Design of Experiments course

Effect of laser and material properties on the depth of laser-affected layer in laser shock peening

DOE proposal – Fall 22

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Contents

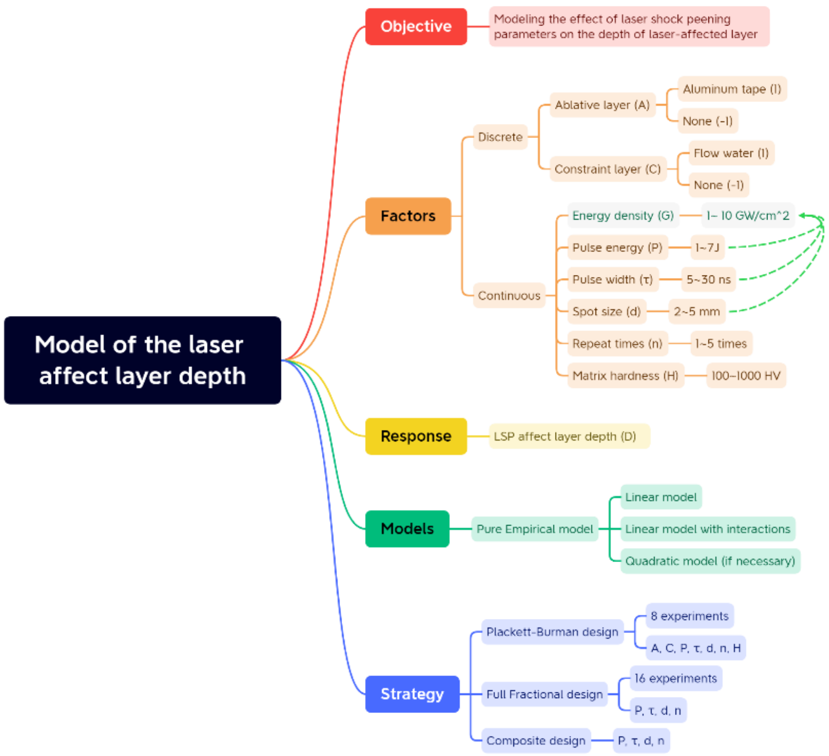
1. Group

We are all from the same lab (LMTM), working on the microstructure and mechanical properties of metallic materials. Yandong Jing is a first-year Ph.D. student at EPFL and has researched laser shock peening (LSP) and additive manufacturing (AM) in the past three years. And now, he mainly concentrates on optimizing the 6xxx series aluminum alloy process Seyyed Ezzatollah Moosavi is a first-year PhD student at EPFL and is mainly concerned with materials characterization and properties optimization. His ongoing project is focused on studying various precipitation-related phenomena in Al 6xxx and on its numerical modeling. Junfeng Xiao is a second-year Ph.D. student working at LMTM. His PhD project concerns the variant selection and reorientation of shape memory alloy under different loading, including laser shock peening (LSP) and conventional deformation using EBSD and TKD.

2. Referee

The referee of our group is Dr. Cyril Cayron, a Senior Scientist at EPFL-LMTM. His research interest is concentrated on crystallography, phase transformations, nanomaterials, and other advanced microstructure characterization. His research scope also includes mechanical behavior and materials processing (including laser shock peening).

3. Mindmap



4. Objective

This project aims to quantify the depth of the laser-affected layer in LSP experiments by considering the effect of the ablative layer, constraint layer, energy density, pulse energy, spot size, repeat times, and matrix hardness. LSP is a powerful surface treatment method widely used in the aerospace and transportation industries. The principle of the LSP is shown in Fig. 2. In the LSP process, an ultra-short pulse laser triggers a plasm explosion on the metal surface, and then a transparent constraint layer is used to compress the shock wave into the sample. An ablative coating is used to protect the sample surface from burning.

