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Modelling and multi objective optimization of laser peening process using Taguchi utility concept

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Abstract. Laser peening is considered as one of the innovative surface treatment technique. This work focuses on determining the optimal peening parameters for finding optimal responses like residual stresses and deformation. The modelling was done using ANSYS and values are optimised using Taguchi Utility concept for simultaneous optimization of responses. Three parameters viz. overlap; Pulse duration and Pulse density are considered as process parameters for modelling and optimization. Through Multi objective optimization, it is showing that Overlap is showing maximum influence on Stress and deformation followed by Power density and pulse duration.

1. Introduction

Laser Shock Peening (LSP) is a surface modification process to improve surface reliability and impart beneficial stresses in material. LSP comes into a category of cold working process in which pressure waves are created by intensifying plasma plastically deforming the surface of a material. LSP Works on the energy conservation law – laser energy is used to increase the internal energy of the plasma as work produce by the shock waves. The plasma blow off obtained when a elevated power pulsed laser is focused onto the surface of a target, induces a pulsed pressure as a result of retreat phenomenon of the ablated material. Generally Nd-YAG (neodymium-doped yttrium aluminium garnet) laser is used for pulsed laser shock peening; the Nd-YAG laser hits the mirror and is directed through the bi-focal lens. The lens then converge the laser beam to the point on the material. The material is partially or fully submerged in the confining medium. As the beam comes in contact with the surface, plasma is formed due to the pulsed pressure. As the pulsed pressure is generated due to the recoil momentum of the ablated material, plastic deformation takes place on the surface of the material and elastic deformation takes place below the surface. So on the surface there is permanent deformation while in the depth; the material retracts its original shape. Also due to this, the surface portion is under compression while the portion beyond the surface is under tension. The distribution of compressive and tensile stresses is shown in the figure below



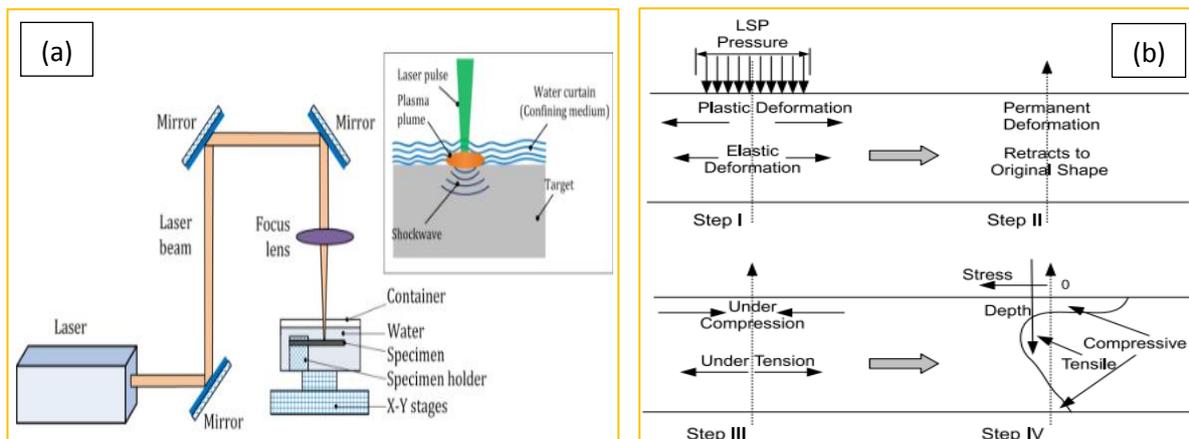


Figure 1(a). Schematic diagram of LSP

(b) Mechanism of LSP.

From past 20 years, LSP turn out to be an economical alternative surface treatment technology for various metals, alloys and super alloys in improving fatigue, wear and corrosion resistance. Initially the LSP is used by Battelle Columbus Laboratories (USA) for strengthening of metallic fasteners holes. Intensifying research in France Laboratories (CLFA, LALP, and LULI) on LSP started inspecting various LSP parameters leads to maximise induced stresses and to make LSP a process for industrial application [Charles S. Montross]. Due to extensive research LSP process gained some advantages over conventional shot peening, for instance decrease in surface damage, increase in compressive stresses penetration depth, and getting more control on process parameters [Robert A. Brockman].

Among the various output parameters most significant performance parameter measures or responses of LSP process are surface roughness (SR), and Residual Stress (RS), are affected by numerous process parameters, e.g. Laser Power Pulse Density, Pulse Duration, Operating Frequency, Ablation Layer, Laser Energy, Laser repetition rate, Laser beam spot Diameter, Focal length between mirror and biconvex lens, confinement layer (water) thickness etc. Enhanced performance of LSP process can only be accomplished by setting the optimal levels for those process parameters.

