RETARDATION OF FATIGUE CRACKS IN WELDED STRUCTURES THROUGH LASER SHOCK PEENING

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Abstract: Aeronautical structures are often subjected to cyclic loading and can therefore fail due to fatigue. In most cases, fatigue cracks develop and propagate from critical areas, so-called stress concentrators, where the highest tensile stresses are present. When a fatigue crack has developed during operation, it has a significant impact on reducing fatigue life. To extend fatigue life, compressive residual stresses can be introduced in the critical areas to reduce the crack-driving tensile stresses and retard fatigue crack growth or even stop existing cracks. In this study, laser shock peening (LSP) is investigated as a promising technique to introduce deep compressive residual stresses in metallic aerospace materials. One positive application scenario of LSP to restore the fatigue life of laser-welded AA6056-T6 butt welds with already existing surface fatigue cracks is discussed. By applying LSP to surfaces of specimens with fatigue cracks, the fatigue life could be restored to the level of specimens in the as-welded condition. A similar positive effect of LSP was demonstrated on AA2024-T3 specimens with a fatigue crack originating from overlap joints manufactured using a solid-state joining process. The positive effect of LSP is also demonstrated on a welded stiffened panel representing a part of a fuselage structure, where the technique was successfully applied for the retardation of skin cracks. The skin-stringer AA2024-AA7050 T-joints were realized through stationary shoulder friction stir welding, a variant of the conventional friction stir welding process. It was shown, that application of LSP led to a 400 % increase in fatigue life. The results of the study show that LSP is an efficient method for extending the fatigue life of welded structural components.

Keywords: fatigue crack, laser beam welding, laser shock peening, residual stress, fatigue life extension

1 INTRODUCTION

Aeronautical structures are often subjected to cyclic loading and are therefore susceptible to fatigue cracking [1]. In most cases, fatigue cracks develop and propagate from critical areas known as stress concentrators where the highest tensile stresses during cyclic loading exist [1-2]. The typical stress-concentrators in the load bearing metallic structures are drilled holes in the case of riveted joints [2] or geometrical surface defects and internal welding defects (pores or cracks) in the case of welded joints [3-4]. When fatigue cracks occur during service, this results in a significant decrease in fatigue life [1-2].

To increase fatigue life, compressive residual stresses can be introduced in critical areas to reduce the tensile stress at the onset of cracking, thereby retarding the growth of fatigue cracks and even arresting of existing cracks [5-6].

Laser shock peening (LSP) is an effective technology for generation of deep compressive residual stresses in metallic materials [7]. During the LSP process complex physical phenomena occur in three different steps: (1) plasma generation on specimen surface, (2) propagation of shock waves through the material and (3) generation of residual stresses caused due to plastic deformations in the material during the propagation of shock waves [8]. LSP is a clean and better controllable residual stress engineering process and has many advantages to the already well established process such as shot peening [7]. LSP has a much deeper effect on generating of compressive residual stresses below the material surface than sandblasting or shot peening [6]. In addition, compressive residual stresses can be generated even through-the-thickness of thin sheet material without causing significant changes in microstructure [9-10] that may not be the case with shot peening [11], for example.

LSP has a very positive effect on the fatigue performance of components, because the compressive residual stress field induced deep in the material significantly retards fatigue crack growth. Therefore, significant improvement and extension of fatigue life can be achieved for both surface cracks [12] and through-thickness cracks [10]. Since the LSP process allows the generation of deep residual stresses, this can potentially retard the growth of through-the-thickness cracks in welded structures as well as surface cracks in welds. Conventional shot peening does not offer these advantages due to the much shallower penetration of residual stresses. Therefore, the introduction of compressive residual stresses through LSP could be seen as a very effective method for improving the fatigue strength of welds [8,13].

The present study describes three examples of possible applications of the LSP process for the improvement of the fatigue behavior of welded specimens. In the first example, an application scenario of LSP to restore the fatigue life of laser-welded AA6056-T6 butt welds with already existing surface fatigue cracks is demonstrated. Laser beam welding (LBW) as an efficient joining technology is already established for lower fuselage applications in Airbus aircraft [14-16]. Laser beam-welded structures show a better buckling behavior under compression loading compared with riveted structures, however, pose some challenges due to their inferior damage tolerance behavior under tension loading [16]. The application example is intended to show how the fatigue life of welds with possible surface cracks developed during service life can be restored.

In the second example, an effect of LSP is demonstrated on AA2024-T3 specimens with a fatigue crack originating from overlap joints manufactured using the refill friction stir spot welding (refill FSSW) [19]. It is a solid-state joining process that was developed and patented by Helmholtz-Zentrum Hereon [17]. The process can join two or more sheet materials in an overlapped configuration and is recognized as a potential alternative for riveting [18]. However, the use of structural weldments presents a significant challenge for the implementation in a damage-tolerant design, where a complete understanding of crack initiation and growth is imperative for the application of refill FSSW in the aerospace industry. In the previous study, the refill FSSW process was optimized to achieve the maximum ultimate lap shear strength of similar AA2024 lap joints. However, under cyclic loading, the fatigue strength of the joints was only 15% of the ultimate lap shear strength [18].

In the third example, LSP is applied on a welded stiffened panel representing a part of a fuselage structure, where the technique is employed for the retardation of skin cracks [20]. The aim of applying LSP, in this case, is to suppress the growth of the possible skin crack from the broken stringer to the neighboring stringer, which is the most dangerous scenario that can occur in the aircraft fuselage. The skin-stringer AA2024-AA7050 T-joints were realized through stationary shoulder friction stir welding, a variant of the conventional friction stir welding process [21].

2 EXPERIMENTAL

2.1 Materials, Welding Processes and Specimen Geometries

The investigation of the effect of LSP treatment on the retardation of surface fatigue cracks was performed on flat fatigue specimens with a laser beam-welded butt joint (Fig. 1a). The alloy AA6056 (Al-Mg-Si-Cu) in the heat treatment condition T6 was used as a rolled sheet with a thickness of 6.2 mm and was butt-welded using two CO_2 lasers with a maximum power of 3.25 kW (two-beam process). The alloy AA4047 (AlSi12) was used as filler wire. Details of the laser beam welding process can be found in [22]. By the use of the LBW process butt joints with a typical V-shaped weld were fabricated (Fig. 1b).

