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Review Article

A Study on Surface Modification of Al7075-T6 Alloy against Fretting Fatigue Phenomenon

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Aircraft engines, fuselage, automobile parts, and energy saving strategies in general have promoted the interest and research in the field of lightweight materials, typically on alloys based on aluminum. Aluminum alloy itself does not have suitable wear resistance; therefore, it is necessary to enhance surface properties for practical applications, particularly when aluminum is in contact with other parts. Fretting fatigue phenomenon occurs when two surfaces are in contact with each other and one or both parts are subjected to cyclic load. Fretting drastically decreases the fatigue life of materials. Therefore, investigating the fretting fatigue life of materials is an important subject. Applying surface modification methods is anticipated to be a supreme solution to gradually decreasing fretting damage. In this paper, the authors would like to review methods employed so far to diminish the effect of fretting on the fatigue life of Al7075-T6 alloy. The methods include deep rolling, shot peening, laser shock peening, and thin film hard coatings. The surface coatings techniques are comprising physical vapor deposition (PVD), hard anodizing, ion-beam-enhanced deposition (IBED), and nitriding.

1. Introduction

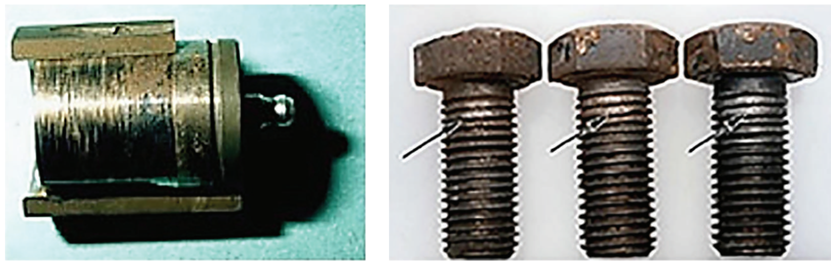
Fretting fatigue phenomenon occurs when two surfaces in contact simultaneously encounter sliding movements and fluctuating loads. Fretting fatigue also occurs when an oscillatory movement with low amplitude between two surfaces is remaining for a large number of cycles [1]. This event can result in two different types of damage: fretting fatigue and fretting wear [2–4]. Bearings, bolted, steel cables, riveted connections and shafts, and steam or gas turbines are common examples of engineering applications facing high fretting fatigue damage risk [5–8]. In contrast to normal fatigue conditions, fretting fatigue may significantly reduce the endurance limit of components. Fretting fatigue may occur in bending, torsion, and even tension forms [9]. Figure 1(a) illustrates the fretting corrosion at an axle-cylinder contact. Figure 1(b) shows fretting wear on the cap screw threads. The fretting fatigue in bolted flanges is presented in Figure 2 [10, 11]. Fretting fatigue is triggered by cracks formed in either surface. It is more serious than fretting wear and fretting corrosion because it can lead to severe component failure.

The fretting fatigue mechanism is schematically arranged and illustrated in Figure 3. Two fretting pads are pushed opposite to the specimen by a load called contact force, P. The component then encounters a cyclic load, Q. Elastic elongation takes place in the sample along the contact zone that causes the fretting fatigue in component. The material's resistivity against fretting fatigue is influenced by contact configuration, slipping amplitude, or surface conditions like lubrication, hardness, friction coefficient, and roughness [12].

Generally, three basic means of choosing preventative measures are introduced.

(1) Change in design: design optimization involves change in contacting materials and component geometry, and it is a basic method of suppressing fretting [13].

(2) Use of lubricants: using a suitable lubricant (e.g., solid, liquid, or grease) is another possible way of providing practical reduction in fretting damage [14].



(a) (b)

Figure 1: (a) Fretting corrosion at an axle-cylinder contact and (b) fretting wear on the threads of the caps crews [11].

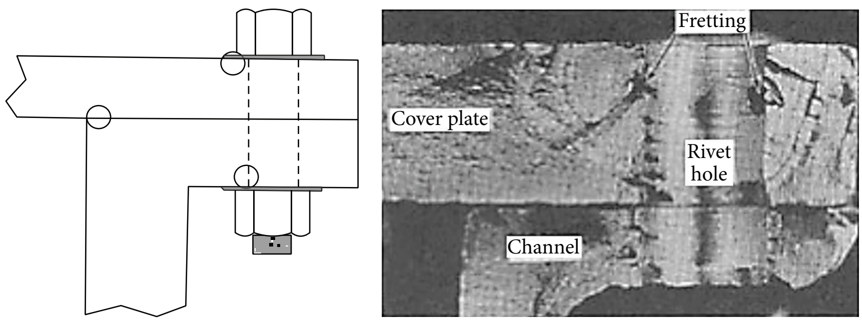


Figure 2: Fretting fatigue in bolted flanges [11].

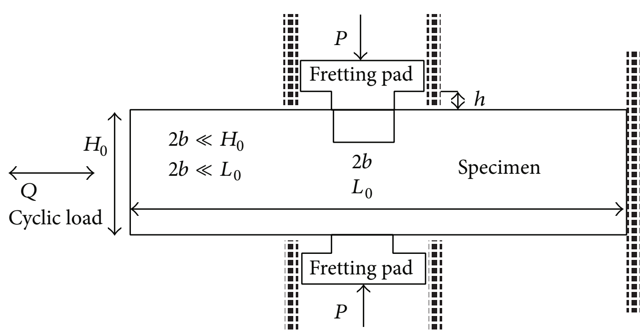


Figure 3: The schematic view of a fretting fatigue arrangement [11].

(3) Application of surface engineering: the introduction of surface treatments is likely an ideal solution to diminish fretting damage [15–18].

As mentioned earlier, the fretting fatigue behavior of materials can be significantly enhanced by different surface treatment techniques [19–23] including induction hardening, nitriding, case hardening, shot peening, roll peening, and laser shock peening [24, 25]. The reduction coefficient of fretting fatigue life for the number of engineering alloys is given in Table 1 [26]. The material's durability to fretting fatigue is significantly increased by enhanced surface conditions such as roughness, hardness, and lowered friction coefficient, something achievable by surface treatment techniques like surface-coatings, deep rolling, and shot peening that may postpone crack initiation.

Improving the mechanical properties of surface by leaving the treated region in compressive residual stress states has the major benefit [27–32].

Automobile parts, fuselage, aircraft engines, and energy saving strategies generally promote the research interest in the area of lightweight materials by mainly aluminum alloys. The pure aluminum is not suggested to be used as structural parts since it does not result in satisfactory mechanical strength. Hence, in practical applications, it is essential to improve the surface properties, especially prior to aluminum coming in contact with other parts [33, 34].

Aerospace structural fastened joints utilize Al 7075-T6 and fretting fatigue damage can result in catastrophic failures under fluctuating loading [35, 36]. Aluminum alloy 7075-T6 has high ratio of strength to weight and low specific weight besides high thermal and electrical conductivity. The formation of thin hard coatings on material surfaces is one

Table 1: The reduction coefficient of fretting fatigue life for some engineering alloys [26].

Fatigue specimen	Contact pad	Contact pressure (MPa)	Fatigue mean stress (MPa)	Fatigue strength unfretted (MPa)	Fatigue strength fretted (MPa)	Strength reduction factor	Relative slip range (μm)
			Steels				
3.5NiCrMoV	1CrMo	30	0	±300	±140	2.1	15
3.5NiCrMoV	1CrMo	30	300	±215	±60	3.6	6.2
3.5NiCrMoV	1CrMo	300	0	±300	±130	2.3	12
3.5NiCrMoV	1CrMo	300	300	±215	±60	3.6	4
3.5NiCrMoV	2014 A	30	0	±300	±140	2.1	1.5
3.5NiCrMoV	2014 A	30	300	±215	±75	2.9	6.8
18M114Cr	3.5NiCrMoV	20.7	0	±250	±100	2.5	10
18M114Cr	3.5NiCrMoV	20.7	300	±125	±50	2.5	4.5
18M114Cr	3.5NiCrMoV	20.7	0	±250	±165	1.5	17.4
18M114Cr	3.5NiCIMoV	20.7	300	±185	±70	2.6	6.7
			Aluminum				
2014A Al	3.5NiCrMoV	30.8	75	±140	±15	9.3	2
2014A Al	3.5NiCrMoV	30.8	125	±135	±12.5	10.8	1.5
2014A Al Peened	3.5NiCrMoV	30.8	125	±135	±50	2.7	9.6
			Aluminum				
2014A	BS S98	103.5	0	±148	±72	2.05	2
2014A	BS S98	103.5	0	±148	±47	3.14	4.2
2014A	BS S98	103.5	0	±148	±36	4.11	8.35
2014A	BS S98	103.5	0	±148	±36	4.11	17.4
			Titanium				
Ti6Al4V	Ti6Al4V	20	61.25	±260	±125	2.1	30

of the best ways to enhance the material wear resistance. Hard coatings also appear to be encouraging by means of the feasibility of approaching high strength, hardness, and concurrently high protective and decorative surface properties [37].

