Effects of Laser Shock Peening on Surface Roughness and Residual Stress of AA 7050-T7451

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Surface treatment techniques such as laser shock peening (LSP) represent a consolidated strategy to induce the presence of compressive residual stresses beneath the surface of various metallic alloys. However, surface roughening caused by the process must be monitored, since it may negatively affect fatigue life, resulting in earlier crack initiation. For this reason, the interplay between the key factors affecting both the surface roughness and the development of residual stresses was experimentally examined. The surface roughness was assessed through the determination of roughness average and roughness total height values, whereas residual stresses were assessed using the x-ray diffraction technique and hole drilling method to obtain information about the stress status of the components. Higher values of laser power density resulted in higher values of maximum compressive stress both along scanning and stepping direction and residual stresses remained approximately constant up to a depth of about 0.7-0.8 mm beneath the treated surface. No substantial difference was observed between the residual stress components in the two main LSP directions. Moreover, it was found that the approach to use lower values of nominal power density together with a higher number of layers allows obtaining the same stress condition determined by the use of the highest value of nominal power density but a significantly lower impact on the surface roughness.

Keywords
AA 7050-T7451, hole drilling method, laser shock peening, residual stress, surface roughness, x-ray diffraction

1. Introduction

The use of surface technologies inducing residual stresses is usually employed in aeronautical industries as a design feature for new-generation aircraft to provide additional integrity margins for identified hot spots by reducing the potential for initiation and propagation of cracks (Ref 1). This engineering approach aims at improving the economic and ecological impact on future aircraft structures by controlling the residual stresses and it is particularly suited to applications where fatigue and crack growth performance cannot be further optimized through standard design techniques (Ref 2). In this context, laser shock peening (LSP) can be considered a rapidly advancing and promising technique for surface treatment of metal parts which guarantees deeper compressive residual stress fields, more uniform stresses distribution, and less impact on surface integrity compared to other conventional surface treatment methods (Ref 3), such as shot peening which represents one of the most established techniques in the aeronautical sector for the surface treatment of different metal alloys (Ref 4-6).

From a technical point of view, the LSP process consists of exposing the sample to short-duration pulses of a laser to initiate the formation of a plasma cloud at the workpiece surface. The component is usually covered with a thin laser absorbent sacrificial coating to absorb the laser energy and permit the formation of plasma between the material surface and the transparent confining layer. The plasma is characterized by a very high pressure which is transmitted into the sample via shock waves that plastically deform the near-surface region causing compressive residual stresses to develop at the surface and up to a certain depth into the component. As a consequence, the effectiveness of the process can be naturally assessed by analyzing residual stress field jointly with plastic strain and surface roughening (Ref 7): The process must ensure a minimum depth of compressive residual stress and a magnitude sufficient to guarantee the part has the desired enhancement in fatigue performance. Hence, it is of paramount importance to investigate the effects of different combinations of LSP parameters on the aforesaid factors and to numerically assess their interdependence.

The area of applicability of LSP technology is exceptionally wide and includes the employment of several different metallic materials (Ref 8-10). Thus far, many researchers have provided their contribution to the understanding of phenomena connected to the LSP technique and to the development of robust and qualified strategies aiming at optimizing the overall performance of laser peened components.

As concerns the application of laser shock peening treatment on aluminum alloy, Toparli and Fitzpatrick (Ref 11) verified the feasibility of the LSP process on thin aluminum plates focusing their attention on the detrimental effects of distortions due to laser peening on the entity of in-plane compressive residual stresses.
stresses. They also confirmed the role of the pulse energy and the number of passes as key factors affecting induced residual stresses. The thickness of the component subjected to LSP can significantly affect the residual stress field due to backscattering of elastic shock waves occurring at the rear surface of the part, this is especially true for thin plates, as confirmed by the above-mentioned study; however, it is worth analyzing the effects of thickness on residual stresses entity of thicker plates or components, especially in conjunction with specific values of pulse energy and spot dimensions.

Glaser (Ref 12) took residual stress measurements on laser peened AA 6056-T4 samples and observed a pronounced residual stress anisotropy between scanning and stepping directions of the laser, especially at lower values of irradiance. Furthermore, surface roughness was observed to increase for both irradiance and spot coverage. Salimianrizi (Ref 13) investigated the effects of beam overlap rates, the number of laser shots, and scanning pattern on surface roughness: Specifically, it was observed that roughness values, as well as residual stress measurements, were different along with scanning and stepping directions due to adopted scanning pattern and overlap rate and that the higher the overlap, the less roughness occurs until a critical threshold is reached. Consequently, it can be stated that the directionality of the process, namely the scanning pattern, as well as some key factors, such as overlap rates, spot size, beam energy, and offset between two consecutive layers, can modify the overall behavior or the component, in terms of residual stresses and surface integrity.

As regards the application of LSP on materials other than aluminum alloys, Tursky (Ref 14) presented an overview of main mechanical surface treatments employed to induce compressive residual stress fields in austenitic stainless steel structure and considered the merits of each of them in terms of their effects on surface roughness and residual stress distribution.

Petan (Ref 15) investigated the influence of different combinations of pulse density and spot size on the surface integrity and residual stress measurements of laser peened Maraging steel X2NiCoMo18-9-5: Larger spot size at constant pulse energy was observed to have a greater mechanical effect due to a lower energy attenuation rate and a higher overlapping rate. Consequently, spot size, or equivalently power density, can be deservedly included in the list of the most influential process parameters.

