An Approach to Predict the Residual Stress-Depth-Profile of Thin Sheet Metal Processed by Laser Shock Peening Without Coating

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Abstract. For conventional laser shock peening, the positive influence of compressive residual stresses on fatigue strength is well understood. To protect the material’s surface from ablation, a sacrificial layer is applied. This, however, leads to an additional process step, which deteriorates its economic efficiency. Thus, laser shock peening without coating (LPwC) is more frequently investigated for industrial applications. However, LPwC increases the thermal impact on the material, which may provoke tensile residual stresses in the surface region. In this regard, understanding the influence of LPwC on the residual stress state and deriving a suitable state, e.g., for subsequent applications or forming operations, result in a design of experiment with numerous residual stress measurements. Residual stress-depth-profiles obtained by X-ray diffraction are time-consuming and cost intensive. Hence, a model is proposed to predict the residual stress-depth-profile of LPwC-processed thin sheets. The analytical model is based on the source stress model and uses experimental results, namely hardness as well as shape change measurements. Sheets made of X5CrNi18-10 and with a thickness of 1 mm are LPwC-processed with a nanosecond fiber laser. In the thermally dominated area where tensile residual stresses are present, the model agrees well with the experimental measurements. Moreover, it is revealed that LPwC leads to a saturation of residual stress level maximum and depth in dependence of pulse energy, repetition rate and number of repetitions. Subsequently, the model is used for tailoring the stress profile of thin sheets by LPwC for subsequent bottom bending.

1. Introduction
Metallic micro components are found in many products of our daily life such as in laptops, smartphones, or tablets [1]. To produce such small components economically, they are often mass-produced in billions per year. Cold forming processes, such as bending or deep drawing, are suitable for mass production because they allow low costs and cycle times [2]. A major challenge in forming thin sheet metal with a thickness \( t \leq 1 \text{ mm} \) is the increased dispersion of springback [3]. Springback is an elastic shape change of material, which appears upon removal of forces e.g., when releasing of constraints after forming [4]. When using the same forming tool and punch force, dispersion of springback is solely affected by material deviations, such as sheet thickness, grain size and residual stress state [5]. It is found that the latter has the strongest effect on dispersion of springback [6]. Residual stress state deviations in a material are the result of the production process: Locally different solidification and cooling conditions...
Processes known to modify the residual stress state of metals are shot peening and laser shock peening (LSP). LSP has a higher depth impact compared to shot peening [8]. Moreover, LSP is applied to enhance the fatigue strength of turbine blades [8]. Still, a major challenge is the prediction of residual stresses in the material to optimize the process for its application. There are only a limited number of models accessible for determining residual stresses in LSP-processed sheets [9]. The reason is that many parameters, such as high strain rates of more than $10^6 \text{s}^{-1}$, stress wave attenuation and dispersion, influence the residual stress state. These increase the complexity of the models [9].

In LSP, a confining medium is applied on the target to increase the peak pressure. Peak pressures of more than 5 GPa can be achieved [10]. Water is best suited for most industrial applications because most common lasers cause wear on glass, which reduces the peak pressure over time [11]. However, water has a lower acoustic impedance in comparison to glasses, which results in lower peak pressures [12]. To protect the base material from ablation, a sacrificial layer is usually applied on the surface [13]. Although, a sacrificial layer increases the peak pressure by at least a factor of 1.4, it also doubles the dispersion of peak pressure [14]. Moreover, the application of a sacrificial layer implies an additional process step. Thus, current studies investigate LSP without sacrificial layers. In literature, this process is referred to as LPwC [15]. LPwC may also enhance the fatigue strength of metals, despite the increase in surface roughness and higher heat deposition [16]. The latter may cause the formation of tensile residual stresses in the surface region [17]. They are the result of elevated temperatures, surface softening and resolidification [18]. To reduce these detrimental effects, it is recommended to achieve intensities in the range of GW/cm² with lower pulse energies, shorter pulse durations and smaller focus diameters [19]. Pulse energies for LPwC are approximately in the range of 6 mJ [20] up to 200 mJ [21].

