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Review of Residual Stress Modification Techniques for Extending the Fatigue Life of Metallic Aircraft Components

A major challenge for the aircraft industry in the future will be the development of effective strategies for maintaining and extending the service life of aging aircraft fleet. In this context, residual-stress-based approaches for extending the fatigue life of aircraft components are believed to have great potential for providing cost-effective solutions. This paper reviews residual-stress-based life extension techniques and published work on the use of these techniques in aerospace applications. The techniques reviewed include cold expansion, shot peening, laser shock peening, deep rolling, and heating. Comparisons of the various techniques with regard to current applications and limitations are given. [DOI: 10.1115/1.4028160]

Keywords: residual stress, aerospace applications, cold expansion, shot peening, laser shock peening, deep rolling/low-plasticity burnishing, heating

1 Introduction

One major challenge for the aircraft industry in the future will be the development of effective strategies for maintaining and extending the life of aging aircraft fleet. In this context, residual-stress-based methods for extending the fatigue life of components can provide cost-effective solutions [1–3].

Although these approaches offer the potential for significant improvements by inducing compressive residual stresses at critical locations [1,3], it is difficult to characterize the levels of residual stress induced in each location under industrial production conditions, and there are concerns that the residual stress state might change during the long service life of a typical aircraft [1]. Since the life improvement factor of a residual-stress-based technique is a function of the applied stress, a general value of this factor cannot be given. Additionally, the residual stress effects are not explicitly addressed in a damage tolerance evaluation. Generally, civil aviation authorities insist that damage tolerance requirements must be satisfied without including the beneficial effects of residual-stress-based life extension processes [4,5].

However, experience has shown that the use of processes such as the cold expansion of rivet holes can significantly decrease maintenance costs [1,2]. Over the last several decades, this economic incentive has motivated manufacturers and operators to continue using such techniques and to attempt to convince the authorities to account for their use.

Currently, civil aviation authorities make exceptions to their general policies in very narrow confines if the manufacturer or operator can prove the effectiveness of the life extension method experimentally and via predictions for the specific application [4,5]. Although this procedure is both time-consuming and expensive for each individual case, it is an important step toward a general acceptance of such extension approaches.

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Because of the existing limitations of the established extension processes, for example, with regard to special geometries or the maximum levels of induced residual stress, the industry is interested in exploring the possible benefits of new approaches. One such new process is laser shock peening.

In summary, there is a substantial economic motive for the industry to extend the use of established residual-stress-based life extension techniques and to explore the potential of promising new approaches.

2 Scope of This Article

This paper will review past work on residual-stress-based fatigue life extension techniques for aircraft applications. Hence, the materials of particular interest are titanium and aluminum alloys, which are commonly used for jet engine parts and airframe structures, respectively. The reviewed processes include cold expansion, shot peening, deep rolling/low-plasticity burnishing, laser shock peening, and heating. A brief explanation of the principle and the typical resulting residual stress distribution is given for each of these processes, followed by a review of recent publications on the use of the technique as a life extension process for aerospace applications. This review will focus on work that was published since 2006. In that year, two major reviews of residual stresses and their use for fatigue life extension were published [1,6]. However, earlier work is considered, in particular, for the heating process because this approach has received only limited attention to date and was not included in the previous reviews.

3 Life Extension Processes

3.1 Cold Expansion

3.1.1 Description of the Cold Expansion Process. Holes in structural members create local stress concentrations and are likely sites for fatigue crack initiation and growth. Cold expansion, which is the most prominent and accepted method for mitigating this tendency in aerospace structures, introduces residual stresses around the hole. The method introduces a compressive stress field in the material around the hole, and this field reduces the tendency for fatigue cracks to develop and grow under a superimposed cyclic mechanical load. However, some components may experience exposure to high temperatures due to operational, maintenance, or accidental factors. The high temperature exposure could lead to relaxation of compressive residual stresses and potentially affect the component properties such as fatigue life and static strength properties [7]. Although many variations of the process have been developed, the basic principle is nevertheless identical. An oversized, tapered mandrel is drawn through a hole or a cut-out to plastically widen the opening, which causes the formation of permanent compressive residual stresses around the hole [3]. These residual stresses are compressive (and therefore beneficial) in an annular region surrounding the hole but are slightly tensile beyond this annular region. The growth of fatigue cracks may be significantly delayed, if not arrested altogether, by these compressive residual stresses. Figure 1 shows the principle of the so-called split-sleeve process and the corresponding induced residual stress field.

3.1.2 Application of the Cold Expansion Process. Over the last 40 years, it has been demonstrated that significant extensions of fatigue life can be achieved with this technique, even when small cracks are already present [8,9]. For sustaining an aging aircraft fleet with riveted metallic airframes, this process offers an effective and simple method of life extension [3]. The cold expansion process has been most widely applied to aircraft structures, and so it should not be surprising that the great majority of the technical literature on cold expansion addresses high-strength aluminum alloys. For example, in Ref. [10], the authors investigated the use of this process as a life extension technique on aircraft structural joints with structural members fabricated from 2024-T351 aluminum alloy. The primary focus was an experimental test program consisting of joint specimens prefatigued to 25%, 50%, and 75% of the baseline fatigue life of plain holes. The joint specimens that were used represented a spanwise attachment of aircraft wing panels, i.e., the skin to stringers, and consisted of two geometrically similar specimens, open hole, and low-load transfer joint, in a reverse double dog-bone design. The results indicated that significant improvements in fatigue life can be obtained through cold expansion when applied at any of the percentages of fatigue life tested, with the optimum stage being approximately 25% of the baseline life. The life extension was obtained mainly through slower crack growth in the short crack stage.

Various finite element (FE) models have been established to study the residual stress fields produced by cold expansion; several are described in Ref. [9]. To verify their simulation results, the authors measured the residual stresses and conducted fatigue tests. The material used for the specimens and in the models was the aluminum alloy LY12-CZ, also called 2A12-T4. The experimental values of the residual stress obtained via X-ray diffraction were consistent with the simulation results. Compressive residual stresses within 2.5–3 mm from the edge of the hole were measured, and the maximum magnitude was approximately −300 MPa. The fatigue tests revealed that the lives of the specimens that were processed by cold expansion were approximately six times longer than those without cold expansion.

A series of fatigue tests were conducted on titanium alloy specimens (TC4 or Ti-6Al-4V) containing cold-expanded and "as drilled" (untreated) open holes in Ref. [11]. From this work, the following conclusions can be drawn:

(1) Cold expansion increased the fatigue life of the holes by a factor of 1.5–3.0;
(2) The compressive residual stress drastically retards the crack propagation rate, especially in the short crack stage;
(3) A corner crack formed at the entrance face of the cold-expanded holes, whereas a face crack formed at the mid-plane of the unexpanded holes;
(4) The lowest compression stress occurred at the entrance surface, whereas the highest stress occurred near the middle of the hole wall.

3.2 Shot Peening

3.2.1 Description of the Shot Peening Process. Shot peening is perhaps the most widely used process for fatigue life extension in metallic structures [1]. As shown in Fig. 2, small particles, such as glass, ceramic, or metal spheres (the medium), are directed at high speed onto the surface of a workpiece, and each particle causes a local plastic deformation or dimple. This procedure results in the formation of compressive residual stresses in a layer near the surface of the material. The compressive residual stresses are offset by tensile residual stresses in the core of the workpiece. The depth of the layer containing the compressive residual stresses is on the order of tenths of a millimeter [12]. The impact dimples created by shot peening increase the surface roughness, particularly in soft materials and at high peening intensities. Deep rolling and laser shock treatments, described later in this paper, can reduce the roughness if the intensity of the treatment is not excessive, keeping still good values of residual stress. Attention must be paid in the usage of the peening media since broken or recycled particles can create discontinuities or damages on the surface. Moreover, the surface being shot peened must be accessible to allow direct impingement of the shot. Blind surfaces may be impossible to effectively shot peen.