This study focuses on the variety of surface treatments available to mitigate the fretting fatigue of aluminum 7075-T6. Deep rolling, shot peening, TiN coating, CrN coating, and nitriding surface treatments are discussed.

2. Surface Treatment Using Mechanical Techniques

2.1. Deep Rolling. Deep rolling (DR) includes a ball or roller type tool to induce surface-compressive residual stress. Such stress enhances the fatigue resistance of engineering components and materials. A deep rolling fixture is illustrated in Figure 4. This technique is distinct from roller burnishing whose main purpose is to achieve an exceptionally well-polished surface. The ball or roller produces a longitudinal groove as it comes in contact with the component's surface. A plastic region along with an elastic zone couples with this groove. Upon separation from the roller, a large, compressive residual stress is produced on the surface as a result of recovering the elastic zone. Surface rolling residual stresses are generally consequent to the interface between the plastic and elastic regions that result from the pressure between the roller and the contact surface. Specific parameters can considerably affect the process of deep rolling followed by near-surface residual stress; force of rolling is recognized to be the main one. Very low level of rolling forces has no serious effect on the behavior of fatigue, but considerably high force may make it even worse, for example, by initiation of microcracks. As such, it appears that only optimized rolling forces are able to promote fatigue strength [38].

The aero and automobile industries (in particular crankshafts) commonly utilize the DR technique to develop fatigue resistance. Compared with other methods, DR has two distinct advantages: (i) lower surface roughness and (ii) greater compressive residual stress depth.

2.2. Shot Peening. Shot peening (SP), for decades, was known as a surface treatment with questionable benefits about cyclic loading [39]. The inconsistent results were partially due to ignorance with respect to the shot peening process and partly result from a lack of proper background that would allow the characterization of the role that surface modifications produced by shot peening play in fatigue damage. Nowadays, the control parameters of shot peening performance, such as intensity, media, and coverage, are well understood, and new designation of controlled shot peening (CSP) has emerged. The CSP or SP is a cold work process accomplished

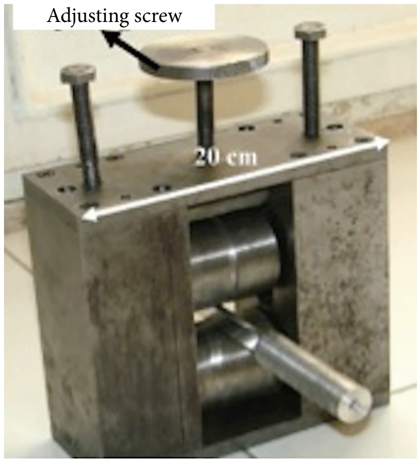


Figure 4: The fixture used for DR the specimens [38].

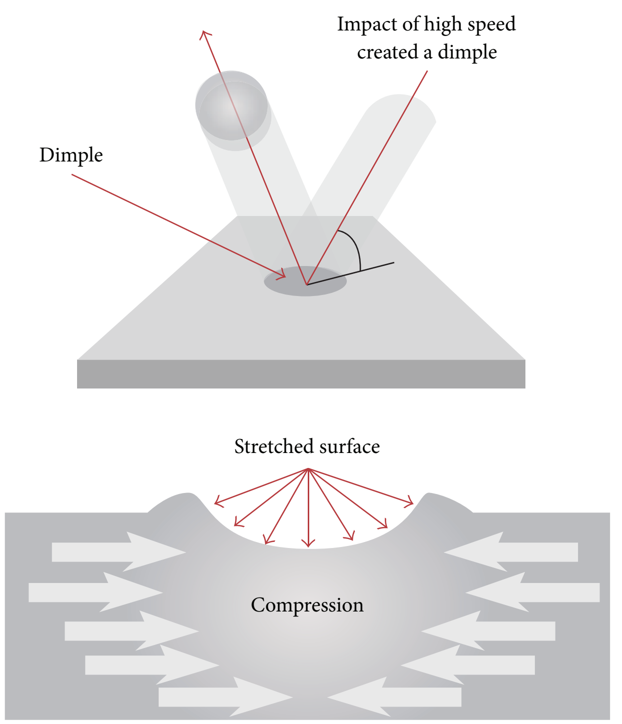


Figure 5: Schematic of shot peening bombardment on a surface with small high quality spherical media [5].

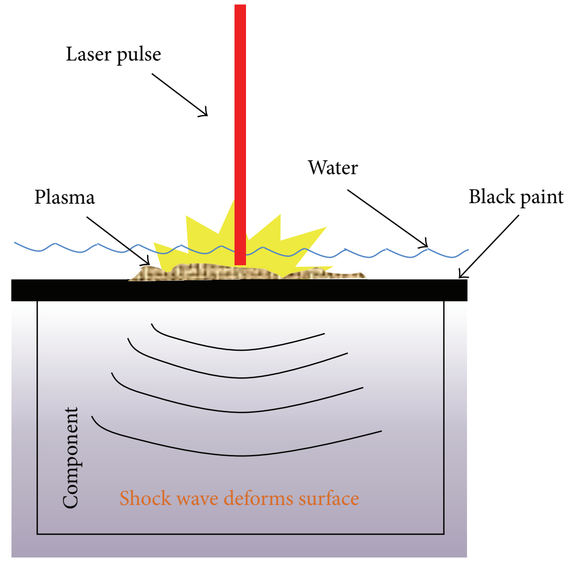


Figure 6: Schematic of the laser peening process.

by bombarding the workpiece surface with small-diameter ferrous and nonferrous spherical shots. A schematic of the shot peening process to induce compressive residual stress is shown in Figure 5.

SP is widely applicable for enhancing the industrial component's fatigue behavior, particularly in the car industry [40–43]. SP even acts as a forming process in the production of large, thin aero industrial components including wide panels. SP is known to harden a material's surface and consequently increase its strength. The surface modifications yielded by SP are (a) surface roughening; (b) an increased, near-surface, dislocation density (strain hardening); and (c) the development of a characteristic residual stress profile [44–46].

2.3. Laser Shock Peening. Laser shock peening (LSP) is a promising surface treatment technique which has demonstrated effectiveness in enhancing the fatigue properties of a number of metals and alloys. The process was originally developed at the Battelle Columbus Laboratory in the 1970s [47–51]. The LSP procedure is illustrated schematically in Figure 6. Since then, considerable attention has been directed to potential LSP applications in the aerospace and automotive industries. The beneficial effects of LSP on the static, cyclic, fretting fatigue and stress corrosion performance of aeronautical and automotive aluminum alloys, steels, and nickel-based alloys have been confirmed [52–59]. LSP has also been successfully engaged in upgrading the resistance of aircraft gas turbine engine blades to foreign object damage. Since laser beams can be easily directed to fatigue-critical areas, LSP technology is expected to be widely applicable to improving the fatigue properties of metals and alloys, particularly those that respond positively to shot peening.

3. Mechanical Techniques for Improving the Fretting Fatigue Life of Al 7075-T6

3.1. Deep Rolling. Majzoobi et al. [38] looked into how deep rolling (DR) affects the fretting fatigue life of Al 7075-T6. In order to assess the effectiveness, they compared shot peening (SP) with deep rolling (DR) on the fretting fatigue behavior of Al 7075-T6. In their study, the following experiments were examined: (i) fretting fatigue tests on roll-peened specimens with high force of rolling, (ii) fretting fatigue tests on intact specimens, (iii) fretting fatigue tests on shot-peened specimens, (iv) normal fatigue tests on virgin specimens, and (v) fretting fatigue tests on roll-peened specimens with low force of rolling.