For the refill friction stir spot welding of lap joints a welding machine of the type RPS 200 from the company Harms & Wende GmbH was used. The tool consisted of a clamping ring with a diameter of 17 mm, a sleeve with a diameter of 9 mm and a pin with a diameter of 6 mm. For the study the alloy AA2024 (Al-Cu-Mg) in T3 heat treatment condition was used. The spot weld (Fig. 2a) was placed in the middle of the overlapping area (Fig. 2b-c) of the sheets of 2.0 mm thickness. The welding parameters (welding time of 2.5 s, plunge depth of 2.35 mm and rotation speed of 1800 rotation/min) in this work were set based on preliminary studies for same material and specimen geometry [18]. A sketch of the refill FSSW joint is shown in Fig. 2a.

To demonstrate a possible application of the LSP process on a component-like structure, integral panels with three skin-stringer T-joints were realized through stationary shoulder friction stir welding (SSFSW), a variant of the conventional friction stir welding (FSW) process. In this innovative SSFSW process, the shoulder does not rotate, which means that heat generation and the area affected by the process can be significantly reduced. Compared to the conventional FSW process, this leads to a significant improvement in the mechanical properties in both static and fatigue tests [23]. In addition, a smooth surface is produced on the weld bead, which does not need to be post-processed. The design solution of the tool schematically shown in Figure 3a was used to fabricate the T-joint (Fig. 3b). In this study, AA2024 sheet material (thickness of 2.0 mm) in T3 heat treatment condition as skin and extruded AA7050 (Al–Zn–Mg–Cu) in T7651 heat treatment condition as extruded stringer were used. For details of the joining process, the reader is referred to [21]. Fig. 3c shows the geometry of the welded 3-stringer panels used for the fatigue crack propagation tests.

2.2 Laser Shock Peening Process

Laser shock peening was performed using a 5 J pulsed Nd:YAG laser with a wavelength of 1064 nm operating at a frequency of 10 Hz. Diffractive optics created a focused square laser beam spot on the specimen surface. During the LSP treatment, a laminar water layer of a thickness between 1 mm and 2 mm flowed over the specimen surface. The LSP process parameters for the used materials were identified based on previous studies of the authors [10, 24-25]. In the case of LSP treatment of laser beam-welded butt joints, a steel foil was used as an ablative layer. Refill FSSW joints and stationary shoulder friction stir-welded 3-stringer panels were LSP-treated without any ablative layer. The used process parameters are listed in Table 1. The positioning of laser shots in sequences applied on surfaces of the considered specimens is schematically shown in Fig. 1b-c (LSP treatment for the retardation of surface fatigue cracks, the LSP treatment was applied on both specimen surfaces), Fig. 2c (LSP treatment on specimens with lap joints) and Fig. 3d (LSP treatment on three-stringer panels).

2.3 Residual Stress Analysis

The hole drilling system "Prism" of the stresstech company was used to determine the depth-resolved residual stress profiles [26]. In this method, the stressed material is removed by drilling a small blind hole in the area of interest. The remaining material around the hole spontaneously establishes a new stress equilibrium, resulting in a deformation of the surface near the hole. The displacements on the surface are measured using optical electronic speckle pattern interferometry (ESPI) and allow reverse calculation of the stresses that were present in the part before drilling. The principle of this technique is described in detail in the work of Steinzig and Ponslet [27].

Table 1: Laser shock peening process parameters.

Parameter	*Value*		
	Laser beam-welded butt-joint	*Refill friction stir spot-welded overlap joint*	*Stationary shoulder friction stir-welded 3-stringer panel*
Laser energy	5 J	3 J; 5 J	5 J
Pulse duration (full width at half maximum	20 ns		
Laser spot size	1 mm × 1 mm	1 mm × 1 mm	1 mm × 1 mm; 3 mm × 3 mm
Calculated power density on specimen surface	25 GW/cm^2	15 GW/cm^2 (3 J); 25 GW/cm^2 (5 J)	25 GW/cm^2 (1 mm × 1 mm); 3.3 GW/cm^2 (3 mm × 3 mm)
Size of LSP-treated area	15 mm × 36 mm	20 mm × 20 mm	15 mm × 100 mm
Number of peening sequences	1	2	3
Ablative layer	steel foil	without	without