3.2.2 Application of the Shot Peening Process. Because of its flexibility, shot peening may be used on components of almost

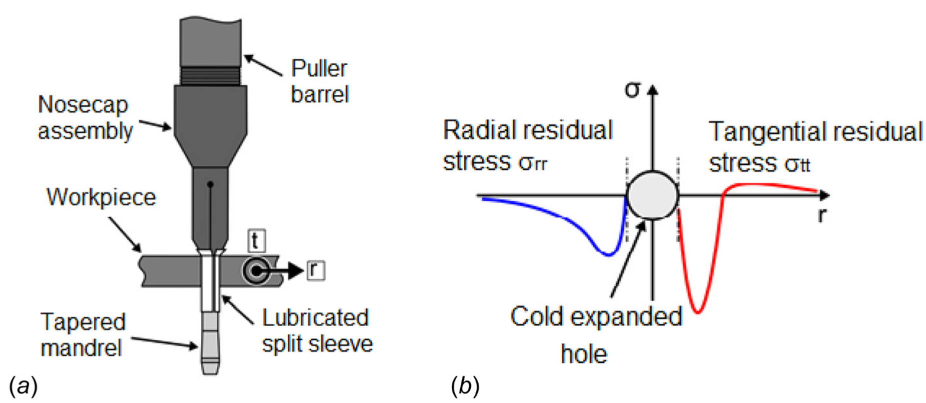

Fig. 1 (*a*) Principle of the split-sleeve cold expansion process and (*b*) the resulting residual stress state following cold expansion [3,8]

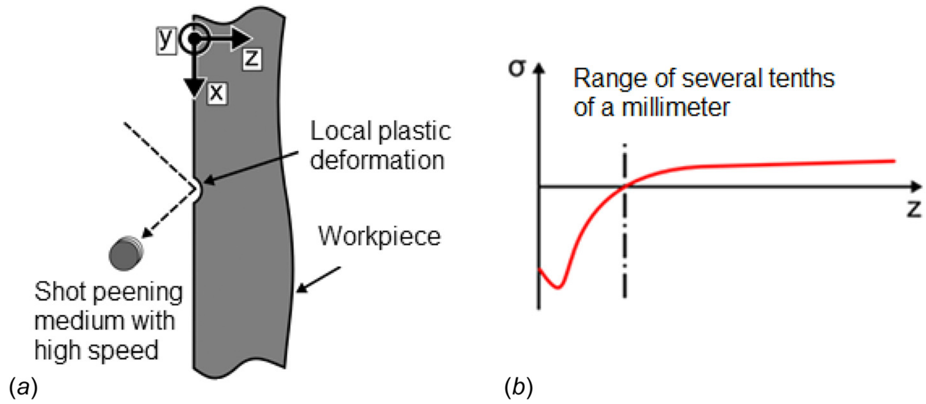

Fig. 2 (*a*) Principle of the shot peening process and (*b*) the resulting residual stress state following shot peening [1,12]

any shape, particularly on those possessing a complex geometry, and is ideal for use on cross-sectional variations, chamfers, boreholes, and bore edges. Components typically shot-peened in mass production include springs, connecting rods, gears, stepped or grooved shafts and axles, turbine vanes and blade bases, and welded joints. Shot peening can be employed also to improve resistance to stress corrosion cracking and corrosion fatigue [6]. The induced residual stresses are mainly effective in retarding surface fatigue crack formation and early crack growth. Because most fatigue cracks in highly loaded aerospace structures and components originate at the surface, shot peening is an effective and accepted process for extending the fatigue life of airframes and jet engine components [1,4,12,13]. However, because of the very limited depth of the compression/tension transition point of the residual stresses, shot peening seems to have little effect if through-thickness cracks are already present [14].

A novel example of shot peening of aluminum structures is discussed in Ref. [15], where the effects of heat treatment and shot peening on the fatigue life of an AA7050 aircraft wheel were studied. A cylindrical sample 40 mm in length and 15 mm in diameter was machined from the wheel. The shot peening was performed with 0.84 mm steel shot. Both the heat treatment and shot peening increased the operational life of the aircraft wheel. However, the peening process was more effective. Moreover, it was shown that the sequence of the treatments affects the degree of life extension; the best results were obtained when the peening process was preceded by the heat treatment. The resulting compressive residual stresses were approximately -300 to -400 MPa in all regions at depths ranging from 0 μm to 200 μm beneath the surfaces of the samples. The resulting fatigue life of the aircraft wheel was 14 times greater when compared with the unpeened wheel.

FE modeling of the shot peening process has been investigated by many authors; several examples can be found in Refs. [16–18]. Many methods of modeling have been proposed, such as 2D indentation, 2D and 3D single impacts, 3D multi-impact, and 2D and 3D angled-impacts. The 2D axisymmetric FE model has been the most frequently used of these methods for the modeling of the impact of one shot as it strikes the surface of an elastic–plastic body. These 2D FE models have been refined further for single-angled impacts and used as the basis for 3D multishot impacts [19–21].

3.3 Laser Shock Peening

3.3.1 Description of the Laser Shock Peening Process. Similar to shot peening, laser shock peening produces compressive residual stresses in a surface layer by a bombardment of the surface. However, as shown in Fig. 3, the principle is different from that of conventional shot peening.

The process of laser shock peening involves irradiating the surface of the target material with short-duration (on the order of nanoseconds) laser pulses. The target surface is generally coated a priori with an ablative layer such as black paint or aluminum tape to increase the absorption of laser energy and to avoid thermal damage to the surface. The laser immediately vaporizes the sacrificial layer, and the vapors continuously absorb laser energy. The continuous laser energy absorption leads to the ionization of atoms into a rapidly expanding plasma. The expansion of the plasma between the target surface and sacrificial layer generates a pressure pulse of short duration and high intensity. Some of this energy travels through the target material as a shock wave, whereby the treatment gets its name. The pressure pulse impinges on the treated area and creates nearly uniaxial compression in the direction of the shock wave propagation and tensile extension in the plane parallel to the surface. As the shock wave propagates into the material, plastic deformation occurs because the pressure exceeds the dynamic yield strength of the material. Through this interaction with the surrounding zones, a compressive stress field is generated within the affected volume and is balanced by a tension stress field in the underlying layers [22,23].

The magnitude of the compressive stress is comparable to that generated with conventional shot peening, but the compressive residual stresses extend to depths in the range of several millimeters. Depending on the laser parameters and the material, the layer of compressive residual stresses developed by laser shock peening can be more than 10 times deeper than that obtained with shot peening [24]. Additionally, laser shock peening results in a rather low surface roughness, and the laser pulse parameters and position can be adjusted and optimized in real time. On the other hand, the laser shock peening technique requires expensive equipment, specially protected environment and skilled operators. Among the benefits of the technology, the authors of Ref. [25] discussed the thermal stability of the residual stresses at elevated temperatures generated by laser shock peening. The results from Ref. [26] showed that for the titanium alloy Ti-8Al-1V-1Mo treated with laser shock peening, no recovery of the residual stress was observed after4 h exposure at elevated temperatures. For other types of materials, such as INCONEL 718 and Ti-6Al-4V, the thermal relaxation of residual stresses induced by laser shock peening exhibited similar results [27].