Very few papers in the literature provide an overview analysis of the various LSP process parameters with specific reference to aluminum alloy 7050-T7451. Moreover, most articles concerning LSP applications on 7050-T7451 aluminum alloy use a single combination of process parameters and do not provide comparative analyses between different process strategies. This material is widely used in aerospace applications for its high strength, stress corrosion cracking resistance, and fracture toughness and can be conveniently designed to suit specific heavy plate applications, such as fuselage frames, bulkheads, and wing skins. Luong (Ref 16) studied the effects of SP and LSP on fatigue performance of AA-7050-T7451 focusing on residual stress measurements and surface quality assessment before four points bending fatigue testing. Based on the reported results, surface quality resulted to be less affected by LSP surface treatment than SP, but it was observed a significant variation in waviness above AM conditions. Moreover, regarding the residual stresses, LSP produced slightly lower near-surface compressive stresses but concurrently the largest depth of compression inside the component. Similarly, Gao (Ref 17) verified the beneficial effects of LSP treatment on fatigue performance of 7050-T7451 aluminum alloy as a consequence of deeper compressive residual stress fields and good surface finish. Jiang (Ref 18) evaluated the influence of power density on fatigue life and fracture characteristics of 7050-T7451 aluminum alloy fastener hole specimens showing a close correlation between the residual stress field induced by the laser peening process and the power density parameter varies and the fatigue properties of the component. Nowadays, however, a comprehensive understanding of the effects of the above-mentioned most influencing laser peening process parameters on the development of residual stresses and on surface roughness has not been achieved yet.

Consequently, the objective of this work was primarily the evaluation of surface roughness of laser shock peened square-shaped AA 7050-T7451 specimens through the determination of roughness average (Ra) and roughness total height (Rt) values as the most commonly employed indicators of the validity of the treatment.

Secondary, residual stress field induced by laser shock peening process on the same specimens was assessed using the XRD technique and HDM to obtain detailed information about the stress status of the components. According to the findings of the reviewed technical and scientific literature, several different sets of process parameters were considered, with a particular focus on the individual role and the interrelation between nominal power density, number of layers, specimen thickness, and peening strategy. In particular, the possibility of using a higher number of layers (greater than or equal to 4) associated with a lower power density will be verified and the results obtained will be compared with those resulting from the use of increasing power density with a constant number of passes to assess the applicability of this new peening strategy.

2. Materials and Methods

2.1 Material

In this study, the effects of the laser shock peening process on the surface roughness and the residual stress induced on Al 7050-T7451 were analyzed. The experimental work was conducted on 7050-T7451 aluminum alloy. The corresponding nominal chemical composition is listed in Table 1, while the mechanical properties of the wrought material are shown in Table 2.

Square-shaped specimens were cut out of an aluminum rolled plate with a thickness of 30 mm. The blocks thus obtained were available in two different thicknesses, namely 10 mm and 30 mm, to further explore and clarify the role of thickness in the development of residual stresses inside the components. The geometrical properties of the test specimens are indicated in Fig. 1.

The LSP treatment was performed at the ZAL Center of Applied Aeronautical Research in Hamburg, Germany. It was applied only to one side of the specimen. The experiments were conducted using a YLF:Nd laser with a wavelength of 1053 nm operating at a maximum 20 Hz pulse frequency. The laser pulse width was set to 18 ns. The beam shape was round and a flattop beam profile was employed. For the sake of completeness, all laser parameters are given in Table 3.
The treated zone is placed in the middle of the upper face of the specimens and has dimensions of approximately 35 mm x 35 mm. The surface of the treated area was covered with a sacrificial adhesive coating (a commercial black paint with a thickness of approximately 30-40 μm) before the peening process, and a water film (distilled water with a thickness of approximately 2 mm) was used as a transparent confining layer. A total of 27 specimens were available for residual stress evaluation and surface roughness analysis: 9 thick samples and 18 thin samples. Samples were divided into groups of three, and each group, identified by a capital letter, differs from each other for the specific combination of the LSP process parameters applied. Consequently, 3 different combinations of parameters were considered for thick samples and 6 for thin samples. Among the most critical parameters, nominal power density (NPD), the number of layers of peening, specimen thickness, and peening strategy have been considered, as shown in Table 4. The values selected for these process parameters derive from a careful analysis of the scientific literature related to the application of the LSP process on AA 7050-T7451 components. The parameters range, including the laser power density, the spot size and the overlap rate, represents the most commonly used for that kind of alloy, as reported in the literature (Ref 8, 10, 11, 15, 18). On the other hand, referring to the additional process parameters such as the number of laser passes or the percentage of offset between consecutive layers, only limited experimental data are available in the literature. It was therefore considered necessary to explore new process strategies for evaluating the effects of the chosen parameters on the properties examined.

The peening pattern can be identified by two conventional directions, namely X and Y, indicating the scanning and stepping direction of the laser beam (Fig. 2), respectively. The overlap percentage indicates the overlapping between two adjacent laser spots measured along with both scanning and stepping directions. The offset parameter represents the mismatch between two consecutive layers and its value is inversely related to the number of layers.

### 2.2 Surface Roughness Analysis

Roughness measurements were taken on each specimen after laser shock peening treatment through a Surtronic 25 contact profilometer (Taylor Hobson), as shown in Fig. 3. First of all, each specimen was cleaned with isopropyl alcohol to prevent the presence of grease or abrasive materials. They were then positioned on a linear translation stage fixed to an optical table with dampers and pneumatic isolation to ensure both the specimen and the profilometer were completely steady and free of vibration during the measurement.

Based on the indications provided by reference standard (Ref 20), a cutoff length of 0.8 mm and an evaluation length of 4 mm were selected. The tip of the stylus had a diameter of 2 μm and the traverse speed was constant and equal to 1 mm/sec. Six individual roughness measurements for each specimen were taken, three of which were aligned with the scanning direction of the laser beam, while the other three were aligned with the stepping direction. Three repetitions of each measure were performed to allow for proper statistical analysis of the results. The measuring lines, along with both scanning and stepping directions, were positioned within the treated area at a distance of approximately 12 mm from each other. The values of roughness average (Ra) and roughness total height (Rt) were evaluated along with the two laser directions, based on an arithmetical average of values obtained along each measuring line.

