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TOPICAL REVIEW

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Laser shock peening and its effects on microstructure and properties of additively manufactured metal alloys: a review

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Abstract

This review paper discusses the recent progress in laser shock peening (LSP) of additively manufactured (AM) parts. LSP is an advanced post-processing technique that optimizes the service lives of critical components for various applications by inducing severe plastic deformation accompanied by the enhancement of surface properties in treated materials. Material improvement is enabled through the generation of high-density dislocations, grain refinement, and beneficial phase transformations. These mechanisms produce high magnitude compressive residual stresses which harden treated regions to depths exceeding 1 mm. However, a major roadblock for AM parts stems from the various fabrication processes themselves where detrimental tensile residual stresses are introduced during part manufacturing, along with near-surface voids and cracks, all of which severely limit their applications. In addition to post-fabrication heat treatment that is typically required to homogenize the microstructure and relieve the residual stresses of AM parts, post-processing surface treatments have also been developed to manipulate the residual stresses of AM materials. Tensile residual stresses generated during manufacturing affect the fatigue life of AM material negatively and could potentially surpass the material's yield strength, resulting in acute geometric distortion. Recent studies have shown the potential of LSP to mitigate these stresses, modify the mechanical properties of the AM parts, and to close near-surface voids and cracks. Furthermore, the thermal stability of favorable microstructural modifications in laser peened AM parts, which allows for its use in high temperature environments, is not well understood and is currently limiting its effective utilization in these scenarios. The main goal of this review is to provide the detailed insight needed for widespread acceptance of this technique as a post-processing method for AM materials.

1. Introduction

Additive manufacturing (AM) has increasingly become the focus of engineering and materials science research endeavors as it allows for the production of geometrically-complex, high-performance material that would otherwise be impossible through traditional manufacturing or machining methods. A multitude of manufacturing techniques have been developed, including selective laser melting (SLM) [1], electron beam melting (EBM) [2], powder bed fusion (PBF) [3], and additive friction stir deposition (AFSD) [4]. These processes yield net shape or near-net shape parts that can be readily implemented without the need for excessive post-fabrication machining, eliminating a significant amount of material waste and energy expenditure. However, certain AM processes such as SLM, EBM, and PBF have been known to introduce material inhomogeneities such as inclusions, voids, and near-surface cracks, and the addition of detrimental tensile residual stresses, all of which facilitate surface-related failure mechanisms [5–7].

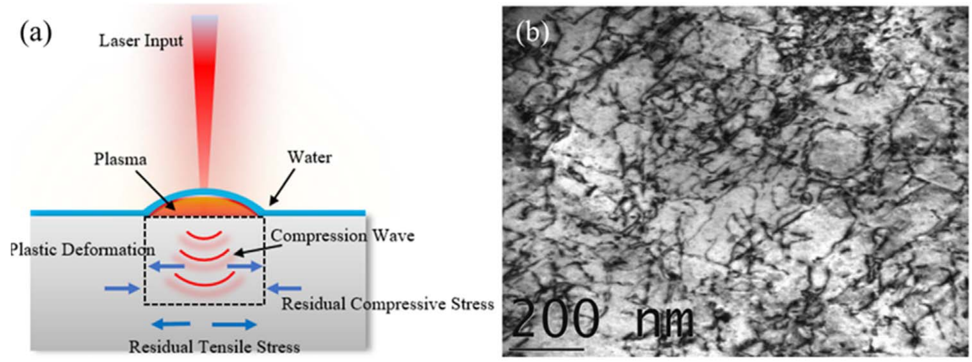

Figure 1. (a) A schematic of the LSP process detailing typical stress development in the material; (b) TEM bright field micrograph showing dislocations in a sample peened with a protective overlay. Adopted with permission from [15, 17].

Although AM process-related challenges remain, and development of AM techniques continues to suggest new opportunities, research into post-processing of printed parts is becoming more prevalent. The importance of developing stable, AM materials in dynamic loading conditions or in extreme environments has prompted the devotion of considerable effort to advance post-processing techniques. LSP is an advanced post-processing method that has shown its potential to increase surface hardness, enhance the mechanical properties of treated materials by creating compressive residual stresses, and removing near-surface cracks and voids, all of which aid in mitigating many surface-initiating failure mechanisms including fatigue, foreign object damage (FOD), wear, and stress corrosion cracking [8–15]. While LSP has garnered the interest of various industries, studies on its use and effect on AM materials are presently limited, and it is the goal of this work to present a contemporary overview of this limited yet advancing field in its current state.