2. Literature Survey

Titanium compounds discover applications in aerospace segments as they are light weight with enormous rigidity and stable even in high temperatures. Mean while components are able to experience cyclic loads in such applications. The majority of the mechanical properties under fatigue conditions are organized by the subsequent surface defects; efforts to change the surface by building a residual compressive stress in sub surface layers the surface are not unusual. These stress states would bring about a close impact on the inconvenient breaks, keeping them from generating. Shot peening is generally used to induce compressive stresses into the material Shot peening is generally reasonable, utilizes dynamic process and can be employ for substantial or little ranges as necessary. Despite, the shot peening process has its confinements. Shot peening results in rough surface which should be removed while using in wear applications and most of the roughness removing processes abolish the compressive layer [1]. Keeping in mind the end goal to positively influence execution, the residual stresses created by Laser Shock Peening (LSP) ought to be compressive near critical areas where failure is probably going to happen [2]. Modifying the surface layer properties of metal components primarily and effectively increases resistance to wear and makes the work material resistant for a range of high temperatures [3] amid the laser treatment, the temperature increments with rapid rates fluctuating from 103 to 105 K/s. These extraordinary warming and resulting cooling conditions

prompt to complex metallurgical and morphological changes of the metal [4]. Laser matter collaboration is said to rely upon a few parameters: fluence, wavelength, and repetition rate and pulse duration [5]. The real drawback of the laser peening procedure has been its cost. Sophisticated optimisation techniques are required to recognize the optimal set of process parameters to attain required response in LSP process. The controlling LSP parameters that are taken into account are: wavelength, power density and spot overlapping. In this paper, the advanced Taguchi-Utility was used to optimise LSP in processing Ti6Al4V material, considering compressive stresses and deformation correlated responses.

A large amount of work has been done on the LP the different applications for different materials. In order to find the effect of LP, many simulations and experimentations have been conducted in past few years. William Braisted et al. [6] carried out FE simulation of LSP, which make use of the business-related FE code ABAQUS to find out both the little shock wave reaction and consequential residual stress state in the object. They found that by giving attention to constitutive process to overview modelling details, conditions for loading, and refinement of mesh, accurate predictions can be made. Yongxiang Hu, et al. [7] used a sequential procedure together with static analysis carried out by ANSYS and dynamic analysis carried out by LS-DYNA is shown in detail to achieve simulation of the single and multiple shot laser shock processing. After simulation of LSP they found that as increment in the Laser shock number, the induced compressive stress and the plastically influenced depth can be improved. Bing Han [8] conducted experiments on FE software. LS-DYNA/ANSYS was practiced to create the residual stress field of steel (SAE1070) surface layer all set by LSP practice. The researchers found that on surface of the treated material, a homogeneous depression with insignificant roughness change in the shock pressure action zone induced by single LSP, with respect to the simulation of surface deformation. Gulshan [9] by using FEA software, a FE capable simulation of the LSP process is developed. The experimental results are validated with the simulations and PMOS (Progressive Multi fidelity Optimization Strategy) technique is used for optimization of residual stress. The PMOS technique employs comparatively low computational intensity models to locate the set of parameters that may offer the optimal solution.

David Mbukwa studied recently developed surface enhancement technique called Laser shock forming. Simulation has been done to predict the different effect of different parameter on the residual stresses and experiment has been performed to validate the result. David Mbukwa concludes that the LSF is mechanical process not a thermal process. The LSF process is now becoming very flexible manufacturing process with short manufacturing time. Rajyalakshmi [10] describes optimization of parametric approach to find out the optimal process parameters in WEDM process. Conventional Taguchi approach was lacking to solve a multi response optimization problem. To overcome this limitation, the concept of utility theory has been put into practice, to convert multi-responses into single equivalent response called overall utility index. Tatjana et al.[11] performed LSP process modelling and optimisation using the advanced, problem-independent method. Responses are recorded using Taguchi's quality loss function, followed by multivariate statistical methods to un-correlate and making them into a single performance measure. ANN's are used for building the process model, and by utilizing simulated annealing the optimal process parameters. Y.B.Guo [12] further studied the LSP effect on the Mg – Ca alloy in order to determine the effect of LSP on surface topography and to predict the residual stress profile. Simulations and experimentation were performed on Mg- Ca alloy. They found that simulated residual stress and deformation geometry was similar to experiment data. Rozmus et al. [13] studied the effect of laser shock peening on Ti6Al4V (Titanium alloy grade 5). A high power operating Nd-YAG laser has been used in 1064 micro meter wavelength range. The Power density was 1 GW/cm^2 and pulse duration was 18 ns, SEM showed that LSP caused melting and ablation of surface and improved the mechanical properties. Hfaiedh et al. [14] studied the FE analysis of LSP of 2050-T8 aluminum alloy. In the experiment 2050-T8 aluminum alloy was processed with Nd-YAG pulsed laser with 10 ns pulse duration with up to 1.5 J per pulse at 0.53 micro meters. In this paper they proposed a 3D model for simulating the residual stress induce by LSP.

Milos et al. [15] used regression analysis, artificial neural network (ANN) and fuzzy logic to simulate the model and optimize the kerf width obtained in CO₂ laser cutting. Statistical values of the coefficient of determination and absolute percentage error were employed to compare the experiments developed using Taguchi's method. Fuzzy logic showed the best overall prediction results while developed ANN model best generation capability. Among all the surface enhancement method, Laser Shock peening was found to be effective because of its characteristics like deeper residual stress, minimum surface roughness impact, thermal and mechanical stability and more fatigue life. Simulations were found to be more effective in the process of optimization because it is lot easier to explore for different set of parameters. The practical applicability of the process of optimization has been learnt by using it to find best set of LP parameters for better surface properties of the materials.