Two different analyses were carried out to estimate the influence of NPD, peening strategy, thickness, and the number of layers on the surface roughness of LSP specimens. Firstly, a 2^3 factorial design was used to statistically estimate the correlation between NPD, peening strategy, thickness, and the considered roughness properties. In this case, the selected design factors were the laser NPD, the number of layers of peening, and the specimen thickness. NPD and number of layers factors were run at three levels (respectively, 2.5, 3.5, and 4.5 GW/cm² and 4, 12, and 20 layers), while thickness factor was run at two levels (10 and 30 mm). The design was replicated three times, as being three the number of specimens characterized by the same set of process parameters. The response variables were the roughness average value (Ra) and the roughness total height value (Rt), commonly employed as indicators of surface roughness. Secondly, a single-factor analysis of variance was employed as a statistical method for the assessment of the influence of the number of layers on roughness properties. In this case, as well, Ra and Rt values were used as response factors in the factorial design.

### 2.3 Residual Stress Analysis

The evaluation of the residual stress field due to the laser shock peening process was performed through two different techniques: XRD and HDM.

Surface residual stresses analysis was performed using Xstress 3000 G3R x-ray diffractometer (Stresstech). It was instrumented with a Cr tube ($\lambda = 0.2291$ nm) and a 2 mm collimator. The residual stress measurements were taken in the center of each specimen along with three different directions: the stepping direction, the scanning direction, and zero direction, as indicated in Fig. 4.

The residual stress measurements were taken using the sine-squared-psi technique as required by UNI EN 15305 standard (Ref 21). The diffracted intensity, the peak width, and the position of K-alpha 1 of the diffraction peak were determined by interpolating the peak profile with the Pearson VII function. Table 5 summarizes the parameters used during the residual stress measurements.

In-depth residual stress fields were evaluated both by the x-ray method and HDM. As concerning XRD, in-depth measurements were taken after removing the material by an electrochemical attack with a Movipol-3 Struers and A2 electrolyte using a voltage of 70 V and a current intensity equal to 0.8 A. At these process parameters, the material removal rate is equivalent to approximately 1 μm/sec. The following nominal depths were analyzed: 0, 10, 20, 30, 40, 50, 100, 150, 200, 250, 500, 750, 1250, 1500, 1750, 2000, 2250, 2500, 2750, 3000 × 10⁻³ mm. In any case, the measure was stopped before 3 mm when traction stress was measured. For the in-depth measurement of residual stresses by XRD, the same diffractometric parameters employed for surface measurements were adopted.

HDM was carried out by using the SINT Technology Hole Drilling system, according to the ASTM E837-13 (Ref 22). Type B strain gauge rosette (CCW) was applied in the middle of the treated surface. The “a” grid was oriented along to the scanning direction of the specimen: It represents the x-direction of the residual stresses. The angle $\beta$ defines the direction of the
The hole was carried out up to 1 mm in 20-hole steps located according to a polynomial distribution. A tungsten carbide end mill, TiAlN coated, inverted cone-shaped 1.6 mm diameter was used. The drilling phase was controlled by a compressed air unit at 400000 rpm speed of rotation (Fig. 5). Residual stress results were evaluated by using the Integral method along the x and y directions.

3. Results and Discussions

3.1 Surface Roughness Results

Surface roughness investigations were performed to infer the effects of variations in NPD, the number of layers, laser pattern and specimen thickness on surface integrity of laser shock peened components. First of all, the combined effects of NPD, laser pattern, and specimen thickness were analyzed. For this purpose, two groups of specimens different in thickness were taken into consideration: Inside every single group, three
different levels of NPD, namely 2.5, 3.5, and 4.5 GW/cm², and two laser directions, specifically scanning and stepping directions, were considered, keeping constant all other LSP parameters. For a clear overview, a summary table reporting the identification code of each specimen and a breakdown of technological aspects is given in Table 6.

The average results of Ra and Rt along both the scanning and the stepping directions of the laser were acquired and employed as response factors in the considered factorial plane, as shown in Table 7. The significance level of the test was fixed to 0.01.

The average results of Ra and Rt are shown in Fig. 6. Higher values of NPD determine a significant and measurable increase in roughness properties both along with scanning and stepping directions, as a consequence of the greater depth and intensity of plastic deformation to which the component is subjected as NPD increases (Ref 15). However, roughness properties seem not to be significantly affected by variation in laser direction at constant values of NPD, confirming the validity of the peening strategy. Indeed, a variation of the roughness parameters in the two main directions of the laser could have indicated a non-uniformity of the process most likely associated with a wrong combination of the LSP process parameters. Moreover, thickness does not play a major role as a parameter affecting surface roughness. The ANOVA was used to confirm the magnitude of the effects of each parameter. The main plot diagrams in Fig. 7 show that the main effect of NPD is highly significant ($P < .001$), suggesting that this factor dominates the process.

The interaction between NPD and thickness factors can also be considered significant according to the chosen value of significance level, but the closeness of the corresponding $p$-value ($P = .079$ for Ra and $P = .091$ for Rt) to the significance level would suggest a greater number of tests to be run to verify the effective influence of this interaction on the process output. All other main effects and factors interactions have a very low value of significance. All findings obtained were briefly and effectively reported in the following contour plots (Fig. 8), where the effect of laser direction was considered negligible for the reasons given above.

As regards the second objective of this research activity, the influence of the number of layers on the surface roughness of laser peened specimens was investigated. In this respect, three different levels of the number of layers factor were considered, namely 4, 12, and 20, and three replicates of the same
experiment were run. Given that the NPD factor has a predominant effect on the roughness properties, these specimens were laser peened by using a lower value of laser NPD, specifically 0.8 GW/cm², to minimize its impact on the surface and better distinguish the specific contribution of each factor. All other process parameters, such as thickness, spot size, and spot overlap, were kept constant, as given in Table 8.

In this case, as well, Ra and Rt values were used as response factors in the factorial plane and single-factor analysis of variance was employed as a statistical method for the assessment of results since only one factor, i.e., the number of layers is investigated (Table 9).

The number of layers parameter results to have a great impact on surface roughness of LSP-treated specimens as testified by diagrams in Fig. 9. Increasing its value from 4 to 20, Ra value shows an increase of 53.7%, while Rt value shows an increase of 84.5%. The ANOVA confirmed that the number of layers significantly affects ($P < .001$) the surface roughness of the component, in terms of both Ra and Rt values. As with the laser power density parameter, the increase in surface roughness caused by the higher number of laser passes is due to the increased degree of plastic deformation of the surface of the treated component. Repeated LSP impacts contribute to extending the depth of the plasticized zone, which is directly reflected in the roughness profile characteristics.