The LSP process draws its benefits from the dynamic mechanical effects of a shock wave imparted by a high-power laser to modify the surface properties of a target material. It does not utilize thermal effects; however, it employs intense laser pulses with pulse energies up to 50 J and duration of 8 to 50 ns. Material interaction with the laser involves the absorption of intense radiation, resulting in the ablation of a thin, micrometer-range layer of the material surface in the region between the surface of the target material and the transparent confining layer (usually de-ionized water). High energy plasma is produced following material ablation, generating a shockwave which propagates into the material. In some cases, direct ablation (i.e. leaving the material unprotected during laser treatment) is avoided to protect the material surface from detrimental thermal effects. In this case, a protective overlay (e.g. black PVC or Al tape) may be applied to the material followed by the addition of the transparent confining layer [16, 17]. In scenarios where a protective overlay is employed, the overlay itself is subjected to ablation, where rapidly expanding, high energy plasma is created. Plastic compression from shockwave propagation is the product of unhindered expansion of the plasma, as well as the obstruction of thermal expansion by the material.

The material is compressed plastically normal to the surface up to a depth at which the peak pressure of the high amplitude stress wave no longer exceeds the metal's Hugonoit (HEL) elastic limit. The HEL is the magnitude of elastic precursor of the shock wave and is related to yield strength σ_y and Poisson's ratio, ν, of the material through $HEL = \frac{1-\nu}{1-2\nu}\sigma_y$ [18].

Metal expands transversely to conserve volume due to the Poisson effect (figure 1(a)). Surrounding material resists the expansion, inducing a residual compressive field near the surface and relatively deep into the subsurface regions with an underlying tensile field where their distribution is determined by the geometry of the specimen. Up to the depth where the stress wave surpasses the HEL, high strain rate plastic deformation result in a significant increase in the dislocation density through formation of dislocation entanglements and slip bands (figure 1(b)). The compressive stress field along with the modified microstructure with a high density of dislocations create a shield at the surface where a crack will need much more energy to initiate and propagate. Moreover, this shield acts as a barrier against the movement of the dislocations towards the surface [19]. Thus, the surface strength is enhanced against failures that initiate at the surface such as foreign object damage (FOD) [20–23] fatigue and fretting fatigue [24, 25], wear [2, 4–7] and corrosion failures [26, 27].

Laser shock peening is a mechanical process accompanied by not only significant changes in surface morphology, but also notable modifications in the underlying material's microstructure and phase [28]. One significant aspect of microstructural modification as a result of LSP is the formation of high density dislocations which are rapidly generated at the wave front due to multidirectional loads as a result of the reflection and refraction of the shock wave [29, 30]. Dislocations act as a primary strengthening mechanism in laser treated