3.3.2 Application of the Laser Shock Peening Process. Because of the numerous advantages, laser shock peening has been intensively investigated for various materials including steel, aluminum and nickel alloys, molybdenum, and copper. Laser shock peening is an established process for extending the fatigue life of aircraft engine turbine blades [28,29], and there is ongoing research in applying the process to extend the life of highly stressed, thick-section aluminum airframe components [25]. Laser shock peening has been successfully used to increase fatigue life [30], reduce fretting fatigue damage [22], improve resistance to corrosion [29], and increase resistance to foreign object damage

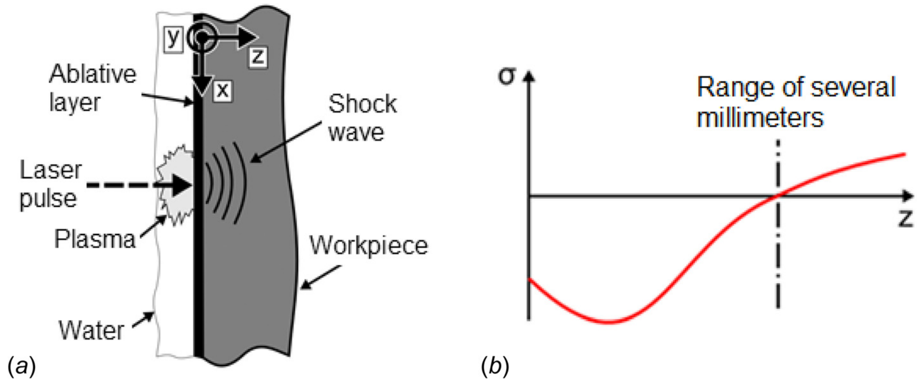

Fig. 3 (*a*) Principle of the laser shock peening process and (*b*) the resulting residual stress state following laser shock peening [1,22]

[31]. Since the development of laser shock peening, the strong interest in its commercialization can be inferred from the number of patents issued for this process. The technology is now commercially available [24,32]. Numerous possible applications of the technology to metallic aircraft structures include:

(1) fatigue-critical components (such as F-16 bulkheads) [24]
(2) wing attachment fittings (F-22 lugs) [33]
(3) landing gear, including wheels and brakes [34]
(4) fasteners and fastener holes (to prevent fatigue, fretting fatigue and stress corrosion cracking) [35]
(5) welded aircraft parts, including aluminum and titanium components, for improved reliability [36]
(6) helicopter components [37].

Although many studies using high-strength aluminum aircraft alloys involved objects with a thickness in the range of 6 mm to 28 mm [38], there is research demonstrating the successful application of the process to thin objects with a thickness of approximately 2–3 mm [39], which is in the same range as aircraft fuselage skins.

In Ref. [36], for example, the authors applied laser shock peening without a coating to fatigue specimens fabricated from friction-stir-welded 6061-T6 aluminum alloy plates with a thickness of 3 mm. In this process, the object to be peened is water-immersed and does not require any coatings that protect the material surface from melting or being damaged. The effects on the fatigue properties were studied through plane bending fatigue tests with a stress ratio of $R = -1$. The results showed that laser shock peening without a coating enhanced the fatigue strength of base material specimens by 60 MPa and enhanced the fatigue of the friction-stir-welded specimens by 30 MPa.

A recent study [39] showed that laser shock peening can induce compressive strain in thin (1.8 mm) 2024-T351 aluminum plates, although some of the compressive strain may be relaxed because of distortion. This study additionally showed that the longitudinal and transverse components of the in-plane strain differ, with the strain component longitudinal to the peening line being more compressive than the component transverse to the peening line, most likely because of the higher distortion of the thin samples perpendicular to the peening direction. Furthermore, it was confirmed that for thin plates, increasing the laser pulse energy and the number of passes induces higher compressive strains.

The effects on mechanical properties, residual stress, and fatigue behavior of 6061-T6 and 6061-T651 aluminum alloys were recently investigated in Refs. [40–44], due to the importance of these alloys in the aircraft industry. In particular, in Ref. [43], the authors used a 3 mm thick AA6061-T6 specimen to evaluate the warm laser shock peening process. Warm laser shock peening is an innovative manufacturing process that integrates laser shock peening and dynamic aging to improve the fatigue performance of a material. The authors proved that this treatment produces higher surface strength, lower surface roughness, less residual stress relaxation, and a more stable dislocation arrangement during cyclic loading when compared with conventional laser shock peening. These effects significantly increase the fatigue resistance in warm laser shock peened samples when compared with conventional laser shock peened and untreated samples. In the conventional laser shock peened samples, the residual stress changes from compressive to tensile at approximately 1 mm beneath the surface, whereas for warm laser shock peened samples this transition occurred at a depth of 1.4 mm. The deeper compressive residual stress leads to greater resistance to crack propagation during fatigue cyclic loading and can significantly influence the fatigue behavior of materials. The fatigue life improvement is greater in the high-cycle region than in the low-cycle region.

The effect of laser shock peening on the initiation and growth rate of fatigue cracks in 2.5 mm thick AA2024-T3 specimens with various notch geometries was investigated in Ref. [45]. The specimens with a pre-existing notch and laser shock peening were characterized and compared with those of the unpeened material. The results clearly showed that laser shock peening was an effective surface treatment technique for suppressing fatigue crack growth in aluminum alloys with various notch configurations. Concerning the fatigue crack growth behavior, the unpeened specimens exhibited typical crack growth behavior wherein the initial crack growth rate was low but increased with the crack length and the applied stress levels. The laser-peened specimen showed different crack growth behaviors: at low stress intensity factor ranges the crack growth rates were similar to those in the unpeened alloy; after propagating to a certain length, the crack growth rates decreased rapidly, and eventually the crack growth stopped near the boundary between the peened and unpeened regions.

A notable finding in Ref. [46] was the influence of the process parameters of laser shock peening. Specimens were prepared from Ti-17, an aerospace titanium alloy, with thicknesses of 1 mm and 9 mm. The following process parameters were analyzed: laser fluency (a measure used to describe the energy delivered per unit area), pulse duration, the number of impacts, and the thickness of the sample. It is found that all of the parameters have an influence on the residual stresses; however, they have a negligible influence on roughness and only a slight influence on work-hardening. The increase in hardness was found to be mainly due to compressive residual stresses, whereas cold working had only a small effect. One unexpected and important finding of the study was the tensile residual stress that occurred on the surface of thin samples that were laser shock peened on one side. The considerable plastic strain imposed on one side created large distortions in the specimens.

A numerical study on the fatigue life of a 2 mm thick ZK60 magnesium alloy plate treated by laser shock peening was conducted in Ref. [47]. The fatigue life predicted by the use of numerical simulation was increased by 70%. In addition, the fatigue life

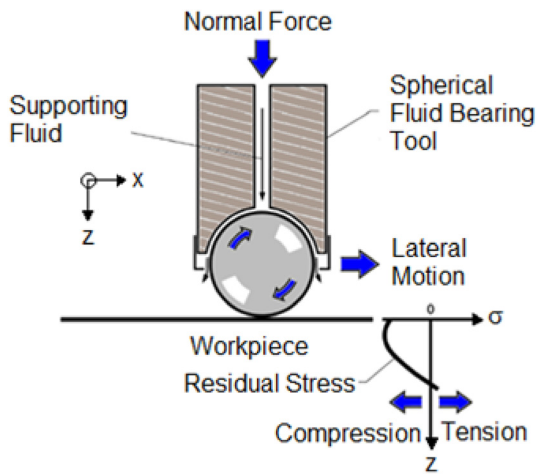

Fig. 4 Principle of the low-plasticity burnishing process and the resulting residual stress state. Illustration reproduced by permission from "Low Plasticity Burnishing," August 23, 2013.[1] Copyright 2013 by Lambda Technologies Group.

for this Mg alloy increased with the number of passes of laser shock peening and plateaued at a certain value. The optimal number of treatment layers was found to be three.

In Ref. [48], the effect of foreign object damage on the residual stresses in an airfoil leading edge that was laser shock peened was investigated. The foreign object damage was inflicted on the leading edge of airfoil-shaped specimens through ballistic impacts at angles between 0 deg and 45 deg to the leading edge. The results suggested that the impact from the foreign object superimposed a significant residual stress on the pre-existing stress associated with the laser shock peening process, predominantly at two critical locations, a small tensile region at the flanks of the impact notch and a large compressive zone directly below the notch. The transition from compression to tension for a laser shock peened leading edge struck at 0 deg by the foreign object was located 6 mm from the leading edge. The induced compressive stresses were approximately one-half the yield strength in the longitudinal direction (crack opening direction) of the airfoil specimen at the leading edge.

Several researchers have compared the performance of conventional shot peening and laser shock peening in retarding the growth of long fatigue cracks [14,49] and their effect on the mechanical properties [50]. In Ref. [14], for example, the influence of shot peening and laser shock peening on the growth of fatigue cracks in friction-stir-welded sheets of 7075-T7351 aluminum alloy was investigated. A systematic investigation of the various peening effects indicated a significant decrease in fatigue crack growth rates in laser shock peened versus untreated welded and base material specimens. In contrast, shot peened specimens did not show a significant reduction in fatigue crack growth. The fatigue striation spacing for the laser shock peened specimens was assessed and found to be small compared with that of the unpeened and shot peened specimens. The reduction in striation spacing indicates a slower fatigue crack growth rate and could be partially attributed to the deeper compressive residual stresses induced by the laser shock peening.