### 3.2 Surface Roughness Discussion

One of the main effects of the laser peening process is the increase of the surface roughness in the treated component compared to the unprocessed one. This phenomenon is a direct consequence of the local plastic deformation caused by the shock waves induced by the controlled expansion of the plasma on the surface of the component. When the pressure of the plasma exceeds the dynamic yield strength of the material, plastic deformation occurs thus altering near-surface microstructure and properties. The peak pressure is strictly related to the laser power density: Generally, higher power density values result in higher peak pressure increasing the depth and the magnitude of plastic deformation (Ref 23-26). This explains the increase in surface roughness associated with the use of higher power densities. The Ra and Rt values found at the three power density levels examined, specifically 2.5, 3.5, and 4.5 GW/cm², are consistent with results presented in other studies conducted on the same or similar materials and using comparable process parameters set (Ref 16, 25, 27). It is important to note that no significant changes in surface properties were observed in the two directions of the laser, i.e., scanning and stepping directions, demonstrating the validity of the peening strategy. Some studies, in fact, associated variation in surface properties along with the two peening directions with the scanning pattern and, specifically, the selected overlap parameter: The higher the overlap, the less roughness occurred until a limit value was reached beyond which a drastic increase in surface roughness was observed due to the consumption of the sacrificial layer and the consequent material ablation (Ref 13). Overlap values of less than 70% along with both directions, such as those used in this study, guarantee the absence of the ablation phenomenon and help to keep the surface roughness of the component within the design requirements.

Similar to laser power density, the use of a higher number of laser passes, i.e., the number of layers, results in a deterioration of the surface roughness of the laser peened component. The repetition of the laser pulses determines a greater amount of local plastic deformation on the component surface, which increases the characteristic roughness parameters. To the best of the authors’ knowledge, few studies in the scientific literature, both numerical and experimental, have addressed the evaluation of the effects of the number of passes on the surface roughness of the component, and none have ever used a number of passes greater than five (Ref 11, 28-31). Therefore, it is not possible to compare the results obtained with those provided by previous studies. However, the low values of surface roughness found in the correspondence of high values of the number of passes suggest the possibility to adopt this peening strategy to applications that require high surface integrity of the component (wear resistance, fretting fatigue, etc.). Moreover, the association of these roughness values with the corresponding residual stress profiles allows the application of this laser peening strategy also for structural applications in fatigue critical points.

### 3.3 Residual Stress Results

Residual stress measurements were taken on the same groups of specimens used for surface roughness evaluation to find an optimal set of parameters that guarantee simultaneously surface integrity and the desired residual stress field.

In Table 10, mean residual stress values along both scanning and stepping directions of the laser obtained through the XRD technique applied on the surface of each specimen in the center of the treated zone were reported.

In Fig. 10, the effects of NDP on the surface residual stresses on 10-mm- and 30-mm-thick specimens were shown. As regards 10-mm-thick specimens, it was observed a decrease in compressive RS from $-184.2 \pm 12.1$ MPa to $-164.9 \pm 14.6$ MPa in the scanning direction and from $-162.0 \pm 15.6$ MPa to $-135.3 \pm 14.7$ MPa in the stepping direction as the NDP increases from 2.5 to 4.5 GW/cm². This reduction in residual stress in the case of 10-mm-thick specimens is not easily explained: It could be associated with the phenomenon of reflection of the elastic waves on the lower surface of the specimen, although this phenomenon is more typically found in components with a slightly lower thickness than that considered
### Table 5  XRD measurement parameters

| Tube | Diffraction angle, ° | Exposure time, sec | No. of Tilt | Tilt angle, ° | Tilt oscillation, ° | Collimator diameter, mm | Voltage, kV | Current, mA |
|------|----------------------|--------------------|-------------|---------------|-------------------|-------------------------|-------------|-------------|
| Cr   | 139.3                | 25                 | 4           | ±45           | ±3                | 2                       | 30          | 8           |

| Miller indexes | Poisson’s ratio | Young’s modulus, GPa | Absorption coefficient, 1/mm |
|----------------|-----------------|----------------------|-----------------------------|
| (311)          | 0.345           | 70.6                 | 42.7                         |
and in correspondence with specific process parameters, as will be highlighted in the following discussion paragraph.

As concerning 30-mm-thick specimens, variations in NPD seems not to significantly affect residual stress measurement on the surface of the components, both along with scanning as well stepping direction.

Therefore, it can be generally stated that an increase in NPD determines a slight decrease in compressive residual stresses on the surface of 10-mm-thick laser peened specimens, independently of the direction of the laser, whereas almost constant values of residual stresses were observed on the surface of 30-mm-thick specimens.

As concerns the influence of the number of layers, it was observed that compressive residual stresses on the surface of the specimens increase with the number of layers. In particular, the compressive stress along stepping direction increases from \(-206.9 \pm 18.0\) to \(-239.2 \pm 29.9\) MPa while the one along with scanning direction increases from \(-162.1 \pm 11.5\) to \(-232.6 \pm 31.8\) MPa when the number of layers increases from 4 to 20, as shown in Table 11 and Fig. 11. This result is a direct consequence of the greater depth of plastic deformation induced by the increased number of laser passes.

As a consequence of the reported results, it is important to point out that it is possible to obtain higher compressive residual stresses at the surface of the component using lower values of NPD but a higher number of layers, with the additional advantage of obtaining lower values of surface roughness, in terms of Ra and Rt, and consequently better surface integrity. In-depth residual stress analysis was carried out through both the XRD technique and HDM. Specifically, specimens identified by ID code 04-05-07-08-13-16, as being representative of the highest values of nominal NPD and both values of thickness, were analyzed using both methods, whereas specimens identified by ID code 22-25, which were obtained using the highest number of layers, were analyzed using only HDM.