3. Methodology for Simulation

With the increasing number of application of surface enhancement techniques, there comes the need to explore various methods to improve surface for different materials. The experimentation of various surface enhancement processes is difficult as in some cases it may be time consuming due to the complexity of the geometry. Thus computational exploration method needs to be introduced for easier study of various processes and there comes the role of finite elemental simulation. But before proceeding to simulation, the modeling of the geometry needs to be done. The modeling of the geometry with overlapped spots of 60% and 70% is achieved using SOLIDWORKS as shown in Fig.2. The important modeling parameters to be considered are the laser spot shape and overlap percentage. These parameters are determined based on experimental setup available for peening. Once the model is obtained the material is defined with the properties as shown in Table 1 and the various boundary conditions like fixed support and pressure load is applied.

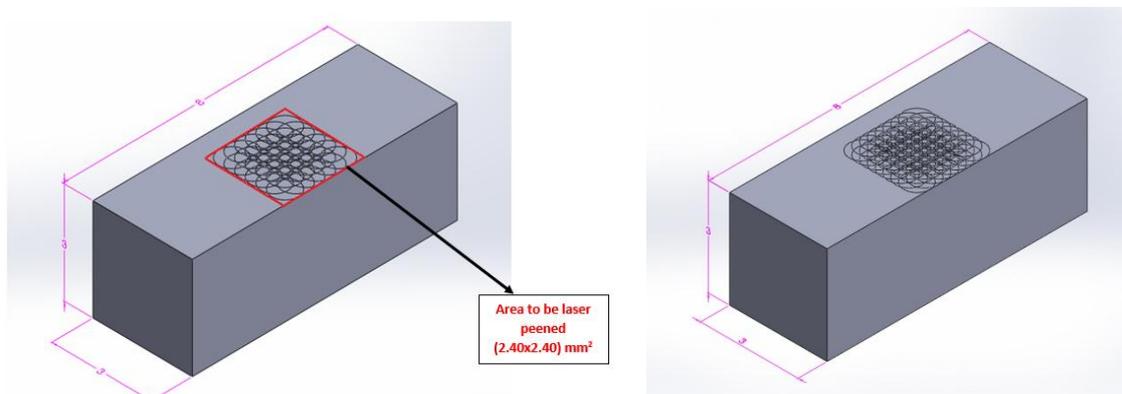


Figure 2. Model with 60% and 70% overlapped spots

The pressure is calculated corresponding to each set of parameters using the formulas mentioned below:-

$$P \text{ (GPa)} = 0.01 \sqrt{\frac{\sigma}{(2\sigma+3)}} \sqrt{I \text{ (GW/cm}^2\text{)}} \sqrt{Z \text{ (g cm s}^{-1}\text{)}}$$

$$\frac{1}{Z} = \frac{1}{Z1} + \frac{1}{Z2}$$

where I is the power density, P is the pressure generated by shock waves, Z is the resultant acoustic impedance of the medium which is equal to product of density of that medium (ρ) and velocity of sound (u) in that medium, $Z1$ is the acoustic impedance of Ti6Al4V = $2.75 \times 10^6 \text{ gcm s}^{-1}$ and $Z2$ is the acoustic impedance of water = $1.65 \times 10^5 \text{ gcm s}^{-1}$ and σ is the efficiency of interaction = 0.1 for water.

Once the material is defined a transient structural study has been created in ANSYS workbench. The model is meshed with medium element size which is shown in Fig 3. This is followed by providing support for the model where all the faces other than top face are provided with fixed support. The pressure type load is applied to each laser spot in the array step-wise where each step is of the duration of 8, 10 and 12 nanoseconds. The magnitude of the pressure is obtained from the calculation which is tabulated in the Table 1. The final model with all the boundary conditions applied is solved for total deformation and equivalent stress. The pressure obtained for each set of parameters is applied on the array of laser spots considering the temporal profile of laser pulse and pressure pulse. The simulation is solved and the maximum Von-Misses stress and maximum deformation obtained over the entire peened region is recorded.