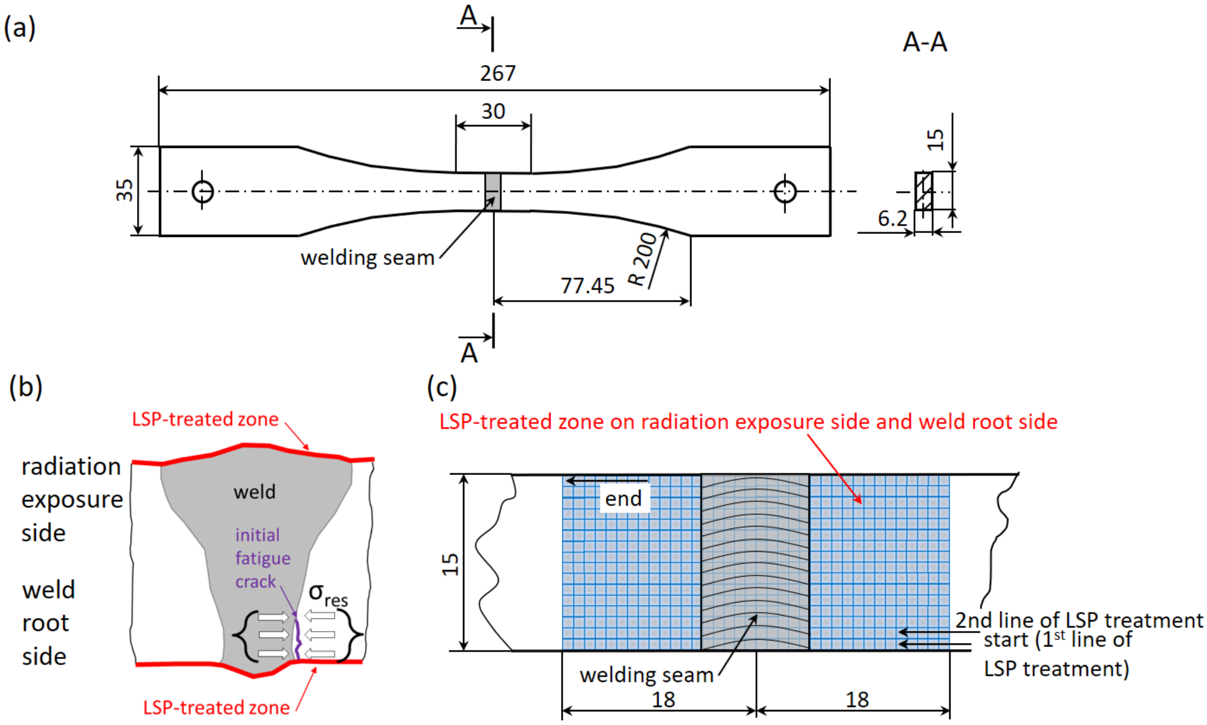

Figure 1: (a) Geometry of the specimen with the weld in the middle for the fatigue test: (b) sketch of the weld with introduced fatigue crack and (c) schematic view of the LSP-treated region of the specimen for the fatigue test. All dimensions are in mm.

2.4 Fatigue and Fatigue Crack Growth Tests

In the case of laser beam-welded AA6056 butt joints, axial fatigue tests were performed on flat specimens (Fig. 1a) on the Testronic 100-kN resonant testing machine under force control in accordance with ASTM E466-07. All fatigue tests were performed at room temperature, a load ratio of $R_F = 0.1$, and a test frequency of approximately 90 Hz. For the fabrication of the specimens with initiated surface cracks of depth 1.2 mm ± 0.1 mm (Fig. 1b), several specimens were subjected to cyclic loading at maximum stress of 130 MPa. With the number of load cycles between 2.5 × 10^5 and 3.5 × 10^5, the test was interrupted every 5,000 cycles and the crack depth was measured by calibrated ultrasonic testing.

When the crack depth reached a value of 1.2 mm ± 0.1 mm, the fatigue test was terminated. The procedure for introducing the surface fatigue cracks is described in detail in the authors' earlier journal publication [25].

The fatigue tests on specimens with lap joints produced using the refill FSSW process were performed on servo-hydraulic 10-kN testing machines. In all tests, the force was applied sinusoidal axially. The stress ratio R_F was always 0.1, so that the specimens were loaded in the tensile threshold range. The test frequency of the servo-hydraulic testing machines was 20 Hz for all tests. The tests were carried out at room temperature. Failure was defined as the complete separation of the sheets. For better force application, specimens were fixed in the testing machine with the help of restraints. In addition, counter-holding plates were used to prevent the specimens from being bent during the fatigue tests.

In the case of welded three-stringer panels, constant amplitude fatigue crack growth tests were carried out at a load ratio, R_F of 0.1, using a servo-hydraulic machine at a frequency $f \leq 5$ Hz in compliance with the standard ASTM E 647. The welded three-stringer panels were notched in the middle using an electro-discharge technique. A notch of $2a_0$= 6 mm was placed in the center of the panel (the stringer in the middle of the panel was cut, Figure 3c-d). The crack length during the fatigue crack growth test was measured optically using a traveling microscope.

