical surface strengthening processes. Peening processes are widely employed in industry for inducing compressive stresses on the metallic surfaces. The present work discusses the basic concepts and their applications of main peening processes namely the shot peening and the laser shock peening. Also, a recently introduced liquid jet peening is discussed.

1. Introduction

The material surface plays an important role in the response of the engineering components. Surfaces are frequently subjected to various surface treatment processes to achieve certain qualities that are not available from the primary manufacturing processes. The process is conducted for various reasons including improving the performance of materials, changing physical properties, varying appearance and altering dimensions. A diverse range of thermal, mechanical and chemical treatments has been developed to modify the surface characteristics. Various surface treatment processes have been used for a wide range of materials from semiconductors to metals, ceramics, polymers, bio and nanomaterials [1]. The quality and performance of a product is directly related to its surface integrity produced from different surface treatment processes. Surface integrity comprises the topography (e.g. roughness, erosion), the mechanical properties (e.g. residual stress, hardness), metallurgical states (e.g. phase transformation, microstructure) and other related property variations of the work material during surface processing procedures [2]. Therefore, alteration of the surface integrity especially in the mechanical related applications has a significant effect on fatigue strength and lifetime of engineering components.

Various mechanical treatment processes can be applied to enhance the surface characteristics of engineering components. These treatments use physical processes to determine the resulting surface condition. The compressive stresses are mainly induced into ductile metals mechanically by localized plastic deformation within the outer surface region. Mechanical surface treatment processes usually available in today's industry can be roughly divided into cutting and non-cutting methods [3]. However, the main focus of cutting methods is on producing a final shape of a product, while achieving optimal surface layer states is only a secondary objective. Therefore, the present study is confined to describing the non-cutting methods which serve to primarily enhance the surface layer state. The methods are generally divided into groups based on the movement between the tools and the workpiece and also the nature of the impacting force, i.e. either a static or an impulsive tool impact [3]. In the present study, the description of methods without relative movement is limited to impulsive impact, which has a repetitive irregular pattern as in shot and liquid peening as well as a repetitive regular pattern as in laser shock peening process.

2. Shot peening process

Shot peening is a cold working process generating a high plastic strain on the surface of metals. In general, it has been applied to the metal parts that require a high level of surface hardness and an elevated resistance to fatigue failure in service [4]. Shot peening is widely used as a mechanical surface treatment method in the automotive and aerospace industries [5]. In the process, peening balls or 'shots' which are normally made of hard materials such as steel, ceramic or glass spheres, strike a surface of metal at high velocity as illustrated in Figure 1. After the strike, the elastically stressed region tends to recover to the fully unloaded state, while the plastically deformed region sustains some permanent deformation. A compressive residual stress region is introduced due to these inhomogeneous elasto-plastic deformations [6].

