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Behavior and Sustainability of Laser Shock Peening Induced Residual Stresses in Complex Fatigue Loading

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14. ABSTRACT

The mechanical soundness with which an engineering structure performs under applied loads defines its structural integrity. In an engineering structure, mechanical fatigue is the temporal response of structural integrity under varying applied loads. Under loading conditions leading to mechanical fatigue, such a temporal response may be characterized by a gradual deterioration in structural integrity. Under those conditions which lead to continued deterioration, a catastrophic failure may manifest even when the applied loads are well within safe limits. Consequently, structural integrity and the various environmental, loading and material factors affecting it have gained great significance in the aerospace industry.

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Background

The mechanical soundness with which an engineering structure performs under applied loads defines its structural integrity. In an engineering structure, mechanical fatigue is the temporal response of structural integrity under varying applied loads. Under loading conditions leading to mechanical fatigue, such a temporal response may be characterized by a gradual deterioration in structural integrity. Under those conditions which lead to continued deterioration, a catastrophic failure may manifest even when the applied loads are well within safe limits. Consequently, structural integrity and the various environmental, loading and material factors affecting it have gained great significance in the aerospace industry.

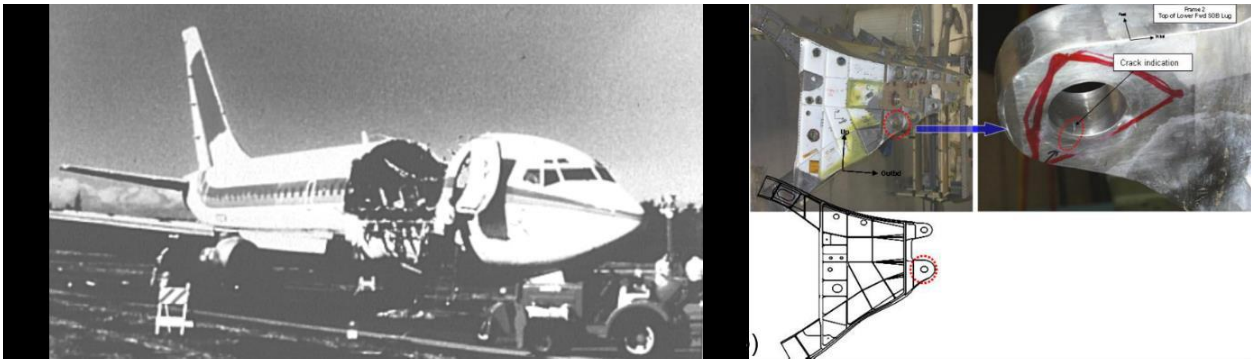

Figure 1-1: Examples of fatigue induced damage in (a) Aloha Airlines Boeing 737 [1] (b) Fatigue crack at the load bearing Titanium lug of F-22 [2]

Load bearing structures critical to the safe operation of an aircraft undergo mechanical fatigue with take-off and landing cycle [3,4], in-flight-load fluctuations due to wind gust [5], pressurization cycles [6] and even aircraft manoeuvers [7–9]. Such fatigue inducing loads increases the probability of structural integrity compromise, thereby increasing the probability of failure. This is mainly caused by structural damage due to fatigue induced crack initiation and propagation. Such damage can be catastrophic as can be seen in the photo in Figure 1-1(a), where an Aloha Airlines Boeing 737 aircraft met with an accident in the year 1988, due to fatigue failure of a riveting assembly. Even to this day in the year 2021, the industry still expects fatigue failure, despite the improvements in materials technology and engineering design techniques. For example, Figure 1-1(b) shows a fatigue crack in a critical load bearing titanium lower lug of F-22, which helps transfer the tensile bending loads from wings to the fuselage. The crack had developed at the end of 2.5 lifetimes of fatigue testing. Given such severity of the damage, it is very important to study those factors concerning fatigue failure, 2

regardless of whether they are detrimental (where they increase probability of failure) or beneficial (where they decrease probability of failure).

Keeping safety and cost effectiveness as additional target design parameters, the aerospace industry has adopted the approach of damage tolerant design [10], where one of the criteria is to decrease the probability of ultimate failure of the damaged structure by ensuring a stable residual strength. The aerospace industry invests significant resources into research and development of techniques aimed at increasing the structure’s ability to maintain a stable residual strength. Some of these techniques are surface treatment techniques, and they mainly work by producing beneficial compressive residual stresses, which can delay crack initiation and deter fatigue crack propagation [11,12]. Shot peening [13] is an example of such a surface treatment technique and Laser Shock Peening (LSP) [14–18] is a recent addition. Examples of applications of LSP in the aerospace industry are provided below.