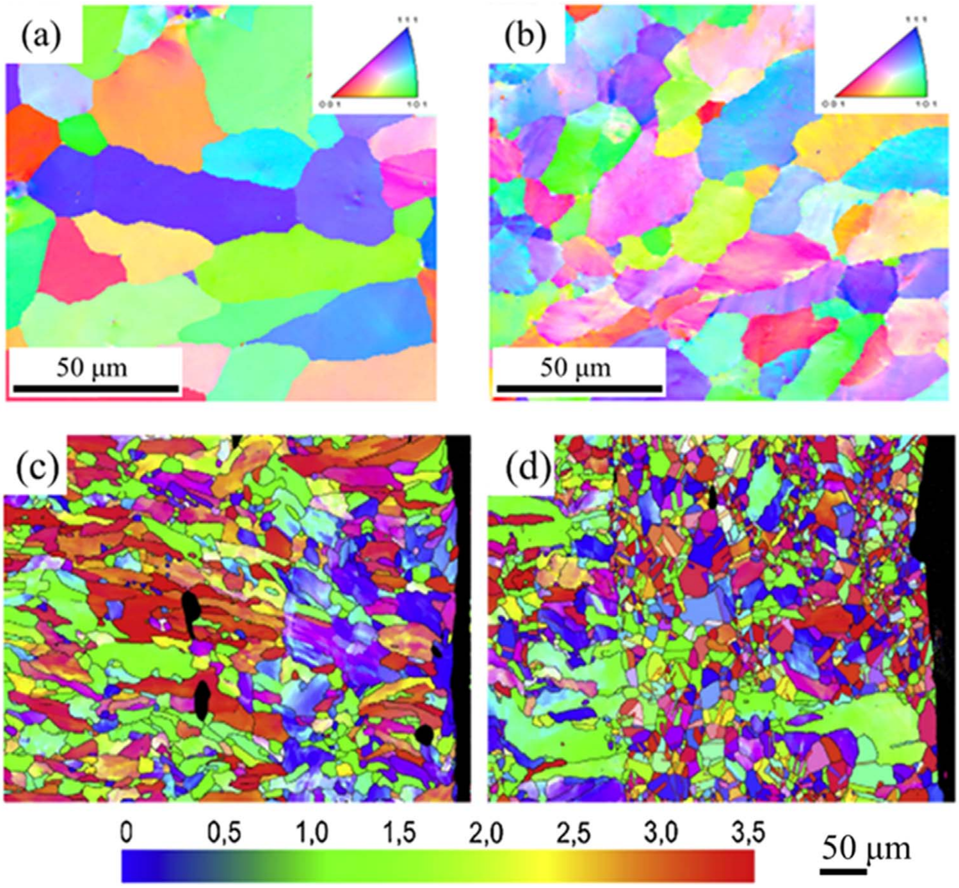

Figure 2. EBSD analysis of inverse pole figure (a) before and (b) after LSP in WAAM AA2319, and EBSD orientation maps of (c) as-built DIAMALLOY 1003 before LSP, and (d) after treatment. It should be noted that while the scale bars are the same for each panel, the magnification is different. Adopted with permission from [35, 36].

materials as the interaction between the stress fields of dislocations can impede dislocation motion, greatly enhancing a material's corrosion resistance, fatigue life [31], surface hardness [32], and fracture resistance [33]. It is therefore the aim of this work to synthesize recent, impactful works on additively manufactured material's response to LSP, including microstructural modifications, phase changes, chemistry, and mechanical properties.

2. Laser shock processing and its effects in additively manufactured materials

Laser shock peening has been recently adopted as a post-processing technique for AM materials as a solution to overcome process-induced accumulation of tensile residual stresses. These unwanted residual stresses originate during the building of AM materials as previously deposited layers are reheated with the addition of new layers and can result in reduced fatigue life or part distortion [34]. The deep compressive residual stresses imparted by the LSP process mitigates or even reverses process-induced tensile residual stresses, resulting in enhanced overall material properties. It should be noted that although AM technologies are being rapidly developed and refined, the technology itself has not yet matured to a state where AM components are being widely utilized, especially in systems where mechanical properties are of critical importance. Therefore, studies pertaining to the laser treatment of AM materials are limited, but it is the goal of this work to provide a comprehensive view of the field's current state.

2.1. Microstructure modifications as a result of LSP

Like traditionally manufactured (TM) materials, AM materials also undergo pronounced microstructural evolution as a result of the intense pressure generated during LSP. Figure 2 illustrates the EBSD characterization of wire-arc additively manufactured (WAAM) 2319 Al alloy before and after LSP treatment. Here, laser treatment was performed using a 15 J pulse energy, 15 ns pulse duration, and a power density of 7.95 GW cm^{-2}. Before LSP (figure 2(a)), the microstructure is shown consisting of coarse, equiaxed grains, resulting from the