3.4 Deep Rolling/Low-Plasticity Burnishing

3.4.1 Description of the Deep-Rolling/Low-Plasticity Burnishing Process. The low-plasticity burnishing process consists of a single pass with a smooth, free-rolling ball pressed with a normal force sufficient to deform the surface of the material. The ball, which is supported in a spherical fluid bearing, is in mechanical contact with only the surface to be burnished and is free to roll in any direction; see Fig. 4. This technique was first used in 1996 by Lambda Technologies, Inc. and has been in commercial use since 2004 [51]. The process can be performed on-site on aircraft using robots, making it easy to incorporate into everyday maintenance and manufacturing procedures. Because of dimensional restrictions, it may not be possible to create the tools necessary to work on certain geometries.

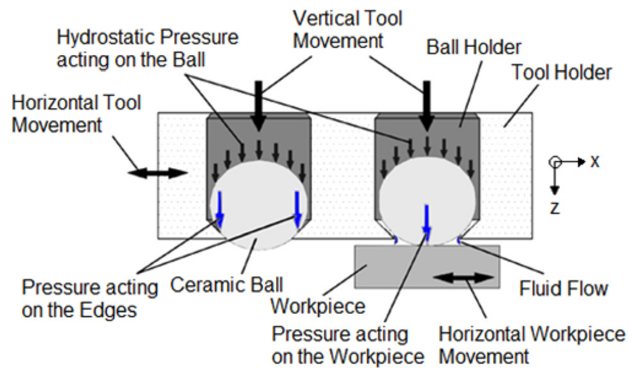

Fig. 5 Principle of the deep-rolling process. Illustration reproduced by permission from Tolga Bozdana, 2005, "On the Mechanical Surface Enhancement Techniques in Aerospace Industry–A Review of Technology," Int. J. Aircr. Eng. Aerosp. Technol., 77(4), pp. 279–292. Copyright 2005 by ECOROLL AG.

The principle of the deep-rolling method is very similar to that of low-plasticity burnishing. When the load is applied on the ball, the force generates a high Hertzian compressive stress state in the material at the contact point, as shown in Fig. 5. Therefore, a 3D stress distribution is created in the workpiece surface, resulting in plastic deformation when the yield stress of the material is exceeded [52].

3.4.2 Application of the Deep-Rolling/Low-Plasticity Burnishing Process. As in the previous mechanical surface treatments, deep rolling, and low-plasticity burnishing can significantly improve the fatigue behavior of highly stressed metallic components and, moreover, are particularly attractive for industry because it is possible to generate deep, compressive residual stresses and work-hardened layers near the surface while retaining a relatively smooth surface finish. In Ref. [53], low-plasticity burnishing was used to mitigate the reduction of the fatigue life due to pre-existing cracks in specimens fabricated from AA2024-T851. Two different features of aircraft structures were simulated: specimens with complex geometries consisting of fillets, radii and steps and thicknesses as low as 2.5 mm (type A); and simple 3 mm thick plates that included a hole (type B). The results of the investigation can be summarized as follows:

(1) Uniform compressive residual stresses of approximately −200 MPa for specimens of type A and approximately −300 MPa for specimens of type B were created, extending to midthickness at critical locations in the samples;
(2) Low-plasticity burnishing significantly improved (by a factor of 6) the fatigue life of both types of specimens;
(3) In both types, in the specimens with pre-existing cracks (1.27 mm long), the average fatigue life of the low-plasticity burnishing treated specimens was nearly the same as the untreated smooth baseline parts, thus showing that low-plasticity burnishing completely mitigated the effects of the precrack damage on the fatigue performance.

Elaborate experimental facilities, time, and expensive measurements are required to determine the optimal process parameters. FE simulations are useful for resolving the high stress gradients with sufficient accuracy, but considerable computation times and memory are normally required. A promising approach that offers

[1] http://www.lambdatechs.com/low-plasticity-burnishing-LPB.html

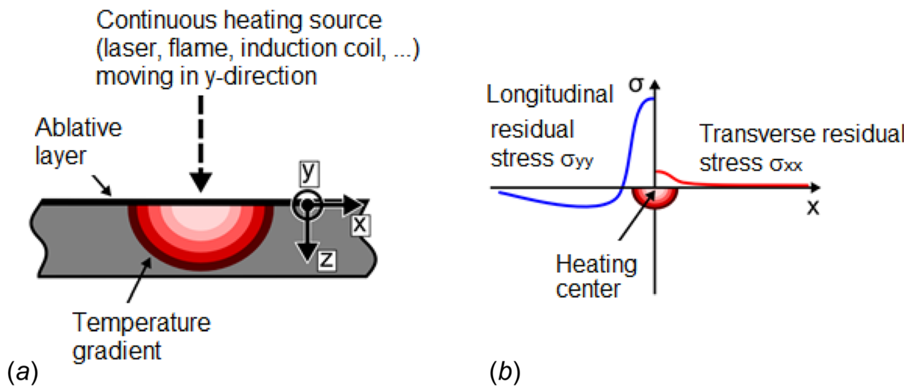

Fig. 6 (*a*) Principle of the heating process and (*b*) the resulting residual stress state following heating with a heat source travelling in the *y*-direction [57–59]

sufficient accuracy and low computation times is the coupling of the FE method with the boundary element method, as proposed in Ref. [54]. This method requires only a surface mesh on the boundary domain, and the stress computations inside the boundary-element-domain are performed using the data on the domain boundary. The coupling was used to predict the surface layer state of a Ti-6Al-4V alloy turbine blade following deep rolling. A quantitative comparison of the residual stresses showed a strong correlation between the numerical and measured results. Following the deep-rolling treatment, the compressive residual stresses reached maximum depths of 0.3–0.4 mm and maximum magnitudes of −600 to −800 MPa.

In Ref. [55], measurements were taken of compressive residual stresses produced by deep cold rolling during shakedown caused by low-cycle fatigue in specimens of the titanium alloys Ti-6Al-4V and IMI679 at room temperature and at elevated temperatures. All of the samples were nominally 5 mm thick. The loads and temperatures were designed to replicate the most extreme conditions expected in the compressor stages of a gas turbine engine. The maximum magnitude of the compressive residual stress was approximately −1000 to −1200 MPa, and the depth of the stress field was 0.6 mm. For all of the samples studied, the residual stress relaxation was limited to a depth of 400 to 500 μm, and thus the depth of the compressive residual stress was unaffected by shakedown. From the comparison of the residual stresses introduced using various surface treatment techniques, it can be concluded that deep rolling induces compressive residual stresses at depths up to five times greater than those produced by traditional mechanical impact (shot peening) techniques.

The effect of deep rolling on the fretting fatigue life of 7075-T6 aluminum was investigated in Ref. [56]. From the results of this work, the following conclusions may be drawn: for high-cycle fatigue, deep rolling increases the fretting fatigue resistance by approximately 700% at high rolling forces; the rate of increase in the fatigue life and the magnitude of the residual stress declined as the rolling force was reduced. The hole drilling measurements showed that for a flat, 4.5 mm thick specimen, deep rolling gave rise to a high compressive residual stress (−350 MPa at high rolling forces, measured at a depth of 0.3 mm beneath the surface).

3.5 Heating

3.5.1 Description of the Heating Process. Figure 6(*a*) shows the process that was used in Refs. [57–59] for the retardation of fatigue crack growth in aircraft-grade aluminum alloy specimens. A heating source, in this case a defocused laser beam, was used to create a heating line by travelling in the *y*-direction on the workpiece surface. The laser is an effective heating tool because the automatic control system guarantees process stability and reproducibility, and there is no physical contact. These characteristics permit the process to be applied on large and/or complex structures. The residual stress state following this treatment is shown in Fig. 6(*b*) and is very similar to welding residual stresses. During heating, the heated material tends to expand, but the free expansion is constrained by the surrounding material. Hence, the stress state in the heated area becomes increasingly negative while the yield stress decreases with increasing temperature. At a specific point, local plastic yielding occurs and leads to the formation of residual stresses. As the heated area cools to room temperature, high longitudinal tensile stresses are produced that are balanced by compressive residual stresses in the specimen outside the heated area.