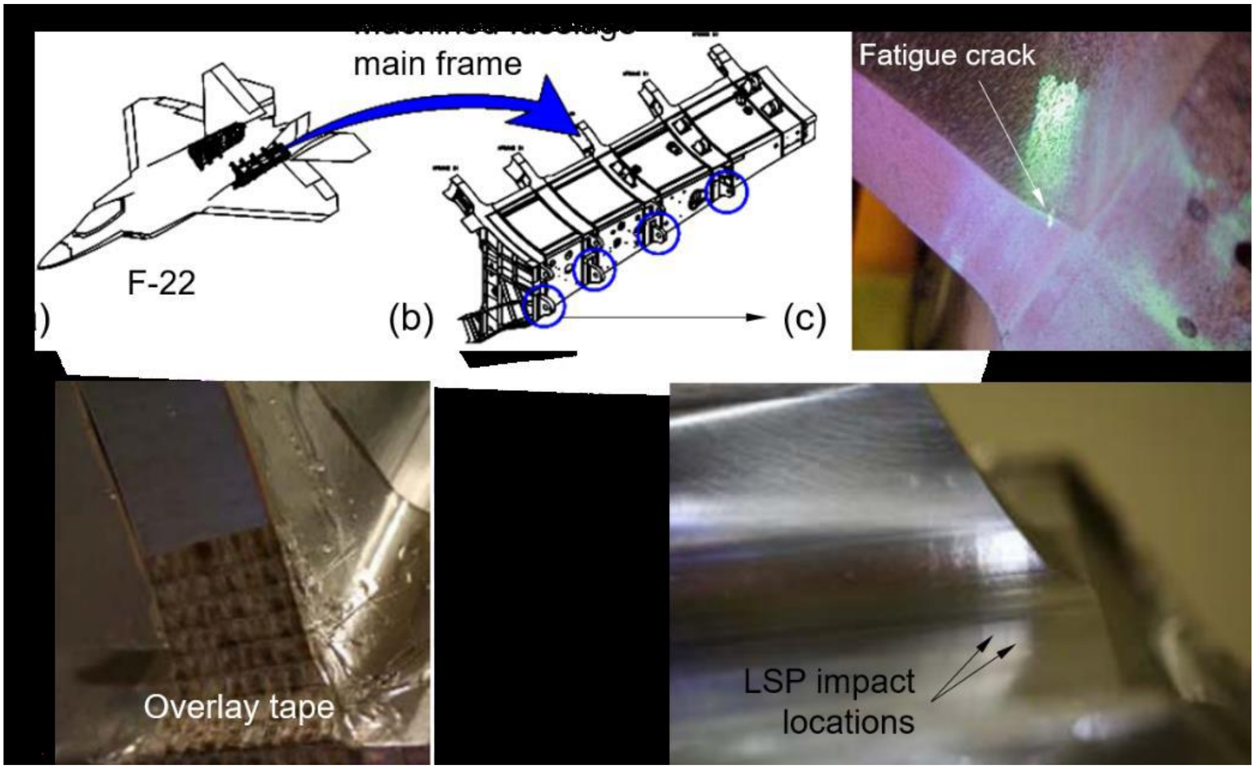

Figure 1-2: LSP treatment applied to lugs attached to frame (a) F-22 aircraft (b) machined fuselage main frame (c) fatigue induced lower fillet crack in the lower lug exposed by dye pentrant test (d) overlay tape during LSP process (e) peened fillet of lug showing Laser impact locations [19]

Laser shock peening has been proven to be effective at enhancing the structural integrity of load-bearing aircraft structures such as titanium lug of F-22 wing [20]. Figure 1-2(a, b) shows the machined fuselage and main load bearing frame of F-22 aircraft [19]. Figure 1-2(c) shows a fatigue crack and the LSP treatment in Figure 1-2(d, e) carried out to deter fatigue crack initiation. LSP has also been used on the aluminium bulkhead of STOVL F-35 joint aircraft fighter [21], wing panel skin of Boeing 747-8 [21], side-brace trunnion of the T-38 main landing gear made from aluminium alloy 7049-T73 [22].

However, these beneficial effects of LSP induced compressive residual stress is not permanent. Compressive residual stress magnitude may decrease under in-service fatigue loading conditions [23]. As a consequence, resistance to crack activity reduces and the probability of failure can increase. Such a decrease in the effectiveness of the stress field can occur when the beneficial stress field is not stable under the applied loads. Apart from the applied load parameters, it is seen from research [24] that material's yield strength plays an important role in this instability. Hence, the material used plays a huge factor in the design of engineering structures and so also in the relaxation of residual stresses [25–27].