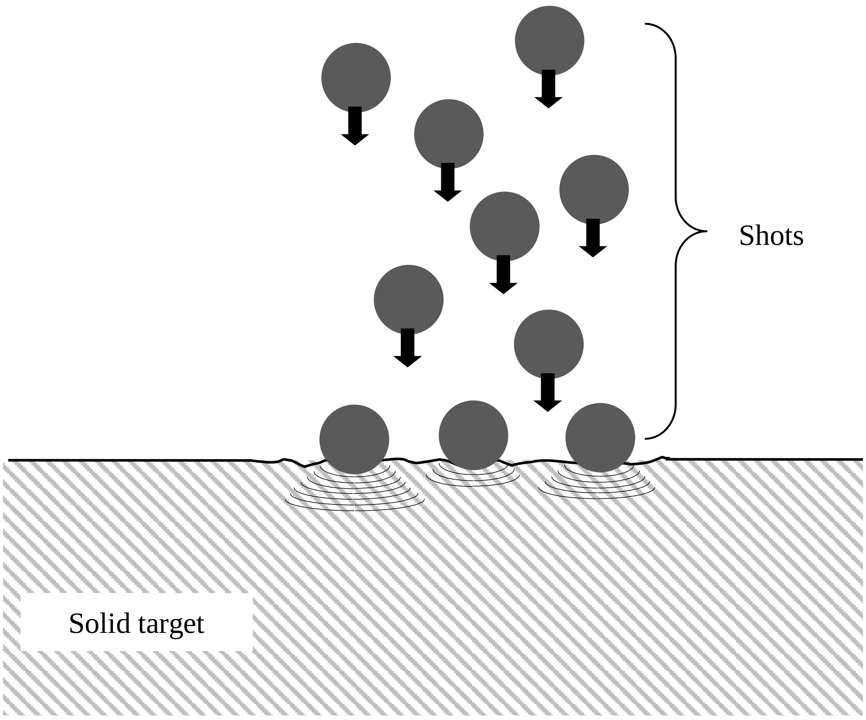

Figure 1. Illustration of shot peening process [7]

A lot of investigations have been conducted to study the effect of shot peening in the formation of a residual stress field and its effect to the fatigue life. Lee et al. [4] investigated the effect of the cementite phase on the surface hardening of carbon steel with three different carbon contents, i.e. 0.1 %C, 0.45 %C, and 0.8 %C, under the shot peening process. All specimens were treated at different peening durations (tp) using rounded cut wire (RCW) hardened steel shots with an average diameter (Ds) of 250 μm. The results show that the surface hardness increases with an increase in carbon content of the steels. They concluded that the surface hardening of the carbon steels in the shot peening is achieved through both the grain refinement and carbon dissolution following the spheroidization of the cementite phase. They observed a higher degree of the grain refinement and also a higher amount of dissolved cementite into the ferrite in the steels with higher carbon contents. This renders the ferrite supersaturated with carbon, upon which the degree of surface hardening markedly increases.

Sanjurjo et al. [5] investigated the effects of the shot peening process on a duplex stainless steel AISI 2205. They have treated the material using the shot peening process in a controlled condition where a significant higher intensity peening was developed. The cast steel S-230 shots were used. The results were compared with the same material treated by an industrial shot peening process but produced a lower intensity peening. As expected, the controlled shot peening treatment was much more effective in inducing a higher compressive residual stress up to 631 MPa as compared to 367 MPa in the case of the industrial peening. In addition, the total thickness of the compressive layer generated by the controlled peening treatment was more than 350 μm deeper than the one generated by the industrial peening.

The effect of hardness, fatigue strength and surface roughness of nitrogen austenitic stainless steel in primary shot peening and double shot peening was investigated by Singh et al. [8]. Initially, both specimens were peened with glass shots however zirconium micro-shots were used for double shot peening. They found that a double shot peening process reduces the surface roughness without significant change in the residual stress. As a result, the fatigue life increases mainly due to the improvement in surface finish from the double shot peening process. Furthermore, Torres and Voorwald [9] evaluated the fatigue life of AISI 4340 steel, used for aircraft landing gears, under four different peening intensities (i.e four different peening pressures were applied from 8 to 45 psi). Steel shots (S 230) with an average diameter of 0.7 mm were used. They found that at the highest stress there is no change in the number of cycles until failure except in the specimen treated with the lowest peening intensity. However, there is an increase in the fatigue life for medium and high cycles. They also found that the best fatigue life conditions were found in the intermediate peening intensities. Perhaps, a lower fatigue life at the highest intensity was due to an effect of overpeening. The surface experiences some defects in the form of microcracks which may act as crack initiation in the fatigue test.

Zhang et al. [10] investigated the influence of different shot peening media namely Zirblast B30, Ce-ZrO2 and glass beads on the fatigue performance of the high-strength wrought magnesium alloy AZ80. They found that peening with Ce-ZrO2 shots resulted in the fewest surface defects, lowest roughness, highest maximum compressive residual stress and highest improvement of the fatigue strength. The different responses in surface integrity of the peened magnesium alloy are possibly due the different properties of the peening media. Since Ce-ZrO2 has a higher density and size than Zirblast B30 and glass beads, thus it has to travel at a significantly lower velocity in order to achieve a similar peening intensity. Consequently, less surface damage was produced from a lower kinetic energy of Ce-ZrO2 shots.