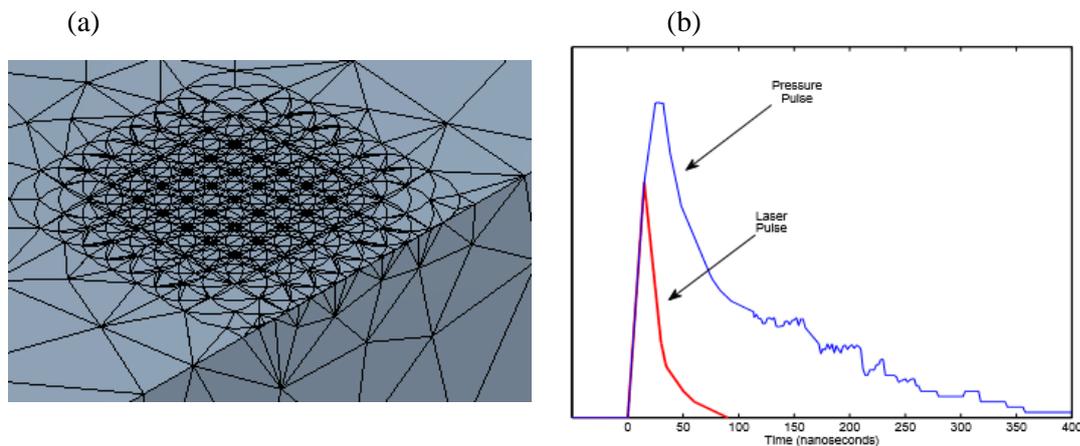


Figure 3 (a) Meshed model (b) Temporal profile

4. Optimization Techniques:

4.1 Taguchi's Design of Experimentation:

A robust design with support of DOE (Design of experiments) was proposed by Taguchi. This method acts as a most excellent technique for designing variable sets of response characteristics. DOE comprise of selecting fitting orthogonal array and transfer of variables and appropriate column collaboration. The number of experiments was reduces by Taguchi method with help of orthogonal array thus dropping the large experimentation efforts.

Taguchi's Design of Experimentation method intends to achieve ambitious value with optimizing deviation of parameters influencing ambitious value. A quadratic equation is used by Taguchi method in shaping of quality loss at any time the variability of parameters departs from its targeted value and considered Signal to Noise (SN) ratio as a performance measure. The outstanding feature of SN ratio is that it merges both dispersion and location of a response variable as a individual response, while, remaining methods inspect mean and variance as a split responses. In Taguchi method the responses are mostly categorized into three classes, e.g. larger-the-better (LTB), nominal-the-best (NTB) and smaller-the-better (STB). The formula for calculation of SN ratio (η_{ij}) for j th reaction corresponding to i th trial ($j = 1, 2, \dots, p; i = 1, 2, \dots, m$) are varying for other types of responses, and these are given as follows:

For LTB response variable,

$$\text{S/N Ratio} = -10 \log_{10} \left(\frac{1}{n} \sum_{i=1}^n \frac{1}{y_{ij}^2} \right) \quad (1)$$

For STB response variable,

$$\text{S/N Ratio} = -10 \log_{10} \left(\frac{1}{n} \sum_{i=1}^n y_{ij}^2 \right) \quad (2)$$

For NTB response variable,

$$\text{S/N Ratio} = -10 \log_{10} \left(\frac{y_{ij}^{-2}}{s_{ij}^2} \right) \quad (3)$$

The ANOVA is employed to experimental results which help to find out impact of every single parameter on response factor beside predefined confidence level. This work focuses on, the impact of three input factors, Overlap (%), Power Density (GW/cm²), Pulse Duration (ns) using L18 orthogonal array. ANOVA and mean effect plot were determined using Minitab16 Software.

4.2 Utility Concept :

The term Utility can be described as helpfulness of a process or a product in testimonial to the expectations range of the consumers. The outcome assessment of any process is relying on various numbers of outputs variables. For that reason, a collective scale is required to weigh its overall attainment, which should consider the percentage of contribution of all the responses. Such complex indicator stands for the whole utility of a process/product. It accommodates a procedural environment for the assessment of optioned attributes created by every single person, factories and societies. Utility concept concerns to the fulfillment that each quality supplies to the decision maker. Hence, utility concept believe that, from the source of maximization principle of utility concept any judgment is prepared, according to which the most excellent option is the one which provides the maximum compensation to the problem solver [8]

According to the utility theory [9, 10] if the scale of effectiveness is X_i of an attribute (or response) i and n attributes are there to calculate the outcome space, then the combined utility function can be articulated as:

$$U(Y_1, Y_2, \dots, Y_n) = f(U_1(Y_1), U_2(Y_2), \dots, U_n(Y_n)) \quad (4)$$

Here, $U_i(Y_i)$ is the utility of the i^{th} attribute.

The addition of individual utilities gives the overall utility function if the responses are independent, and is given as follows:

$$U(Y_1, Y_2, \dots, Y_n) = \sum_{i=1}^n U_i(y_i). \quad (5)$$

The overall utility function after assigning weights to the attributes can be expressed as:

$$U(Y_1, Y_2, \dots, y_n) = \sum_{i=1}^n W_i U_i(Y_i) \quad (6)$$

The preference number can be expressed on a logarithmic scale as follows:

$$P_i = A \times \log \left(\frac{Y_i}{Y_i^*} \right) \quad (7)$$

Here, Y_i is the value of any response i , Y_i^* is just acceptable value of response i and A is a constant. The value A can be found by the condition that if $Y_i = Y_i^*$ (where Y_i^* is the optimal or best value), then $P_i = 9$

Therefore,

$$A = \frac{9}{\log \frac{y_i^*}{y_i}} \quad (8)$$

The whole utility can be expressed as follows:

$$U = \sum_{i=1}^n W_i P_i \quad (9)$$

Subject to the condition:

$$\sum_{i=1}^n W_i = 1$$

For single objective optimization, overall utility index is considered. In various response types, viz. Higher-the-Better (HB), Nominal-the-Best (NB), Lower-the-Better (LB) and recommended by Taguchi method, the utility function should be higher. In the planned methodology, utility values of each parameter responses are gathered to compute overall utility catalogue.

A Taguchi DOE table is fabricated as tabulated in Table 1 using Taguchi Design which considers various laser parameters like overlap, power density and pulse duration. There are three LP parameters of which one of the parameters has 2 levels and the rest two parameters have 3 levels each. The resultant table will have an L18 run which means a total 18 set of experiments.