Figure 12 shows the comparison between the RS profiles of specimen 05 (NPD = 3.5 GW/cm²) and specimen 08 (NPD = 4.5 GW/cm²) along both scanning and stepping directions. The actual evaluation depths, residual stress values, and corresponding measurement errors are given for both Specimen 05 and Specimen 08 in Table 12a, b, respectively. In general, specimens that were laser peened using the highest value of nominal NPD show higher values of compressive stresses in

| ID codes | Thickness, mm | Nominal power density, GW/cm² | Spot size, mm | Overlap | Nominal energy, J | Layers | Offset |
|----------|---------------|-------------------------------|---------------|---------|-------------------|--------|--------|
| 01-02-03 | 30            | 2.5                           | 3.5           | 30%/30% | 5.31              | 3      | 33%/33%|
| 04-05-06 | 30            | 3.5                           | 3.5           | 30%/30% | 7.43              | 3      | 33%/33%|
| 07-08-09 | 30            | 4.5                           | 3.5           | 30%/30% | 9.55              | 3      | 33%/33%|
| 10-11-12 | 10            | 2.5                           | 3.5           | 30%/30% | 5.31              | 3      | 33%/33%|
| 13-14-15 | 10            | 3.5                           | 3.5           | 30%/30% | 7.43              | 3      | 33%/33%|
| 16-17-18 | 10            | 4.5                           | 3.5           | 30%/30% | 9.55              | 3      | 33%/33%|

Fig. 5  HDM setup

Table 6  Identification codes and technological properties of specimens for surface roughness and residual stress evaluation
Table 7 Factorial plane for surface roughness evaluation: analysis of power density, thickness, and peening strategy influence

| Run | Power Density, GW/cm² | Thickness, mm | Laser Direction | Ra, µm | Rt, µm |
|-----|-----------------------|---------------|-----------------|--------|--------|
|     |                       |               |                 | Replicate 1 | Replicate 2 | Replicate 3 | Replicate 1 | Replicate 2 | Replicate 3 |
| 1   | 2,5                   | 10            | Scanning        | 0,96 (±0.11) | 0,93 (±0.15) | 1,34 (±0.14) | 4,70 (±0.7)  | 4,30 (±0.7)  | 6,20 (±0.7)  |
| 2   | 2,5                   | 10            | Stepping        | 1,28 (±0.06) | 1,32 (±0.14) | 1,13 (±0.12) | 5,80 (±0.6)  | 6,10 (±0.5)  | 4,90 (±0.5)  |
| 3   | 2,5                   | 30            | Scanning        | 1,38 (±0.12) | 1,33 (±0.14) | 1,07 (±0.14) | 6,60 (±0.7)  | 6,60 (±0.9)  | 5,20 (±0.7)  |
| 4   | 2,5                   | 30            | Stepping        | 1,22 (±0.21) | 1,18 (±0.12) | 1,42 (±0.16) | 6,10 (±0.7)  | 6,20 (±0.9)  | 6,90 (±0.7)  |
| 5   | 3,5                   | 10            | Scanning        | 1,89 (±0.27) | 1,67 (±0.41) | 2,00 (±0.37) | 9,60 (±1.5)  | 8,90 (±2.9)  | 11,40 (±2.8) |
| 6   | 3,5                   | 10            | Stepping        | 1,36 (±0.31) | 1,78 (±0.19) | 2,02 (±0.44) | 6,30 (±1.9)  | 8,40 (±2.3)  | 11,10 (±2.3) |
| 7   | 3,5                   | 30            | Scanning        | 1,78 (±0.23) | 1,33 (±0.14) | 1,24 (±0.17) | 8,70 (±1.7)  | 6,30 (±0.9)  | 6,10 (±1.1)  |
| 8   | 3,5                   | 30            | Stepping        | 1,38 (±0.21) | 1,60 (±0.17) | 1,73 (±0.14) | 6,20 (±1.4)  | 7,10 (±0.6)  | 8,10 (±1.1)  |
| 9   | 4,5                   | 10            | Scanning        | 2,27 (±0.22) | 2,08 (±0.2)  | 1,98 (±0.44) | 11,60 (±1.4) | 10,10 (±1.5) | 11,30 (±4.0) |
| 10  | 4,5                   | 10            | Stepping        | 1,98 (±0.29) | 1,84 (±0.26) | 1,69 (±0.11) | 11,40 (±2.4) | 10,30 (±1.9) | 8,80 (±1.0)  |
| 11  | 4,5                   | 30            | Scanning        | 1,98 (±0.16) | 1,67 (±0.40) | 1,67 (±0.26) | 9,90 (±1.1)  | 8,40 (±2.4)  | 8,90 (±1.5)  |
| 12  | 4,5                   | 30            | Stepping        | 1,64 (±0.31) | 2,02 (±0.19) | 2,00 (±0.14) | 9,00 (±2.5)  | 10,20 (±1.4) | 10,00 (±1.3) |

Fig. 6  Effects of NPD, thickness, and peening direction on roughness properties of LSP specimens

both directions compared to those characterized by lower values of NPD. As concerning specimen 05, the maximum
compression stress in stepping direction is $\sigma_{St} = -296.7 \pm 39.1$ MPa at a depth of 0.248 mm while in scanning direction is $\sigma_{Sc} = -310.3 \pm 35.5$ MPa at a depth 0.502 mm. As regards specimen 08, the maximum compression stress in stepping direction is $\sigma_{St} = -341.8,7 \pm 18.9$ MPa at a depth of 0.155 mm while in scanning direction is $\sigma_{Sc} = -349.7 \pm 14.3$ MPa at a depth of 0.251 mm.

In Fig. 13, the comparison between the RS profile measured by XRD and HDM was shown. They refer, respectively, to specimens 04-05 and 07-08. Results show a good concordance
between the two measurement methods. For both methods, in fact, at a depth between 0.1 and 0.7 mm, with an NDP of 3.5 GW/cm², the RS is quite constant between −250 MPa and −350 MPa. Moreover, using an NDP of 4.5 GW/cm², it was found very good accordance along the scanning direction, increasing tension from −400 to −250 MPa, while some discrepancies were found in the stepping direction.

