Features of laser shock processing application to titanium alloys with shape memory

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Abstract. The paper presents the features of applying the methods of dimension analysis and finite element simulation in relation to the processes occurring during laser shock processing (LSP) of titanium alloys with the shape memory effect (SME). It is found out that the main dimensionless parameters that control the depth of the plastic zone that occurs during LSP are the dimensionless duration of the laser pulse and the peak pressure in the shock wave. A comparative assessment is made between the simulated dependence of the dimensionless depth of the plastic zone on the dimensionless peak pressure in the shock wave and the corresponding experimental studies from the existing publications.

Key words: alloys with shape memory, laser shock processing, dimensionless parameters, dimensional analysis, depth of the plastic zone

1. Introduction
Shape memory alloys are one of the most popular materials that are increasingly being used as potentially best materials for biomedical devices and various structural applications. Their unique properties, such as shape memory and superelastic effects, are obtained as a result of the thermoelastic martensitic transformation between the high-temperature, high-symmetric austenitic phase and the low-temperature, low-symmetric martensitic phase [1]. Several methods of intensive plastic deformation, such as shot blasting, cold rolling, high-pressure torsion, and equal-channel angular pressing, have previously been used to generate strain-induced martensite and increase its stability in NiTi alloys (Ni - 50.9%, Ti-49.1%, hereinafter referred to as NiTi) with the shape memory effect. Recently, strain-induced martensite generated by laser shock processing (LSP) in NiTi alloys has been reported [2]. Thus, among other things, this makes LSP one more promising technology with great potential for processing SME and creating there localized deformation-induced martensitic structures for specific practical applications.

LSP is an innovative method for improving the surface quality of metal structures, which is widely used in the aerospace and automotive industries to improve the mechanical properties of key machine components [3]. As shown in Figure 1, during LSP, a laser pulse with a high radiation power density (1) through the lenses 2 focuses on the absorbing layer 5 (usually black paint), previously applied to the metal surface of the test sample (6), passing through a transparent limiting layer 3 (usually water or...
glass). The heated surface instantly evaporates, and through ionization turns into plasma (4). The plasma is trapped between the transparent confining layer and the test sample, continuing to absorb the laser energy. In this case, the plasma generates high pressure, which is transmitted to the material under study in the form of shock waves. Usually, generated plasma pressure can reach several HPA in dozens of nanoseconds. When the shock wave propagates in the near-surface layer of the material under study, plastic deformation occurs, which leads to the generation and certain redistribution of residual stress throughout the entire depth of the plastic zone. For traditional metal materials, such as various aluminum alloys, titanium alloys, and stainless steels, extensive experimental studies on LSP were conducted, for which the influence of such parameters as the shape and size of the laser spot, the intensity of laser radiation on the residual stresses arising from LSP was studied [4]. Analytical and numerical models were also developed based on the description of the physical processes occurring in the LSP. They successfully predicted the distribution of residual stresses and the depth of plastic zones depending on the parameters of the laser action [5]. However, the use of LSP for shape memory alloys has been poorly studied both experimentally and analytically.

![Figure 1. Schematic diagram of the LSP technology.](image)

1– laser pulse, 2 – focusing lens, 3 – transparent layer, 4 – plasma, 5 – absorbing layer, 6 – test sample, 7 – substrate

2. Problem statement
For SME, it is of great practical importance to establish the optimal impact parameters for LSP and the corresponding degrees of hardening of materials. However, certain difficulties arise when conducting such experiments [2]. It is also difficult to determine the optimal processing parameters using theoretical analysis, since LSP is a complex physical and mechanical process that is influenced by many parameters, such as laser parameters, environmental parameters, and material parameters. In this paper, using the methods of dimension analysis and finite element modeling, the results of the study of LSP in relation to SME alloys (NiTi) are presented.

3. Theory
To analyze the physical processes occurring in NiTi alloys with shape memory effect (SME) subjected to LSP, the method of dimension analysis was used. The main parameters that control all the main processes during LSP are the peak pressure in the shock wave $P_m$, the pulse duration $\tau$, and the radius of the laser spot $R$ [2].

It is known [1] that there are only 11 basic parameters that completely determine the mechanical behavior of the shape-memory alloy material (Fig. 2). It is the elastic modulus of austenite $E_A$, the
elastic modulus of martensite $E_M$, material density $\rho$, Poisson's ratio $\nu$, the initial strain of the direct martensitic transformations $\sigma_{AM}^M$, the final stress of the direct martensitic transformation $\sigma_f^M$, the initial stress of the reverse transformation $\sigma_{AN}^M$, the final stress of the reverse transformation $\sigma_f^M$, module $E_p$ of the strain hardening, the yield strength of martensite $\sigma_y^M$, and flexibility modulus $E_p$. It is assumed that the volumetric compression of the material is described by a hydroelastic model, so the studied material parameters also include the coefficients of martensite and austenite, which occur in the determining ratio of Mi-Gruneisen: the adiabatic index $\gamma$, and the coefficients $b_A, b_M, c_A, c_M$ [1].