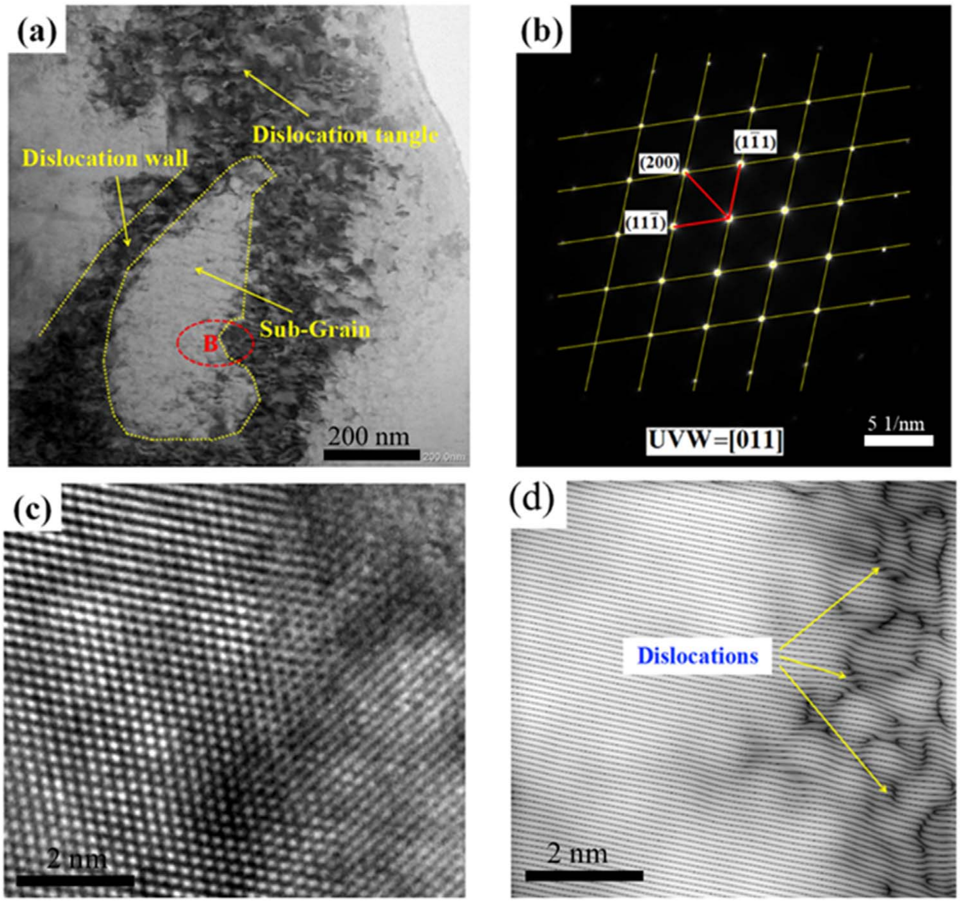

Figure 3. Typical TEM images in the surface layer of specimen after LSP. (a) High density of dislocations, (b) corresponding SAED pattern of ellipse [B] in (a), (c) HRTEM image, (d) reduced IFFT. Adopted with permission from [35].

thermal input required for the layer-by-layer fabrication of the alloy [35]. After LSP treatment (figure 2(b)), grain refinement was observed with the average grain size decreasing by 22% from 59.7 μm to 46.7 μm. Alternatively in direct metal laser sintered Diamalloy 1003, no significant grain refinement was observed after laser treatment using a 0.4 J pulse, 6.3 ns pulse duration at 1064 nm wavelength, 7.3 GW cm^{-2} an 80% spot overlap rate. The average, as-built and untreated grain size was determined to be 14.61 μm (figure 2(c)), and 14.5 μm (figure 2(d)) after LSP [36]. These findings prove valuable as with similar LSP parameters (i.e. power densities), different material responses were observed.

Further TEM investigations of WAAM AA 2319 can be seen in figures 3(a) and (b). The surface layer is considered severely plastically deformed where the presence of dislocation wall and tangles were observed (figure 3(a)). Subgrain formation was obtained, surrounded by high-density dislocations. Figure 3(b) is the corresponding selected area diffraction (SAED) pattern captured from the ellipse [B] in figure 3(a) with [011] being the direction of the crystal axis. A high resolution TEM (HRTEM) image taken from [B] in figure 3(a) is depicted in figure 3(c). Here, subgrain interatomic spacing was observed to be uniformly distributed, with a reduction in spacing from 0.24 nm to 0.21 nm after LSP treatment. This reduction in interatomic spacing is clearly attributed to the high magnitude shock wave present during laser treatment that offered to plastically deform the near surface region. Reduced IFFT was performed to obtain a clear observation of atomic dislocations, as shown in figure 3(d).

2.2. Micro-hardness distribution in AM parts

LSP has proven to be effective in increasing material hardness at the material surface as well as in near surface regions and increasing the effective depth of these hardness enhancements is a significant aspect of LSP process development. Figure 4(a) displays micro-hardness distribution of wire-arc additively manufactured 2319 Al alloy measured to a depth of 1.5 mm before and after LSP treatment. It can be seen that before LSP, average microhardness values hovered around 75 HV throughout the depth of the material. Significant increases in micro-hardness were found in the topmost and the middle layers of the affected region after laser treatment. An increase from 75 HV to 110 HV was observed in these regions, with micro-hardness values decreasing and

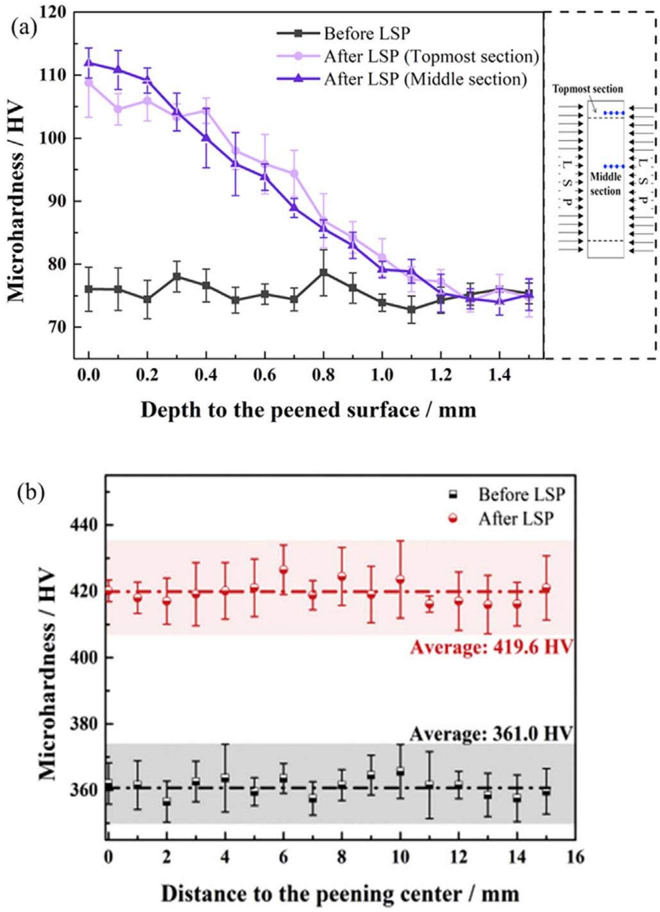

Figure 4. (a) Micro-hardness distributions in the depth direction before and after LSP of AM 2319 Al alloy, (b) Micro-hardness profiles of laser additively manufactured Ti-6AL-4V before and after shock treatment. Adopted with permission from [35, 37].