Table 1. Pressure corresponding to each set of parameters

Set. No.	Overlap (%)	Power Density (GW/cm ²)	Pulse Duration (ns)	Pressure (GPa)
1	60	3	8	1.708
2	60	3	10	1.708
3	60	3	12	1.708
4	60	6	8	2.416
5	60	6	10	2.416
6	60	6	12	2.416
7	60	9	8	2.959
8	60	9	10	2.959
9	60	9	12	2.959
10	70	3	8	1.708
11	70	3	10	1.708
12	70	3	12	1.708
13	70	6	8	2.416
14	70	6	10	2.416
15	70	6	12	2.416
16	70	9	8	2.959
17	70	9	10	2.959
18	70	9	12	2.959

5. Results and Discussion

Finite element simulation of Laser shock peening has been performed on the Titanium alloy (grade 5-Ti6Al4V) and various results such as total deformation, Von-Misses stress and plot of residual stress vs. depth from surface have been found out.

5.1 Total Deformation

The area which is simulated for peening deforms under the action of pressure. This large pressure is applied for a time in nanoseconds. This results in the deformation of the test surface. The more is the pressure applied more will be the deformation of the surface. Similarly if the pressure is applied for more amount of time, then also the deformation will be more. The effect of various parameters on deformation is discussed below.

5.1.1 Effect of Overlap of Laser Shots on Total Deformation

It has been found that when the overlap percentage of laser spot is kept on increasing keeping all other LP parameters constant, the surface is deformed more for the case with higher overlap percentage. The effect of overlap of laser spot can be seen in the below figure where the power density is kept constant as 3 GW/cm^2 , pulse duration as 10ns and the overlap is varied as 60% and 70%.

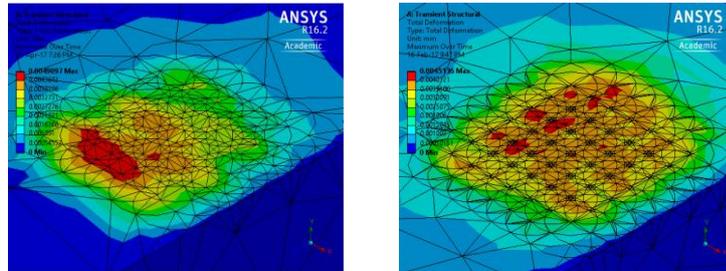


Figure 4.Total deformation of 60 and 70% overlap, 10ns pulse duration and 3 GW/cm^2 power density

5.1.2 Effect of Power Density of Laser Shots on Total Deformation

It has been found that when the Power density of laser spot is kept on increasing keeping all other LP parameters constant, the surface is deformed more for the case with higher overlap percentage. The effect of power density of laser spot can be seen in the below figure where the overlap is kept constant as 70%, pulse duration as 10 ns and the power density is varied as 3, 6, 9 GW/cm^2 .

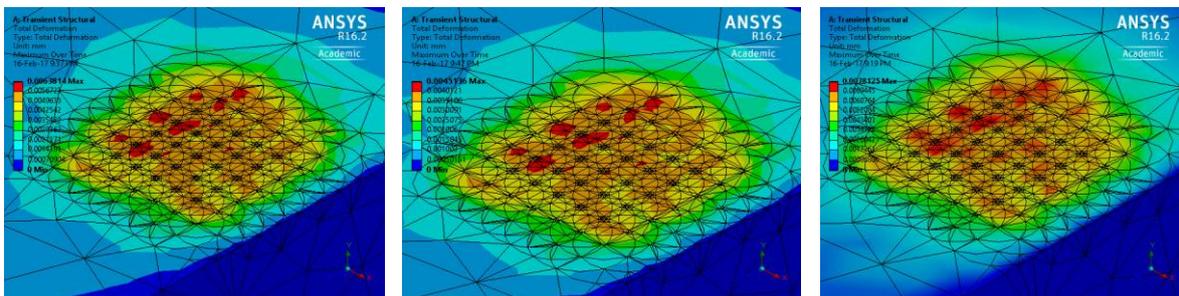


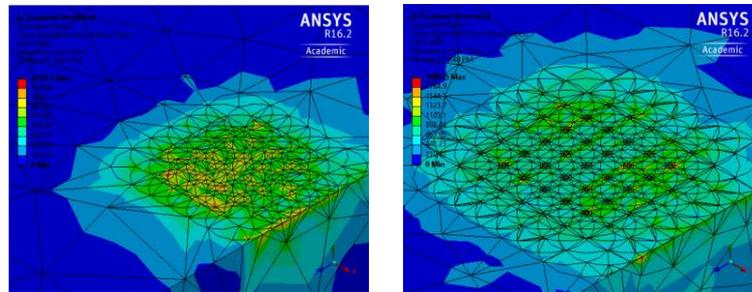
Figure 5.Total deformation for 70% overlap, 10ns pulse duration and 3, 6, 9 GW/cm^2 power density

5.2 Residual Stress (Equivalent stress)

The process of hardening involves inducing of stress on the material. These stresses are of compressive type. This induced compressive stress is responsible for the action of surface hardening. The more is the magnitude of the compressive stress the harder will be the surface. Moreover greater the depth of penetration more will be the surface hardening. The effect of various LP parameters on the inducing of residual stress is discussed below.