As a rule, during LSP, the thickness of the test sample is quite large compared to the LSP zone of influence, and, accordingly, the thickness can be considered infinitely large. Therefore, it is logical to assume that the main influence of the LSP on the S, and, accordingly, the thickness can be considered infinitely large. Therefore, it is logical to assume that the main influence of the LSP on the SME is characterized by the depth of the plastic zone along the axis of the laser beam $L_p$ and the surface residual stress in the center of the LSP $\sigma_m$, which, in turn, are functions of the control parameters that characterize the laser effect and the properties of the material:

$$L_p = f_1\left(\frac{p_m}{\sigma_y^M}, \frac{\tau}{R/\sqrt{E_M/\rho}}, \frac{E_A}{E_M}, \frac{E_{tr}}{E_M}, \frac{E_p}{E_M}, \frac{\sigma_{AM}^M}{E_A}, \frac{\sigma_f^M}{E_A}, \frac{\sigma_{AN}^M}{E_A}, \frac{\sigma_y^M}{E_A}, \gamma, b_A, c_A, b_M, c_M\right)$$

$$\sigma_m = f_2\left(\frac{p_m}{\sigma_y^M}, \frac{\tau}{R/\sqrt{E_M/\rho}}, \frac{E_A}{E_M}, \frac{E_{tr}}{E_M}, \frac{E_p}{E_M}, \frac{\sigma_{AM}^M}{E_A}, \frac{\sigma_f^M}{E_A}, \frac{\sigma_{AN}^M}{E_A}, \frac{\sigma_y^M}{E_A}, \gamma, b_A, c_A, b_M, c_M\right)$$

**Figure 2.** The ($\sigma$-$\varepsilon$) curve of the shape-memory alloy and its main mechanical characteristics

Taking the pulse duration $\tau$, the martensitic modulus of elasticity $E_M$, and the material density $\rho$ as values with independent dimensions, and applying the pi-theorem [5] to equations (1) and (2), we obtain the following dimensionless relations:

$$\frac{L_p}{R} = f_1\left(\frac{p_m}{\sigma_y^M}, \frac{\tau}{R/\sqrt{E_M/\rho}}, \frac{E_A}{E_M}, \frac{E_{tr}}{E_M}, \frac{E_p}{E_M}, \frac{\sigma_{AM}^M}{E_A}, \frac{\sigma_f^M}{E_A}, \frac{\sigma_{AN}^M}{E_A}, \frac{\sigma_y^M}{E_A}, \gamma, b_A, c_A, b_M, c_M\right)$$

$$\frac{\sigma_m}{\sigma_y^M} = f_2\left(\frac{p_m}{\sigma_y^M}, \frac{\tau}{R/\sqrt{E_M/\rho}}, \frac{E_A}{E_M}, \frac{E_{tr}}{E_M}, \frac{E_p}{E_M}, \frac{\sigma_{AM}^M}{E_A}, \frac{\sigma_f^M}{E_A}, \frac{\sigma_{AN}^M}{E_A}, \frac{\sigma_y^M}{E_A}, \gamma, b_A, c_A, b_M, c_M\right)$$

In total, we have 16 independent dimensionless parameters:
\[ \xi_1 = \frac{P_m}{\sigma^M_y}, \xi_2 = \frac{\tau}{R/\sqrt{E_M/\rho}}, \xi_3 = \frac{E_A}{E_M}, \xi_4 = \frac{E_t}{E_M}, \xi_5 = \frac{E_p}{E_M}, \xi_6 = \frac{\sigma^{AM}}{E_A}, \xi_7 = \frac{\sigma^{AM}}{E_M}, \xi_8 = \frac{\sigma^{MA}}{E_M}, \xi_9 = \frac{\sigma^{MA}}{E_A}, \]
\[ \xi_{10} = \frac{\sigma^M}{E_M}, \xi_{11} = \frac{c_A}{\sqrt{E_M/\rho}}, \xi_{12} = \frac{c_M}{\sqrt{E_M/\rho}}, \xi_{13} = \gamma, \xi_{14} = b_A, \xi_{15} = b_M, \xi_{16} = v. \]