eventually stabilizing at a depth of 1.2 mm, as seen in figure 4(a) [35]. The difference in the improvement rate in different depths is attributed to the attenuation of the shock wave throughout the thickness of the material where it is unable to generate significant plastic deformation. In laser additively manufactured Ti-6Al-4V titanium alloys, average micro-hardness values of approximately 420 HV were observed in LSP treated AM samples, a 17% increase from 360 HV before LSP. The thickness of the hardness-affected layer was found to be 900 μm, 200 μm thicker than the compressive residual stress layer [37]. Useful comparisons can be made here between TM, and AM Ti-6Al-4V to gauge its effects with respect to fabrication methods. When compared to AM Ti-6Al-4V, TM Ti-6Al-4V exhibits similar microhardness distribution and microhardness values. After LSP treatment on TM Ti-6Al-4V, a 15% increase from 335 HV to approximately 385 HV was observed after one pass, and a 24% increase to 420 HV was observed after two passes [38]. In both cases (TM and AM), hardness enhancement is attributed to higher density dislocations closest to the material surface. Figure 4(b) displays the surface hardness profile of treated, AM Ti-6Al-4V with a maximum microhardness value of 420 HV. Here, a clear trend can be seen with hardness decreasing drastically outside of the shocked region.

Figure 4(c) illustrates hardness versus depth of K417 Ni alloy with respect to LSP-induced microstructural changes. Here, maximum hardness values of 20.8 GPa (non-annealed) were found closest to the surface within regions of high density dislocations, with it eventually decreasing with depth as a result of shockwave attenuation throughout the material [39]. Enhanced hardness was realized up to depths of approximately 100 μm where values returned to that of the material's matrix hardness.

2.3. Residual stress distribution in AM parts

Imparting the target material with beneficial compressive residual stresses is the ultimate goal of the LSP process and analyzing residual stress distribution within treated materials will aid in further developing the process. Residual stress measurements were performed in WAAM 2319 aluminum alloy to a depth of 750 μm before and after LSP using a 15 ns pulse duration, 4 mm circular spot size, pulse energy of 15 J, and a 50% spot overlap rate [35]. Before laser peening, tensile residual stresses were present in the topmost, and middle layers of the affected region, fluctuating from 0 to 60 MPa and 0 to 40 MPa, respectively. The tensile residual stresses observed in these

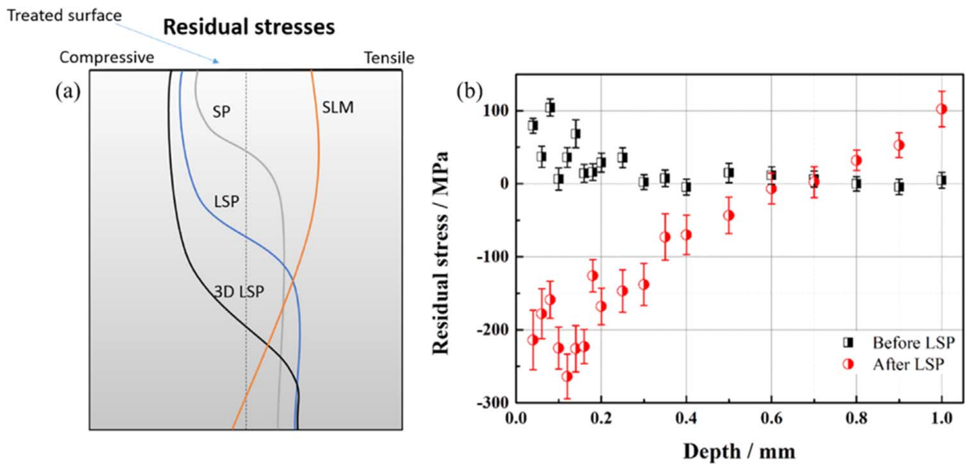

Figure 5. (a) Schematic representation of residual stresses in selective laser melting (SLM) 316L, showing the influence of shot peening (SP), laser shock peening (LSP), and 3D LSP; (b) residual stress profile measured before and after LSP in laser additively manufactured Ti-6Al-4V. Adopted with permission from [37, 40].

sections are the result of the repeated heating of previously built layers during the build process. After LSP, maximum compressive stresses of up to 100 MPa were imparted into the material to an effective depth of 750 μm [35].