Lee at al. [11] studied the influence of shot peening on the microstructure, surface roughness and corrosion resistance of AISI 304 stainless steel. Based on microstructures at the surface, they found the formation of nano-sized grains, multi-directional mechanical twins and strain-induced martensite. Also, the plastically deformed region with multi-directional mechanical twins and slip bands on the surface layer was formed to a depth of 200–250 μm. The hardness was increased by about 40 % with respect to the as-received specimen up to a depth of 300 μm. However, the surface roughness was increased significantly after the shot peening treatment which leads to a lower corrosion resistance mainly because the practical area for corrosion per unit area also increases with increasing surface roughness. Shen et al. [12] studied the effect of plasma nitriding of AISI 304 austenitic stainless steel with a pre-shot peening process. The material was peened with industrial steel shots having a diameter of 0.8 mm. They found that the substrate suffered severe deformation and the grain boundary became obscure within the outmost layer below 20 μm in depth. Beyond that depth, a huge change in the substructure within the grains and different systems of slip bands were observed for most of the grains.

3. Laser shock peening process

In principle, laser shock peening (LSP) is similar to other peening processes with the aim of enhancing the fatigue life of engineering components. It is the latest peening technology initially introduced in the aerospace industry [7]. In the process, a laser beam is directed toward the surface of a metal component coated with an ablative layer (e.g. paint or tape) and covered with a thin layer of transparent material, usually water as illustrated in Figure 2. This creates high energy plasma that generates a pressure shock wave and propagates the compressive stress through the material [7]. The material will experience an extensive plastic deformation when the magnitude of the shock wave exceeds its dynamic yield strength. After the flow of the shock wave, the elastically stressed subsurface layer tends to recover to its original condition but the continuity of the material in the elastic and plastic zone prevents this to happen. As a result, it develops a compressive residual stress at the surface thus contributing to the improvement of yield strength and hardness of laser peened material [13, 14, 15].

