Amirkabir Journal of Mechanical Engineering

Amirkabir J. Mech. Eng., 52(10) (2021) 721-724
DOI: 10.22060/mej.2019.16071.6305

Multi-Objective Optimization of Laser Peening Process Parameters Using Taguchi Orthogonal Array and Gray Relational Analysis

R. Bikdeloo[1], A. Kiani[2], H. Salavati [3]*

[1]Department of Mechanical Engineering, Sharif University of Technology, Tehran, Iran.
[2] Department of Mechanical Engineering, University of Eyvanekey, Garmsar, Iran.
[3] Department of Mechanical Engineering, Shahid Bahonar University of Kerman, Kerman, Iran.

ABSTRACT: Laser peening is a life-enhancing process. Radiation of laser pulse with sufficient energy at a very short time on the surface of the material results in the penetration of shock waves into the material and the formation of compressive residual stresses inside it. The purpose of this research is the multi-objective optimization of the laser peening process parameters. The finite element method is used for modeling, Taguchi orthogonal array for design of experiment and the gray relational analysis for multi-objective optimization. The diameter, pressure, time, and overlap rate between two adjacent laser pulses are considered as design factors that change in 4 levels and the Taguchi L16 orthogonal array is used for the experiment layout. The average residual stress at the surface of first pulse, minimum and maximum residual stress and the average of the residual stress depth in the center of two laser pulses were considered as optimization target functions. By performing gray relational analysis, the gray relational grade for each experiment was calculated and the optimal level of each parameter was obtained. The results indicate that the optimal state of each parameter of diameter, pressure, time and the overlap rate are at the fourth, fourth, first and fourth levels, respectively which are 8 mm, 4 GPa, 30 ns, and 75%.

Review History:

Received: 26 Apr. 2019
Revised: 13 Sep. 2019
Accepted: 22 Sep. 2019
Available Online: 2 Oct. 2019

Keywords:

Laser peening
Finite element method
Multi-objective optimization
Grey relation analysis

1. Introduction

Laser peening is one of the life-improvement processes in which a laser beam is irradiated on a metal surface in a very short time (several nanoseconds) [1] On the metal surface, an absorbent coating is painted to protect it and a transparent overlay like water flows over it. As the laser is radiated, it passes through the transparent overlay and encounters the absorbent coating and evaporates it and plasma forms. The plasma is trapped between the metal and the transparent overlay and its expansion delayed so the pressure increases to several Gigapascal. As a result, shock waves are generated and penetrated into the material [2]. Shock waves result in the deformation of the subsurface material and the stresses exceed the Hugoniot elastic limit of material (the compressive strength of the material under shock conditions) and eventually, the compressive residual stress will remain in the material [3]. Despite various studies on laser peening modeling, few studies have been performed to optimize this process. Amarchinta et al. [4] modeled residual stresses generated by the laser peening by inverse optimization of material models for the two materials Inconel718 and Ti-6Al-4V. Wang et al. [5] optimized laser parameters by multi-island genetic algorithm. Hamar et al. [6] also optimized the laser parameters to improve the flexural fatigue properties of Ti-6Al-2Sn-4Zr-2Mo alloy.

The purpose of this study is to apply Taguchi orthogonal array and gray relational analysis for multi-objective optimization of laser peening parameters.

*Corresponding author's email: hadi_salavati@uk.ac.ir

2. Methodology

2.1. Simulation

Ding et al report [7] is used for modeling and verification. They used a two-dimensional model in their study, but it is not possible to investigate effects of overlap rate on surface stresses by two-dimensional model. In this study, for simulation of the laser pulse, a three-dimensional model developed which is shown in Fig 1. In laser peening simulation, the model is divided into two zones: a finite area where laser peening is performed in this area and an infinite

Fig. 1. 3-D Model developed in this study

area around it that is used to damp the stress waves. The finite area has a rectangular shape with elastic and plastic properties, while infinite elements are used around and below the finite area, and only have elastic properties to damp stress waves. C3D8R square elements were used to mesh the finite area and CIN3D8 elements were used for infinite area. ABAQUS explicit is used to analyze the wave propagation and residual stresses. Also a triangular estimation was applied for loading where the laser pressure increased linearly at half of the time to reach the peak and then decreased linearly to zero for the rest of the time.

2.2. Design of Experiments

The traditional design of experiment methods are very complex, costly and time-consuming, and when the number of parameters increases, a lot of experiments must be performed. To solve this problem, Taguchi method greatly reduced the number of experiments using orthogonal arrays. These arrays are selected with specific features from the total number of experiments in the full factorial method. As shown in Table 1 the controllable factors include laser diameter, laser pressure, laser time, and overlap rate between two adjacent laser pulses that each varying in 4 levels. Accordingly, from the proposed Taguchi tables, the L16 experiment is selected, which provides 16 different experiments. Also, average residual stress under the surface of first pulse, maximum residual stress, minimum residual stress and average depth of residual stress at the center of two laser pulses were selected as optimization outputs.