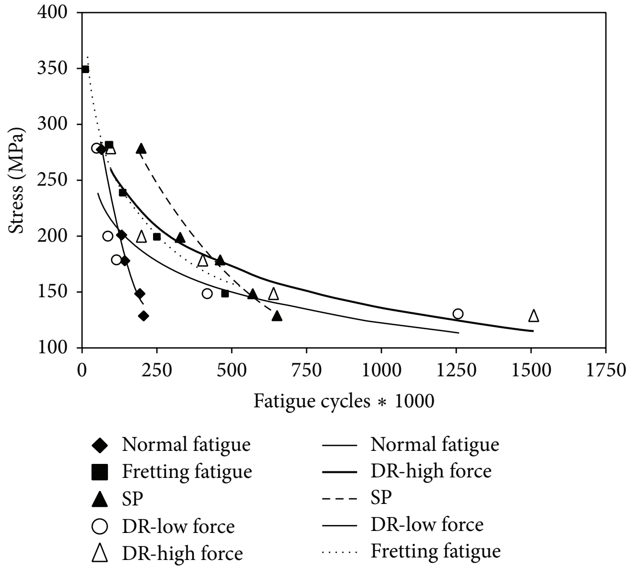


Figure 7: S-N curves for various fatigue testing conditions [38].

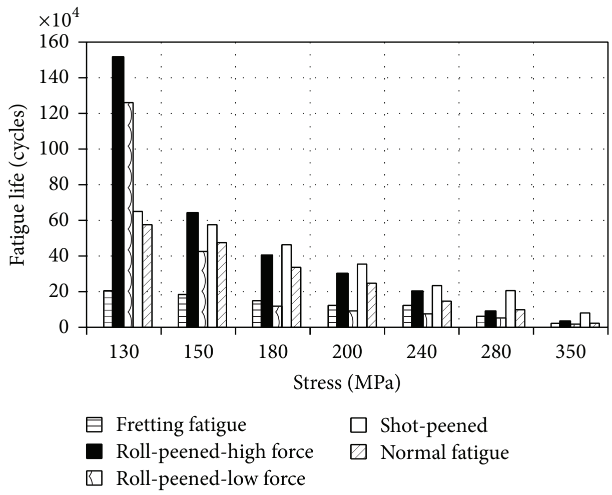


Figure 8: Bar chart for various fatigues testing conditions [38].

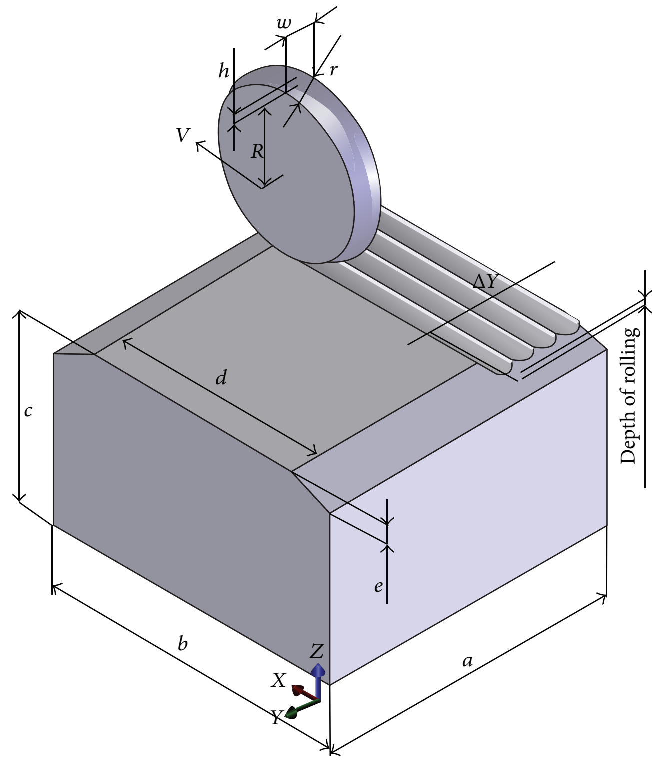


Figure 9: Residual stress profiles induced by DR in three directions [38].

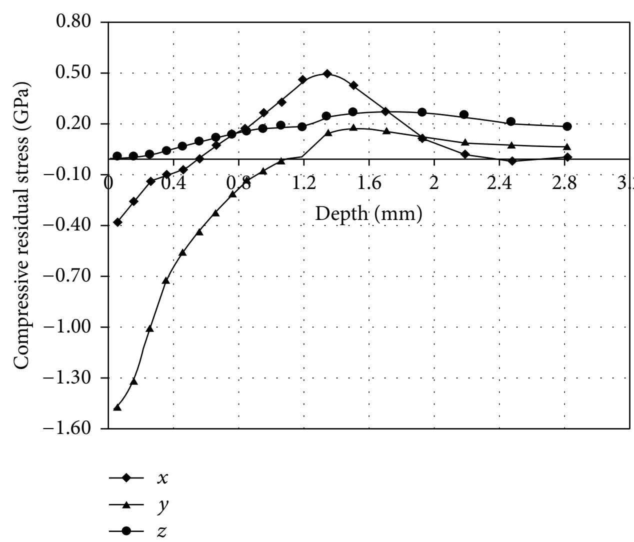


Figure 10: The model of deep rolling (not scaled) used in the simulations [38].

The experimental results are graphically illustrated in Figure 7, where it is evident that the fretting fatigue tests on intact samples (with no surface treatment) produced the lowest fatigue life. However, the situation differed in the case of the surface-treated samples. The bar chart in Figure 8 depicts the influence of different surface treatment techniques on the fretting fatigue behavior of the material. Also, apparently, the results (Figure 7) indicate that fretting fatigue decreases normal fatigue life at a stress of 130 MPa by roughly 67%. The fatigue life reduction rate, though, diminishes with rising stress [38].

The profiles of residual stress formed by DR in the x, y, and z directions are shown in Figure 9 for the roller's linear motion xx, the roller's transverse displacement yy, and load zz (Figure 10). Obviously, the stress in the y-direction is more significant than the other two components, and it runs perpendicularly to the rolling direction. It should be mentioned that the oscillatory motion of contacting surfaces in the fretting fatigue tests, for example, between the specimen and pad, is in the x-direction [38].

Results provide evidence that for low cycle fatigue (LCF) SP remains exceptionally high, up to approximately 300,000 cycles. For more than 300,000 cycles, the influence of DR on resistance to fretting fatigue is superior to SP where fatigue

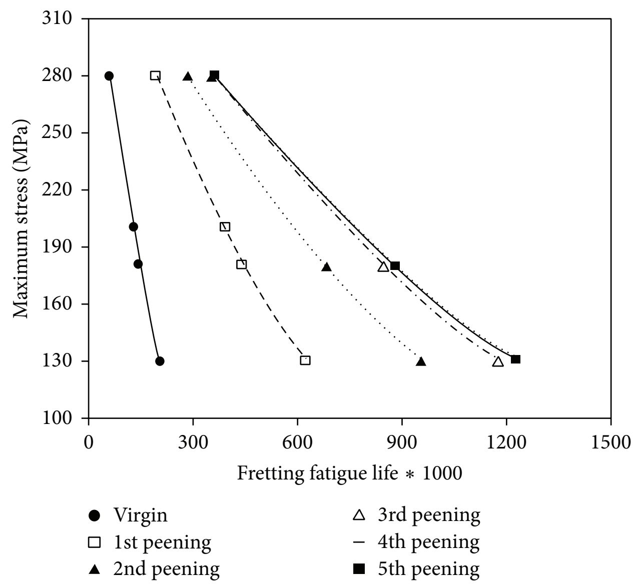


Figure 11: Variation of fatigue life versus maximum stress for multiple reshot peening [60].