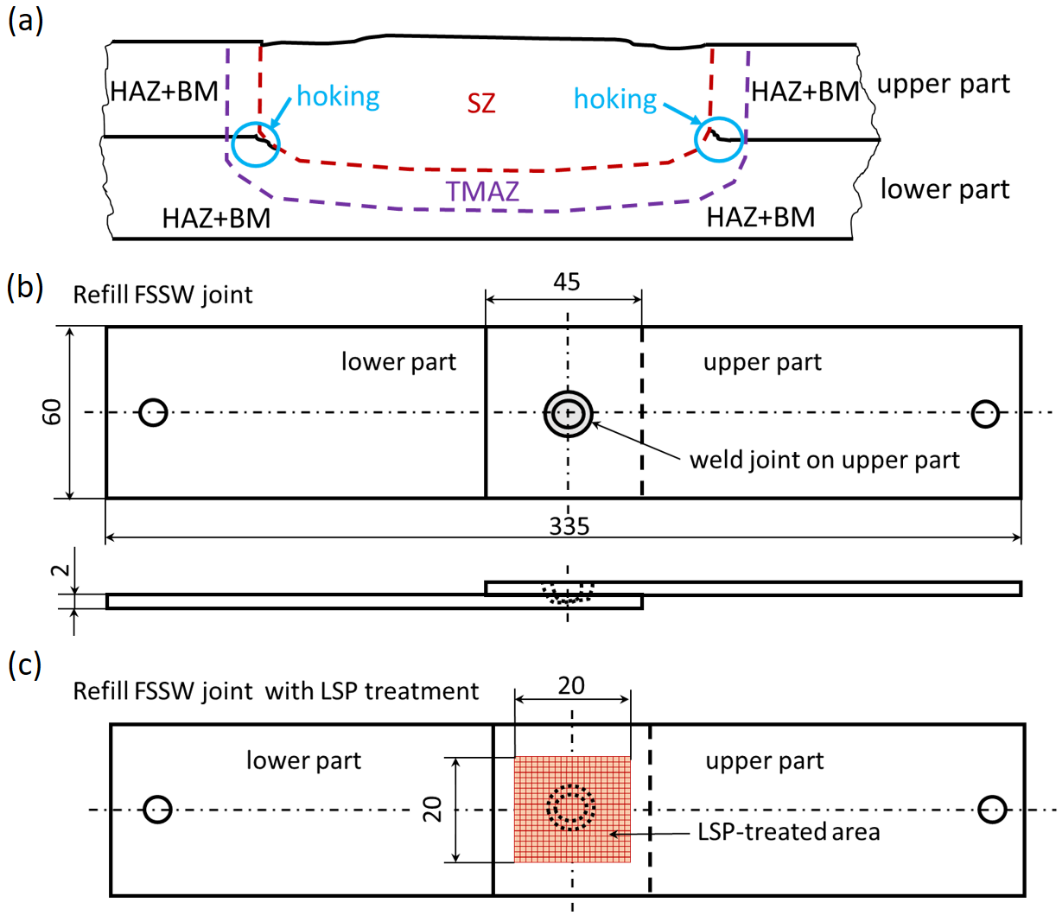

Figure 2: (a) Sketch of the refill friction stir spot welding (refill FSSW) joint. The abbreviations SZ, TMAZ, HAZ, and BM denote the stir zone, thermo-mechanically affected zone, heat-affected zone, and base material, respectively. Depicted and adopted from [18]. (b)-(c) Sketch of the specimens for the fatigue test: (b) as-welded specimen with overlap refill FSSW joint, (c) refill FSSW joint with LSP treatment on the upper part. All dimensions are in mm.

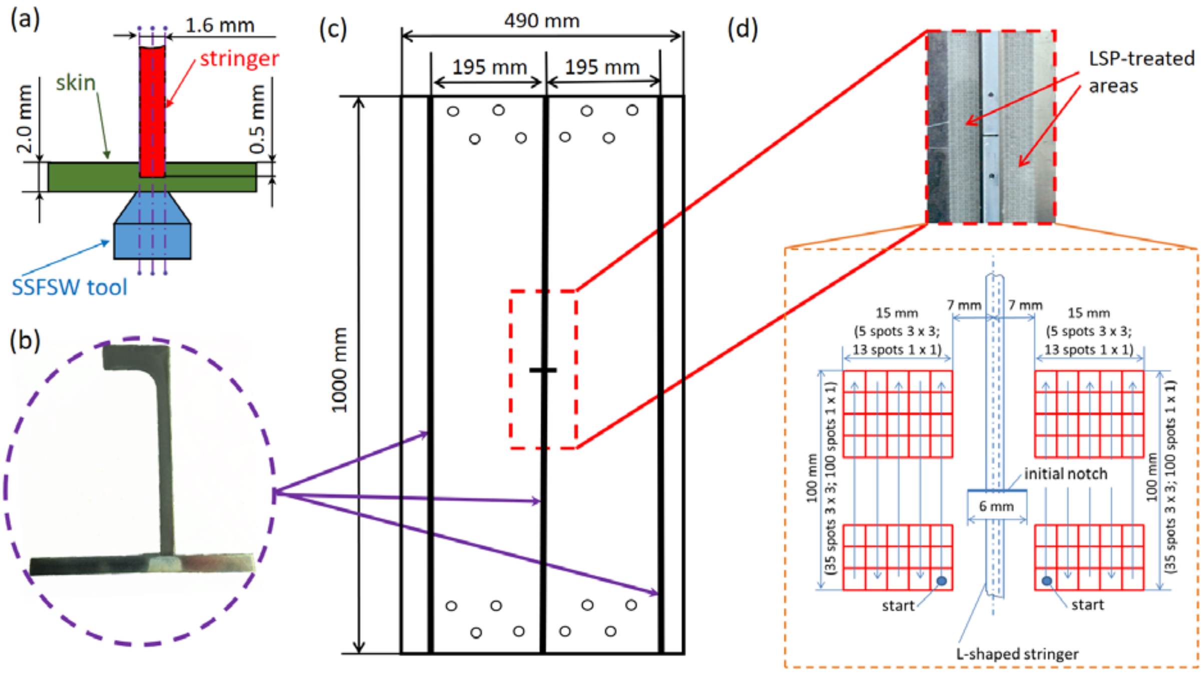

Figure 3: (a) Sketch of the design solution of the tool for the welding of T-joint in two parts with partial penetration and (b) photo of the AA2024-AA7050 T-joint. (c) Geometry of the welded 3-stringer panel and (d) photo and sketch with details regarding the two LSP-treated areas. Depicted and adopted from [20].

3 RESULTS AND DISCUSSION

3.1 Residual Stress Analysis

In the case of the aluminum alloy AA6056-T6, the objective of the application of LSP was to introduce compressive residual stresses into welded specimens with already existing fatigue cracks with a depth of 1.2 mm in order to restore the fatigue life of the pre-cracked specimens. To achieve this goal, it is necessary to introduce compressive residual stresses to a depth of more than 1.2 mm. In this case, LSP process parameters were selected to produce the highest possible power density in a laser spot with the available laser. In addition, steel foil was used as an ablative layer. To investigate the effect of the LSP treatment, base material specimens were peened in an area of 20 mm × 20 mm (Figure 4a). The determined depth-resolved residual stress profiles are shown in Figure 4d. A clear difference is visible between the residual stresses determined in the longitudinal direction (σ_{xx}) and in the transverse direction (σ_{yy}). The reason for the non-equibiaxiality of the residual stress profiles could be due to the LSP treatment sequence and/or the material texture, as reported in the literature in the case of LSP treatment of high-strength Al alloys [28-29]. Near the specimen surface, the absolute value of the longitudinal compressive residual stresses is about 250 MPa, which is about 70% of the yield strength of the base material (about 350 MPa). Chupakhin et al. [30] studied the effect of elastoplastic material behavior in determining residual stress profiles using the hole-drilling technique. In a subsequent work [31], the authors proposed a correction method for the calculated residual stresses due to plastic deformation, which may occur during stress relaxation when residual stresses are close to the yield strength of the material. However, when the absolute value of residual stresses does not exceed 80% of the material yield strength, it has been shown that the error in determining residual stresses is less than 10% [31]. Therefore, it can be considered that reasonable quantitative results are shown in Figure 4d. The results show that deep compressive residual stresses can be generated in 6.2 mm thick AA6056 specimens up to a depth of 2 mm using the applied LSP process parameters. Since the compressive residual stresses are introduced deeper into the material than the crack depth of 1.2 mm, the applied LSP treatment should be able to reduce the resulting stress concentration at the crack tip of the pre-damaged specimens.