So far, it was demonstrated that a favorable residual stress state can be induced in the forming zone of a sheet metal prior to bending by means of LPwC [22]. In the experiments, the dispersion of bending angle was decreased by the factor 2 because of LPwC. Consequently, the residual stress state, present in the initial state, only played a subordinate role. However, it has not been fully understood yet, how it is possible to obtain a suitable residual stress state of thin sheet metal for subsequent forming processes. Deriving a suitable residual stress state from experiments would result either in numerous residual stress measurements or in Finite element modelling (FEM). Residual stress-depth-profiles obtained by X-ray diffraction are cost and time-intensive. FEM becomes complex when considering all the mechanisms and need suitable data and validation. Hence, a simple model is proposed to predict the residual stress-depth-profile of LPwC-processed sheets. The analytical model is based on the source stress model [23] and uses results from hardness-depth as well as shape change measurements. Here, solution annealed sheets made of X5CrNi18-10 with a thickness of 1 mm are LPwC-processed with a nanosecond fiber laser. Subsequently, bottom bending experiments with a nominal bending angle of 90° are performed on these sheets. The dispersion of bending angle is compared to those obtained with the initial state.

2. Experimental Setup and Methods

2.1. Laser peening without coating

LPwC experiments are conducted on solution annealed sheets made of X5CrNi18 10 (initial state). The dimensions of the sheets are shown in Fig. 1a. The sheets were processed single-sided with a single-mode fiber laser (YLP-HP) from IPG. The laser has a beam quality factor of $M^2 < 1.1$, and a wavelength of 1064 nm. All the investigated laser parameters are listed in Tab. 1.

The laser beam was deflected via a scan head intelliSCAN 20 from Scanlab and focused on the sheet surface. The scan head has a F-Theta lens and a focal length of 160 mm resulting in a spot diameter of 35 µm. The intensity distribution of the laser beam is a Gaussian distribution. The laser was focused on the sheet metal, which was positioned in a sheet holder (see Fig. 1b). Spot diameter, scan speed and repetition rate result in a pulse overlap of 67 %. Parallel scanning is used to process the sheets. The hatching distance is set to 12 µm to enable a similar overlap compared to the pulse overlap. The scan
direction is transverse to the rolling orientation and the sheets are processed only in the center region, which is affected by the subsequent bending process (see Fig. 1c). The sheet metal surface was continuously supplied with laminar water flow. The water layer had a thickness of 4 mm.

Shape changes of the sheets and ablation depth prior to bending were measured with a Keyence confocal microscope (model VK 9700). The deflection of each sheet was measured with a 10x objective. Here, thermal as well as mechanic induced shape changes are characterized by the deflection of the sheets (see Fig. 2). The ablation depth describes the maximum depth that was removed on the sheet after LPwC.

**Figure 1**: Process chain of LPwC-processed and bended sheets: a) dimensions of solution annealed sheets made of X5CrNi18 10, b) setup for LPwC with continuous water supply in sheet holder unit, c) setup for bottom bending with a nominal bending angle of 90°.

**Table 1**: Experimental design of investigated parameters.

| Pulse duration $t_p$ in ns | Repetition rate $f$ in kHz | Pulse energy $E_p$ in mJ | Scan speed $v_s$ in m/s | Scan repetitions $n$ | Average laser power $P_l$ in W |
|---------------------------|---------------------------|--------------------------|------------------------|---------------------|-----------------------------|
| 120                       | 200                       | 1.00                     | 2.3                    | 1, 4, 8, 12, 15, 30, 60 and 100 | 200                      |
| 120                       | 200                       | 0.20                     | 2.3                    | 15                  | 40                         |
| 120                       | 100                       | 1.00                     | 1.2                    | 15                  | 100                        |
| 120                       | 100                       | 0.20                     | 1.2                    | 15                  | 20                         |
| 120                       | 20                       | 1.00                     | 0.2                    | 1, 4, 8, 12, 15 and 30 | 20                         |
| 120                       | 20                       | 0.20                     | 0.2                    | 15                  | 4                          |
| 30                        | 200                       | 0.20                     | 2.3                    | 15                  | 40                         |
| 30                        | 200                       | 0.15                     | 2.3                    | 15                  | 30                         |
| 30                        | 150                       | 0.20                     | 1.7                    | 15                  | 30                         |
| 30                        | 150                       | 0.15                     | 1.7                    | 15                  | 23                         |
| 30                        | 100                       | 0.20                     | 1.2                    | 15                  | 20                         |
| 30                        | 100                       | 0.15                     | 1.2                    | 15                  | 15                         |