5.2.1 Effect of Overlap of Laser Shots on Residual stress

It was observed that when the overlap percentage of laser spot is kept on increasing keeping all other LP parameters constant, the magnitude of residual stress is more for the case with higher overlap



percentage. The effect of overlap of laser spot can be seen in the below figure where the power density is kept constant as 3 GW/cm^2 , pulse duration as 10 ns and the overlap is varied as 60% and 70%.

Figure 6. Residual stresses for 70% overlap, 10ns pulse duration and 3 GW/cm^2 power density

5.2.2 Effect of Power Density of Laser Shots on Residual stress

It was observed that when the Power density of laser spot was kept on increasing keeping all other LP parameters constant, the surface is deformed more for the case with higher overlap percentage. The effect of power density of laser spot can be seen in the below figure where the overlap is kept constant as 70%, pulse duration as 10 ns and the power density is varied as 3, 6 and 9 GW/cm^2 .

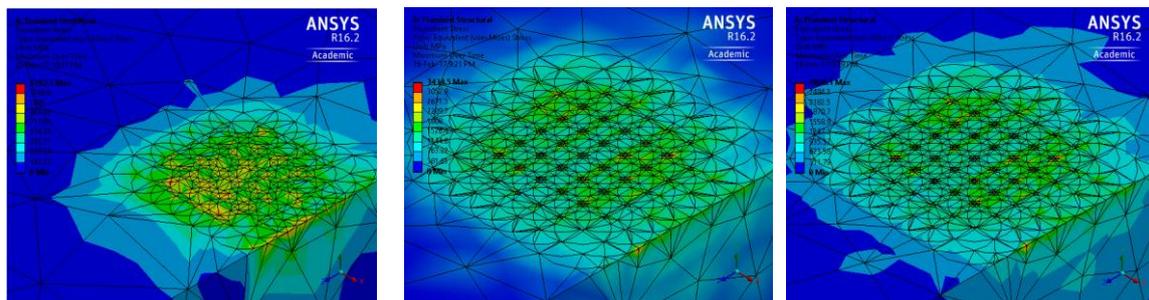


Figure 7. Residual stress for 70% overlap, 10ns pulse duration and 3, 6, 9 GW/cm^2 power density

The values of Average equivalent stress and maximum deformation corresponding to each set of parameters is recorded. These values are used for the purpose of optimization and determination of best set of parameters for deep penetration of compressive stress.

Table 2. Avg. Eq. Stresses and Deformation corresponding to each set of parameters

Set. No.	Overlap (%)	Power Density (GW/cm^2)	Pulse Duration (ns)	Average equivalent stress	Maximum Deformation
1	60	3	8	309.36	0.0045647
2	60	3	10	339.35	0.0049097
3	60	3	12	403.5	0.0051303
4	60	6	8	438.2	0.0064538
5	60	6	10	465.15	0.0069394
6	60	6	12	566.18	0.0072504
7	60	9	8	572.2	0.0079016

8	60	9	10	598.97	0.0084939
9	60	9	12	672.32	0.0088737
10	70	3	8	362.21	0.0045702
11	70	3	10	412.33	0.0045136
12	70	3	12	491.93	0.0045558
13	70	6	8	529.63	0.0064587
14	70	6	10	582.68	0.0063814
15	70	6	12	667.87	0.0064394
16	70	9	8	648.63	0.0079048
17	70	9	10	702.16	0.0078125
18	70	9	12	788.68	0.007882

5.3 Single objective optimization using Taguchi method:

5.3.1 Effect on Deformation

To determine the effect of process parameters on Deformation, response values are evaluated and presented in Table 3. Figure 8 signifies the average effect plot of maximum deformation as overlapping spot, pulse time and power density on deformation at the selected set of parameters. The average values of deformation for each parameter at levels 1, 2 and 3 for raw data plotted in Figure 8. It shows that the deformation increases with the increase in power density. Pulse duration has very slight effect on deformation. Deformation is increased negligibly for spot overlapping.

Table 3. Response table for Deformation.

Level	A	B	C
1	0.006724	0.004707	0.006309
2	0.006280	0.006654	0.006508
3	-	0.008145	0.006689
Rank	2	1	3