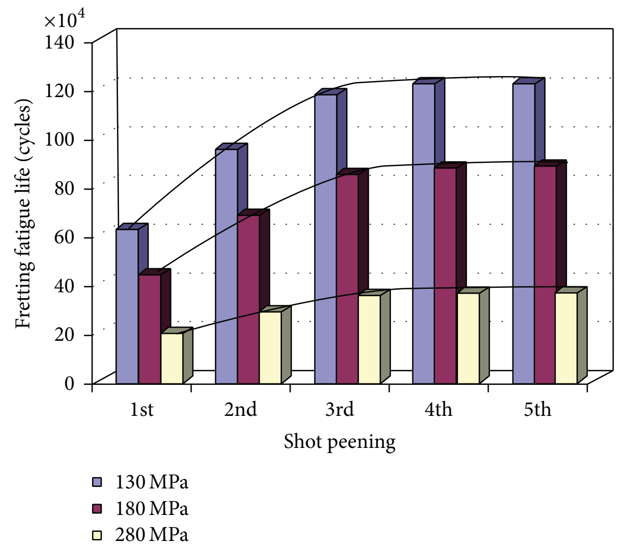


Figure 12: Variation of fatigue life versus the number of reshot peenings for different maximum stresses [60].

cycles increase by 700% (at 130 MPa stress) at high rolling force deep rolling. The rate of increase in fatigue life slows down as the applied stress diminishes so that for the stress of 150 MPa the fretting fatigue life increases about 400%, while for the stress of 280 MPa the fatigue life increase is only about 50% [38].

3.2. Shot Peening. Much like DR, SP produces a layer of compressive residual stress near the workpiece surface. The distribution and depth of residual stress are potentially affected by a variety of parameters such as material, shot diameter, target material, duration, intensity of exposure, and shot velocity. SP is widely utilized for enhancing the fatigue life of industrial components, more so in the car industry [40–43].

Majzoobi et al. [38] studied the influence of shot peening and deep rolling on the fretting fatigue life of Al 7075-T6. Based on their results, which are illustrated in Figures 7 and 8, the SP technique maintains a superior performance position to DR at low cyclic fatigue (LCF). The shot peening technique improves fretting fatigue life by a significant 300%. Majzoobi and Ahmadkhani in a similar endeavor investigated the influence of regular reshot peening on the resistance of Al7075-T6 against fretting fatigue [60]. They found that it is possible to considerably enhance the material's behavior against fretting fatigue with reshot peening. After 5 reshot peening processes, the fretting fatigue life of Al7075-T6 improved by 600%. Figure 11 presents the variation of fretting fatigue life versus maximum stress for each stage of reshot peening. It is clear that the gap between the curves becomes wider at less stress, which is supported by the bar chart in Figure 12 where fretting fatigue life improvement at lower stresses is more considerable than at higher stresses [60].

Reshot peening is more efficient during initial processes. For example, an almost 100% increase in fatigue life was observed for a first round of reshot peening. This increase is logarithmically decreased for subsequent reshot peenings. It is reported that the 5th reshot peening produced a negligible improvement of less than 2%.

The improvement in fatigue life as a result of reshot peening can be credited to (i) the closing of small cracks that had already initiated and grown on the component's contacting surface, (ii) removal of debris created by wear and the fretting phenomenon from the shot peening process, (iii) the recreation of a layer of compressive residual stress through the reshot peeing process, and (iv) a combination of reasons (i) to (iii) [60].

From a comparative study between DR and SP, it is concluded that (i) at low cyclic fatigue the SP technique improves the material's fretting fatigue behavior more efficiently than DR; (ii) a 300% improvement has been attained for the SP-tested specimen; however, (iii) the influence of DR on fretting fatigue resistance proved more effective for high cycle fatigue; for example, there was an increase of up to 700% for DR at higher forces of rolling; (iv) with decreasing the force of rolling, the trend of increase in fatigue life slowed down; (v) the surface modification technique has direct impact on the friction coefficient such that the highest and lowest friction coefficients, 0.70 and 0.45, were achieved for the low force deep-rolled and intact sample, respectively.

3.3. Laser Shock Peening. The resistance of alloys and metals to fretting fatigue and fatigue is normally increased by laser shock peening (LSP) and laser peening [61]. The boost in resistance is accomplished by a high energy pulsed laser that creates residual compressive stresses and strain hardening into the surface of the part being laser peened. Compared with shot peening, the compressive residual stresses produced by laser shock peening penetrate deeper into the surface than those obtained by shot peening. Thus, significantly

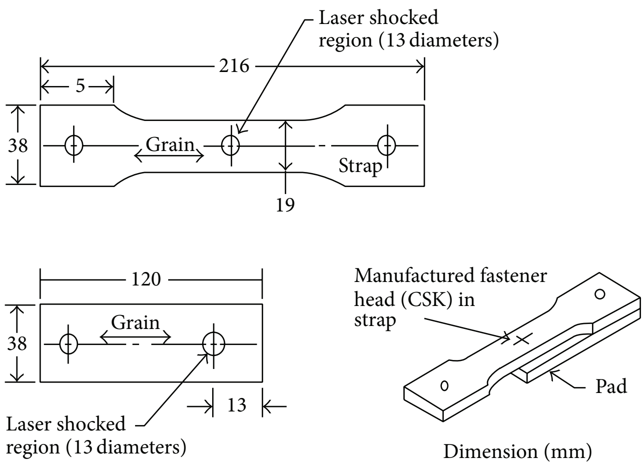


Figure 13: Ferreting fatigue specimen configuration [62].

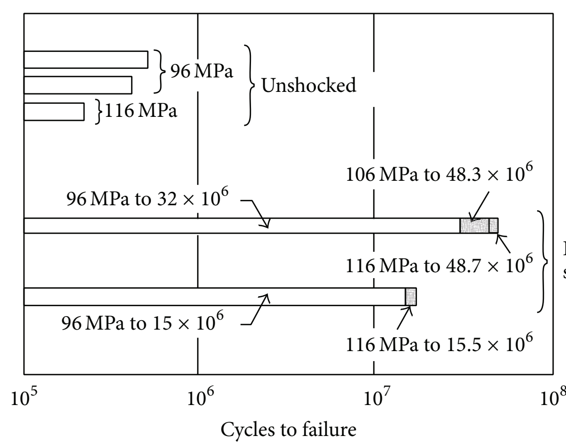


Figure 14: Increased resistance to ferreting fatigue around fastener holes after laser shock peening aluminum 7075-T6 [62].

greater fatigue resistance promotion is noted after laser shock peening.

Laser shock peening is the most effective against fretting fatigue [62]. Dog-bone specimens and pads of aluminum 7075-T6 alloy were laser treated around a simulated fastener hole located in each piece (Figure 13); the pieces were then fixed firmly together through the holes with a manufactured fastener. The fatigue test at $R = 0.1$ was carried out on this combination. The stress differential between the smaller cross-section of the dog-bone and the larger cross-section of the pad created an elongation differential between each piece during a cycle, leading to fretting around the fastener hole. The results are provided in Figure 14. The tests were initially conducted at 96 MPa. Upon achieving a lengthy life, the stress was increased by 10% until failure occurred after a few hundred thousand cycles. LSP expanded fretting fatigue life even at 113 MPa.

Earlier, it has been discussed that SP is a successful technique, whereby the component surface is deformed plastically using multiple overlapping impacts of ceramic or metal shot [63, 64]. However, the depth of the compressive residual stress is practically only about 250 μm, maintaining low fretting fatigue resistance. Accordingly, King et al. [52] demonstrated a comparison between SP and LSP. Compared to SP, LSP is able to produce compressive stresses to greater depths, ~1.5 mm, while at the same time keeping lower work hardening levels [65–67].

King et al. [52] claimed that the fretting fatigue loading of dovetail biaxial rig samples with contact surfaces treated with combined SP and LSP results in considerable stress relaxation that penetrates 0.5 mm deep. The penetration of compressive residual elastic strain (~1.5 mm) is unaffected. Their study reports that fretting results in plastic relaxation of the misfit parallel to the fretting direction which extends roughly 0.4 mm below the fretted and laser peened surface, despite the less significant misfit relaxation that is usual to the fretting direction. Basically, the extended depth of compressive residual stress produced by laser shock peening as opposed to shot peening (1.5 mm instead of 0.3 mm) is a significant consideration in enhancing the tolerance of components to fretting damage.