Table 1 . Laser peening parameters and their levels

Parameter	unit	Level 1	Level 2	Level 3	Level 4
Diameter	Mm	2	4	6	8
Pressure	GPa	2.5	3	3.5	4
Time	ns	30	50	70	90
Overlap rate	%	0	25	50	75

2.3. Grey Relational Analysis

In the gray relational analysis, three steps must be taken. A) Data preprocessing: which is a computational method for normalizing raw data to be comparative. B) Gray relational coefficient: After data preprocessing, gray relational coefficients must be calculated to obtain the relationship between the normalized and the ideal data. C) Gray relational grade: After obtaining gray relational coefficients, by averaging gray relational coefficients, the gray relational grade is calculated.

3. Discussion and Results

The results of calculating the gray relational coefficients and gray relational grades for various experiments are shown in Table 1. Based on these results, experiments 6 and 16, that gray relational grade for them is larger than the other experiments, are near-optimal.

Table 2. Response table for the grey relational grade

factors	Diameter	Pressure	Time	Overlap rate
1	0.5239	0.5392	**0.6926**	0.5631
2	0.5798	0.5926	0.5900	0.5594
3	0.6064	0.5857	0.5248	0.5853
4	**0.6244**	**0.6171**	0.5271	**0.6268**
Delta	0.1005	0.0779	0.1678	0.0674
Rank	2	3	1	4

In order to determine the optimized level of each factor, the average gray relational grade for each factor at each level must be calculated. The results are shown in Table 2. According to Table 2, the optimum levels of diameter, pressure, time, and overlap rate are at the fourth, fourth, first and fourth levels, respectively. Therefore, when the laser diameter is 8 mm, the laser pressure is 4 GPa, the laser time is 30 ns and the overlap is 75%, each factor is optimized and the best result is obtained. Also, the higher delta for a factor means the greater effect of that factor. As shown in this table, the difference between the highest and lowest values for the time is 0.1678. So, this factor has the greatest effect on the results. After that, the diameter, pressure, and overlap rate are effective on the results respectively.

4. Conclusions

In this study, the multi-objective optimization of laser

Table 3. Grey relational coefficients and grey relational grade for each experiment

Exp. Num	Average residual stress	Minimum stress	Maximum stress	Depth of residual stress	Grey relational grade
1	0.4978	0.3576	1.0000	0.3333	0.5472
2	0.4606	0.4500	0.7058	0.3917	0.5020
3	0.3788	0.5176	0.4996	0.5403	0.4839
4	0.3333	0.5838	0.3333	1.0000	0.5626
5	0.5541	0.3624	0.8917	0.4399	0.5621
6	1.0000	0.8307	0.7909	0.4019	0.7559
7	0.3451	0.5243	0.4590	0.6391	0.4919
8	0.3859	0.5373	0.4759	0.6391	0.5096
9	0.5294	0.3333	0.6705	0.5998	0.5332
10	0.4178	0.4887	0.5116	0.7404	0.5396
11	0.8469	0.8059	0.7851	0.3917	0.7119
12	0.4670	1.0000	0.5819	0.5139	0.6407
13	0.4580	0.3365	0.6818	0.5807	0.5143
14	0.4890	0.5902	0.6310	0.5807	0.5727
15	0.6542	0.6585	0.5626	0.7457	0.6553
16	0.8473	0.9558	0.7120	0.5067	0.7555

peening parameters was performed by gray relational analysis. The optimization results showed that the optimum state of diameter, pressure, time and overlap rate were in the fourth, fourth, first and fourth levels, respectively, which were 8 mm, 4 GPa, 30 nanoseconds, and 75%, respectively.

References

[1] J.-E. Masse, G. Barreau, Laser generation of stress waves in metal, Surface and Coatings Technology, 70(2-3) (1995) 231-234.

[2] P. Peyre, R. Fabbro, P. Merrien, H. Lieurade, Laser shock processing of aluminium alloys. Application to high cycle fatigue behaviour, Materials Science and Engineering: A, 210(1-2) (1996) 102-113.

[3] J.-M. Yang, Y. Her, N. Han, A. Clauer, Laser shock peening on fatigue behavior of 2024-T3 Al alloy with fastener holes and stopholes, Materials Science and Engineering: A, 298(1) (2001) 296-299.

[4] H.K. Amarchinta, R.V. Grandhi, A.H. Clauer, K. Langer, D.S. Stargel, Simulation of residual stress induced by a laser peening process through inverse optimization of material models, Journal of Materials Processing Technology, 210(14) (2010) 1997-2006.

[5] W. Wang, J.Z. Zhou, S. Huang, Y.J. Fan, C. Wang, J. Fan, Parameters Optimization of Laser Shot Peening Based on Multi-Island Genetic Algorithm, in: Applied Mechanics and Materials, Trans Tech Publ, 2011, pp. 387-390.

[6] S. Bhamare, G. Ramakrishnan, S.R. Mannava, K. Langer, V.K. Vasudevan, D. Qian, Simulation-based optimization of laser shock peening process for improved bending fatigue life of Ti–6Al–2Sn–4Zr–2Mo alloy, Surface and Coatings Technology, 232 (2013) 464-474.

[7] K. Ding, L. Ye, Simulation of multiple laser shock peening of a 35CD4 steel alloy, Journal of Materials Processing Technology, 178(1-3) (2006) 162-169.