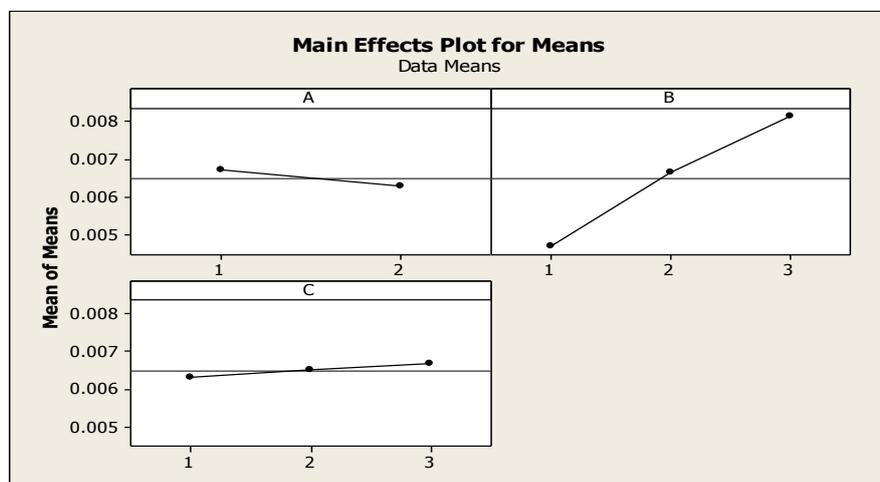
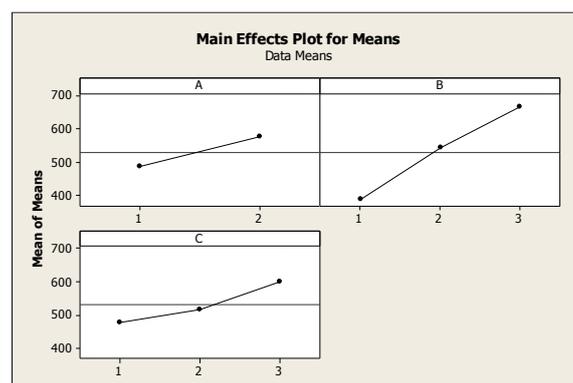


Figure 8. Response graph of Deformation*5.3.2 Effect on Residual Stresses:*

To determine the effect of process parameters on residual stresses, responses are premeditated and presented in Table 4. Figure 9 represents the mean effect plot of residual stresses as overlapping spot, pulse time and power density on deformation at the selected set of parameters. The average values of deformation for each parameter at levels 1, 2 and 3 for raw data plotted in Figure 9. It is seen from the Figure 9 that residual stress increases with the increase of power density and spot overlap. Pulse duration time showing little effect on residual.

Table 4. Response table for Residual Stress

Level	A	B	C
1	485.0	386.4	476.7
2	576.2	541.6	516.8
3	-	663.8	598.4
Rank	3	1	2

**Figure 9.** Response graph of Residual Stresses*5.4 Multi Response Optimization:*

The favorite scales for determining overall utility was builds pending Eq. 7. For building of preference scale for deformation, the least value of deformation was taken into account from the analysis (Table 2) as the least possible acceptable value since this characteristic is “smaller-the-better” type. As shown in Eq. 8, best value of chosen characteristics is preferred for computation of value of A under purpose of preference scale. Single objective optimization was done for deformation using Taguchi’s design. The vales are plotted using Minitab 16 software best optimal combination (A-2 B-1 C-1) was determined (Figure. 8). The predicted optimal value of deformation (0.0045702mm) was calculated using Taguchi approach.

Preference scale construction deformation:

X^* = optimum value of deformation = 0.0045702mm

X^1 = minimum permissible value of deformation =0.0088737mm supposed, as all the observed values of deformation in Table 4 are in between 0.0045647 and 0.0088737

Substituting these values and the equations (4) and (5), the favorite scale for deformation was constructed as

$$P_{\text{deformation}} = -31.23 \log [X_{\text{deformation}}/0.0088737] \text{ ----- (8)}$$

Preference scale construction Residual stresses:

For building of preference scale for residual stress, the leading value of for residual stresses was taken into account from the simulation (Table 2) as the maximum permissible value since this representative is “higher-the-better” type. As indicated in Eq. 8, best value of chosen characteristics is preferred for estimation of value of ‘A’ under purpose of preference scale. Single objective optimization was done for surface roughness attempting Taguchi’s design. The values are plotted using Minitab 16 software best optimal combination (A-2 B-1 C-3) was determined (Figure. 9).

The forecasted optimal value of for residual stress (2.08 μ m) was calculated using Taguchi approach.

X^* = optimum value of Residual stress=788.68

X^1 = minimum acceptable value of Residual =309.36Mpa (expected, as all the experiential values of residual stress in Table 2 are in between 309.36Mpa to 788.68Mpa)

With these results and the equations (4) and (5), the favorite scale for SR was built as

$$P_{\text{Res. Str.}} = 22.1436 \log [X_{\text{Res. Str.}}/309.36] \text{ ----- (9)}$$

Table 5.Utility Values and Ranks

Set. No.	Preference value Stress	Preference value Deformation	Overall utility	Rank
1	0	9.015867	4.507933417	10
2	0.889812	8.027665	4.458738238	11
3	2.554915	7.431553	4.993233743	12
4	3.348294	4.318773	3.833533579	13
5	3.922271	3.334827	3.628549121	14
6	5.812482	2.740207	4.276344257	16
7	5.914194	1.57367	3.743932434	15
8	6.353905	0.593295	3.473599887	17
9	7.46487	0	3.732435221	18
10	1.516754	8.999535	5.258144389	3
11	2.763096	9.168556	5.965825613	1
12	4.460588	9.042337	6.751462509	2
13	5.170717	4.308479	4.739598118	7
14	6.088736	4.471785	5.28026074	4
15	7.401006	4.349069	5.875037675	5
16	7.119895	1.568179	4.344037016	9
17	7.8825	1.727478	4.804989197	6
18	8.999971	1.607355	5.303663194	8

5.5 Utility value calculation:

The utility result of each peened part was computed using the subsequent overall utility function:

$$U(n, R) = PMRR * WMRR + PSR * WSR + PSG * WSG \text{ (11)}$$

Where, n = test number,

$n = 1, 2, \dots, 18$;

R = reproduction number, R = 1, 2, 3

The utility results thus computed are accounted in Table 5.