2.2. Bottom bending

Bottom bending experiments were performed on a testing machine AllroundLine Z250 from Zwick. The positioning accuracy of the testing machine is ±2 μm. The crosshead speed was set to 1 mm/s for bending experiments. The sheet was placed on top of a V-die in a blank holder unit (see Fig. 1c). The V-die hard a nominal bending angle of 90°. The LPwC-processed surface faced toward the punch.

The bending angle was measured with a coordinate measuring machine Crysta-Apex C from Mitutoyo. A touch probe stylus from Renishaw was used to access the bending angle. The coordinate measuring machine has a length measurement deviation below 1.7 μm and a resolution of 0.1 μm. On the bent sheets, 6 measuring points were recorded on both sides of the inner leg. The distance between...
each measuring point was set to 0.5 mm. A measurement line was derived for each side from the measuring points. The bending angle was derived from the two measurement lines.

2.3. Metallography

Vickers micro hardness measurements at 0.01 kgf (HV0.01) were performed with a DuraScan hardness tester from Struers. A hardness matrix was created in the cross sections of the solution annealed and LPwC-processed sheets.

An X-ray diffractometer with Cr-Kα radiation and a beam diameter of 1 mm was used to detect the sheets’ residual stress states. To determine residual stresses in dependence of the depth of the sheet, a defined amount of material was removed by electrochemical etching.

3. Analytical Model

3.1. Approach

The goal of the model is to predict the residual stress state of sheet metal processed by LPwC. Instead of directly measuring the residual stress state in dependence of the sheet thickness with an X-ray diffractometer, the residual stress state is derived from hardness-depth as well as shape change measurements. The approach is based on the theoretical description of plastically deformed layers by the stress source model [23]. Moreover, Hooke’s law is applied to determine the residual stresses [24].

First, the source stress is determined. It is a measure of the bending moment, which acts on the sheet leading to its deflection (Fig. 2). A bending moment \( M \) acting on the sheet with a length \( l \) and a second moment of area \( I \) causes a maximal deflection \( u \) in dependence of the Young’s modulus \( E \) [25]. All the constant material parameters are listed in Tab. 2.

\[
M = -\frac{12 w E l}{l^2} \\ \ \ \ (1)
\]

\[
I = \frac{w t^3}{12} \\ \ \ \ (2)
\]

\( w \) is the width of the sheet along which the residual stresses are assumed to be constant, and \( t \) is the sheet thickness. The bending moment acting on a sheet after LPwC is the result of the plastically deformed surface region and can be calculated by integrating the source stresses \( \sigma_{\text{source}} \) along the transition depth \( z_0 \) [25].

\[
\sigma_{\text{source}} = \frac{M}{w \int_0^{z_0} (z - \frac{t}{2}) dz} = \frac{2M}{w z_0 (z_0 - t)} \\ \ \ (3)
\]

| Material parameter | Value |
|--------------------|-------|
| Sheet length \( l \) | 25 mm |
| Sheet thickness \( t \) | 1 mm |
| Sheet width \( w \) | 12 mm |
| Second moment of area \( I \) | 1 mm³ |
| Young’s modulus \( E \) | 195,000 N/mm² [26] |

Figure 2: bending moment which leads to characteristic deflection of sheets.
Further, the sheet’s cross section is divided into a laser-affected surface region and a core region to estimate the sheet’s residual stress-depth profile (see Fig. 3). The transition depth from a harder surface to softer core region is determined according to [27] via the hardness-depth-profile. A “u-shaped” hardness-depth-profile is typically found after LPwC. Thus, a 2nd degree polynomial function $f$ is derived for each hardness-depth profile. Moreover, the maximum hardness value in the surface region ($z < 0.1$ mm) and the mean hardness value from the core region ($0.4 \text{ mm} < z < 0.6 \text{ mm}$) are estimated. A mean hardness value is derived from the surface and core region. The transition depth $z$ is determined via the 2nd degree polynomial function. A transition depth of $z_0 = 0.165$ mm is obtained from Fig. 3.

