Optimization of Laser Forming Parameters Using Genetic Algorithms

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ABSTRACT

The use of lasers is being considered as a modern method for forming process in recent years. This method has been used in various industries, such as aerospace, marine and oil industry. Extensive research has been done in the field of modeling and optimization of direct paths parameters with process of laser forming. Although forming in circular paths can be used for producing complex parts, due to some technical reasons, it is considered less. The main purpose of this paper is to detect the proper estimation model and obtain optimal variables conditions for complete circular paths in perforated circular parts by means of genetic algorithms. In this process the outer edges are fixed and the inner edges are being formed by laser. At first, the finite element simulation model is studied then the estimation model has been discussed, after that multi-objective functions have been examined with the least error and energy. Furthermore, the optimization results of the internal hole diameters are reported and analyzed in terms of Pareto charts. In conclusion, optimum forming conditions have been reported in terms of accuracy and energy for different diameters of holes. This study shows with acceptable increasing in the error rate, the required energy could be reduced. Also, increasing in the diameter of inside hole cause to increase energy and decrease of accuracy.

1-Introduction

Laser forming process is one of the advanced techniques among forming processes which is being used in industries such as shipbuilding, automotive, microelectronics and aircraft [1]. In this method, sheet metals are given form by non-uniform thermal stress. In compare to other common methods of forming, laser-assisted forming has significant advantages such as lower costs, less production time and higher precision in low production rates [1]. Creating complex shapes with curved profiles and forming small parts also can be done by laser forming method. Brittle materials such as Titanium alloys, Nickel alloys and ceramics can be formed in this method [1]. Since the numerical simulations are time consuming and due to difficulties of solving analytical models their results are not enough satisfactory, studies over methods with precise estimations in less time and high accuracy are taken into consideration.

Chang and Lin [2] used three supervised neural networks to estimate the curve angles in laser forming by using laboratory test data. Part of the experimental data were used for training the networks and rest of them has been used to evaluate model performance. Their results

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showed that the neural network's response was much quicker and easier than using multiple regression analysis. In another research which was conducted by Chang et al. [3], a new hybrid fuzzy neural network has designed in order to predict bending deformation of a sheet metal with laser. The main characteristic of this type of networks is that fuzzy rules and fuzzy membership functions can be automatically learned. Which is an excellent capability to predict and control complex systems. Shimizu et al. [4] developed a method that allow the genetic algorithms to decide the path of the laser, laser power and scanning velocity to form a spherical shape provides simple. Cheng and Yau [5] was presented an approach based on genetic algorithm, to examine the possibility of using this algorithm in laser-assisted forming process, a set of two-dimensional shapes and profiles selected for this purpose. Hosseinpur et al. [6] evaluate the linear regression model using data that is obtained from Taguchi's experimental design. The results of this model and the experimental have shown good agreement. Gysaryv et al. [7] control back phenomenon flexibility in the process of bending aluminum examined during a combined process. They used a high power laser diode to prevent deformation of sheets that have already been pre-bended after releasing from constraints fixtures and used the perceptron multilayer neural networks to predict, control and management of recurrent flexibility during the V-bending process of thin aluminum sheets. Kantl Majy et al. [8] proposed software computational methods to predict deformations made in laser-assisted machining process for a set of heating conditions and direct paths in order to achieve a specific form. They use both genetic-neural network and adaptive fuzzy-neural network sharing system in order to analysis process of laser forming. They use beam power, swap speed, beam diameter and number of swaps as inputs and bending angle as output. Both tools were involved in their work showed that were well able to predict the bending angles, so it can be used in the process of inverse problem to find a relationship between the results obtained and process of laser forming parameters. Moslemi Naeini et al. [9] estimate bending angles by using data that are obtained from interpolation relationship between experimental and simulation results. R.Tarkesh. E et al. [10] used a single objective genetic algorithm for optimizing the mesh density for FEM in modeling the forming process in circular path. They employed ANFIS for estimating the deflection for different FEM densities.

In this paper, evaluation and optimization of laser forming process parameters on circular paths is considered, according to pervious researches which are conducted in the field of parameter optimization of laser forming. First the finite element simulation model is studied. Then the estimator models is investigated. Finally, the issue of multi-objective optimization considering the least amount of energy with maximum deflection constraints is discussed.

2. The finite element simulation model

In the process of shaping laser radiation, heat transfer is available due to the heating caused by the laser beam on the workpiece surface. Heat transfer is conducted in various forms such as conduction, convection and radiation. Part of sheet heats transfer by conduction and others transferred to the environment by convection and radiation. The temperature distribution in the sheet is obtained by using the finite element method.

2.1 Assumptions

Some conditions and assumptions are considered in this study for the process of laser forming, which are described in following.

1- Heat source distribution: the distribution of laser power (thermal flux) is assumed to be Gaussian. [11, 12].

2- Three-dimensional transient of heat transfer conductivity: the laser beam moves at a constant speed causes semi statics heat distribution. In the beginning and end of the process the heat distribution is non-stationary and three-dimensional transient occurs during transportation of sheet surface [13].