4. Coating Surface Treatments

4.1. Physical Vapor Deposition (PVD). PVD coatings are popular in many cutting applications mostly due to their high hardness [68, 69]. Other applications are known to take advantage of these coatings for upgrading the fretting fatigue and wear resistance of contacting components [70–72]. With the advent of modern technologies like vacuum processing, high power laser, and progress in materials such as composites and ceramics, surface modification methods based on current technologies have found additional demand with respect to traditional surface modifications ranging from painting and glazing to electroplating and gas carburizing over the past decade [22]. Vacuum coating procedures carry the potential to apply higher-hardness coatings than any metal. PVD is one of the vacuum coating techniques known to condensate from vapor phase to solid phase, having the film material deposited atom by atom on the substrate. PVD metal coatings like silver and gold were conventional means of avoiding fretting failure [73]. Studies have reported that under fretting amplitudes of about 50 ± 100 mm metal coatings like zirconium and chromium make durable films [74]. This technology permits coating deposition at temperatures as low as 200°C (390°F). Maintaining a low temperature facilitates the coating of materials with neither loss of hardness, distortion nor reduction in corrosion resistance, while PVD coatings experience no performance deterioration in comparison with materials deposited at higher temperatures. Improved surface hardness and higher service temperatures are obtainable with PVD [75–77]. Thermal evaporation, ion plating, and sputtering are the three main techniques of applying PVD coatings [78]. More recently, PVD coating has become probably one of the most widely used and successful sorts of coating meant to improve fretting fatigue life [79].

4.2. Hard Anodizing. Hard anodize coating is a very effective surface treatment employed with the aim of reducing

Table 2: The list of the aluminum alloys which should be avoided to hard anodizing [83].

Difficult Al alloys for hard anodizing
2011
2017
2024
7075
Cast and wrought alloys with
Cu > 4% or Si > 7%

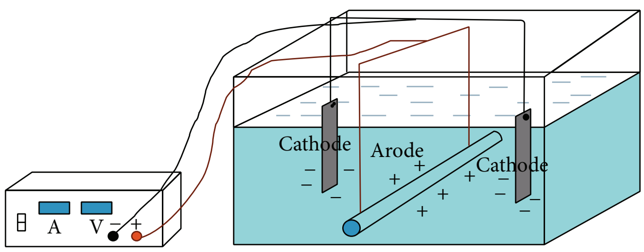


Figure 15: The schematic of hard anodizing process [83].

the destructive influence of fretting fatigue. Hard anodizing is encouraging to obtain high strength and hardness, while simultaneously presenting fine surface decorative and protective properties. This coating resulting by an electrochemical process performs stable oxide layers on the surface of the metal. Anodic coating can be deposited to surfaces of aluminum through different electrolytes with AC, DC, or a combination of both, to enhance the metal hardness. Hard-anodized coating is not accepted by all types of aluminum alloys and thus is not applicable in such cases. Aluminum alloys with high silicon or copper content are prone to not being very hard and porous. Table 2 lists some of the alloys that are difficult to be coated and should be practically avoided [80–83]. Pure aluminum coating via magnetron sputtered Al7075-T6 alloy may facilitate substrate hard anodizing.

Optimizing the effect of each parameter during the hard anodizing process is a critical requirement to improve surface hardness [84, 85]. Anodizing equipment (Figure 15) comprises electrolytic solution, a power supply, cathode (stainless steel), and anode (substrate material). A thin oxide layer is formed on account of the reaction between the oxygen and the substrate; the layer is abrasion-resistant and durable, while hydrogen is produced at the cathode. The anodizing generates uniform oxidation layer (coating) that is much denser and harder than natural oxidation. Moreover, thanks to the hard anodizing coating, the substrate melting point is augmented from about 650°C to approximately 2000°C, which is enough to sustain the mechanical properties at elevated temperatures.

4.3. Ion Beam Enhanced Deposition (IBED). Ion beam enhanced deposition (IBED) is a process in which PVD coated films are bombarded by an independently produced flux of ions at the same time [86, 87]. Atomic displacements at the bulk and the surface and the amplified migration of atoms within the surface are two results of the massive energy applied to the deposited atoms [88]. The ensuing atomic motions are responsible for improving the film properties as opposed to similar films generated by PVD in the absence of ion bombardment. The advantages of ion-beam-assisted deposition are low deposition temperature, control of stress level, high density, control of microstructure (nanocrystaline, metastable crystalline, or amorphous), precise modulation of composition with depth and high versatility for metals, ceramics, semiconductors, and dielectrics. The limitations of ion-beam-assisted deposition are relatively high cost and line-of-sight [89]. When ions are reactive, compounds such as TiN, Si3N4, and BN can be synthesized at fairly low temperatures [90–92]. Thin films of varying stoichiometry or functionally graded thin films can also be produced by adjusting the ratio of reactive ions to atoms reaching the substrate surface [93].

4.4. Nitriding. Nitriding is a heat-treating process that diffuses nitrogen into a metal surface to create a casehardened surface. It is commonly used on steel, aluminum, titanium, and molybdenum. The major types comprise ion, plasma, laser, and gas nitriding.

Plasma nitriding is a thermochemical treatment method with several advantages such as control of nitrided layer depth and phase formation [94, 95]. This kind of treatment requires special equipment and high ionizing energy. The two major plasma processes developed for titanium nitride synthesis are ion nitriding and PVD [96]. One disadvantage of plasma nitriding is that it reduces the fretting fatigue strength of aluminum alloys, a problem that can nevertheless be overcome by lowering the processing temperature [97]. Ion-beam nitriding, which includes the high-energy end spectrum, is an alternative method of hardening aluminum and titanium alloy surfaces. The treated surface is encountered to the ion beam using N_2 and Ar [98, 99].

Laser nitriding melts the surface, up to 1.5 am deep, using a focused laser beam in a nitrogen gas environment to produce a hard layer of titanium nitride. Surface cracking is the main drawback with laser nitriding of titanium alloys [100]. The main disadvantages are special equipment requirement and dependency on the material's geometry.

Gas nitriding is deemed a promising method for engineering applications, as it forms harder layers on material surfaces effortlessly. Gas nitriding has the key benefit of being independent from the sample's geometry and it does not involve special equipment. A great disadvantage entails the high temperatures necessary, around 650–1000°C, as well as lengthy nitriding times of 1–100 h, as reported in the literature. It is also common knowledge that gas nitriding reduces the fretting fatigue limit of aluminum alloys [101].

Plasma nitriding or ion nitriding is more preferred than gas nitriding because of advantages such as the ability to select either an ε or a γ monophase layer or even to remove the lower treatment, white layer, temperatures, and better control of thickness of the case [102]. The heat treatment makes it easier to control the dimensions and in some cases eliminate machining altogether [102]. Fatigue strength is notably improved by nitriding. The formation of precipitates in the diffusion layer tends to increase the hardness and create compressive residual stresses. These beneficial stresses lower the magnitude of the applied tensile stresses and hence increase the fretting fatigue life of the component.

5. Applying Different Types of Coatings to Improve the Fretting Fatigue Life of Al 7075-T6

5.1. PVD Coating. Puchi-Cabrera et al. [103] explored the effect of TiN coating on Al 7075-T6 substrate by magnetron sputtering PVD coating technique. The TiN-PVD coating layer contributed to considerably enhancing the fretting fatigue life of the Al 7075-T6 substrate by 400% up to 2119% depending on the maximum alternating stress applied to the material. The improvement in fatigue life was a result mainly of the compressive residual stresses within the coating of roughly 7.08 GPa and the excellent adhesion between the coating and the substrate. It was also reported that TiN-PVD coatings maintain fine adhesion to the substrate under fretting fatigue loads [103].

Zalnezhad et al. studied the fretting fatigue life of Al7075-T6 by application of TiN coating using PVD magnetron sputtering technique with the highest adhesion strength and surface hardness as well as minimum surface roughness achieved by improving the parameters of TiN coating [104]. Reportedly, fretting decreases the fatigue life for uncoated Al7075-T6 by 30% in a low cycle region and 57% in a high cycle region. The fretting fatigue lives of TiN-coated samples with high surface hardness and high adhesion increased at high cyclic fatigue by 39% and 77% and low cyclic fatigue by 61% and 16%, respectively, in comparison with the uncoated samples.