Let us give the physical meaning of the above dimensionless parameters:
\[ \frac{P_m}{\sigma^M_y} \] characterizes the degree of plastic deformation;
\[ \frac{\tau}{R/\sqrt{E_M/\rho}} \] characterizes the ratio of the laser pulse duration to the duration of its relaxation in the sample under study;
\[ \frac{E_A}{E_M}, \frac{E_t}{E_M}, \frac{E_p}{E_M} \] characterize the elastic modulus of austenite, the modulus of strain hardening, and the modulus of plasticity, respectively;
\[ \frac{\sigma^{AM}}{E_A}, \frac{\sigma^{AM}}{E_M}, \frac{\sigma^{MA}}{E_M}, \frac{\sigma^{MA}}{E_A} \] characterize the elastic deformation at the beginning of the direct martensitic transformation, at the end of the direct martensitic transformation, at the beginning of the reverse martensitic transformation and at the end of the reverse martensitic transformation, respectively;
\[ \frac{\sigma^M}{E_M} \] characterizes the elastic strain limit;
\[ \frac{c_A}{\sqrt{E_M/\rho}}, \frac{c_M}{\sqrt{E_M/\rho}} \] characterize the longitudinal sound velocities in the austenitic and martensitic phases, respectively;
\[ \gamma, b_A, b_M \] are the adiabatic exponent, and the coefficients in the defining Mi-Gruneisen ratio, respectively;
\[ v \] represents the Poisson’s ratio of the sample (TiNi).

In the case where the sample under study is fixed and pinched at the edges (as in our case), 14 of the 16 dimensionless parameters in the right-hand sides of equations (3) and (4) associated with the material (the last 14 terms) are constant values. Therefore, for this case, these equations are significantly simplified (only the parameters related to laser radiation are the same):
\[ \frac{L_P}{R} = f_1 \left( \frac{P_m}{\sigma^M_y}, \frac{\tau}{R/\sqrt{E_M/\rho}} \right), \] \[ \frac{\sigma^M}{\sigma^M_y} = f_2 \left( \frac{P_m}{\sigma^M_y}, \frac{\tau}{R/\sqrt{E_M/\rho}} \right). \] 

This fact indicates that the method of dimension analysis is fully applicable to the study of the impact of LSP on SME [5]. From equations (5) and (6), it also follows that an important conclusion from a practical point of view is that the same residual stress distributions will be induced in the material under study for each laser pulse with the same exposure parameters, since the dimensionless parameters \( \frac{P_m}{\sigma^M_y} \) and \( \frac{\tau}{R/\sqrt{E_M/\rho}} \) stay unchanged in the LSP process.

4. Obtained simulation results and their comparison with the experiment

Figure 3 shows a comparison of the experimental results from [2] of the dependence of the dimensionless depth of the plastic zone \( L_P/(\sqrt{E_M/\rho} \cdot \tau) \) on the dimensionless peak pressure in the shock wave \( P_m/\sigma^M_y \) with the results obtained by the dimensional analysis. It can be seen that the calculated linear relationship between the dimensionless depth of the plastic zone and the dimensionless peak pressure in the shock wave is in good agreement with the experimental results.
Figure 3. Comparison of the experimental results from [2] of the dependence of the dimensionless depth of the plastic zone $L_P / (\sqrt{E_M / \rho \cdot \tau})$ (round points) on the dimensionless peak pressure in the shock wave $(P_m / \sigma_y^M)$ with the results of numerical moderation (straight line)

5. Results and discussion
As we can see (Fig. 3), the maximum peak pressure of the shock wave in the experiments was 8.8 hPa. Due to the natural limitations of complex experimental studies, it has not yet been possible to conduct LSP experiments at higher peak pressures. Therefore, the verification of the nonlinear characteristic obtained by analyzing the dimensions at shock wave pressures greater than 8.8 hPa requires further experimental confirmation.

6. Conclusion
The features of the application of dimension analysis and finite element modeling in the laser shock processing of titanium alloys (NiTi) with shape memory are investigated. The main conclusions are as follows:

1. It is established that the main dimensionless parameters that control the distribution of residual stresses and the depth of the plastic zone that occur during LSP are the dimensionless duration of the laser pulse and the peak pressure in the shock wave.

2. A comparative assessment was made between the modeled dependence of the dimensionless depth of the plastic zone on the dimensionless peak pressure in the shock wave and the corresponding experimental studies from the literature, which at pressures less than 8.8 hPa showed acceptable convergence between them, which confirms the reliability of the numerical models developed in this paper for analyzing the behavior of SME subjected to LSP.

7. References
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