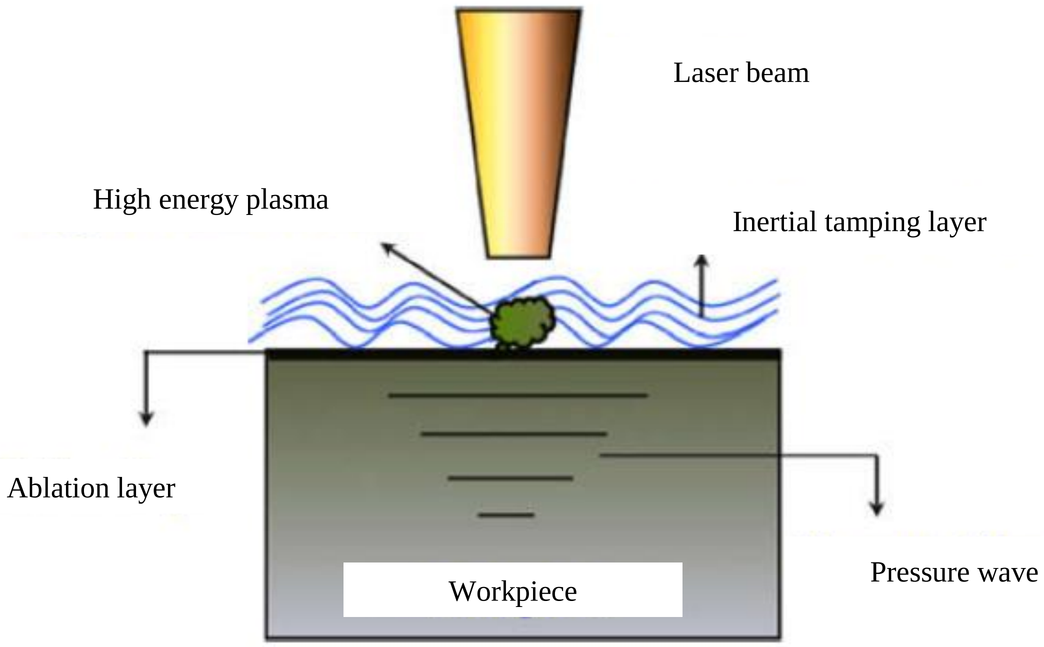

Figure 2. Illustration of laser peening process [13]

There are two distinctive aspects of the laser peening as compared to the shot peening process [7]. Firstly, the surface to be peened is immersed in a thin layer of water which prevents the high energy plasma from expanding, thus driving the energy into the workpiece surface. Secondly, the ablative layer is used as a sacrificial layer to prevent a possible burning of the surface from high energy plasma. In general, a depth of laser peening induced stresses between 0.5 to over 1 mm can be attained depending on processing conditions and material properties [15]. In some cases, laser peening induces higher residual stresses as well as deeper depths [16]. The fatigue life enhancement of metallic components may be accomplished with the inducement of the compressive residual stresses in surface layers. Gao [16] determined the improvement of fatigue property in 7050–T7451 aluminium alloy by laser and shot peening. Laser peening was done under different treatment times, (i.e. 2, 4, 6 and 8 times). While, shot peening was done using different shots (i.e. glass beads, ceramic beads and cast steel shots). The author found that the laser peening had produced the depth of compressive residual stress layer up to 1200 μm compared to only 250 μm for shot peening. Moreover, the fatigue strength of the laser peened specimen was increased by 42 % with respect to the as-machined specimen, while there was an increase of 35 % in fatigue strength for the shot peened specimen.

Other researchers reported the effect of laser shock peening without a coat or ablation layer in the workpiece material [17, 18]. The laser beam is directly in contact with the workpiece surface, thus requiring the use of a smaller output power as to avoid severe melting of the surface. Maawad et al. [17] investigated the high cycle fatigue performance of titanium alloy after a laser shock peening process without coating. They varied few parameters in the laser shock peening process namely the laser pulse energy, laser spot diameter and laser pulse density. They also compared the results with a similar material treated by a shot peening process. The outcomes indicated that the laser shock peening process without coating produced a better performance of high cycle fatigue than the conventional shot peening process due to a larger amount of compressive residual stress and a deeper strengthening layer. However, the laser shock peening process without coating produced a higher surface roughness caused by easily induced surface vaporization and later on re-solidification of the molten droplets. Furthermore, Sathyajith [18] reported the effect of laser peening without coating on aluminium alloy 6061-T6. Their results show that the laser peening without coating had significantly improved the surface compressive stress and hardness with a little increase in surface roughness.

Lim et al. [19] investigated the enhancement of abrasion and corrosion resistance of duplex stainless steel using a pulsed Nd:YAG laser in the laser shock peening process. They treated the surface at a condition which may result in the maximum increase of surface hardness because a higher abrasion resistance may be achieved for metals with a higher surface hardness. They found that the compressive residual stress at the laser peened sample was enhanced by about three times from that of unpeened material with the depth profile extended up to about 0.8 mm. They also found that at the optimal process parameters, wear volume and corrosion rate of duplex stainless steel were reduced by 39% and 74.2%, respectively which a lower density and size of corrosion pits were produced on wear track as a result of laser shock peening.

Peyre et al. [20] compared the performance of laser and shot peening in surface modifications of 316L stainless steel. In the laser peening process, the laser intensities as well as number of laser impacts were varied accordingly. The results show that the work hardening levels consistently increase with higher laser intensities and number of laser impacts. Furthermore, the microstructures of laser peened specimens show a lot of deformation twins and persistent slip bands especially for specimens treated with higher laser intensities and numbers of impacts. They also found that the laser peening treatment generated lower residual stresses and work hardening levels than shot peening treatment possibly due to the nature of laser peening process which involves no contact.