From the study of Figures 16 and 17, it can be concluded that the fretting fatigue life of the TiN-coated specimens with high adhesion enhanced more than the coated specimen with higher surface hardness at low cyclic fatigue, while at high cyclic fatigue the results are reversed. This result is due to the brittleness of the TiN hard coating, where at high cyclic fatigue the cracks are propagated in the coating and then developed inside the specimen.

In another undertaking [105], ZrN-PVD coatings with 3 μm thickness seemed to experience drastic decline in both the tensile and fatigue properties of an Al 7075-T6 substrate. Decrease values of 28% and 43% were noted in the ultimate strength and yield strength of aluminum substrate, respectively, besides 73% to 82% reduction in fretting fatigue life. The adhesion between the coating layer and substrate appeared good under tensile loading, whereas major delamination occurred under high fatigue loads [105].

5.2. Hard Anodizing. Sarhan et al. [83] studied how the fretting fatigue life of hard-anodized aluminum alloy (AL7075-T6) can be influenced by surface hardness by a series of rotary bending fatigue tests. As previously stated, pure aluminum is incapable of accepting hard anodizing. For this reason, pure

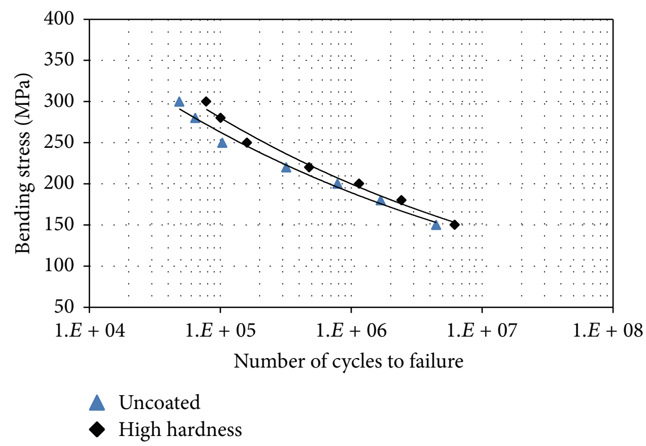


FIGURE 16: S/N curve of fretting fatigue for uncoated and TiN coated specimens with highest surface hardness [104].

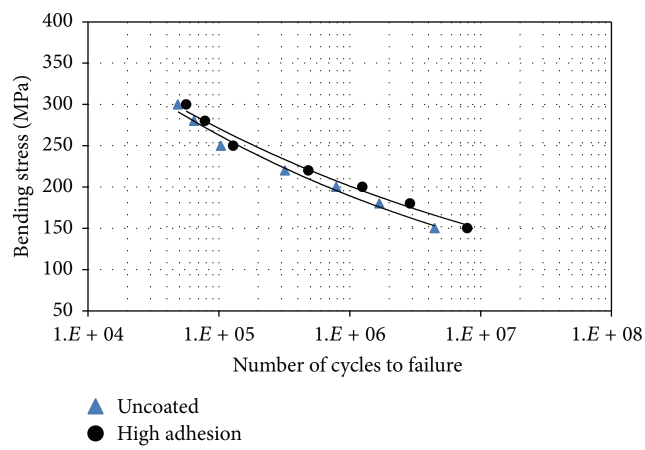


FIGURE 17: S/N curve of fretting fatigue for uncoated and TiN coated specimens with highest surface adhesion [104].

aluminum was coated on the AL7075-T6 surface. Taguchi optimization method was employed to study the influence of hard-anodized coating parameters including temperature, voltage, time, and solution concentration on surface hardness. Figures 18(a) and 18(b) demonstrate the fretting fatigue life of hard-anodized and uncoated samples with 393 and 360 HV surface hardness, respectively. Figure 18(a) indicates that at low bending stress the fretting fatigue life of hard-anodized specimens with hardness of 360 HV increased in comparison with uncoated specimens. Nonetheless, from 250 to 300 MPa, the results were reversed at high bending stress. Figure 18(b) illustrates the fretting fatigue life of uncoated and hard-anodized specimens with 393 HV as the highest surface hardness obtained. The fretting fatigue lives of hard-anodized samples increased only at low bending stresses from 150 to 200 MPa, but at a hardness of 393 HV fretting fatigue life decreased when bending stress increased from 200 to 300 MPa. Figures 18(a) and 18(b) also indicate that the fretting fatigue lives of hard-anodized samples with surface hardness of 360 HV increased even at 220 MPa bending stress, while at

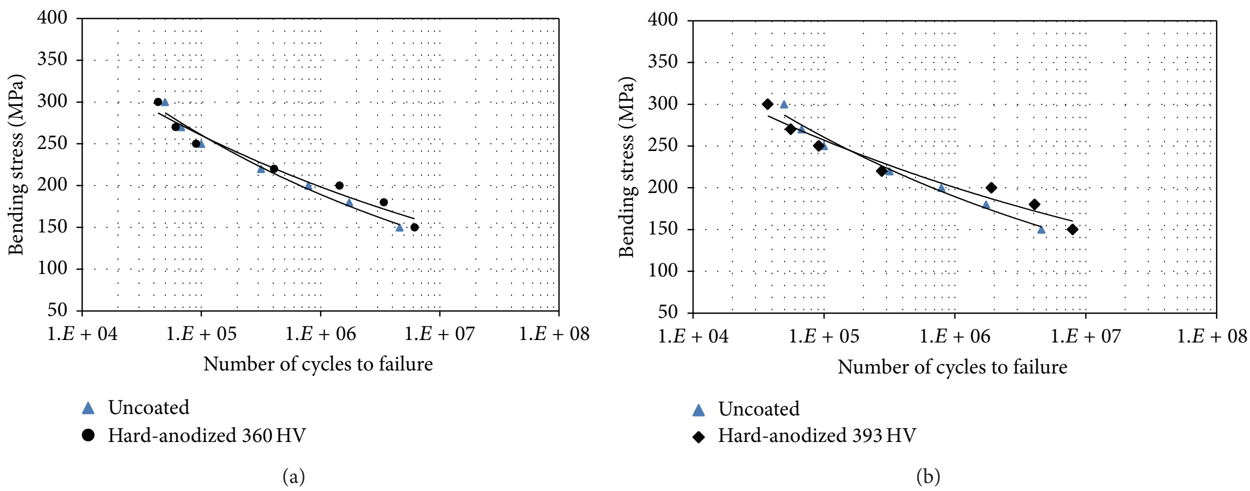


Figure 18: Comparison of S/N curve of fretting fatigue for uncoated and hard-anodized specimen. (a) S/N curve of fretting fatigue for uncoated and hard-anodized specimens (360 HV) and (b) S/N curve of fretting fatigue for uncoated and optimum hard-anodized parameters specimens (393 HV) [83].

this bending stress the fretting fatigue lives of hard-anodized specimen with 393 HV hardness are decreased compared to uncoated samples. This event is due to the microcracks generation and brittleness (ceramic) of the hard-anodized specimen with higher surface hardness (higher hardness causes higher brittleness) [106–108].

It is supposed that cracks of fretting fatigue appear in regions with frictional shear stress that is locally focused on the contacting surface. Therefore, the diminishing fatigue life resulting by fretting damage is assumed to be due to shorter crack initiation life owing to concentration of local stress caused by fretting, along with accelerated propagation of initial cracks by fretting [109]. One of the principle mechanisms in the acceleration of initial cracks by fretting is considered to be the wedge effect whereby wear debris moves into the small, initial fretting fatigue crack [110]. If the crack is already completely filled with wear debris, the effect tends to be reduced because the wear debris is unable to enter the crack any more [83].

Considerable improvement is achievable through a hard anodizing surface treatment layer, which has the potential to be applied to Al 7075-T6 and has the benefit of pure aluminum as an initial layer coated by PVD magnetron sputtering. However, this improvement is conditional to stress level.

5.3. IBED Technique. The fretting resistance and mechanisms of IBED CrN films have been assessed by Fu et al. [111]. The results were weighed against those of CrN films coated onto Al 7075-T6 via PVD. The researchers claimed that the hard IBED CrN film with sufficient substrate adhesion is capable of decreasing ploughing and subsurface distortion, consequently increasing the fretting fatigue resistance considerably, especially during operation. Also, the CrN phase can enhance the antioxidative and anticorrosive resistance of Ti alloy substrate during long-term fretting [79, 111].