One limitation of the technique is the reduction of hardness in the heating zone. This fact raises concerns regarding the impact of the laser heating on static strength when applied to lightweight structures [57]. Concerns are also to achieve uniform hardness when treating a larger surface area. When a larger surface area is heat treated, the application of multiple layers of treatment may generate a tempered microstructure. This tempering effect, in addition to hardening, will affect the microstructures and hardness uniformity [60]. However, if multiple lines are applied without overlapping for retarding the fatigue crack growth, these are placed at an optimized distance, such that the residual stress fields are maximal efficient with regard to the approaching crack [61].

3.5.2 Applications of the Heating Process. Although the heat-induced residual stresses are normally considered a detrimental side effect, especially from welding, several researchers examined the possibility of deliberately inducing residual stresses with heat to improve the fatigue performance of structures and components. Because there are only a few published studies on heating as a life-extension technique and because this approach has received little attention regarding aerospace applications, research published before 2006 and without a direct relation to aerospace applications is included in this section.

In an early paper [62], local spot heating was used as a life-extension and repair technique. Spot heating was used to generate various stress states at the run-in and run-out positions of double-fillet-welded mild steel specimens. Significant improvements in the S-N behavior were found. By comparing the results with those of specimens subjected to local mechanical pressing with a punch to produce compressive stresses in critical positions, it was concluded that the observed effect in the heated specimens was mainly due to residual stresses. This work was later extended in Ref. [63], where the spot heating technique was used to repair welded fatigue specimens in which premature cracking was observed at the run-in position. It was shown that by the application of spot heating, the fatigue life of the specimens could be extended significantly.

In the experimental work of Refs. [64–66], the retardation effects on fatigue crack growth rates in steel specimens treated with either spot heating or single overloads were compared. The authors examined the effects of the process parameters such as the spot heating position and the heating temperature and concluded that the effects of spot heating and of single overloads are comparable. However, the underlying physical effects were not investigated further.

Several authors combined heating and mechanical loading of cracked specimens and components [67–72]. However, the purpose of these procedures was not the direct generation of thermally induced residual stresses. Rather, heating was applied to promote plastic yielding by lowering the yield stress under an applied load at the crack tip. This approach showed very promising results. In one case [70], it was possible to completely arrest the growth of a crack in a mild steel plate with an applied stress intensity $K_{\text{appl}} = 20\,\text{MPa}\sqrt{\text{m}}$. However, the method is applicable only to specimens or structures already containing cracks or sharp notches and where mechanical loads can be applied easily. If these two conditions are met, this method is suitable for fatigue life extension, as demonstrated with aluminum gas cylinders in Ref. [71], for example.

In the work presented in Refs. [73–75], a laser was used to create heating lines on stainless steel compact-tension C(T) specimens, after which fatigue crack growth tests were performed. It was concluded that the observed retardation effects were caused by the heating-induced residual stresses because the effect vanished following a stress-relieving heat treatment. This research included a limited numerical analysis [76]. An analytical approach to predict the thermal profile due to heating was used in conjunction with an elastic–plastic FE model to obtain an estimate of the induced residual stresses. Although the development of the residual stress state under subsequent crack extension was studied, no quantitative analysis of the effect on the crack growth rates was performed.

In Ref. [77], a gas torch was used to create a heating line in mild steel C(T) specimens, and fatigue crack growth experiments were performed. Two specimens with different heat inputs were examined, and the measured fatigue crack growth was compared to a base material specimen. For the specimen with a high heat input, a complete arrest of the crack growth was found, and the specimen with the lower heat input showed retarded fatigue crack growth compared with the base material specimen. The heating-induced residual stresses were predicted using thermo-mechanical FE analysis. The resulting model containing the final predicted residual stresses was used to estimate the opening load of the crack faces as a function of the crack length. These calculated opening loads were then used in a crack closure model for the prediction of fatigue crack growth. The results indicated that this approach can qualitatively predict the measured retardation effect. However, the crack closure approach employed for the prediction of fatigue crack growth, including the residual stresses, was not ideal because it does not describe the experimental conditions sufficiently.

Only few authors dealing with the evaluation on the laser heating technique for reducing the growth rate of fatigue cracks in aluminum alloy sheet materials. Based on the study in Ref. [78], the laser energy heating technique appears to be suitable for retarding fatigue crack growth in aircraft skin structures made of aluminum alloy 2024-T3, with thickness of 1.6 mm. In a recent study [57], it was experimentally demonstrated that it is possible to significantly retard fatigue crack growth via laser heating in C(T)100 specimens composed of the new aircraft aluminum–lithium alloy 2198 with the peak-aged T8 temper. These results demonstrated the eligibility of laser heating as life extension method for aircraft applications. However, one observed side effect was an alteration of the precipitation state in the laser affected zone. Because damage-tolerant design must address fatigue crack growth and residual strength, the possible impact of heating on the residual strength must be examined. An extended numerical method in Ref. [58] to predict fatigue crack growth combined a numerical process simulation for predicting the heating-induced residual stresses with numerical fracture mechanics simulations. The predictions were consistent with the measurements, and the validated prediction methodology was used to find the heating line position that maximized the total lifetime [79–81]. The fatigue life was improved by a factor of between 2 and 10.

Table 1 Comparison of the processes reviewed in this paper (plastic affected distance = distance at which residual stress changes from compressive to tensile; SCG = slow crack growth; SCS = short crack stage; CPR = crack propagation rate; HCF = high cycle fatigue; FFR = fretting fatigue resistance; HZ = heating zone)

Process	Material and source	Plastic affected distance (mm)	Compressive peak (Mpa)	Fatigue life improvement
Cold expansion	AALY12-CZ [9]	2.5–3 from hole edge	ca. −300	6 times
	AA2024-T351 [10]	1–2 times the hole radius from the hole edge	ca. −300	2.2 to 3.8 times, major through SCG in SCS
	Titanium alloy TC4 [11]	1.1–1.8 from the hole edge	ca. −400	1.5–3 times, minor CPR in low stress and SCS
Shot peening	Magnesium alloy GW103 [17]	ca. 0.2 in depth	ca. −80	HCF strengths improvement of ca. 40%
	AA7075 [15]	ca. 0.2 in depth	−300 to −400	14 times
	St52 (S355) steel [82]	ca. 0.2 in depth	−100 to −200	ca. 75%
Laser shock peening	AA6061-T6, 2 mm thick [40]	0.6 in depth	−210	7.3%–99.4%
	AA6061-T6, 3 mm thick [43]	1 in depth	−250 to −300	HCF strengths improvement of 25%
	Magnesium alloy ZK60, 2 mm thick [47]	0.5–1 in depth	−160 to −200	From 72.9 to 78.5%
	Ti-6A1-4V, 34.3 mm thick [48]	ca. 6 in depth	ca. −400	
Deep rolling/ low-plasticity burnishing	AA2024-T851, 2.5 mm thick [53]	12–25 from the edge	−200 to −300	6 times; full restoration in precracked
	Ti-6Al-4V [54]	0.3–0.4 in depth	−400 to −800	
	Ti-6A1-4Y [55]	0.6 in depth	ca. −1000	
	AA7075-T6, 4.5 mm thick [56]	ca.1 in depth	ca. −500	700% of FFR for HCF
Heating	AA2198-T8, 5 mm thick [57]	6 from the middle HZ	−30 to −50	300%
	304SS, 4.6 mm thick [76]	ca.10 from the middle HZ, 0.6 in depth at the middle HZ	−200	increase of fatigue crack resistance; decrease of CPR
	SS400,15 mm thick [77]	12 from the notch	−300 to −350	8 times of FCG or crack growth arrest

4 Comparison of Processes

With regard to the final residual stress state, it can be stated that shot peening and laser shock peening create a residual stress gradient through the thickness of the workpiece, with compressive stresses near the treated surface and tensile stresses in deeper regions. Cold expansion creates compressive residual stresses in the vicinity of the treated holes with a nearly constant magnitude through the thickness, and these stresses are balanced by moderate tensile residual stresses inside the specimen. In contrast, heating produces an area of high tensile residual stresses in the vicinity of the heating area, causing balancing compressive residual stresses with moderate magnitudes in a large surrounding area. As for the other techniques, the heating-induced residual stresses are a result of nonuniform plastic deformation. Whereas the established processes create this plastic deformation purely mechanically, the deformation from heating is the result of nonuniform thermal expansion that leads to local yielding.