Therefore, to design a laser shock peened structure for a suitable application or to design the peening [19] or repeening strategy [20] for an in-service structure, the extent of influence of various material parameters on residual stress stability must be well understood. The reason for this is to enable accurate fatigue life estimation of a peened component. If relaxation is not taken into consideration, the risk of over-estimating the fatigue life will be introduced [20], with which structural damage can appear earlier than expected during in-service conditions.

Of the influencing material parameters, crystallographic texture and grain structure are very prominent. Many engineering structures made from rolled or forged or extruded metallic alloys, which have a unique texture and grain structure. No research till date in the open literature has tried to understand their effects on the stability of residual stresses. This thesis presents investigations carried out to fill this gap.

Motivation

In the worldwide aerospace community, LSP is being explored as an alternative to shot peening. This effort is largely motivated by the fact that LSP can induce higher [28] and deeper [16] compressive residual stresses with lesser microstructural damage [17] in comparison to shot peening. Additionally, numerous research work [29] has proven that LSP can also significantly improve the fatigue life of mechanical structures, mainly due to the introduction of compressive residual stresses [18,29–31]. However, research has also proven that residual stresses can relax [32–35] and the positive effects of LSP can decrease with time under certain applied loading conditions. Hence, investigations are needed to understand how fast the beneficial residual stress decreases and what and how material and applied load factors influence it.

Regardless of the obvious benefits, LSP can also have unintended consequences, which may be beneficial or detrimental. For example, it is known to affect grain structure (see [31,36] for 4

examples) and crystallographic texture (see [31] for example), though very few works have exposed the latter effect. Coupled with the advantageous material hardening which LSP can induce below the peened surface, peened material ductility could be lower than unpeened material ductility, depending on the material. These effects of LSP on grain structure, texture and hardness, whether beneficial or detrimental, can play a significant role in influencing the material's structural integrity by influencing residual stress stability. In the below, motivations to individual studies carried out are provided, in the order in which they are dealt in the thesis.

Effects of LSP on crystallographic texture

Aluminium alloys such as 7050 and 2099 are used in the aerospace industry [37,38] in various tempers, owing to their unique advantages such as high strength, high fracture toughness, resistance to stress corrosion cracking, etc. [39]. Aircraft structures made from thermo-mechanically processed aluminium alloys can be processed with laser shock peening to increase their operational life, as demonstrated previously [21,22]. Rolling, extrusion and forging are the common thermo-mechanical processes, which introduce crystallographic texture [40–44] as a consequence of collective crystal re-orientation during plastic deformation [45,46]. Rolling can introduce spatial gradients of texture [47–49] and so can extrusion [50–52]. It is well known that plasticity can texture [53–55] and also that LSP can induce plasticity [18,29,56,57]. Hence, there is a possibility that LSP can induce texture changes in already textured aluminium alloys, which needs to be investigated. Additionally, due to dissipation and absorption of shock energy during LSP, depth gradient plasticity is generated where, accumulated plastic strain decreases with depth. Therefore, LSP has may induce a depth gradient texture change, which also needs to be investigated. As texture significantly influences mechanical properties [58,59] and as mechanical properties infleunce residual stress stability [24], investigations are needed to probe possible LSP effects on texture.

Effects of LSP on grain structure

Plastic deformation introduces intra-granular misorientations [16] and alters the grain structure [60,61]. In fact, shot peening, a much older surface processing technique than LSP can effect grain structure [62] and as also can LSP [16]. Additionally, the non-homogeneous intra-granular plastic strain distribution will create non-homogenous crystalline re-orientations and hence non-homogeneous changes to grain structure. LSP can therefore alter the metal's grain structure by introducing non-homogenous misorientation distributions, grain and sub-grain boundaries. Grain structure has a significant effect on the mechanical behaviour [63]. It is known that residual stress relaxation can happen through micro-plasticity [20] in the grain structure. Therefore, any changes to grain structure would influence the mechanics under residual stress relaxation, thereby affecting residual stress stability. Hence, investigations are needed to understand the LSP effects on grain structure.

Effects of LSP on plastic strain accumulation in the grain structure

It follows, from theory of crystal plasticity [64], that favourably oriented grains/crystals undergo early plastic deformation [41] and hence yield before the entire poly-crystal has yielded. Therefore, the plastic deformation of a poly-crystal is non-homogeneous. Deformation inside a grain, as permitted by the strain compatibility condition at the grain boundaries, will also be non-homogeneous and this will introduce a non-homogeneous plastic strain distribution inside the grain [65]. Hence, LSP could introduce spatially non-homogenous inter and intra grain plastic strain accumulation. This, therefore, also indicates, a non-homogeneous distribution of material hardening in the grain structure. The extent of plasticity influences the mechanical behaviour significantly. Hence, investigations are needed to understand the LSP effects on plastic strain accumulation in the grain structure.