4. Liquid peening process

In the liquid peening process, high impacts of water droplets are used to impinge a metal surface thus causing local plastic deformation. Mostly water is used but some researchers performed experiments with oil. Others used a water-oil emulsion. A basic principle of liquid jet peening is shown schematically in Figure 3. The nozzle is moved at a desired feedrate (traverse speed), in the linear direction across the surface to be peened. The process parameters that may influence the residual stress formation and coverage area are the traverse speed of the nozzle, the water pressure, at the nozzle entrance, the nozzle to specimen's surface distance (i.e., standoff distance), the nozzle diameter and the inclination angle of attack. p_i is the impact pressure that strikes the metal surfaces.

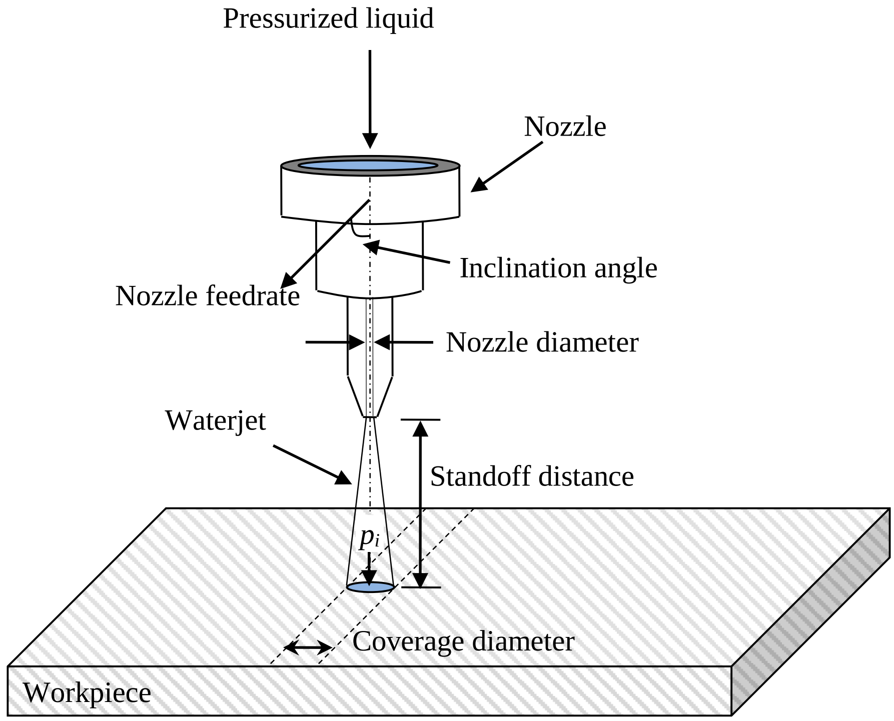

Figure 3. Basic principle of liquid jet peening

Quite a number of research in WJP process has been conducted to study its potential applications and associated sciences. Chillman et al. [21] explored the effects of high pressure WJP at 600 MPa on the surface finish and integrity of the titanium alloy (Ti–6Al–4V). They varied the traverse rates and the standoff distance. They found that WJP at 600 MPa induces a plastic deformation to higher depths in the subsurface layer and also a higher degree of plastic deformation. Grinspan and Gnanamoorthy [22] substituted water with oil in a peening process (OJP) of aluminium alloy where the depth of residual stress was noticed to be more than 250 μm below the surface. Azhari et al. [23] found a higher hardness on the aluminium specimens treated with a higher number of passes during waterjet treatment.