![Figure 3: Determination of transition depth from surface to core region via hardness-depth-profile.](image)

As one condition, the net sum of all residual stresses over a cross-section must be equal to zero. By assuming a step function, the mean stress for surface $\bar{\sigma}_{\text{sur}}$ and core $\bar{\sigma}_{\text{cor}}$ region is described accordingly:

$$0 = z_0 \cdot \bar{\sigma}_{\text{sur}} + (t - z) \cdot \bar{\sigma}_{\text{cor}}$$  \hspace{1cm} (4)

As second condition, there must be a force equilibrium between the source force $F_{\text{source}}$ and the forces of the surface $F_{\text{sur}}$ and core region $F_{\text{cor}}$.

$$F_{\text{source}} = F_{\text{sur}} + F_{\text{cor}}$$  \hspace{1cm} (5)

where $F = A \cdot \sigma$ and $A$ is assumed to be constant. From Eq. (4) and Eq. (5) following step functions are derived:

$$\sigma_{\text{rs}}(z) = \begin{cases} 
  z < z_0 & \Rightarrow \bar{\sigma}_{\text{sur}} = \frac{\sigma_{\text{source}}(t - z_0)}{(t - z_0) - z_0} \\
  z \geq z_0 & \Rightarrow \bar{\sigma}_{\text{cor}} = \sigma_{\text{source}} - \frac{\sigma_{\text{source}}(t - z_0)}{(t - z_0) - z_0}
\end{cases}$$  \hspace{1cm} (6)

The core region is assumed to be constant in the following. However, it is expected that the residual stress profile is continuous over the entire depth of the sheet. Furthermore, it is assumed that the residual stress is maximal on the surface. The value then approaches the core region’s one. A simple function that satisfies both conditions for the surface region is a 2nd degree polynomial function:

$$\sigma_{\text{rs,sur}}(z) = a_1 \cdot z^2 + a_2 \cdot z + a_3$$  \hspace{1cm} (7)

Following, three conditions must be met:

I) Surface function and core have an intersection at $(z; \bar{\sigma}_{\text{cor}})$. 


\[ \bar{\sigma}_{\text{cor}} = a_1 \cdot z^2 + a_2 \cdot z + a_3 \]  

(8)

II) The slope in the core region is 0 since it is assumed to be constant. Thus, the slope at the intersection must also be 0.

\[ 0 = \frac{d}{dz_0}(a_1 \cdot z_0^2 + a_2 \cdot z_0 + a_3) = 2 \cdot a_1 \cdot z_0 + a_2 \]  

(9)

III) The integral of the surface function must remain constant

\[ \bar{\sigma}_{\text{sur}} \cdot z_0 = \int_{0}^{z_0} (a_1 \cdot z^2 + a_2 \cdot z + a_3) \, dz = \frac{1}{3} \cdot a_1 \cdot z_0^3 + \frac{1}{2} \cdot a_2 \cdot z_0^2 + a_3 \cdot z_0 \]  

(10)

Accordingly, by inserting the three conditions in Eq. (7), the surface function can be written as follows:

\[ \sigma_{rs,\text{sur}}(z) = \frac{3 \cdot (\bar{\sigma}_{\text{sur}} - \bar{\sigma}_{\text{cor}})}{z_0^2} \cdot z^2 + \frac{6 \cdot (\bar{\sigma}_{\text{cor}} - \bar{\sigma}_{\text{sur}})}{z_0} \cdot z + 3 \cdot \bar{\sigma}_{\text{sur}} - 2 \cdot \bar{\sigma}_{\text{cor}} \]  

(11)

By inserting Eqs. (1), (2), and (3) in Eq. (11), the following expression for residual stresses at depths \( z < z_0 \) is derived:

\[ \sigma_{rs,\text{sur}}(z) = \frac{2 \cdot E \cdot t^3 \cdot [3 \cdot t \cdot (z^2 - 2 \cdot z_0^2) + z_0^2] - z_0^3]}{t^2 \cdot z_0^3 \cdot (t - 2 \cdot z_0) (t - z_0)} \]  