One of the rationales behind IBED CrN thin film coating technique for improving fretting fatigue resistance making it superior compared to CrN film by PVD is likely attributed to the generation of a comparatively dense and fine structure due to ion beam bombardment throughout the IBED process [86, 87]. The high adhesion strength of IBED films to the substrate is another potential explanation for the higher fretting fatigue resistance [88, 90, 91]. Under high normal load and very small slip amplitude, long cracks are generated on the surface of the fretting scar on IBED CrN films, representing fretting fatigue failure [110].

5.4. Nitriding. Nitriding treatment on Al 7075-T6 alloy has been studied by Majzoobi and Jaleh [22]. They compared fretting fatigue tests (a) without any surface modification, (b) nitriding in the absence of substrate temperature control, (c) nitriding with substrate temperature control, (d) titanium coated by magnetron sputtering PVD technique, (e) titanium coated by ion coating technique, (f) nitriding followed by titanium coating using magnetron sputtering PVD technique, and (g) nitriding followed by titanium coating done by ion coating technique. The relation of fretting fatigue versus maximum stress for the untreated aluminum alloy is illustrated in Figure 19. It is obvious that the drop in fretting fatigue life develops as long as the applied stress increases. For instance, at a stress of about 150 MPa, the decrease is approximately 60%.

The fatigue test result regarding the surface modified specimens, illustrated in Figure 20, reports that fretting fatigue life for intact samples with no surface modification is much higher than nitrided samples. A couple of test series were conducted on nitrided samples in their study. In the first series of the tests, the temperature was not controlled but allowed to reach about 350°C during nitriding. The outcome of this series is designate by HT (high temperature) in Figure 20. In the second test series, the temperature increase along surface modification was monitored by cooling the

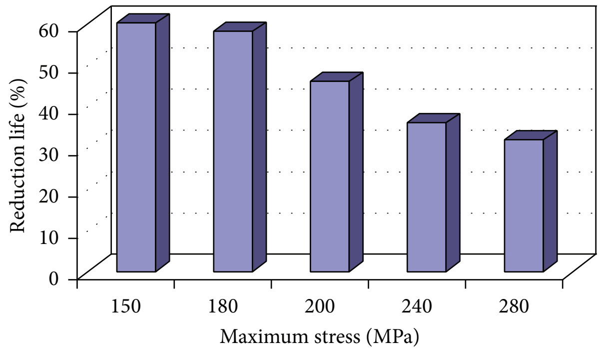


Figure 19: Reduction percentage of fretting fatigue life versus stress [22].

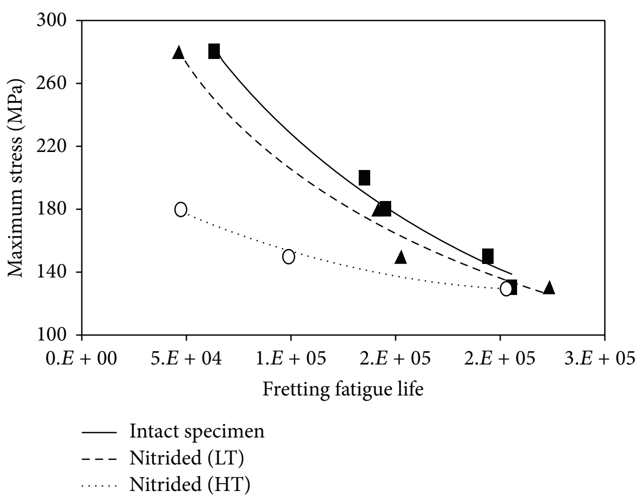


Figure 20: S-N curves for nitrided and normal specimens [22].

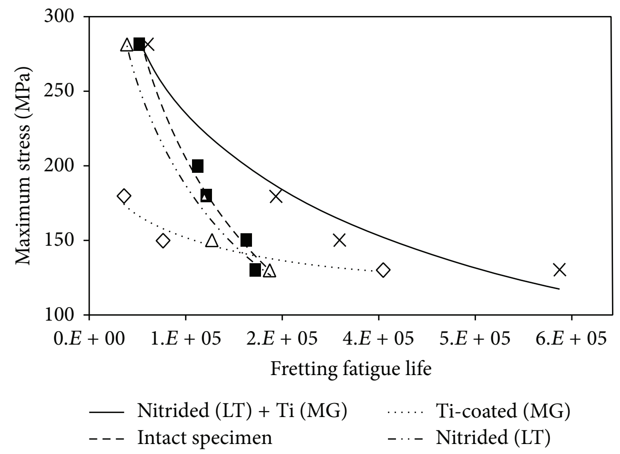


Figure 21: S-N curves for the duplex surface treatment, (Ni (LT) + Ti (MG)) [22].

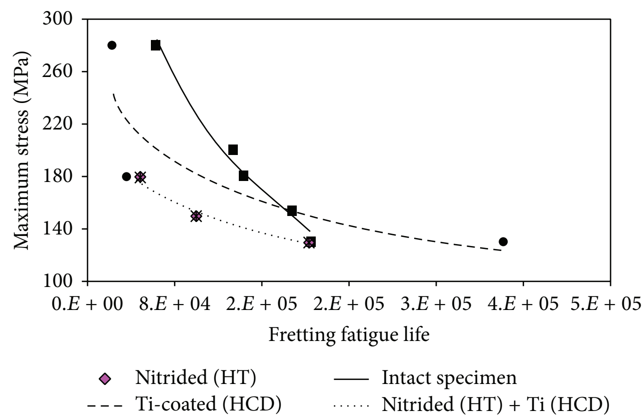


Figure 22: S-N curves for duplex surface treatment, (Ni (HT) + Ti (HCD)) [22].

specimens. The result is indicated by LT (low temperature) as shown in Figure 20. It can be concluded that the fatigue life drastically shortened for the first series of nitrided specimens. This potentially results from the nature of the nitriding process itself, which dramatically alters the material properties, particularly its ultimate strength and yield stress. Therefore, it can be deduced that nitriding alone does not enhance the material's fretting fatigue behavior.

Majzoobi and Jaleh [22] have also studied the outcome of titanium-coated specimens and determined that none of the nitriding and titanium coating satisfactorily improved the fretting fatigue response of AL7075-T6. For this reason, further investigation was done on the influence of a duplex surface treatment technique including titanium coating plus nitriding on the Al7075-T6 fretting fatigue behavior. Two test series were assessed. The first one was conducted with the specimens initially nitrided under controlled temperature conditions followed by coating using magnetron sputtering PVD technique. The results are illustrated in Figure 21. The figure clearly demonstrates that the duplex surface treatment technique significantly enhanced the material's fretting fatigue life in testing condition. It was also observed that the influence of the duplex treatment is much better at lower stress. As an example, the fretting fatigue life improved by nearly 100% at a stress of 130 MPa, whereas at a stress of 280 MPa it improved only by 13%.

In the second test, nitriding was followed by coating via hollow cathode deposition technique. As reported in Figure 22, a comparison of the S-N curves in the nitriding with titanium ion coating duplex treatment with the single nitriding treatment suggests that the former does not prompt any change in the performance of material with respect to resistance of fretting fatigue.

Consequently, it is asserted that the duplex surface nitriding treatment at a low temperature followed by titanium coating by PVD magnetron sputtering technique generates the optimum AL7075-T6 performance in encountering fretting fatigue damage.

6. Discussion

A multitude of surface modification techniques exists for decreasing fatigue damage. Significantly different mechanisms are reportedly capable of attaining this goal. At least,

Table 3: Effect of surface modification techniques on fretting damage.

Surface modification method	Decrease the coefficient of friction	Introduce compressive stress	Increase in hardness	Increase in surface roughness	Durability or adhesion	Economy	Mitigation of fretting wear	Mitigation of fretting fatigue
Nitriding	√	√√	√√	D	√√	√	√	√
Electroplating (Cr, Ni, etc.)	D	××	√	D	×	√	√	××
Hard anodizing	D	×	√	D	√	—	√	D
Shot peening	×	√	√	√√	—	√√	√√	√√
Laser shock peening	D	D	D	√	××	√	D	√
Deep rolling	√	√√	√	D	√√	√√	√	√√
IBED hard film	√	√	√	××	√	××	√√	√√
PVD hard coating	√	D	√	×	D	×	√	D

D: depending on condition; ×: bad effect; √: good effect; √√: very good effect, and ××: very bad effect.

five diverse methods of increasing fretting fatigue resistance are applying compressive residual stress, reducing the friction coefficient, enhancing surface hardness, changing the surface chemistry, and increasing surface roughness. Table 3 tabulates a number of typical surface modifications applicable to Al7075-T6 alloy accompanied by their effects on fretting phenomena.