The impact dimples created by shot peening increase surface roughness, particularly in soft states and at high intensities. Deep rolling and laser shock peening, however, produce less roughness compared with shot peening.

Concerning the applicability of the processes, heating has the potential to create through-thickness compressive residual stresses over large areas. However, when a larger surface area is heat treated, if multiple layers of treatment are applied, these may affect the hardness uniformity; if multiple lines are applied without overlapping, these are placed at an optimized distance, such that the residual stress fields are maximal efficient with regard to the approaching crack. Whereas the cold expansion process is limited to holes and cut-outs, the other processes can be applied to arbitrary geometries. Laser shock peening can be applied to fillets or complex geometries that are not reachable by shot peening. However, care should be taken when this treatment is applied to thin sections (less than 2 mm) because of the possible distortions following peening.

Shot peening effectively retards only the initiation and the early growth of surface cracks, but laser shock peening, cold expansion, and heating can be used to retard the growth of through-thickness cracks. This property makes these other methods attractive for damage tolerance improvement because the basis for evaluation is always an initial small (macroscopic) flaw or crack. Shot peening and cold expansion have been used for the past several decades in aircraft production and maintenance. Laser shock peening can be viewed as a promising new approach with a broad field of potential applications. Although laser shock peening is an established process in the production and maintenance of jet engine parts, its application to other structural airframe components is the subject of ongoing research. In contrast, life extension by heating has received little attention for aircraft applications to date but is a promising technique for life extension in cases concerning long through-thickness cracks.

Table 1 is a compendium of the results of the research described in this work and allows a quick comparison of the various surface enhancement techniques.

References

[1] McClug, R., 2007, "A Literature Survey on the Stability and Significance of Residual Stresses During Fatigue," Fatigue Fract. Eng. Mater. Struct., **30**(3), pp. 173–205.

[2] Ball, D. L., and Lowry, D. R., 1998, "Experimental Investigation on the Effects of Cold Expansion of Fastener Holes," Fatigue Fract. Eng. Mater. Struct., **21**(1), pp. 17–34.

[3] Reid, L., 2003, "Sustaining an Aging Aircraft Fleet With Practical Life Enhancement Methods," Proceedings at the RTO Applied Vehicle Technology Panel Specialists' Meeting, St. Joseph Print Group Inc., eds., Ottawa, ON, Canada, October 8–11, Vol. 32, pp. 1–10.

[4] Department of Defence, USA, 2006, "Joint Service Specification Guide for Aircraft Structures", downloaded August 23, 2013, from http://www.everyspec.com

[5] Air Force Laboratory, 1958, "Handbook for Damage Tolerant Design," downloaded August 23, 2013, from http://www.afgrow.net

[6] Schulze, V., 2006, *Modern Mechanical Surface Treatment: States Stability Effects*, Wiley-VCH, Weinheim.

[7] Liu, Q., Baburamani, P., and Loader, C., 2008, "Effect of High Temperature Exposure on the Mechanical Properties of Cold Expanded Open Holes in 7050-T7451 Aluminium Alloy," Air Vehicles Division, DSTO Defence Science and Technology Organisation, Report No. DSTO-TN-0844.

[8] Pavier, M. J., Poussard, C. G. C., and Smith, D. J., 1999, "Effect of Residual Stress Around Cold Worked Holes on Fracture Under Superimposed Mechanical Load," Eng. Fract. Mech., **63**(6), pp. 751–773.

[9] Yongshou, L., Xiaojun, S., Jun, L., and Zhufeng, Y., 2010, "Finite Element Method and Experimental Investigation on the Residual Stress Fields and Fatigue Performance of Cold Expansion Hole," Mater. Des., **31**(3), pp. 1208–1215.

[10] Zhang, X., and Wang, Z., 2003, "Fatigue Life Improvement in Fatigue-Aged Fastener Holes Using the Cold Expansion Technique," Int. J. Fatigue, **25**(9–11), pp. 1249–1257.

[11] Yan, W. Z., Wang, X. S., Gao, H. S., and Yue, Z. F., 2012, "Effect of Split Sleeve Cold Expansion on Cracking Behaviours of Titanium Alloy TC4 Holes," Eng. Fract. Mech., **88**, pp. 79–89.

[12] Metal Improvement Company, 2005, "Shot Peening Applications, Paramus," downloaded August 23, 2013, from http://www.metalimprovement.co.uk/documents/english_lit/MIC_Green_Book_9th_Edition.pdf

[13] Barter, S., Molent, L., Sharp, K., and Clark, G., 2000, "Repair and Life Assessment of Critical Fatigue Damaged Aluminium Alloy Structure Using a Peening Rework Method," Proceedings of USAF ASIP Conference, San Antonio, TX, December 5–7.

[14] Hatamleh, O., Lyons, J., and Forman, R., 2007, "Laser and Shot Peening Effects on Fatigue Crack Growth in Friction Stir Welded 7075-T7351 Aluminium Alloy Joints," Int. J. Fatigue, **29**(3), pp. 421–434.

[15] Aghaie-Khafri, M., Amin, M., and Momeni, A. H., 2012, "Life Assessment and Life Extension of an Aircraft Wheel," Adv. Mech. Eng., **2012**, p. 326971.

[16] Frijia, M., Hassine, T., Fathallah, R., Bouraoui, C., and Dogui, A., 2006, "Finite Element Modelling of Shot Peening Process: Prediction of the Compressive Residual Stresses, the Plastic Deformations and the Surface Integrity," Mater. Sci. Eng., A, **426**(1–2), pp. 173–180.

[17] Song, X., Liu, W. C., Belnoue, J. P., Dong, J., Wu, G. H., Ding, W. J., Kimber, S. A. J., Buslaps, T., Lunt, A. J. G., and Korsunsky, A. M., 2012, "An Eigenstrain-Based Finite Element Model and the Evolution of Shot Peening Residual Stresses During Fatigue of GW103 Magnesium Alloy," Int. J. Fatigue, **42**, pp. 284–295.

[18] H-Gangaraj, S. M., Alvandi-Tabrizi, Y., Farrahi, G. H., Majzoobi, G. H., and Ghadbeigi, H., 2011, "Finite Element Analysis of Shot-Peening Effect on Fretting Fatigue Parameters," Tribol. Int., **44**(11), pp. 1583–1588.

[19] Kim, T., Lee, H., Kim, M., and Jung, S., 2012, "A 3D FE Model for Evaluation of Peening Residual Stress Under Angled Multi-Shot Impacts," Surf. Coat. Technol., **206**(19–20), pp. 3981–3988.

[20] Schulze, V., Zimmermann, M., and Klemenz, M., 2008, "State of the Art in Shot Peening Simulation," Proceedings of 10th International Conference on Shot Peening, Tokyo, Japan, September 15–18.

[21] Al-Obaid, Y. F., 1990, "A Rudimentary Analysis of Improving Fatigue Life of Metals by Shot-Peening," ASME J. Appl. Mech., **57**(2), pp. 307–312.

[22] Ding, K., and Ye, L., 2006, *Laser Shock Peening: Performance and Process Simulation*, Woodhead Publishing Limited, Cambridge.

[23] Sathyajith, S., and Kalainathan, S., 2012, "Effect of Laser Shot Peening on Precipitation Hardened Aluminium Alloy 6061-T6 using Low Energy Laser," Opt. Lasers Eng., **50**(3), pp. 345–348.