3- Boundary conditions, convection and radiation: high temperature difference between the workpiece and surrounding area causes convection and radiation. If the air blown onto the workpiece, forced displacement will also happen [13].

4- Non-linear physical properties: thermal physical properties such as conductivity and specific heat are strongly dependent on the temperature [13].

5- Change phase and phase transformation: workpiece surface does not melt during the process and the effects of changing phase and latent heat are not considerable.

Furthermore, assumptions and conditions in physical aspects of mechanical simulation include:

1- Non-linear mechanical properties of materials: mechanical properties are strictly dependent on temperature. Coefficient of thermal expansion increases gradually with increasing of the temperature. Young's modulus, yield stress, Poisson's ratio and modulus of hardening strain are temperature dependent.

2- Boundary conditions: in laser forming process, it is assumed that there is no external load on workpiece and one edge of the workpiece is bounded.

3- Thermo-elastic and thermos plastic: during the laser forming process, the conditions are thermos-elastic-plastics. Also a plastic area is created around laser beam line.

In heat transfer analysis, Sheet metal mesh is made by DC3D20 elements. Each DC3D20 element is a three-dimensional element with 20 nodes, such as in Figure 1. This element is a diffusive element that are made in ABAQUS in order to use for heat transfer analysis (Non-coupled heat transfer analysis) and allow them to store heat (specific heat and latent heat effects) and have thermal conductivity. These elements provide temperature output which can be used directly as tension input elements, which is C3D20R. When this element is used in heat transfer analysis, it has only temperature-based degree of freedom. This a solid type of elements therefore it can be used in non-linear analysis [14].

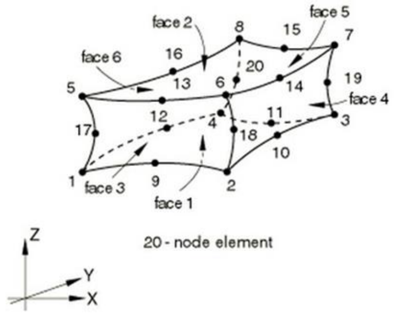

Fig. 1. the schematic of elements used in thermal analysis

Heat transfer elements type should be compatible with thermal stress analysis. In other words, elements that can be used to model non-linear mechanical analysis, such as thermal stress (The temperature history can be made from another heat transfer analysis with diffusive input elements) are suitable.

Elements with reduced integration points F41, can reduces run time particularly in three-dimensional mode. For example, C3D20 has 27 integration points while C3D20R has only 8 integration points. Due to the time consuming simulation of elements with complete integration, reduced integration elements are considered. However, if these elements are used because of the possibility of reducing the accuracy of the solution, the problem should be examined with different network densities. In [14, 15], it is suggested to use six-sided cube as much as possible for the three-dimensional analysis and problems with large deformations. Because these elements produce best results with the lowest cost of computing and if there is any transformation in network, reduced integration is used. According to above discussion, C3D20R element is used to gridding the sheet for mechanical analysis.

Although adaptive network planning techniques reduce the total number of degrees of freedom, the calculation is still highly time consuming [16]. Therefore, it is important to determine the finite element model with the lowest degrees of freedom. Consequently, the discretization model sheet or in other words a decision on finite element model mesh, will have a significant impact on the solution and ensures a proper simulation. As suggested in [17, 18], non-uniform grid pattern is used in discrete particle model. So as shown in Figure 2, superfine mesh has been used near the scanning area due to the presence of high flux heat around it but coarser meshes have been used in areas that will not be scanned. According to the results of [19] three elements in thickness, two elements for beam diameters in the path of the laser and one element normal to the beam diameter direction, are required.

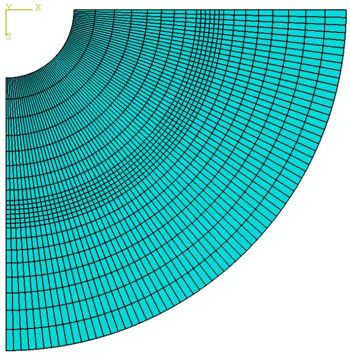

Fig. 2. the proposed non-uniform Meshing according to scan paths

With this type of mesh, the number of degrees of freedom of equations in each development is reduced in comparison to the initial uniform model (Figure 3). (It leads to decreasing the taken time about 30-50%, while increasing the error for about 1-3%).

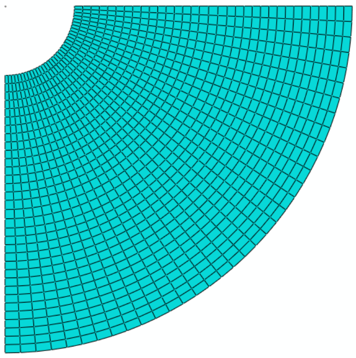

Fig. 3. the initial uniform mesh network according to scan paths

2.2 The finite element model validation with Experiment

AISI 1010 sheets with 0.8mm thickness has been used to conduct experimental tests which is shown in Figure 4. Exterior and interior diameters of raw components are assumed to be 100 and 10mm respectively. For better absorption of the laser beam samples were coated with graphite. CO_2 laser with a maximum power of 150 Watts has been used. Laser has guided by a table with two-axis controller (CNC). To simplify the process, laser scanning speed, radius of the radiation (R), laser power and laser beam diameter has been set by 720 mm per minute, 30 mm, 80 W and 1 mm respectively.