Ju and Han [24] investigated the influence of water cavitation peening (WCP) treatment on the microstructure of pure titanium. WCP refers to a technique in the waterjet peening process in which suitable air can be inserted into the extra high-velocity flow in the nozzle. The combined high pressurized water with air can generate a uniform bubbles cloud which then collapse on the surface of the components thus producing a high impact of water cavitation [25]. Normally, the same nozzle arrangement in abrasive waterjet treatment is used for WCP. The air is led into the inlet instead of the abrasive particles. Ju and Han [24] observed that a longer peening duration of WCP produces higher residual stresses. Qin et al. [26] investigated the influence of the inclination angle on the process capability of water cavitation peening. They found that the impact pressure and residual stresses obtained at various inclination angles were almost equal to each other within the effective process area.

The effect of waterjet peening conditions on the improvement of residual stress on the surface of stainless steel 304 has been investigated by Hirano et al. [27]. Using a surface layer removal technique, they measured the residual stresses by X-ray diffraction from the surface to a depth of 250 μm. They found that the initial residual stress at the surface was tensile in nature from 60 to 100 MPa. After WJP, the residual stresses were compressive in nature with the maximum stress at the surface of about 500 MPa and decreased with an increase in surface depth. They also found that the residual stress was still compressive at a depth of about 250 μm. In terms of the influence of various WJP conditions, they found that the residual stress increased with the peening duration. Azhari et al. [28] investigated the effect of multiple jet passes in waterjet peening of austenitic stainless steel 304. A higher hardness and a deeper hardening layer were produced on the specimens treated with a higher number of passes. Furthermore, cross-sectional microstructures showed a higher density of slip bands in the deformed grains of the specimen treated with a higher number of jet passes.

Tönshoff et al. [29] measured the m of induced compressive residual stresses on case hardened steel 16MnCr5E under waterjet peening impact. With increasing peening duration, they observed that the amount of compressive residual stress increased up to a maximum level of about 560 MPa. However, for longer peening durations, a distinct decrease of compressive residual stress was noticed. Interestingly, they also observed that somehow the water pressure had no influence on the level of the maximum compressive residual stress, but higher water pressures shifted the maximum to shorter peening durations. The increase in surface hardness was also related to longer peening durations [29]. In contrast, Arola et al. [30] noted that the induced compressive residual stresses resulting from waterjet peening of titanium alloy Ti6Al4V and pure titanium increased with the water pressure. However, the amount of residual stresses resulting from WJP of the pure titanium was higher than the Ti6Al4V. They explained that the lower yield strength of the pure titanium enabled more extensive near-surface deformation and resulted in a larger compressive residual stress.

In water cavitation peening (WCP) of steel 1045, the maximum compressive stress induced was up to 215 MPa with a depth of strengthening layer up to 110 μm [31]. Under waterjet peening, the hardness of the treated specimens of steel 1045 had increased up to 70 % with respect to the base material with an increase in the number of jet passes and pressure [32]. In WCP of steel 1070, Qin et al. [26] observed an increase in compressive stress of around 600 MPa from the original compressive stress of 350 MPa. By varying the inclination angles of the nozzle, they however found that the induced residual stresses were almost uniform and equibiaxial. In contrast Daniewicz and Cummings [33] found a higher increase in compressive residual stresses measured in parallel to the rolling direction than those measured transversely to the rolling direction. They argued that it might be a result of crystallographic texture influences on the measurements. They further found that a decrease in the magnitude of the compressive residual stress with an increase in the water pressure which is in disagreement with the trend observed by Arola et al. [30]. This decrease in surface compressive residual stress was potentially the result of a higher surface roughness due to an increase in the water pressure which eventually reduces the accuracy of X-ray diffraction (XRD) residual stress measurements.