It was found that high laser spot overlap rates (80%) and the introduction of LSP during the build process (known as '3D LSP') led to higher and deeper compressive residual stress profiles due to a larger density of dislocations closest to the treated surface [40]. 3D LSP allows for the internal treatment of a material as peening is performed during fabrication, usually several layers at a time. Resulting maximum residual stresses of over 750 MPa were observed on selectively laser melted 316L stainless steel layers treated 10 at a time with 80% overlap rates. Substantially high compressive stresses of 250 MPa were located at depths upward of 1 mm into the material; afterwards enhancement effects were seen to dissipate with depth (figure 5(a)) [40]. Conventional LSP (i.e. 2D LSP) only targets the surface of the material, localizing its beneficial effects; however, this technique imparts residual stresses throughout the depth of the material during its fabrication, distributing material property enhancement. Although the effects of LSP are amplified with this method, a larger time commitment is required as multiple laser treatments are needed throughout the build process. While this may not be suitable for mass-produced materials, it could be adopted for critical parts where the effects of LSP are crucial for enhanced part longevity and performance.

In laser additively manufactured Ti-6Al-4V, residual stress distributions were found to follow similar trends with high magnitude compressive residual stresses closest to the treated surface, and eventually decreasing with increased depth, regulated by the penetrative capability of the shock wave (figure 5(b)) [37]. High magnitude compressive residual stresses were found to be a product of successive laser shocks, and the addition of an ablative layer which was found to enhance plasma formation and facilitate pressure wave transmission into the material. The cyclic deformation behavior of the material is beneficial for the treatment process as multiple irradiations result in plastic deformation being introduced into deeper regions of the material. This process results in an increase in thickness of the plastically deformed layer, therefore enhancing compressive residual stresses [41].

2.4. Tensile property modifications in AM parts

Applications of LSP on AM materials have shown that laser treatment appears to have varying effects on materials' tensile properties. For instance, tensile property investigations of WAAM 2319 Al alloy before and after LSP found the measured yield strength to increase from 103.7 MPA to 178.3 MPa after treatment. Serrated patterns were located on the specimens before and after LSP, indicating dynamic strain aging effects. This effect, otherwise known as the Portevin-le Chatelier effect (or serrated yielding), is related to solid-solution strengthening [42, 43]. It relates to the discontinuity of dislocation motion where dislocation motion is temporarily arrested by the presence of obstacles such as forest dislocations. During this time, solutes such as interstitial particles diffuse around the dislocations further strengthening the obstacles. The process is then repeated as the system undergoes sufficient stress to move dislocations to the next obstacle [42]. This effect, however, was more pronounced after LSP as the density of obstacles which act to hinder dislocation motion increased after laser treatment [35].

Table 1. Summary of tensile and fatigue properties of various additively manufactured materials treated with laser shock peening. Data presented are adopted from [35, 37, 46–48, 50].

Material	YS (MPa)		UTS (MPa)		E (%)		Fatigue Strength Improvement after LSP (%)
	AB	LSP	AB	LSP	AB	LSP	
AM Al alloys [35]	103.7	178.3	247.7	240.3	12.3	6	
AM Ti-6Al-4V [37, 48]	948.1	1003.1	1071.2	1170.4	10	16.4	17%
AM Ti alloy [46]	896	962	953	1058	4.3	6.2	24%
AM 316L [47, 50]	398	464	569	570.3	5.1	4.9	60%

AB = as built; YS = yield strength; UTS = ultimate tensile strength; E = Elongation.

In laser additively manufactured Ti-6Al-4V titanium alloy, increases in the material's yield strength, ultimate tensile strength, and modulus were observed after LSP [37]. Studies on laser treated AM Inconel 718 found nearly negligible changes in the material's Young's Modulus after LSP treatment and the minute variations were attributed to inherent dissimilarities in each sample [15, 44]. This phenomenon has also been observed previously in 6061-T6 Al where after LSP, any changes in the material's elastic modulus were associated with material variations instead of a consequence of laser treatment [45]. A table summarizing the tensile properties of various AM alloys is presented in table 1.