As concerning specimens 22 and 25, characterized by a number of layers equal to, respectively, 12 and 20, the RS profiles obtained through HDM are shown in Fig. 14. To provide complete information, the value of residual stress on the surface of each component previously achieved by XRD was indicated on the same diagrams. It is possible to observe that when the NPD is the same, the greater number of layers generates higher compressive stresses. Moreover, the increasing trend of the RS profile starts at a depth deeper than the corresponding value at the lowest value of the number of layers.

3.4 Residual Stress Discussion

The development of a compressive residual stress field can be considered as the primary objective of the laser shock peening process. The physical phenomenon on which the development of compressive residual stresses is based recalls concepts related to processes involving plastic deformations: When the plasma pressure exceeds the dynamic yield stress of the material, the irradiated region undergoes an expansion in the plane as a direct consequence of the mechanical action exerted by the shock waves. This expansion, however, is constrained by the presence of the surrounding material whose confinement action determines the development of residual compressive stresses. The analysis of the experimental results showed that all the examined samples present high compressive stresses at the surface: This aspect can be related primarily to the employment of the absorbent coating which protects the substrate from thermal ablation (Ref 32) and prevents surface tensile stresses to develop during the LSP process; secondly, the development of tensile residual stresses on the surface of the peened component is usually associated with the occurrence of the “reverse straining” effect due to LSP process performed with smaller spot diameters (Ref 33). Under this assumption, the surface release waves starting from the edge of the laser spot propagate toward the center of the laser spot, increasing in intensity, thereby changing the residual stress field. Based on past research, this phenomenon occurs up to spots as small as 3 mm in size (Ref 33); however, based on the available experimental results, it is not possible to draw any conclusion about the possible occurrence of this phenomenon in the case of the study under examination.

Moreover, it was observed that an increase in NPD determined a slight decrease in compressive residual stresses on the surface of 10-mm-thick specimens compared to 30-mm-thick ones. This behavior can be associated with the phenomenon of the back-reflected shockwaves typical in the LSP process: The induced plastic deformation can be altered by the arrival of the back-reflected stress waves, especially in thin samples, thus altering the residual stress profile within the thickness of the component. In components of reduced thickness, multiple reflections of the shock waves can interfere destructively by hindering the plastic deformation phenomenon still in progress near the irradiated surface of the component and consequently altering its distribution. A critical thickness of 2.5 times the spot diameter has been identified as the limit within which this phenomenon occurs (Ref 33). In the case of 10-mm-thick samples belonging to groups D-E-F defined in Table 4, 3.5 mm spot size was employed. Therefore, the critical thickness beyond which the effect of back-reflection of stress waves is theoretically negligible is approximately 8.75 mm, a value quite close to the thickness of the above-mentioned groups of specimens. The absence of this phenomenon cannot be therefore excluded with certainty. It is also important to note that no other factors were found that could induce a reduction in the surface residual stress field, such as burns or surface cracks.

In addition, the analysis showed that the two in-plane stress components along scanning and stepping directions show similar trends, thus highlighting the absence of distortion of the component that would have otherwise led to the relaxation of some of the compressive stresses (Ref 11).

As regards residual stresses into the depth of the material, it is important to point out some aspects: Minimum residual stress field requirements for fatigue critical applications include a maximum magnitude of approximately 75% of the material yield strength at 1.5% of the component thickness and the zero-
Table 10  Summary of surface residual stress measurements: analysis of NPD, thickness and peening strategy influence  

| Specimens’ ID | Nominal PD, GW/cm² | Thickness, mm | $\sigma_{St, \ 30 \ mm}$, MPa | $\sigma_{Sc, \ 30 \ mm}$, MPa | $\text{Err}_{St}$, MPa | $\text{Err}_{Sc}$, MPa |
|---------------|------------------|--------------|------------------|------------------|----------------|----------------|
| 01-02-03      | 2,5              | 30           | 180,9            | 205,8            | 15,3           | 14,8           |
| 04-05-06      | 3,5              | 30           | 217,4            | 222,1            | 16,0           | 13,1           |
| 07-08-09      | 4,5              | 30           | 184,7            | 196,4            | 16,1           | 12,8           |
| Specimens’ ID | Nominal PD, GW/cm² | Thickness, mm | $\sigma_{St, \ 10 \ mm}$, MPa | $\sigma_{Sc, \ 10 \ mm}$, MPa | $\text{Err}_{St}$, MPa | $\text{Err}_{Sc}$, MPa |
| 10-11-12      | 2,5              | 10           | 162,0            | 184,2            | 15,6           | 11,5           |
| 13-14-15      | 3,5              | 10           | 128,8            | 173,4            | 16,2           | 12,8           |
| 16-17-18      | 4,5              | 10           | 135,3            | 164,9            | 14,7           | 14,6           |
crossing point located at about 10% of the component thickness. As it is possible to observe in Fig. 12 and 13 where the RS profiles measured by XRD and HDM are shown, 30-mm-thick samples which were laser peened using NPD values of 3.5 and 4.5 GW/cm² accurately meet the design requirements. As concerning specimens characterized by a higher number of layers and lower NPD values (Fig. 14), the maximum value of compressive residual stresses is located approximately between 0.1 and 0.2 mm depth, but its magnitude is lower than expected, as a consequence of using lower NPD values compared to the samples considered above. The zero-crossing point is instead located at the desired depth.

The information gathered so far regarding the residual stress field characteristics and the roughness properties at different combinations of process parameters represent an ideal starting point for the evaluation of the fatigue properties of mechanical

Table 11  Summary of surface residual stress measurements: analysis of the number of layers influence

| Specimens’ ID | Number of layers | $\sigma_{St}$ [MPa] | $\sigma_{Sc}$ [MPa] | Err$_{St}$ [MPa] | Err$_{Sc}$ [MPa] |
|---------------|------------------|---------------------|---------------------|------------------|------------------|
| 19-20-21      | 4                | -206.9              | -162.1              | 18.0             | 11.5             |
| 22-23-24      | 12               | -221.3              | -241.5              | 19.5             | 18.3             |
| 25-26-27      | 20               | -239.2              | -232.6              | 29.9             | 31.8             |

Fig. 11  Effects of number of layers on surface residual stress values of LSP specimens
components treated with LSP, as these are among the main factors influencing the fatigue life of a component. Future work will test from an experimental point of view the ability of the LSP processes analyzed in this work to enhance the resistance of load-bearing components to various types of stress-induced damage, particularly about applications in the aeronautical field.