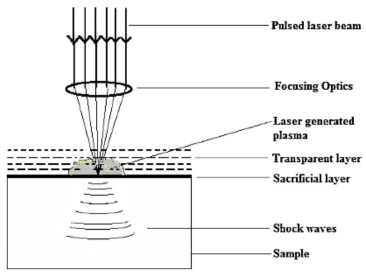


Fig 1. Schematic diagram of LSP

5. Factors

The factors of this project consist of discrete parameters and continuous parameters. Discrete variables include whether to select an ablative layer and a constraint layer. Based on the experiment results, using both will positively impact the response, so when using aluminum tape and water, both factors are set to 1, while not using them is recorded as -1.

The continuous factors include energy density (G), pulse energy (P), pulse width (τ), spot size (d), repeat time (n), and matrix hardness (H). G could be calculated by using Eq. (1):

$$G = 4P/(\pi d^2 \tau) \quad (1)$$

Generally, a higher energy density will lead to a deeper affected layer. However, even with the same energy density, different pulse widths and spot sizes may change the response. Increasing the repeat time will increase the affected layer thickness. In addition, the laser-affected layer depth is also highly dependent on the hardness of the matrix material. The harder the matrix material, the harder it is to produce plastic deformation, i.e., the affected layer is shallow.

6. Response

The response of this model is the depth of the laser-affected layer, which is a crucial property to evaluate the effectiveness of the LSP process. There are several ways to measure the thickness of this layer, e.g., hardness, hold-drilling residual stress measurement, and microstructure characterization. To make things simple, in this project, we will measure the hardness distribution along the vertical axis of the LSPed surface. Since LSP will increase the hardness, when hardness drops to the matrix value, we will consider the depth as the thickness of the affected layer. Generally, the value of the laser-affected depth will be 0~3.00mm.

7. Models

Due to the physical base of the response being quite complex, in this project, we will use pure empirical models to describe the effects of factors on the response. In the first beginning, to make things simple, the approach will be a first-degree model without considering interaction. Based on this model, we will develop a first-degree model with interactions to eliminate the residual. After this, if the result shows that the model could be further promoted, a second-degree model will be further developed.

8. Strategy

Since the energy density can be calculated by pulse energy and pulse width, to develop the first-order model without interactions, seven factors (A, C, P, τ, d, n, H) will be involved in the Placket-Burman design. By using Hadamard, the main effect of these parameters will be evaluated.

Based on the existing knowledge about LSP, the effect of A, C, and H are less interesting. Therefore, the linear model with interaction will only be considered between P, τ, d and n. In that case, a full factorial design of 2^4 will be considered, and for that purpose, 16 runs of the experiments are needed.

After we got the linear model with interaction, if the team members still have more energy to devote to this project, we will consider developing a quadratic model to improve the accuracy of our model. After weighing up the accuracy and cost of the 3-level factorial, composite, Doehlert, and Box-Behnken design, this project will apply composite design to develop a 2^{nd}-degree model.

9. Program

This project is planned to be completed within two months of a positive evaluation of the proposal due to the spread of project time among the three members.

- Firstly, the project will be officially started after acceptance of the proposal by gathering related data, regarding the factors mentioned in the mind map and given information. This phase will be done in the first half of January.
- In the next stage, first linear model and linear model with interactions will be carried out, and the results will be evaluated in order to verify their validity. In case of any inconsistency in a model, it will be either rerun after modification or replaced by another model. This phase will be done in the last two weeks of January.
- Finally, depending on the accuracy of existing model, the necessity of a further quadratic model will be evaluated. Also, the project report will be finished in this section, this phase will be done in the February.

As a summary, the final project report will be submitted no later than the end of February 2023.

10. Remarks

It is worth mentioning that the real need for using such models, and more generally, design of experiments is arisen from the fact that, in the case of carrying out all possible experiments, due to complexity of interactions between different factors and their nonlinear impacts, also extensive ranges of variables that can be applied on each factor, it can be indeed time-consuming. As a result, a fitting designing regarding experiments would make it possible to focus on the most essential factors playing role in the final responses.