2.5. Fatigue of AM parts

Reports have only recently started coming out highlighting the effects of LSP on the fatigue of AM parts [46–48]. One study comparing the fatigue lifetime improvement of AM 316L stainless steel parts treated using traditional shot peening and LSP found that after LSP treatment, a specimen containing a 0.35 mm-deep notch (K_t factor of 3) did not fail after 2500k-cycles of sinusoidal-loading fatigue testing at a 400 MPa stress level. This result was found to be 20 times greater than the untreated, notched AM specimen [47]. A second study of AM TC17 Ti alloy observed a 23.6% fatigue strength improvement after LSP treatment from 365 MPa to 451 MPa [46]. Fatigue strength enhancement was found to be the result of residual stress transformation from tensile to residual after LSP, and the formation of high density dislocations. As built TC17 Ti alloy contained tensile residual stresses introduced during manufacturing which facilitate crack initiation and propagation through the increase of the effective mean stress during fatigue loading [46]. After LSP, shockwave-induced plastic deformation resulted in the formation of high density dislocations, generating a compressive stress gradient throughout the depth of the material. In electron beam melted Ti-6Al-4V, grain refinement through dislocation generation and deformation twinning was found to reduce pre-existing crack size, suppress crack initiation, and increased the required work for fatigue fracture [48]. Here, laser shock peening yielded a 17% increase in fatigue strength. The high work hardening produced after LSP creates a barrier to restrict the movement of dislocations to the surface, increasing the required cycles leading to crack initiation. Additionally, the presence of compressive residual stresses reduced the effective mean stress during fatigue loading [49]. Table 1 summarizes the most recent attempts at understanding fatigue and tensile performance in laser treated, additively manufactured alloys.

3. Modified laser shock peening techniques

Although LSP has been widely utilized to improve the durability of metallic components, its success in high temperature environments has been hindered by the thermal degradation of LSP-induced microstructural and property modifications. At elevated temperatures, typically above $0.5T_m$ (where T_m is the material's melting temperature), significant microstructural evolution occurs in the annihilation and reorganization of meta-stable crystalline defects, creep-controlled dislocation rearrangement, and material softening [51]. These mechanisms result in the relaxation of beneficial compressive residual stresses, reducing the effectiveness of the laser treatment and limiting its implementation to ambient or low temperature ($>0.5T_m$) applications [52–55]. Moreover, solid state diffusion has also been observed to occur at sufficiently high temperatures introducing further difficulties in obtaining thermal stability in laser peened materials. In this scenario, dislocation recovery, precipitate and grain coarsening render available microstructural barriers against stress relaxation inoperable [56].

Following this understanding, several attempts have been made to elucidate the thermal stability of LSP-induced residual stresses and associated property enhancements (e.g., see [17, 57, 58]). Kattoura *et al* scrutinized the thermal stability of LSP-induced microstructural changes in traditionally manufactured nickel-based superalloys. Residual stress relaxation experiments of multi-layered laser peened Inconel 718/718 Plus found a 35% loss of near surface compressive residual stresses after 120 h at 650 °C [19, 59]. It was discovered that LSP-

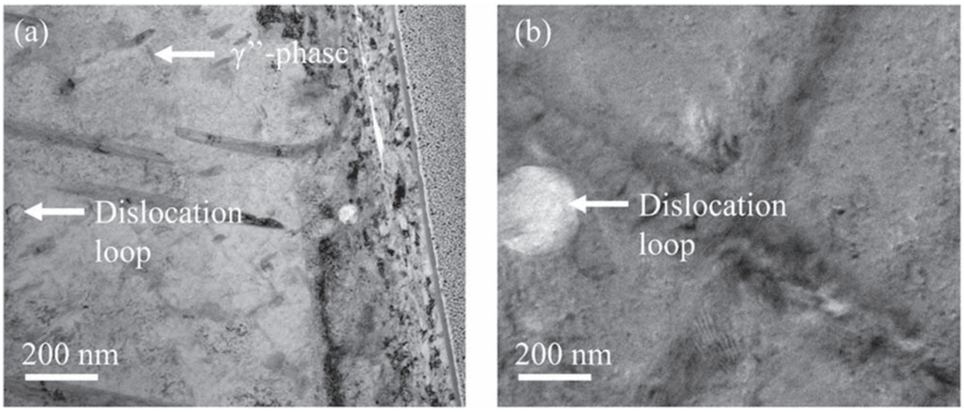

Figure 6. (a) Dislocation loop located in the near-surface region of LP + TME-treated Inconel 718 amongst precipitated γ''-phases, (b) magnified. Figures included here are part of the author's unpublished work on stabilizing mechanisms of LSPed AM Inconel 718.

induced residual stresses preserve between 25% and 60% of their initial values after one million fatigue loading cycles at 650 °C. Davami *et al* reported that measured stress values of 827 MPa in LSPed Inconel 718 decreased to approximately 512 MPa after 50 h at 600 °C [15].