In the case of AA2024 lap joints, residual stresses were determined in the center of the weld joint for both as-welded and welded and peened specimens. The holes were placed in the center of the welds on the upper part (Figure 4b-c), and the results are represented as the average of three residual stress measurements from three specimens for each depth value (Figure 4e). It should be noted that in the case of the investigated specimens, the hole-drilling technique provides only a qualitative analysis of residual stresses, because a significant gradient of residual stresses is expected not only in the depth direction but also in longitudinal (x-direction) and transverse (y-direction) directions. This could be a reason for the high scatter of the determined values. High gradients of residual stresses in all directions are typical for welded joints. The results for the as-welded specimens show significant tensile residual stresses exceeding 80% of the yield strength (about 380 MPa) of the material at a depth of about 0.4 mm. On the other hand, for the specimens after LSP treatment, deep compressive residual stresses, with the maximum absolute values of approx. 275 MPa and approx. 375 MPa for the LSP treatments with 3 J and 5 J, respectively, are present at the depth of approx. 0.4 mm. The reason that the LSP treatment with 5 J led to lower absolute values of compressive residual stresses could be due to the fact that dielectric breakdown was achieved, which in turn limits the peak possible pressure [32-33]. The peculiarity of the dielectric breakdown is that it leads to the generation of a plasma in the air outside the substrate surface, which absorbs the incoming laser pulse and limits the energy to generate a shock wave [8]. Similar to Al alloy AA6056, non-equibiaxial residual stresses were also observed in lap joints. The additional reason for this non-equibiaxiality of the residual stress state with regard to longitudinal and transverse directions could be the significant heterogeneity of the microstructure of the welded joints. In summary, it can be concluded that despite the qualitative character of the performed residual stress analysis, it indicates that through LSP treatment it is possible to transform the post-weld tensile residual stress state into a compressive residual stress state. This should significantly reduce the notch effect of the welded joint in the case of cyclic loading.

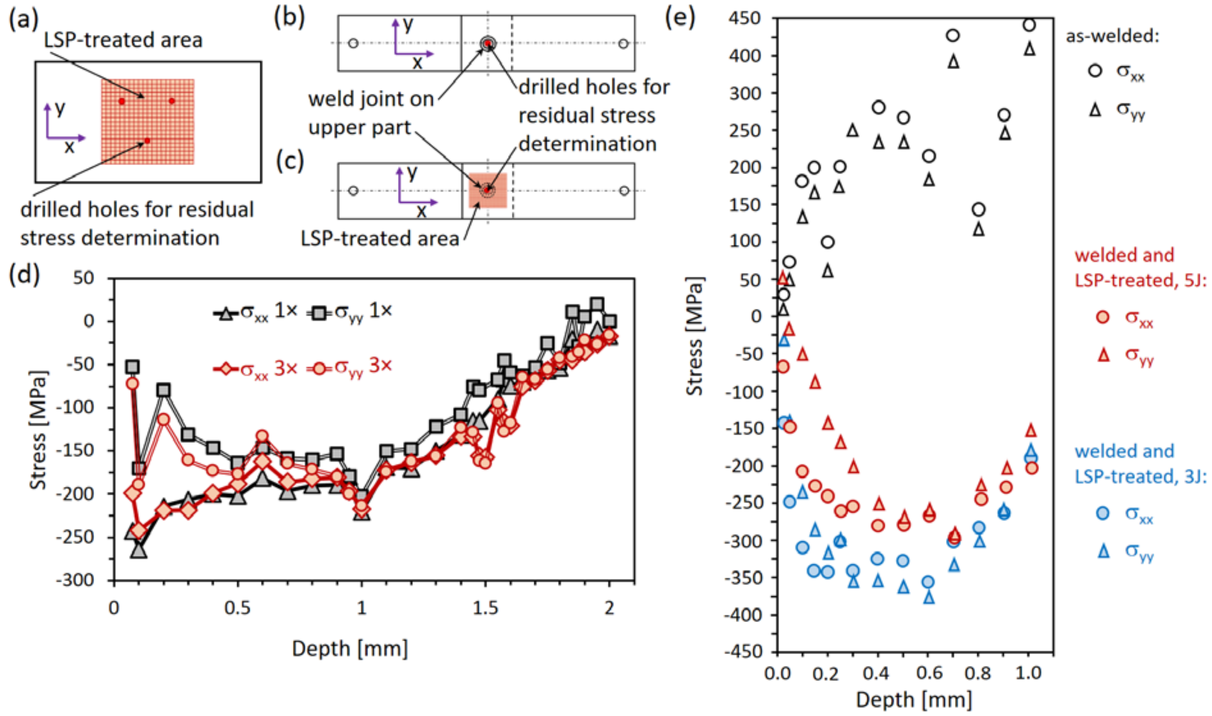

Figure 4: Sketch of specimens with positions for drilled holes used for the residual stress analysis: (a) AA6056 sheets of 6.2 mm in thickness, (b) AA2024 specimen with refill FSSW joint and (c) LSP-treated specimen with refill FSSW joint. (d) Depth-resolved residual stress profiles obtained in the case of LSP-treated AA6056 specimen and (e) AA2024 lap-joint in as-welded as well as welded and LSP-treated condition.

The process parameters for LSP treatment of the three-stringer panels were identified based on a preliminary study for the Al alloy AA2024 [24]. The determined residual stress profiles for the two selected LSP treatment strategies are shown in Figure 5. The depth-resolved residual stress profiles were determined in the center of the LSP zone at three locations and are represented in Fig. 5. First, the strategy with 5 J and spot size of 1 mm × 1 mm was investigated, which leads to the maximum applied energy density in this work. As a second strategy, the LSP treatment with the energy of 5 J was applied using diffractive optics resulting in a spot size of 3 mm × 3 mm. This results in a power density of 3.3 GW/cm^2. The results of the residual stress analysis show that significant compressive residual stresses were induced in 2-mm-thick AA2024 specimens for both cases, with higher compressive residual stresses induced for the 1 mm × 1 mm treatment compared to 3 mm × 3 mm spot size. The absolute values of the residual stresses exceed 80% of the yield stress of the material at about 0.2 mm, so above this depth an error in the determination of the values must be expected. Nonetheless, these results provide a qualitative analysis that significant compressive residual stresses were generated deep below the surface during the LSP treatments.