Grinspan and Gnanamoothy [34] treated aluminium alloys 6063-T6 and 6061-T4 with oil jet peening. They found the magnitude of induced surface compressive residual stress decreased with increasing in standoff distance in both materials possibly due to reduction in impact pressure with increasing standoff distance. The increase of compressive residual stress was higher in 6063-T6 than 6061-T4 due to the former higher yield strength. The depth of induced compressive residual stress in both samples was more than 200 μm. In case of hardness, they found that the surface hardness increased by 34 - 44% compared to unpeened material hardness. While the hardened layers extended up to a depth of approximately 350 and 400 μm for both materials respectively. In oil jet treatment of another material steel 1040, they found the surface compressive residual stress increased with decreasing nozzle traverse rate with a depth of the strengthening layer of about 50 μm [35]. The increase in hardness was about 14 - 22% of the base material hardness. Kunaporn et al. [36] found that the hardness increased in some conditions by about 10-15% from the base material hardness during waterjet treatment of aluminium alloy 6061-T6. The degree of surface hardening was extended to a depth of about 200 μm. Islam et al. [37] also observed a similar increase in hardness of about 15% during waterjet treatment of Al-Si alloy.

The improvement of fatigue strength in abrasive waterjet peening of stainless steel 304 and titanium alloy Ti6Al4V has been reported by Arola et al. [38]. They compared the fatigue strength of both specimens treated with two parametric conditions that gave a high and low induced compressive residual stresses respectively. They found a rather limited increase in the fatigue strength for both materials (< 10 %). They further treated a new set of Ti6Al4V specimens at a higher intensity (peening duration) as to produce a higher level of induced residual stresses. Apparently, the endurance strength increased to nearly 25 %. Kunaporn et al. [39] reported a maximum increase in the fatigue strength by 20-30 % in waterjet peening of aluminium alloy 7075-T6. However, they also noted that the degree of fatigue improvement was strongly dependent on the peening conditions. They observed that increasing the pressure and the peening time might yield an increase in surface hardness, but the fatigue limit would rapidly decline due to an increase in surface erosion as well. It is well known that surface irregularities may encourage fatigue crack initiation at the specimen surface [40].

During oil jet peening of carbon steel 1040, an improvement of fatigue strength by about 19 % was reported [35]. They further reported that the fatigue life was higher in specimens peened at a higher pressure probably because of the difference in magnitude of the induced compressive residual stress at the surface as well as of the hardening effect. In contrast, they found that the fatigue strength of peened specimens seemed to be almost similar regardless of the nozzle traverse rate since the residual stress and hardening showed also not much difference. Han et al. [31] reported an increase of fatigue life of about 15-20 % in water cavitation peening of carbon steel 1045. They compared the fatigue life of peened and unpeened specimens of original as well as oil quenched carbon steel 1045. They also noticed that the improvement of fatigue life was obviously apparent at higher cycles.

The fatigue strength of stainless steel 316 under cavitating jets in air (CJA) and water (CJW) has been investigated by Soyama [41]. The cavitation peening in water takes place inside a water-filled chamber. It is obvious that the improvement of the fatigue strength using the cavitating jet is better in air than in water. The lower fatigue strength of CJW is possibly due to the interference between the jet and water. Interestingly, although he found the induced residual stress in CJW at two different standoff distances were nearly the same, but the fatigue strength was barely improved for the specimens treated at lower standoff distance. This could be due to some cracks occurred in the peened area of specimens treated with a lower standoff distance. Azhari et al. [42] investigated the combined effect of waterjet peening and smoothing on the surface of austenitic stainless steel 304. They conducted the waterjet treatment in steps with multiple passes. The surfaces treated with multiple steps of decreasing energy produced a smoother surface with lower peak heights and a slightly higher increase in the hardness than the surface treated with only a single step. The hardening layer was also maintained during the later step treatment.

5. Conclusion

Many studies have reported that various peening processes were employed to modify material surfaces by introducing compressive residual stresses which consequently increased the fatigue life of the materials. In general, the treated surfaces had experienced different levels of hardening and strengthening effects through these peening processes. The depth of hardening layers would be up to several hundred micron meters. Furthermore, material surfaces had also experienced different degree of erosion. However, in most cases, the beneficial effect of strengthened layer has outweighed the negative effect of surface erosion in enhancing the fatigue life of the components.

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