(12)

4. Results

Fig. 4 shows the base material’s residual stress depth profile and the comparison between model and experiment of residual stress depth profiles of LPwC-processed sheets. The residual stress depth profile of the base material shows that the residual stresses fluctuate around 0. In contrast, the results for the LPwC-processed sheets reveal a strong increase in tensile residual stress in the surface region in comparison to the base material. Although the pulse energy is the same for both illustrated profiles, the increase in tensile residual stress on the surface is stronger for the material processed with a repetition rate of \( f = 200 \, \text{kHz} \) in comparison to \( f = 20 \, \text{kHz} \).

The model agrees well with the experimental results. When considering the standard deviations of the residual stress measurements, the relative deviation between calculated and measured residual stresses is on average 5 %.

\[ \text{Figure 4: Residual stress depth profile of base material and comparison between model and experiment of residual stress depth profiles of LPwC-processed sheets.} \]
In Fig. 5, the measured and predicted residual stress on the surface are compared. The dotted line shows the expected trend. It is to be expected that the measured residual stresses correspond equally to the determined ones. The dispersion of the predicted residual stresses is derived from the determined dispersion of deflection (shown in Fig. 9). The predicted values agree relatively well with the measured ones. Significant increases in deviation between predicted and measured stresses are observed for smaller stresses. The residual stresses are underestimated for lower deflections.

![Comparison of measured and predicted residual stress on the surface of LPwC-processed sheets.](image)

**Figure 5:** Comparison of measured and predicted residual stress on the surface of LPwC-processed sheets.

Induced stresses can cause a shape change of sheets. Almost no deflection is detected for the solution-annealed sheets before LPwC treatment. Their average deflection is $u = 0.53 \mu m \pm 1.50 \mu m$. Fig. 6 shows the deflection and ablation depth in dependence of scan repetitions for two different repetition rates. For both, the deflection increases until 8 scan repetitions. After 8 scan repetitions, the deflection seems to decline. In contrast, the ablation depth increases constantly for both repetition rates. Deflection and ablation rate are higher for larger repetition rate.

![Deflection of sheets and ablation depth in dependence of scan repetitions.](image)

**Figure 6:** Deflection of sheets and ablation depth in dependence of scan repetitions.

Fig. 7 shows the derived transition depths in dependence of the scan repetitions. In these and all the other experiments (as listed in Tab. 1), no trend can be identified. An average transition depth of $0.14 \text{ mm} \pm 0.04 \text{ mm}$ is derived from all the experiments.

![Deflection in dependence of average laser power for 15 repetitions.](image)

**Fig. 8:** Deflection in dependence of average laser power for 15 repetitions. The deflection seems to increase when higher average laser power is used. In Fig. 9 the maximum residual stresses
obtained from the model are compared with the bending angle dispersion. Dispersion decreases with increasing tensile residual stress. 0 MPa residual stress is taken for the base material. A linear trend is observed between bending angle dispersion and maximum residual stress with a coefficient of determination of $R^2 = 0.31$. The largest bending angle dispersion is found for the initial base material.

**Figure 7:** From hardness-depth profiles determined transition depth $z$ in dependence of the total deposited energy.

**Figure 8:** Deflection in dependence of the average laser power.

**Figure 9:** Bending angle dispersion in dependence of maximum residual stress.
Fig. 10 compares the bending angle dispersion with the residual stress integral. The residual stress integral describes the sum of tensile residual stresses up to the depth where the residual stresses change from tensile to compressive residual stresses. The bending angle dispersion declines with increasing residual stress integral. Here, a linear trend can also be observed between bending angle dispersion and residual stress integral, but with a stronger coefficient of determination of $R^2 = 0.61$.