4. Conclusions

In this paper, the effects of different combinations of laser shock peening process parameters on the surface roughness and residual stress development of treated components were examined. The following observations emerged from the analysis of the results:

- NPD and number of layers turned out to be the most influential factors affecting roughness properties, determining an increasing trend of both Ra and Rt values shifting from the lowest to the highest level of each parameter. No significant variation in roughness properties was observed along with the scanning and stepping directions of the laser and as the thickness of the treated component varied.
- Surface residual stress measurements obtained using the XRD technique pointed out that 10-mm-thick specimens present lower values of compressive stress on the surface than 30-mm-thick specimens when all other process parameters were kept constant. Moreover, it was observed that compressive residual stresses on the surface of the specimens increase with the number of layers and that the maximum compressive stress is comparable with that obtained using the maximum NPD. In addition, similar

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**Table 12** In-depth RS measurements by XRD on specimens 05 (a) and 08 (b)

| Depth [mm] | \( \sigma_{\text{XRD}} \) [MPa] | \( \text{Err} \sigma_{\text{XRD}} \) [MPa] | \( \sigma_{\text{Sc XRD}} \) [MPa] | \( \text{Err} \sigma_{\text{Sc}} \) [MPa] |
|-----------|-----------------|-----------------|-----------------|-----------------|
| 0,000     | 220,9 ± 13,6 | -209,1 ± 5,2 |                |                |
| 0,014     | 227,8 ± 19,1 | -216,8 ± 18,7 |                |                |
| 0,021     | 217,0 ± 22,4 | -271,3 ± 21,2 |                |                |
| 0,030     | 208,9 ± 12,1 | -268,7 ± 17,0 |                |                |
| 0,039     | 239,5 ± 17,3 | -261,4 ± 12,0 |                |                |
| 0,053     | 264,6 ± 15,0 | -262,2 ± 12,1 |                |                |
| 0,101     | 251,2 ± 18,6 | -289,3 ± 17,1 |                |                |
| 0,150     | 212,2 ± 13,9 | -223,2 ± 17,9 |                |                |
| 0,202     | 249,8 ± 14,5 | -216,4 ± 24,6 |                |                |
| 0,248     | 296,7 ± 39,1 | -268,6 ± 16,1 |                |                |
| 0,502     | 238,9 ± 37,9 | -310,3 ± 35,5 |                |                |
| 0,760     | 257,9 ± 32,1 | -300,9 ± 38,4 |                |                |
| 1,001     | 219,3 ± 26,4 | -240,3 ± 7,5  |                |                |
| 1,258     | 116,7 ± 24,9 | -229,9 ± 11,8 |                |                |
| 1,500     | 201,9 ± 18,2 | -258,8 ± 39,2 |                |                |
| 1,749     | 149,5 ± 10,8 | -227,6 ± 11,4 |                |                |
| 2,003     | 107,6 ± 19,6 | -181,1 ± 18,5 |                |                |
| 2,251     | 142,6 ± 29,1 | -112,7 ± 38,2 |                |                |
| 2,506     | 87,3 ± 36,6  | -105,6 ± 26,6 |                |                |
| 2,760     | 92,1 ± 47,8  | -165,6 ± 42,5 |                |                |
| 3,002     | 65,9 ± 34,5  | -241,0 ± 62,9 |                |                |

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**Fig. 12** Comparison of residual stress profiles at different values of employed NPD and peening direction
• In-depth residual stress analysis revealed that specimens that were laser peened using higher values of NPD showed higher values of maximum compressive stress both along scanning and stepping direction and that residual stresses remained approximately constant up to a depth of about 0.7-0.8 mm beneath the treated surface. Moreover, the influence of the number of layers on in-depth RS profiles was examined. When the number of layers increases, higher compressive stresses are induced and greater stability of residual stress value was observed. It was observed that 30-mm-thick samples which were laser peened using NPD values of 3.5 and 4.5 GW/cm² accurately met the residual stress design requirements for fatigue critical applications.

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References

1. D. Furfari, U.C. Heckenberger, V. Holzinger, E. Hombergmeier, J. Vignot, and N. Ohloff. (2020). Is the Civil Aerospace Industry Ready to Implement Laser Shock Peening into Maintenance Environment? Questions to Be Answered and Minimum Requirements from Aircraft Manufacturer’s Perspective, in ICAM 2019 – Structural Integrity in the Age of Additive Manufacturing. ICAM 2019, Lecture Notes in Mechanical Engineering, A. Niepokolczczyk, J. Komorowski, Ed., Springer. Cham. https://doi.org/10.1007/978-3-030-21503-3_52

2. D. Furfari, Laser Shock Peening to Repair, Design and Manufacture Current and Future Aircraft Structures by Residual Stress Engineering, in Advanced Materials Research, Vol. 891–892, Trans Tech Publications, Ltd., 2014, p 992–1000. https://doi.org/10.4028/www.scientific.net/AMR.891-892.992

3. S. Gencalp Irizarp, and N. Saklakoglu, 1.14 Laser Peening of Metallic Materials, in Comprehensive Materials Finishing Elsevier, 2017, p 408–440. https://doi.org/10.1016/B978-0-12-803581-8.90160-8

4. A.M. Kovac, Y.B. Boxurt, A.F. Yetim et al., The Effect of Surface Plastic Deformation Produced by Shot Peening on Corrosion Behavior of a Low-Alloy Steel, Surf. Coat. Technol., 2019, 360, p 78–86. h https://doi.org/10.1016/j.surfcoat.2019.01.003