[24] LSP Technology, "What is Laser Peening," August 21, 2013, http://www.lsptechnologies.com/

[25] Liu, Q., 2008, "An Effective Life Extension Technology for 7xxx Series Aluminium Alloys by Laser Shock Peening," Technical Report, Air Vehicles Division, Australia, Report No. DSTO-TR-2177.

[26] Lykins, C., Prevéy, P., and Mason, P., 1995, "Laser Shock Peened Compressive Residual Profile After Exposure to Temperature," Wright-Patterson AFB, Aero Propulsion and Power Directorate, Technical Report No. WL-TR-95-2108.

[27] Prevey, P., Hombach, D., and Mason, P., 1998, "Thermal Residual Stress Relaxation and Distortion in Surface Enhanced Gas Turbine Engine Components," Lambda Research, Cincinnati, OH, Technical Report No. ADA447008.

[28] McElhone, M., and Rugg, D., 2005, "Experimental Evaluation of the Fatigue Performance of Aero-Engine Fan Blade Dovetails," AeroMat, downloaded August 23, 2013, from http://www.metalimprovement.com/premium/PDF/mce_aeromat_2005_V2.pdf.

[29] Clauer, A., 2001, "Laser Shock Peening as a Surface Enhancement Process," Key Eng. Mater., **197**, pp. 121–144.

[30] Rubio-Gonzales, C., Felix-Martinez, C., Gomez-Rosas, G., Ocana, J. L., Morales, M., and Porro, J. A., 2011, "Effect of Laser Shock Processing on Fatigue Crack Growth of Duplex Stainless Steel," Mater. Sci. Eng., A, **528**(3), pp. 914–919.

[31] Spanrad, S., and Tong, J., 2011, "Characterisation of Foreign Object Damage (FOD) and Early Fatigue Crack Growth in Laser Shock Peened Ti-6Al-4V Aerofoil Specimens," Mater. Sci. Eng., A, **528**(4–5), pp. 2128–2136.

[32] Metal Improvement Company, "Laser Peening," August 21, 2013, http://www.metalimprovement.com/laserpeening.php

[33] Spradlin, T. J., 2011, "Process Sequencing for Fatigue Life Extension of Large Scale Laser Peened Components," Ph.D. thesis, Wright State University, Dublin, OH.

[34] Tran, K. N., Hill, M. R., and Hackel, L. A., 2006, "Laser Shock Peening Improves Fatigue Life of Lightweight Alloys," Welding J., pp. 28–31.