Figure 10: Bending angle dispersion in dependence of residual stress integral

5. Discussion
A pragmatic model is proposed to predict the residual stress-state caused by LPwC. The idea is to derive the change in residual stress depth profile of LPwC-processed sheets from experimentally determined shape deviations and hardness depth profiles. The advantage of this model is that numerous residual stress measurements by X-ray diffractometry can be avoided. The comparison between model and experiments shows in Fig. 4 that the derived residual stress depth profiles correlate well with the measured profiles. Tensile residual stresses are undesirable in many applications, as they e.g., reduce the fatigue strength. Still, they can be estimated with the model based on hardness and deflection. The relative deviation between calculated and measured residual stresses is on average 5%. Tensile residual stresses are also described by Peyre et al. in the surface region when using LPwC [17].

However, the relative deviation increases on the surface and for smaller sheet deflections (see Fig. 5). This increase can be explained by the formation of martensite. LPwC leads to material ablation because no sacrificial layer was applied. Material ablation with a nanosecond-pulsed laser can cause melting and rapid cooling [28] resulting in the formation of a martensitic layer on the surface [22]. Although, the martensitic content on the surface differs in dependence of the laser parameters, the martensitic layer thickness stays below 10 µm independent of the investigated laser parameters. The martensitic layer counteracts thermal-induced sheet deflections. Accordingly, the measured sheet deflection is the result of both mechanisms. However, thermal-induced tensile residual stresses are dominant for all the investigated laser parameters. Thus, it is suggested that the influence of counteracting forces by the martensitic layer become stronger relative to the thermal-induced forces when sheet deflections are below 10 µm (see Fig. 5).

Deflections and accordingly, tensile residual stresses are higher on the surface with increasing repetition rate although the transmitted energy per unit length is the same (see Fig. 4). In contrast to the measured deflection, the transition depth is not affected within the observed parameter spectrum (see Fig. 7). When increasing the repetition rate, the heat may not be removed fast enough by heat conduction into the sheet leading to higher thermal impact and therefore, to higher tensile residual stresses [29]. Moreover, when heat accumulation occurs in the material [30], the ablation depth may increase because the energy required to vaporize the material is reduced. The latter is observed in Fig. 6 for higher repetition rates.
When considering a larger deflection created with many scan repetitions, the ablation depth may also deteriorate the predictability of the model. The sheet thickness decreases by LPwC, which may overestimate the residual stress, as can be derived from Eq. (8).

Despite material ablation (see Fig. 6) and the deflection prior to bending (see Fig. 8), subsequent bending experiments reveal a positive impact of LPwC on bending angle dispersion (see Fig. 9). It is demonstrated that sheets with tensile residual stresses on the surface have smaller bending angle dispersion. For the observations to be consistent with the descriptions by Reissner et al. concerning the influence of deviations in material state on springback [5], this means that the residual stress should saturate at a maximum level in dependence of the laser parameters. This also means that LPwC minimizes the influence of the initial sheet state. A quantity that better describes the observations by Reissner et al. is the residual stress integral. The model reveals that a larger residual stress integral (see Fig. 10) has a positive effect on bending angle dispersion. Consequently, two main parameters are found to achieve low bending angle dispersion with LPwC. Firstly, the residual stress must be maximal at the surface. Secondly, the transition depth from tensile to compressive residual stress must be as deep as possible in the sheet. Moreover, it is expected that the method is neither limited to LPwC nor to thin sheets. This effect may be the key to derive favorable stress-profile for subsequent forming operations. It is suggested that a residual stress-depth-profile can be created by LPwC, which locally converges to the one induced by bending operations.

6. Conclusion
A simple model based on hardness-depth profiles and deflection was successfully derived to determine the residual stress-depth profile of LPwC-processed sheets. From the model, it is concluded that two parameters are essential for low bending angle dispersion, which increases the robustness of subsequent bending operations:
- Higher tensile residual stresses on the surface are beneficial
- The transition depth from tensile to compressive residual stress must be deep in the sheet

Since the transition depth is nearly constant at about 0.14 mm ± 0.04 mm in the observed parameter spectrum, the model can be used for tailoring the stress profile of thin sheets by LPwC for subsequent bending processes. To achieve higher tensile residual stresses on the surface, it is revealed that higher repetition rates are advantageous for low bending angle dispersion because of heat accumulation effects.

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