5. H. Kovaci, Y.A.F. Hacsalhögü and, A. Çelik, Effects of Shot Peening Pre-Treatment and Plasma Nitriding Parameters on the Structural, Mechanical and Tribological Properties of AISI 4140 Low-Alloy Steel, Surf. Coat. Technol., 2019, 358, p 256–265. https://doi.org/10.1016/j.surfcoat.2018.11.043

6. S. Bagherifard, S. Slawik, I. Fernández-Pariente et al., Nanoscale Surface Modification of AISI 316L Stainless Steel by Severe Shot Peening, Mater. Des., 2016, 102, p 68–77. https://doi.org/10.1016/j.matdes.2016.03.162

7. A. Siddaiah, B. Mao, Y. Liao and, P.L. Menezes, Surface Characterization and Tribological Performance of Laser Shock Peened Steel Surfaces, Surf. Coat. Technol., 2018, 351, p 188–197. https://doi.org/10.1016/j.surfcoat.2018.07.087

8. X. Shen, P. Shukla, S. Nath and, J. Lawrence, Improvement in Stress State and Microstructure of Stainless Steel with Mechanical Surface Treatments, Surf. Coat. Technol., 2016, 307, p 262–270. https://doi.org/10.1016/j.surfcoat.2016.08.088

9. H. Luong and M.R. Hill, The Effects of Laser Peening and Shot Peening on High Cycle Fatigue in 7050–T7451 Aluminum Alloy, Mater. Sci. Eng., 2010, 527, p 699–707. https://doi.org/10.1016/j.msea.2009.08.045

10. Y.K. Gao, Improvement of Fatigue Property in 7050–T7451 Aluminum Alloy by Laser Peening and Shot Peening, Mater. Sci. Eng., 2011, 528, p 3823–3828. https://doi.org/10.1016/j.msea.2011.01.077

11. Y.F. Jiang, B. Ji, X.D. Gan et al., Study on the Effect of Laser Peening with Different Power Densities on Fatigue Life of Fastener Hole, Opt. Laser Technol., 2018, 106, p 311–320. https://doi.org/10.1016/j.optlastec.2018.04.025

12. J.R. Davis & Associates, and ASM International. Aluminum and Aluminum Alloys, ASM International, Materials Park, OH, 1993

13. ISO (1998) BN EN ISO 4288:1998. Geometrical Product Specifications (GPS)- Surface texture: Profile method- Rules and procedures for the assessment of surface texture. Geometrical product specifications (GPS) 1–8

14. European Committee for Standardization, EN 15305:2008 E, Non-destructive Testing—Test Method for Residual Stress analysis by X-ray Diffraction (2008)

15. ASTM E837-13a, Standard Test Method for Determining Residual Stresses by the Hole-Drilling Strain-Gage Method. Standard Test Method E837-13a 1–16 (2013)

16. A.K. Gujba and M. Medraj, Laser Peening Process and Its Impact on Materials Properties in Comparison with Shot Peening and Ultrasonic Impact Peening, Materials (Basel, Switzerland), 2014, 7(12), p 7925–7974. https://doi.org/10.3390/ma7127925

17. M. Montross, T. Wei, L. Ye et al., Laser Shock Processing and its Effects on Microstructure and Properties of Metal Alloys: A Review, Int. J. Fatigue, 2002, 24, p 1021–1036

18. P. Peyre, R. Fabbro, P. Merrien and, H.P. Lieurade, Laser Shock Processing of Aluminium Alloys. Application to High Cycle Fatigue Behaviour, Mater. Sci. Eng., A, 1996, 210, p 102–113. https://doi.org/10.1016/0921-5093(95)00084-9

19. R. S., G., R. K. Gupta, G. R., B. Pant, V. Kain, K. R., Kaul, and K. S. Bindra, Laser Peening and its Applications: A Review, Lasers Manuf. Process. Mater. Sci. Eng., 2019, https://doi.org/10.1016/s40516-019-00098-8

20. H. Luong and M.R. Hill, The Effects of Laser Peening on High-Cycle Fatigue in 7085–T7651 Aluminum Alloy, Mater. Sci. Eng., A, 2008, 477, p 208–216. https://doi.org/10.1016/j.msea.2007.05.024

21. Y. Hu, Z. Yao and, J. Hu, 3-D FEM Simulation of Laser Shock Processing, Surf. Coat. Technol., 2006, 201, p 1426–1435. https://doi.org/10.1016/j.surfcoat.2006.02.018

22. S. Huang, J.Z. Zhou, J. Sheng et al., Effects of Laser Peening with Different Coverage Areas on Fatigue Crack Growth Properties of 6061–T6 Aluminum Alloy, Int. J. Fatigue, 2013, 47, p 292–299. https://doi.org/10.1016/j.ijfatigue.2012.09.010

23. X.C. Zhang, Y.K. Zhang, J.Z. Lu et al., Improvement of Fatigue Life of Ti-6Al-4V Alloy by Laser Shock Peening, Mater. Sci. Eng. A, 2010, 527, p 3411–3415. https://doi.org/10.1016/j.msea.2010.01.076

24. A. Umapathi and S. Swaroop, Residual Stress Distribution and Microstructure of a Multiple Laser-Peened Near-Alpha Titanium Alloy, J. Mater. Eng. Perform., 2018, 27, p 2466–2474. https://doi.org/10.1007/s11665-018-3336-4

25. P. Peyre, L. Berthe, X. Scherpereel and, R. Fabbro, Laser-Shock Processing of Aluminium-Coated 55Cr1 Steel in Water-Confinement Regime, Characterization and Application to High-Cycle Fatigue Behaviour, J. Mater. Sci., 1998, 33, p 1421–1429. https://doi.org/10.1023/A:1004331205389

26. P. Mylavarapu, C. Bhat, M.K.R. Perla et al., Identification of Critical Material Thickness for Eliminating Back Reflected Shockwaves in Laser Shock Peening—a Numerical Study, Opt. Laser Technol., 2021, 142, p 107217. https://doi.org/10.1016/j.optlastec.2021.107217

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