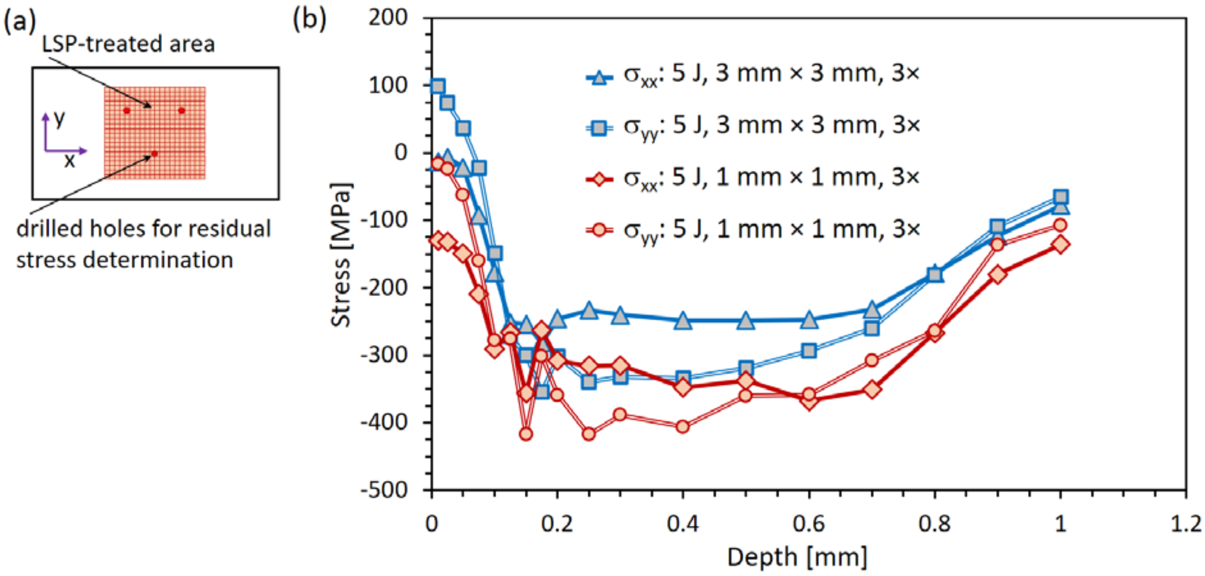

Figure 5: (a) Sketch of specimen with positions for drilled holes used for the residual stress analysis and (b) depth-resolved residual stress profiles obtained in the case of LSP-treated AA2024 specimens.

3.2 Retardation of Surface Fatigue Cracks in Laser Beam-Welded Joints

In order to quantify the effect of LSP treatment on the fatigue life of the laser-welded specimens with pre-existing surface cracks, specimens with initiated surface cracks of a depth of approximately 1.2 mm were divided into two groups. The first group of specimens was tested at different maximum stresses of cyclic loading to establish a fatigue curve for the "with damage" condition (1.2 mm crack). For the specimens of the second group, LSP treatment was applied on both sides as shown in Figure 2b (1.2 mm crack + LSP). Then, these specimens were cyclically tested accordingly to the previous group. The results of all fatigue tests are shown in Figure 6.

The presence of a surface crack significantly reduced the fatigue strength of the pre-damaged specimens compared to the specimens without damage in the "as-welded" condition. The fatigue strength was thereby reduced from about 85 MPa for welded specimens without damage to about 70 MPa for the pre-damaged specimens. Applying the LSP treatment to the pre-damaged specimens significantly improved the fatigue strength. The experimentally determined fatigue strength of the pre-damaged specimens is comparable to the fatigue strength of the specimens tested in the as-welded condition, whereas the fatigue limit is even higher and is about 100 MPa. Thus, the residual compressive stresses generated around an initiated surface fatigue crack by the LSP treatment significantly slows down the growth rate of this crack during fatigue loading.

At this point, some comments should be made for the interpretation of the fatigue test results. The S-N approach for evaluating the results of the fatigue tests allows us to estimate the influence of the initiated surface fatigue cracks on the magnitude of the allowable stress. In this context, the fatigue limit at 10^7 load cycles, i.e., fatigue strength, could be referred to as the allowable stress. It can be seen from Figure 6 that the existence of a surface crack in the weld of a depth of about 1.2 mm leads to a degradation of the load-bearing function of the welded joint. This degradation is accompanied by a reduction of the fatigue strength from about 85 MPa to 70 MPa. In other words, the external stress has to be reduced by about 20% in order to remain in safe operating condition.

The introduction of compressive residual stresses around an existing surface crack by means of LSP leads to a slowing down of the growth under cyclic loading or even to crack arrest, as can be seen in Figure 6. Moreover, the maximum stress of cyclic loading required for further crack growth in the vicinity of compressive residual stresses is about 100 MPa, which is even higher than in the case of a welded joint without surface crack (85 MPa). This means that the allowable stress for this damaged welded joint after LSP treatment is at least equal to the value of the welded joint without damage. For practical application, this means that the load-bearing function of this welded joint with damage can be restored by a targeted LSP treatment. Thus, LSP treatment allows recovery of damaged components to a fail-safe operating condition without having to reduce the allowable load. This can bring significant advantages in terms of maintenance and replacement costs.