Table 6. Response table for Utility

Level	A	B	C
1	4.072	5.323	4.405
2	5.369	4.606	4.602
3	-	4.234	5.155
Rank	1	2	3

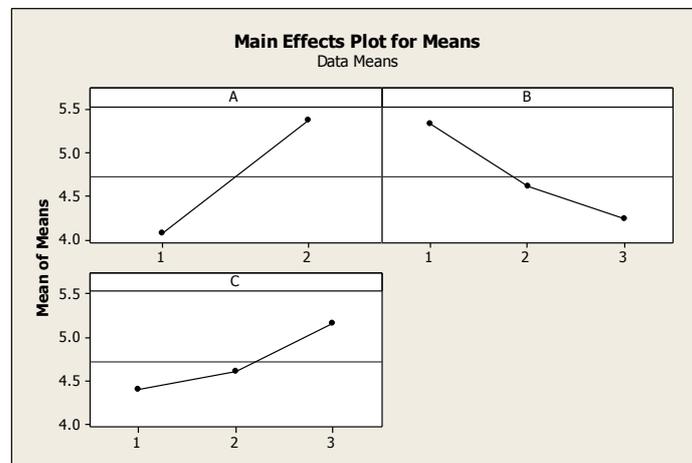


Figure 10. Response graph of Utility Values

5.6 Analysis of the data and determination of optimal settings of process parameters:

The results are analysed for SN ratio. While utility is a “higher the better” (HB) kind of feature, (SN) HB has been utilised (Ross, 1996):

The Response table for overall utility results are represented in Table 6. The mean responses and key effects of utility values are evaluated and accounted in Figure 10.

From Utility graph, the optimal set of peening parameters for multi objective optimization is suggested as A-2 B-1 C-3.

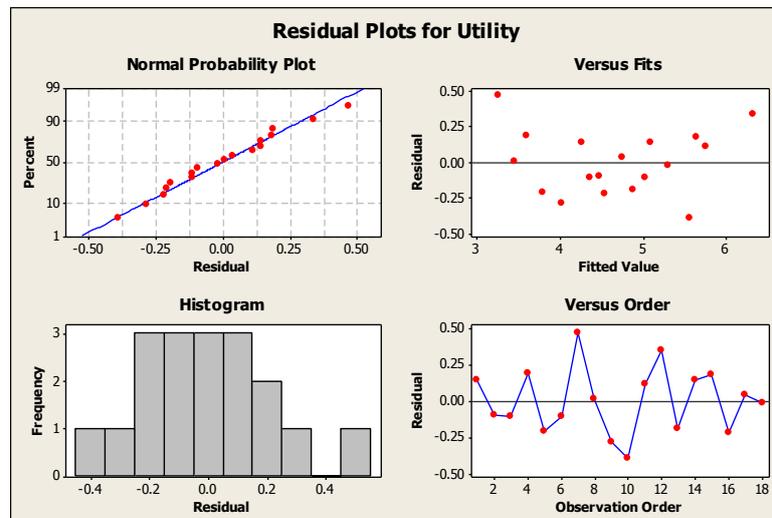


Figure 11. Statistical plots of Utility values

Table 7. ANOVA for Utility

Source	DF	Seq. SS	Adj. MS	F	% Contribution
A	1	7.4652	7.4652	104.14	60.36
B	2	3.1892	1.5946	22.24	25.78
C	2	1.8527	0.9263	12.92	14.98
Error	12	0.8602	0.0717		
Total	17	12.3673			

$S = 0.267740$ $R\text{-Sq} = 93.56\%$ $R\text{-Sq (adj.)} = 90.88\%$

It is understandable from the Fig.10 that the Overlap second level, the power density First level, pulse duration third level, will yield best result in terms of utility value within the particular range of responsive parameters.

The ANOVA for utility values are given in Table 7. Proximity of points to the straight line denotes that assumptions are not offended, since errors are normally and independently distributed. Residual versus run number plot (Figure 11) explains that there is no complicated pattern and unused structure, which uncovers that separate and fixed deviated assumptions are not opposed and no correlation between residuals has been noticed. Since actual and predicted values lie on a straight line Fig 11 denotes that the normal distribution of errors. The above explanation concludes the abundance of the suggested model. There is no reason existed to suspect any violator of independence or fixed variation assumptions.

Conclusions

Laser peening has been successfully done and the following conclusions are drawn.

- Deformation increases with the increase in power density. Pulse duration has very slight effect on deformation. Deformation is increased negligibly for spot overlapping.
- Residual stress enhanced with the raise of power density and spot overlap. Pulse duration time showing little effect on residual stress.
- Second level of Overlap, the First level of power density, third level of pulse duration, will yield best results in terms of utility value within the particular range of responsive parameters.

- From ANOVA of utility, overlap showing maximum influence on combined parameters followed by power density and pulse duration. It is concluded that utility concept is giving better optimization approach for laser peening process

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