To remedy the loss of critical property enhancements and microstructural modifications, several modified laser peening techniques have been developed on the basis of stress retention mechanisms at high temperatures including: (1) low amounts of cold work, (2) the formation of high density dislocations and strong slip bands as a result of laser treatment, and (3) pinning effects of intermediate phases at elevated temperatures. Cheng *et al* performed warm laser shock peening (WLSP), or LSP performed at elevated temperatures (160 °C) on various materials, and found significant overall increases in microstructure stability, fatigue life, and surface strength when compared to conventional, room temperature treatment in Al 6061 [58], AL 7075 [60], Ti-6Al-4V Ti alloys [61], AISI 4140 [62], and 1042 [63] stainless steels. These increases are thought to be mainly contributed to the pinning effect of precipitates and subgrain formation [64]. Additionally, thermal engineered LSP (TE-LSP), which is the combination of a single WLSP and subsequent one-step annealing was found to increase the pinning effect of precipitates [65, 66].

Recently, Metal Improvement Company, Surface Technologies, Curtiss Wright (CA, USA) developed a modified laser peening (LP) technique incorporating cyclic laser treatments and intermittent heat treatments performed between each individual laser shocks, coined thermal microstructure engineering (LP + TME) [67]. *Munther et al* in collaboration with Metal Improvement Company studied the mechanical properties and microstructure of specimens processed with this newly developed technique [68]. In their work, LP was performed four times with an 8 h, 600 °C heat treatment performed after each laser treatment. Compared to as-built, untreated AM Inconel 718, the LP + TME-treated sample exhibited a ~30% (from 490 HV to 630 HV) increase in surface hardness. When the LP + TME-treated specimen was subjected to a 350 h thermal exposure at 600 °C, measured surface microhardness was reported to decrease by approximately 3%. Stabilization was reported to be the result of two dominant mechanisms including the modification of intermediate phase precipitation kinetics through repeated strain input and precipitate pinning effects. Figure 6(a) presents a transmission electron microscope (TEM) micrograph of an identified dislocation loop amongst precipitated γ''-phases in the near-surface region (top ~1 μm) of LP + TME-treated, AM Inconel 718. Figure 6(b) displays a magnified micrograph of an instance of the Orowan bypassing mechanism

4. Discussion

The commercialization and general acceptance of LSP, while currently limited as a result of the number of uncertainties surrounding this process, is a major source of motivation for future LSP-related endeavors. Adopting this technology at an industrial scale would require a comprehensive and rigorous understanding of the process itself, and the effects of external influence in the form of heat treatment conditions, material properties, fabrication processes, etc. Establishing LSP at a fundamental level will facilitate the ability to predict process-related outcomes for a number of diverse scenarios, aiding in the effective implementation of treated materials in a wide range of applications.

Another source of uncertainty in the advancement of LSP stems from the rapid growth of additive manufacturing with its potential to replace traditional manufacturing techniques. More and more studies on LSP are becoming the focus of AM materials, but few are presenting a comparison of the effects of traditional and additive manufacturing techniques on the LSP process. AM processes have been shown to introduce material inhomogeneities, defects, and microstructural changes not seen in TM materials which would require both material and fabrication process dependent treatment parameters.

Additionally, there are limited studies outlining the integrity of LSP-induced compressive stresses and microstructural modifications in high heat environments. Many target materials subjected to LSP are widely employed in high temperature applications, such as Ni-based superalloys. The few studies investigating compressive stress retention in treated materials have observed the partial removal of microstructural modifications responsible for stress development and found it to be the product of annealing-like mechanisms. The ability for a treated material to retain the beneficial effects of LSP at high temperatures is paramount if the system incorporating treated materials is designed around their enhanced properties. Developments in this specific area of LSP would most likely require the addition of modified LSP techniques, and the careful manipulation of process parameters.

5. Conclusion

Both additive manufacturing and laser shock peening have proven to be effective in facilitating the implementation of high strength, geometrically-complex additively manufactured material in critical applications meant to enhance target system efficiency and performance. Laser peening was found to improve surface properties of a wide variety of AM metals and alloys, mitigating a host of surface-related failure modes including stress corrosion cracking, fatigue cracking, and foreign object damage. In addition, it was concluded that the high magnitude compressive residual stresses imparted through LSP were found to reverse the detrimental tensile residual stresses present in AM after manufacturing. While there is a growing base of fundamental knowledge delineating the mechanistic origins of material improvement from a microstructural perspective, still further work must be undertaken to develop an exhaustive grasp on various AM material responses to LSP. Additionally, an immediately pressing aspect concerning the utilization of LSP with respect to AM involves the thermally-driven degradation of favorable microstructural modifications owing to appreciable material enhancement, barring it from use in high temperature environments. Promising attempts have been made, however, to combat these phenomena, leading to the development of novel, modified LSP processes aimed at retaining LSP-induced structural modifications in AM materials. With AM and LSP being integral to the advancement of advanced material production and improvement, correctly identifying barriers to their effective implementation is of utmost importance to the continuation of these technologies.

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