Introducing compressive residual stresses into surface layers by means of surface modification is possibly among the most substantial mechanisms of decreasing fretting damage and consequently fretting fatigue [112]. Compressive stress causes fretting fatigue crack surfaces to close up, preventing crack propagation. Not only that, but compressive stress also decreases the tensile stress of fretting, subsequently lowering the rates of wear and crack propagation [113].

Selective deposition technique and surface treatments, such as ion implantation, shot peening, nitriding, and ion beam enhanced deposition, could induce compressive residual stress. Hence, such techniques are highly recommended to obtain better fretting resistance, mainly to improve the fretting fatigue strength. It is important to be noted that some types of surface modification including laser treatments and electroplating Cr are not proper to be applied for fretting fatigue life improvement as tensile residual stresses are often generated [114, 115].

The coefficient of friction plays an important role in fretting damage since greater friction force leads to higher strain fatigue or shear stress on surfaces and at interfaces. As such, delamination cracks or intensified fatigue failure could ensue. Lower friction coefficients can enhance the fretting fatigue strength in response to the minimized alternating tensile shear stresses. Elevated alternating stresses are a cause of high local strain fatigue and rapid fatigue crack initiation. Another concern is surface hardness, whereby a dramatic increase in surface hardness is followed by high residual tensile stress and reduced toughness in the surface layer, all of which are detrimental to fretting fatigue strength.

Changing the chemistry of the surface also possibly influences fretting damage. The fundamental function of oxidation during fretting and the important influence of oxide debris are understood by many scientists. Altering the surface chemistry by nitride, oxide, or carbide layer formation may help to enhance fretting resistance by having a lubricating effect.

The surface roughness influences on fretting resistance are fairly intricate and inconsistent. Good surface finishing emphasizes fretting damage, and to minimize such damage increasing surface roughness using different treatment techniques like shot peening is sometimes helpful. In some cases, increasing surface roughness may be the cause of a rising friction coefficient, which is not proper for fretting fatigue resistance. A rough surface has the potential to elevate stress, something very dangerous, especially under fatigue conditions [116–124].

Considering surface treatment means of mitigating fretting damage, specifically for Al 7075-T6, seven techniques have been drawn and discussed in this study. These particular methods are in great demand due to the positive effect on the fretting fatigue life of this aluminum alloy [125–129].

Deep rolling is absolutely successful in increasing fretting fatigue life at high cyclic load. The rolling force affects fatigue life in elevated rolling forces to enhance fatigue life by more than two times. It is thus concluded that by increasing rolling force an improvement in fatigue life is achievable. Deep rolling is also known to maintain low surface roughness. Compared to other techniques, deep rolling creates deeper compressive residual stress layers. Nevertheless, rolling force has the drawback of necessitating optimization and control.

Shot peening also follows the deep rolling's theory. They both produce a compressive residual stress layer. The distribution and depth of residual stress are affected by a variety of parameters like shot material and diameter, duration, target material, intensity of exposure, and shot velocity.

At low cycle fatigue (LCF) tests, SP enhances the material's fretting fatigue behavior much better than DR.

SP increased fretting fatigue life by 300% for the tested specimens. The effect of DR on fretting fatigue resistance was more pronounced in high cycle fatigue, with a recorded improvement of about 700% at higher rolling forces.

A study of reshot peening techniques shows that the fretting fatigue lives of Al7075-T6 alloy are enhanced significantly. The fretting fatigue life of Al7075-T6 improved by 600% after 5 reshot peenings. It indicates that reshot peening has superior effect than simple shot peening.

Like shot peening and deep rolling, the mitigation of fretting fatigue life of specimens by using laser shock peening depends on the compressive residual stress layer. The deeper layer penetration can be achieved by LSP compared to SP. After laser shot peening treatment, significant improvement in fretting fatigue resistance can be obtained compared to other similar techniques.

Among the heat treatment methods meant to enhance the fretting fatigue of Al alloy 7075-T6, nitriding has always been an excellent option. In some cases, however, the results show that the fretting fatigue life of specimens with no surface modification is much higher than nitrided specimens.

PVD metal coatings including silver and gold were traditionally used to avoid fretting failure. The augmented fatigue life with PVD comes as a result of mainly compressive residual stresses during coating, in some cases at magnitudes of 7.08 GPa, and the excellent adhesion of coating to substrate.

In surface treatments by hard thin coating techniques, it is useful to be noted that fretting has a deleterious effect on the fatigue life of AL7075-T6 in uncoated and coated conditions at any bending stress [130].

Consequently, fretting can reduce the fatigue life of uncoated Al7075-T6 by about 30% in low cycle regions and by 57% in high cycle regions. Magnetron sputtering PVD coating in combination with hard anodizing substantially enhanced the fretting fatigue of AL7075-T6. As opposed to uncoated samples, a 119.55% enhancement in surface hardness of hard-anodized Al7075-T6 with a hardness of 393 HV was gained. At low bending stress, the fretting fatigue life of Al7075-T6 alloy is improved by the hard-anodized coating with hardness of 360 HV [131–134].

IBED technique demonstrates better film properties than similar films produced by PVD.

The superior ability of nitriding to enhance fretting fatigue is more evident when this technique is paired with magnetron sputtering PVD. Different studies have reported that none of nitriding and titanium coating could suitably enhance the fretting fatigue life of Al7075-T6. Hence, investigations showed the dramatic development in the fretting fatigue behavior of Al-7075-T6 when subjected to duplex surface treatment including nitriding followed by titanium coating. The duplex treatment is much more effective at lower stress. At a stress of 130 MPa, the fretting fatigue life improved by 100% but only by 13% at 280 MPa.

Accordingly, it is recognized that duplex surface treatment entailing nitriding at low temperature followed by titanium coating using magnetron-sputtering PVD technique results in the greatest Al7075-T6 performance against fretting fatigue damage.

7. Summary

The effects of various methods including deep rolling, shot peening, laser shock peening, thin film hard coating using physical vapor deposition (PVD), hard anodizing, ion-beam-enhanced deposition (IBED), and nitriding to diminish the effect of fretting on the fatigue life of Al7075-T6 alloy are studied in detail. The following conclusions are derived.

(a) The deep rolling technique effectively improves the fretting fatigue behavior at high pressure. Increasing the rolling force increases fretting fatigue accordingly. DR maintains low surface roughness and great depth of compressive residual stress. The effect of DR on fretting fatigue resistance is deeper with high cycle fatigue, with up to 700% recorded. For low cycle fatigue (less than 10^5 cycles), SP improves fretting fatigue more effectively than DR, by 300%. Reshot peening technique seems to be much better than simple shot peening. After 5 reshot peenings, the fretting fatigue life of Al7075-T6 is improved by 600%.

(b) The fretting fatigue life for nitrided specimens with no surface modification is significantly lower than the intact samples. However, the duplex surface treatment comprising nitriding at a low temperature plus titanium coating using magnetron sputtering technique improved the fretting fatigue of Al 7075-T6 up to 100% at low stress. This technique could not sustain the same outcome at high stresses such as 280 MPa where fretting fatigue rose by merely 13%.

(c) Thin film hard coating is found to be a good choice for enhancing the fretting fatigue life of Al7075-T6. Fretting decreased the fatigue life of uncoated Al7075-T6 by 57% in high cycle regions and 30% in low cycle regions. The fretting fatigue lives of TiN-coated specimens are improved at high cyclic fatigue by 39% and 77% and at low cyclic fatigue by 61% and 16%, respectively, compared to the uncoated specimens.

(d) IBED technique demonstrates superior film properties to similar films prepared by PVD technique. Titanium coating via IBED reportedly increased the fatigue life of Al alloy 7075-T6 by 100% at low working stresses.

Conflict of Interests

There are no competing or financial interests in this paper.

Acknowledgments

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