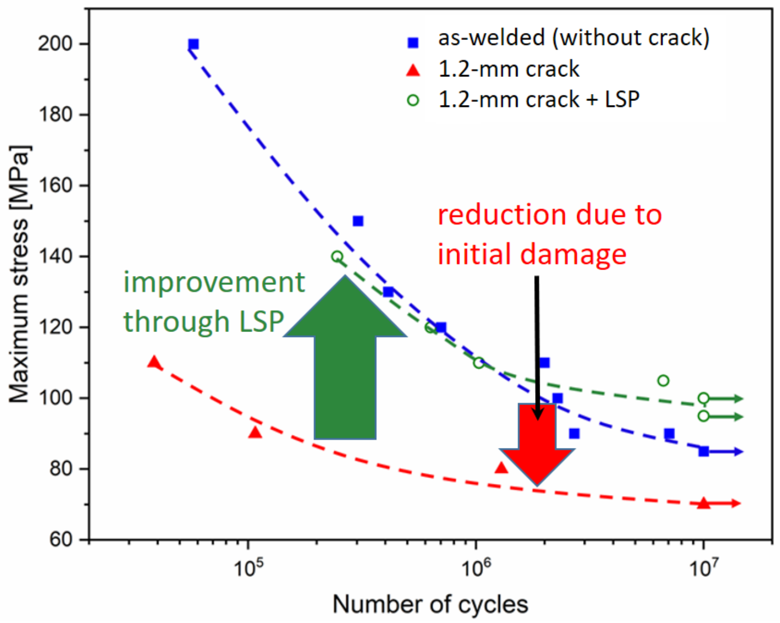

Figure 6: Fatigue test results of laser beam-welded specimens (as-welded), laser beam-welded specimens with initial fatigue cracks (1.2-mm crack), as well as laser beam-welded specimens with initial fatigue cracks and the subsequent LSP treatment (1.2-mm crack + LSP). Depicted and adopted from [25].

<u>3.3 Fatigue Life Extension of Refill Friction Stir Spot-Welded Joints</u>

The results of the fatigue test for specimens with refill FSSW joints are shown in Fig. 7. Due to the presence of the compressive residual stresses generated by the LSP treatment in the weld area, the fatigue strength of the lap joint was significantly increased compared to that in the "as-welded" condition, both in the finite fatigue life region and in the fatigue limit region. Thus, the fatigue strengths of the LSP-treated specimens are 2.31 kN (LSP treatment with 3 J) and 2.49 kN (LSP treatment with 5 J), which is a factor of 3 higher than that obtained for the as-welded specimens (1.49 kN). The difference in fatigue life between the two LSP treatments is not significant. This suggests that the difference between the two LSP treatments (Figure 4e) concerning the compressive residual stress field introduced in the refill FSSW joint area is not significant concerning the effect of residual stresses on fatigue behavior.

The results of the fracture surface investigations provide information regarding the fracture behavior of the lap joints and the effect of the LSP treatment on it. Basically, two mechanisms can be distinguished: (1) separation of the two plates in the case of fatigue crack in the weld spot itself and subsequent residual fracture of the weld at higher forces (Figure 7b-c) and (2) a long fatigue crack developed in the plate originating from the weld spot in case of low forces (Figure 7d-e).

The fracture behavior in case (1) is observed from 2.5 kN for as-welded specimens and from 4 kN for welded and LSP-treated specimens. The separation of the sheets is done due to the fracture of the weld spot in the area between the two sheets. No cracks are present through the entire width of the plate. Only these welded joints show two incipient cracks perpendicular to the load direction. In the final stage of the failure, breakout of the spot weld from the upper side of the sheet occasionally occurred in the as-welded specimens. This phenomenon is observed in individual specimens and cannot be attributed to specific loading conditions.

In case (2), the crack propagates from the weld spot across the entire width of one of the plates perpendicular to the load direction. In the case of as-welded specimens, the crack propagates through the upper plate, whereas in the case of welded and LSP-treated specimens, the crack propagates through the lower plate. An additional distinguishing feature between LSP-treated and LSP-untreated specimens is the maximum applied load. Fracture behavior occurs up to 2 kN for as-welded specimens and up to 3.5 kN for welded and LSP-treated specimens. Both LSP treatments result in the same failure behavior of welded and LSP-treated specimens.

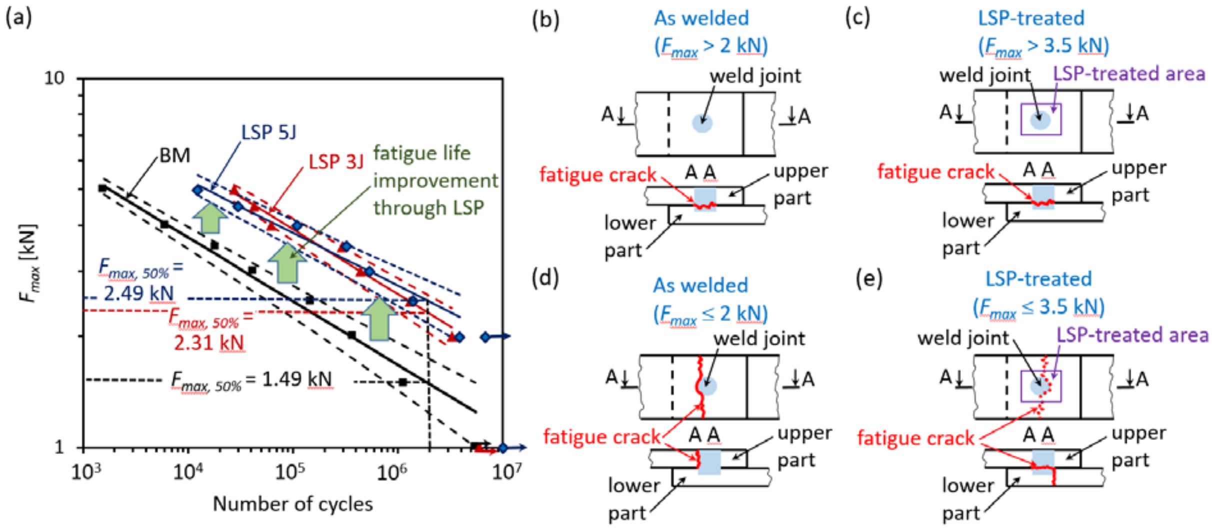

Figure 7: (a) Fatigue test results. In the diagram the mean S-N curves (survival probability of 50 %) with the values of maximum loads at 2×10^6 loading cycles (Basquin fatigue strength) together with 10% and 90% confidence intervals for the three investigated cases – base material (BM) specimen with refill FSSW joint, BM specimen with refill FSSW joint and LSP treatment at 3 J laser energy and at 5 J laser energy – are shown. (b)-(c) Schematic representation of failure mechanisms for tested specimens: (b) as-welded specimens at maximum levels of cyclic loading more than 2 kN, (c) welded and LSP-treated specimens at maximum levels of cyclic loading more than 3.5 kN, (d) as-welded specimens at maximum levels of cyclic loading equal or less than 2 kN and (e) welded and LSP-treated specimens at maximum levels of cyclic loading equal or less than 3.5 kN.