Effect of texture and grain structure on the stability of LSP induced residual stress

A simple way of representing residual stress stability is through relative temporal changes in its magnitude. Mechanistically, the stability aspect of compressive residual stresses is controlled by the phenomenon of relaxation [24,66] and re-distribution [23,66,67]. It is well known from mechanics that, under the right mechanical loading conditions [32–35] (when plasticity local to the region of interest, is induced), the compressive residual stress magnitude decreases local to the region of interest. Many research works have focussed on understanding the stability of compressive residual stress fields under applied cyclic and static mechanical loads [27,29,33,34,66,68–72] and thermal loads [73–75]. Different loading and material parameters are considered in these studies to explain residual stress relaxation. Of the many material parameters available, the most prominent ones which are used are yield strength and material hardening. But, no work in the open literature has explicitly considered texture and grain structure effects on the stability of residual stresses. The following could be the reasons for this.

(1) Texture and grain structure influence yield strength and the metal’s elastoplastic response. Most research has directly considered yield strength as the influencing parameter with no regard to the underlying texture or grain structure.

(2) Crystallographic texture and grain structure have too many parameters and considering them together requires a very detailed model.

The following three texture-controlled factors are dominant in deciding when grains experience plasticity and hence also the relaxation of residual stresses local to the grain(s) of interest.
(1) The first is the relative orientation between its slip system components and applied load vector [45,64], described in terms of Schmidt factor (M).
(2) The second is the hardening characteristics of uniquely oriented grains.
(3) The third is dislocation [76] and slip activity in the grains [77].

Mechanically induced residual stress relaxation involves residual stress re-distribution [23,68,78] and microstructural phenomena such as dislocation motion [29,66,71,72] and slip [79]. From this, in combination with the definition of texture, it follows that texture has a significant potential in influencing the overall dislocation and slip activity in the material. Grain structure also controls dislocation and slip activity as grain boundaries can act as barriers to dislocation motion and slip [80,81]. It is also affected by the presence of sub-structuring in the grains [29]. Therefore, both texture and grain structure have great potential in influencing residual stress stability. Hence, investigations are needed to bring out and understand the nature and extent of this influence.

Objectives of the research project

Objectives were multi-fold and are listed below:

1. To understand the multi-scale influence of LSP on crystallographic macro- and micro- texture, and grain structure
2. To understand the LSP induced effects on surface roughness, hardness and residual stresses
3. To carry out mechanical fatigue experiments and understand relaxation of LSP induced residual stresses
4. To investigate the nature of relationship between parameters of texture and grain structure, and experimentally observed relaxation in residual stresses
5. To develop a crystal plasticity based finite element simulation model to investigate texture and grain structure effects on residual stress relaxation
6. To use the results of computer simulation to understand the experimental findings and to further probe the dependency of LSP induced residual stress stability on texture and grain structure

Outcomes of the research carried out

Understanding the effects of LSP on texture and grain structure and the effects of texture and grain structure on the stability of LSP induced residual stresses can advance the scientific and engineering knowledge in the following ways:

1. LSP effects on texture and grain structure will reshape and progress the scientific understanding of how the material changes under very high pressure and extremely high strain rate deformation.
2. The study will help understand how texture and grain structure contribute to residual stress stability at a microstructural level.
3. Research outcomes could help make better material selection based not only on the characteristics of mechanical properties, but also on their texture and grain structure, in view of decreasing residual stress instability.
4. Insights into texture and grain structure dependent resisual stress stability will help service interval estimation of an aerospace structure, based on accurate fatigue life estimation which takes into account residual stress relaxation.
5. Insights into texture and grain structure dependent resisual stress stability will help in better tailoring LSP process parameters which can produce minimum residual stress instability.

Together, the above outcomes are contributions which could be made to the scientific and engineering community at the end of this thesis. They highlight the importance of investigating the complex aspects of residual stress stability under fatigue loading conditions.

Structure of investigations

This thesis has carried out a three part investigation.

1. 1st set of investigations characterizes the effects of LSP on the peened material
2. 2nd set of investigations probe the relationship between fatigue-stability of LSP induced compressive residual stress and the parameters of crystallographic texture and grain structure; using fatigue experiments and computer simulations.