[35] Ivetic, G., Meneghin, I., Troiani, E., Molinari, G., Ocaña, M. J. L., Morales, F. M., Porro, G. J. A., Lanciotti, A., Ristori, V., Polese, C., Plaisier, J., and Lausi, A., 2012, "Fatigue in Laser Shock Peened Open-Hole Thin Aluminium Specimens," Mater. Sci. Eng., A, **534**, pp. 573–579.
[36] Sano, Y., Masaki, K., Gushi, T., and Sano, T., 2012, "Improvement in Fatigue Performance of Friction Stir Welded A6061-T6 Aluminium Alloy by Laser Peening Without Coating," Mater. Des., **36**, pp. 809–814.
[37] Sano, Y., Adachi, T., Akita, K., Altenberger, I., Cherif, M. A., Scholtes, B., Masaki, K., Ochi, Y., and Inoue, T., 2007, "Enhancement of Surface Property by Low-Energy Laser Peening Without Protective Coating," Key Eng. Mater., **345–346**, pp. 1589–1592.
[38] Hombergsmeier, E., Furfari, D., Ohlroff, N., Heckenberger, U. C., and Holzinger, V., 2013, "Enhanced Fatigue and Damage Tolerance of Aircraft Components by Introduction of Residual Stresses–A Comparison of Different Process," Proceedings of 27th ICAF Symposium, A. Brot, eds., Paragon Israel, Jerusalem, June 5–7, Vol. 2, pp. 597–611.
[39] Toparli, M. B., and Fitzpatrick, M. E., 2011, "Residual Stresses Induced by Laser Peening of Thin Aluminium Plates," Mater. Sci. Forum, **681**, pp. 504–509.
[40] Zhou, J. Z., Huang, S., Sheng, J., Lu, J. Z., Wang, C. D., Chen, K. M., Ruan, H. Y., and Chen, H. S., 2012, "Effect of Repeated Impacts on Mechanical Properties and Fatigue Fracture Morphologies of 6061-T6 Aluminum Subject to Laser Peening," Mater. Sci. Eng., A, **539**, pp. 360–368.
[41] Huang, S., Zhou, J. Z., Sheng, J., Lu, J. Z., Sun, G. F., Meng, X. K., Zuo, L. D., Ruan, H. Y., and Chen, H. S., 2013, "Effects of Laser Energy on Fatigue Crack Growth Properties of 6061-T6 Aluminum Alloy Subjected to Multiple Laser Peening," Eng. Fract. Mech., **99**, pp. 87–100.
[42] Huang, S., Zhou, J. Z., Sheng, J., Luo, K. Y., Lu, J. Z., Xu, Z. C., Meng, X. K., Dai, L., Zuo, L. D., Ruan, H. Y., and Chen, H. S., 2013, "Effects of Laser Peening With Different Coverage Areas on Fatigue Crack Growth Properties of 6061-T6 Aluminum Alloy," Int. J. Fatigue, **47**, pp. 292–299.
[43] Ye, C., Liao, Y., and Cheng, G. J., 2012, "Warm Laser Shock Peening Driven Nanostructures and Their Effects on Fatigue Performance in Aluminium Alloy 6160," Adv. Eng. Mater., **12**(4), pp. 291–297.
[44] Xu-dong, R., Yong-kang, Z., Jian-zhong, Z., and Ai-xin, F., 2006, "Effect of Laser Shock Processing on Residual Stress and Fatigue Behavior of 6061-T651 Aluminum Alloy," Trans. Nonferrous Met. Soc. China, **16**, pp. s1305–s1308.
[45] Tan, Y., Wu, G., Yang, J.-M., and Pan, T., 2004, "Laser Shock Peening on Fatigue Crack Growth Behaviour of Aluminium Alloy," Fatigue Fract. Eng. Mater. Struct., **27**, pp. 649–656.
[46] Cellard, C., Retraint, D., Franois, M., Rouhaud, E., and Le Saunier, D., 2012, "Laser Shock Peening of Ti-17 Titanium Alloy: Influence of Process Parameters," Mater. Sci. Eng., A, **532**, pp. 362–372.
[47] Jiang, S. Q., Zhou, J. Z., Fan, Y. J., Huang, S., and Zhao, J. F., 2009, "Prediction on Residual Stress and Fatigue Life of Magnesium Alloy Treated by Laser Shot Peening," Mater. Sci. Forum, **626–627**, pp. 393–398.
[48] Zabeen, S., Preuss, M., and Withers, P. J., 2013, "Residual Stresses Caused by Head-On and 45° Foreign Object Damage for a Laser Shock Peened Ti-6Al-4V Alloy Aerofoil," Mater. Sci. Eng., A, **560**, pp. 518–527.
[49] Hatamleh, O., 2009, "A Comprehensive Investigation on the Effects of Laser and Shot Peening on Fatigue Crack Growth in Friction Stir Welded AA2195 Joint," Int. J. Fatigue, **31**(5), pp. 974–988.
[50] Hatamleh, O., Mishra, R. S., and Oliveras, O., 2009, "Peening Effects on Mechanical Properties in Friction Stir Welded AA 2195 at Elevated and Cryogenic Temperatures," Mater. Des., **30**, pp. 3165–3173.
[51] LAMBDA Technology Group, "Low Plasticity Burnishing," August 23, 2013, http://www.lambdatechs.com/low-plasticity-burnishing-LPB.html
[52] Tolga Bozdana, A., 2005, "On the Mechanical Surface Enhancement Techniques in Aerospace Industry–A Review of Technology," Int. J. Aircr. Eng. Aerosp. Technol., **77**(4), pp. 279–292.
[53] Jayaraman, N., Hornbach, D. J., and Prevéy, P. S., 2007, "Mitigation of Fatigue and Pre-Cracking Damage in Aircraft Structures Through Low Plasticity Burnishing (LPB)," Proceedings of ASIP, Palm Springs, CA, December 4–6.
[54] Baecker, V., Klocke, F., Wegner, H., Timmer, A., Grzhibovskis, R., and Rjasanow, S., 2010, "Analysis of the Deep Rolling Process on Turbine Blades Using the FEM/BEM-Coupling," IOP Conf. Series: Mater. Sci. Eng., **10**, p. 012134.
[55] Gill, C. M., Fox, N., and Withers, P. J., 2008, "Shakedown of Deep Cold Rolling Residual Stresses in Titanium Alloys," J. Phys. D: Appl. Phys., **41**(17), p. 174005.
[56] Majzoobi, G. H., Azadikhah, K., and Nemati, J., 2009, "The Effects of Deep Rolling and Shot Peening on Fretting Fatigue Resistance of Aluminum-7075-T6," Mater. Sci. Eng., A, **516**(1–2), pp. 235–247.
[57] Schnubel, D., Horstmann, M., Ventzke, V., Riekehr, S., Staron, P., Fischer, T., and Huber, N., 2012, "Retardation of Fatigue Crack Growth in Aircraft Aluminium Alloys via Laser Heating-Experimental Proof of Concept," Mater. Sci. Eng., A, **546**, pp. 8–14.
[58] Schnubel, D., and Huber, N., 2012, "Retardation of Fatigue Crack Growth in Aircraft Aluminium Alloys via Laser Heating-Numerical Prediction of Fatigue Crack Growth," Comput. Mater. Sci., **65**, pp. 461–469.
[59] Schnubel, D., Horstmann, M., Staron, P., Fischer, T., and Huber, N., 2012, "Laser Heating as Approach to Retard Fatigue Crack Growth in Aircraft Aluminium Structures," Proceedings of 1st International Conference of the International Journal of Structural Integrity, Porto (P), June 25–28, pp. 52–59.
[60] Soundarapandian, S., and Narendra, B. D., 2013, "Laser Surface Hardening," *ASM Handbook, Vol. 4A: Steel Heat Treating Fundamentals and Process*, J. Donssett and G. E. Totten, eds. ASM International, Materials Park, OH.
[61] Schnubel, D., Horstmann, M., and Huber, N., 2013, "Retardation of Fatigue Crack Growth in Aircraft Aluminium Alloys via Laser Heating," Int. J. Struct. Integrity, **4**(4), pp. 429–445.
[62] Gurney, T. R., 1960, "Influence of Residual Stresses on Fatigue Strength of Plates With Fillet Welded Attachments," Br. Weld. J., **7**, pp. 415–431.
[63] Harrison, J. D., 1965, "Exploratory Fatigue Tests on Local Heating as Repair Technique," Br. Weld. J., **12**, pp. 258–260.
[64] Verma, B. B., and Ray, P. K., 2002, "Fatigue Crack Growth Retardation in Spot Heated Mild Steel Sheet," Bull. Mater. Sci., **25**(4), pp. 301–307.
[65] Ray, P. K., Verma, B. B., and Mohanthy, P. K., 2002, "Spot Heating Induced Fatigue Crack Growth Retardation," Int. J. Press. Vessels Pip., **79**(5), pp. 373–376.
[66] Ray, P. K., and Verma, B. B., 2005, "A Study on Spot Heating Induced Fatigue Crack Growth Retardation," Fatigue Fract. Eng. Mater. Struct., **28**(7), pp. 579–585.
[67] Lam, Y. C., and Griffiths, J. R., 1990, "The Effect of Intermittent Heating on Fatigue Crack Growth," Theor. Appl. Fract. Mech., **14**(1), pp. 37–41.
[68] Cole, G. K., and Lam, Y. C., 1991, "Fatigue Life Enhancement of Specimens With Stress Concentrators Using a Thermo-Mechanical Technique," Scr. Metall. Mater., **25**(12), pp. 2849–2853.
[69] Lam, Y. C., and Cole, G. K., 1993, "Fatigue Life Enhancement of Butt Welds Using a Thermo-Mechanical Technique," Fatigue Fract. Eng. Mater. Struct., **16**(9), pp. 983–994.
[70] Chen, B. D., Griffiths, J. R., and Lam, Y. C., 1993, "The Effects of Simultaneous Overload and Spot Heating on Crack Growth Retardation in Fatigue," Eng. Fract. Mech., **44**(4), pp. 567–572.
[71] Ibrahim, R. N., Sayers, R. S. D., and Ischenko, D., 1998, "Retardation of Crack Growth Next Term in an Aluminium Alloy Using a Thermo-Mechanical Conditioning Cycle," Eng. Fract. Mech., **59**(2), pp. 215–224.
[72] Singh Raman, R. K., Ibrahim, R. N., Wu, F., and Rihan, R., 2008, "Thermo-Mechanical Manipulation of Crack-Tip Stress Field for Resistance to Stress Corrosion Crack Propagation," Metall. Mater. Trans. A, **39**(13), pp. 3217–3223.
[73] Tsay, L. W., Liu, Y. C., Lin, D. Y., and Young, M. C., 2004, "The Use of Laser Surface-Annealed Treatment to Retard Fatigue Crack Growth of Austenitic Stainless Steel," Mater. Sci. Eng., A, **384**(1–2), pp. 177–183.
[74] Tsay, L. W., Young, M. C., Chou, F. Y., and Shiue, R. K., 2004, "The Effect of Residual Thermal Stresses on the Fatigue Crack Growth of Laser Annealed 304 Stainless Steels," Mater. Chem. Phys., **88**, pp. 348–352.
[75] Tsay, L. W., Yang, T. Y., and Young, M. C., 2001, "Embrittlement of Laser Surface Annealed 17-4 PH Stainless Steel," Mater. Sci. Eng., A, **311**(1–2), pp. 64–73.
[76] Shiue, R. K., Chang, C. T., Young, M. C., and Tsay, L. W., 2004, "The Effect of Residual Thermal Stresses on the Fatigue Crack Growth of Laser Surface Annealed AISI-304 Stainless Steel—Part I Computer Simulation," Mater. Sci. Eng., A, **364**(1–2), pp. 101–108.
[77] Jang, C. D., Song, H. C., and Lee, C. H., 2002, "Fatigue Life Extension of a Through-Thickness Crack Using Local Heating," Proceedings of the 12th International Offshore and Polar Engineering Conference, Kitakyushu, Japan, May 26–31, pp. 224–229.
[78] Yee, R. K., and Sidhu, K. S., 2005, "Innovative Laser Heating Methodology Study for Crack Growth Retardation in Aircraft Structures," Int. J. Fatigue, **27**(3), pp. 245–253.
[79] Schnubel, D., Horstmann, M., and Huber, N., 2013, "Retardation of Fatigue Crack Growth in Aircraft Aluminium Structures via Heating Induced Residual Stresses–Experiments, Numerical Prediction and Design Optimization," Proceedings of 27th Symposium of the International Committee on Aeronautical Fatigue, ICAF 2013, Vol. 2, Jerusalem (IL), June 5–7, pp. 583–596.
[80] Schnubel, D., Horstmann, M., and Huber, N., 2011, "Prediction of Fatigue Crack Growth Propagation Rates in Compressive Residual Stress Fields," *Review of Aeronautical Fatigue Investigations in Germany During the Period 2009-2011*, C. Dalle Donne and K. Schmidtke, eds., EADS Innovation Works, Munich, Germany, pp. 40–42.
[81] Schnubel, D., and Huber, N., 2012, "The Influence of Crack Face Contact on the Prediction of Fatigue Crack Propagation in Residual Stress Fields," Eng. Fract. Mech., **84**, pp. 15–24.
[82] Farrahi, G. H., Majzoobi, G. H., Mahmoudi, A. H., and Habibi, N., 2012, "Fatigue Life of Shot Peened Welded Tubular Joint," Proceedings of the World Congress on Engineering, Vol. III. London, UK, July 4–6.