The conclusion is that the introduction of compressive residual stresses in the weld zone by means of LSP leads to an increase in service life, as can be seen in Figure 7a. For a practical application, this means that the load-bearing function of this welded joint can be increased by a targeted LSP treatment. The results of this study show a new way of the application of LSP treatment for increasing the service life of lap joints, whereas in order to achieve the positive effect LSP can be applied not only to the surface of the drilled holes in the case of the classical riveted joint [34-36], but directly to the weld, as is the case in the refill FSSW joint [19].

3.4 Fatigue Life Extension of Welded Integral Structures

The purpose of the last example is to show how LSP treatment can be applied to a structural component to retard the growth of long fatigue cracks, which is important to evaluate the technology for potential aerospace applications [10, 37-40]. For this purpose, three-stringer panels were fabricated, where LSP treatment was applied on the skin surface between the middle stringers. The purpose was to investigate the most critical scenario, where the long crack grows from the broken stringer to the neighboring stringer, and its growth must be slowed down. The testing setup is shown in Figure 8a. The results of fatigue crack growth testing for three-stringer panels are shown in Figure 8b, where a significant effect of LSP treatment on fatigue crack growth behavior was observed. For the stationary shoulder friction stir-welded specimen with two LSP-treated regions, the LSP process parameter set: 5 J, 3 mm × 3 mm, 3× (Table 1) increased the fatigue life by more than a factor of two compared to the stationary shoulder friction stir-welded specimen without LSP treatment. LSP process parameter set: 5 J, 1 mm × 1 mm, 3× (Table 1) resulted in an increase in fatigue life by a factor of more than four. The obtained results show that LSP is an effective process to extend the fatigue life of aircraft components. It can be successfully applied to thin-walled aircraft structures to increase their resistance to fatigue crack growth.

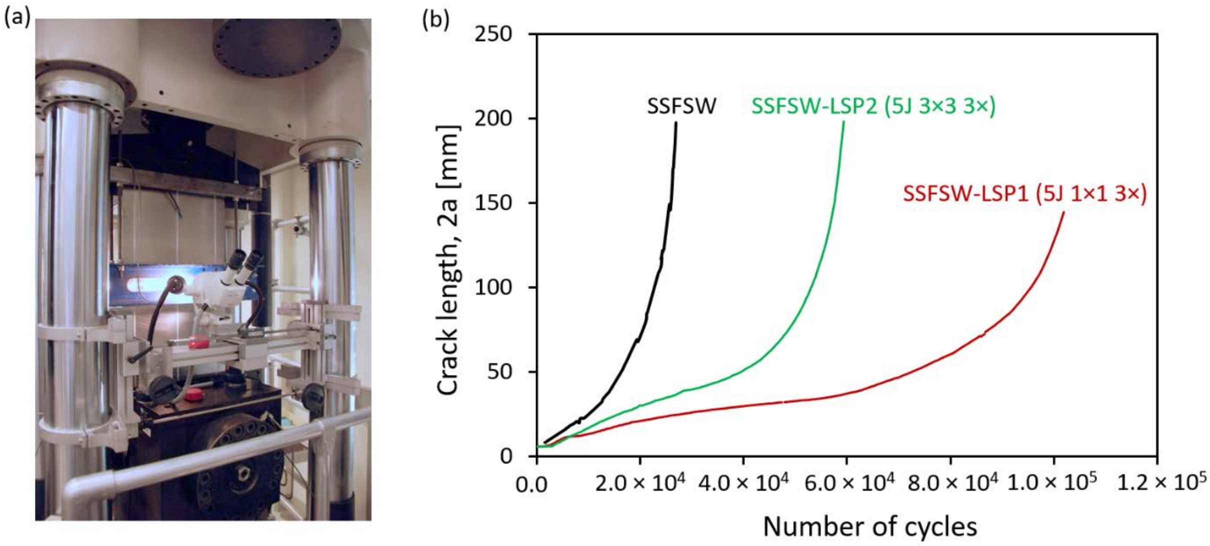

Figure 8: (a) Photo of a three-stringer panel fixed in a 250-kN servo-hydraulic testing facility and (b) fatigue crack growth test results of stationary shoulder friction stir-welded three-stringer panels with LSP treatments. Depicted and adopted from [20].

4 CONCLUSIONS

Based on the obtained results of the study the following conclusions are drawn:

1. LSP is an effective technique for introducing high and deep compressive residual stresses in thin aluminum sheets.
2. LSP treatment can increase the service life of welded joints with pre-existing surface cracks of a depth of about 1.2 mm to a level of welded joints without pre-damage, even increasing the fatigue limit.
3. LSP represents a promising post-processing technique to increase the service life of refill FSSW joints without adding weight to the structure, thus making this innovative joining technique a competitive replacement for classical riveting.
4. The effectiveness of the LSP process was demonstrated on the sub-component level, resulting in a 200 to 400% increase in fatigue life.

Overall, the results of the study show that LSP can be successfully applied to improve the fatigue performance of components where fatigue cracks may occur in critical areas such as welds. Therefore, LSP can be also used as a prophylactic residual stress engineering technique to extend the fatigue life of critical structures in aging aircrafts where fatigue cracks have not yet reached the detectable size. In this regard, LSP could reduce the required safety margins (safety factors) of the fatigue-critical component or structure, thereby reducing its weight.

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