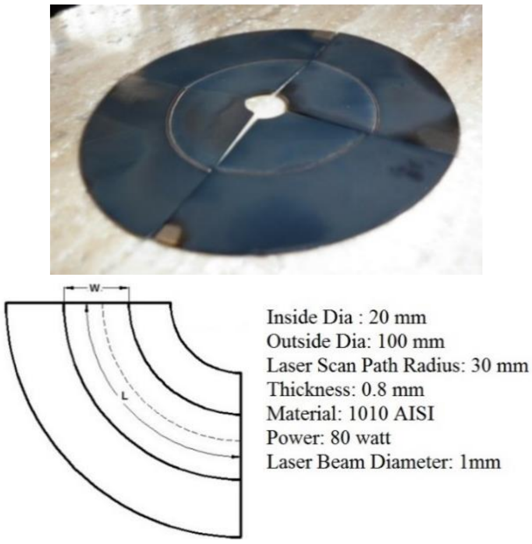

Fig. 4. the experimental test configuration: a) variable assumptions b) samples of produced pieces

In order to confirm the deformation behavior of process simulation, a model with constant process parameters and various number of laser scanning was developed to predict the amount of bending. Finite element configuration model is shown in Table 1.

Table 1. the assumptions of geometric condition and device settings

Laser beam diameters (mm)	Sheet thickness (mm)	Speed (mm/s)	Power (w)
1	0.8	12	80

Figure 5 shows a sample piece obtained from experimental testing and Figure 6 compares the amount of deflection between finite element results and experimental test results.

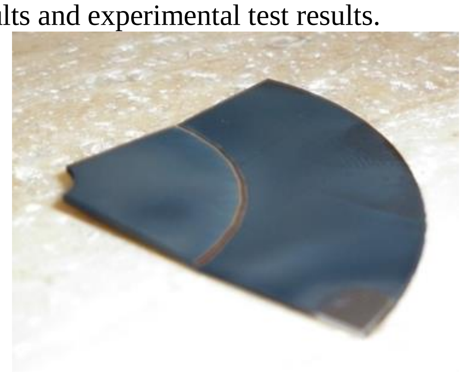

Fig. 5. Experimental test sample

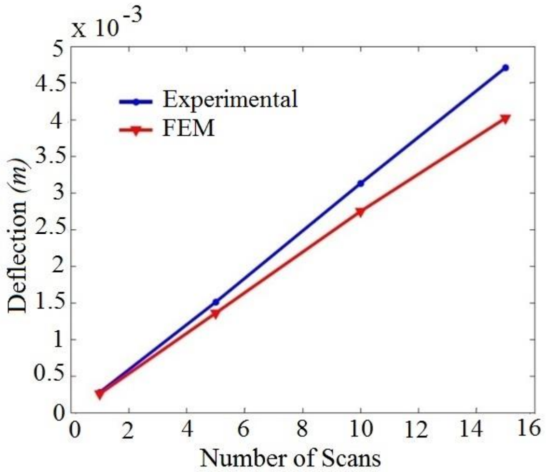

Fig. 6. Comparison of experimental and simulation results in different scans

As shown in Figure 6, deflection of experimental test results have good agreement with finite element model, especially when the number of scans is low. By increasing the number of scans, finite element model estimates lower deflection than experimental tests which causes increasing in estimation error. Table 2 shows this error for different number of scans. It should be noted that the deflection at the midpoint has been measured in both experimental tests results and simulation results.

Table 2. the effect of the number of scans on the deflection error in simulation and experimental test

Number of scans	Edge deflection - Experimental test (m)	Edge deflection -FE(M)	Error (%)
1	0.00028	0.0002612	6.70
5	0.00151	0.0013785	8.1
10	0.00313	0.0027960	10.67
15	0.00471	0.0041373	12.16

3. Deflection estimation using linear regression model

In order to achieve the regression optimization equation, it is required to extract accurate estimator model from results which is obtained by FE simulation model, experiments design and different modeling results. Table 3 shows changes levels and their factors that are considered to design forming process experiments on the edge of perforated sheets. Full factorial experiment layout requires 81 tests for these 4 factors. According to two-steps simulation, this number will be doubled. This number will repeat once for each different radius compositions. Because of time consumption of its finite element method simulation, costs of this type of experiment is not economical. Due to this reason, fractional factorial designs is used.

Table 3. Effective factors in laser forming process and the variations considered for them in the Taguchi method

Factors		Level of changes		
		1	2	3
P	Laser power)Watt(	200	300	400
bd	Laser beam diameter (mm)	2.4	2.8	3.5
V	Scanning velocity(mm/s)	40	50	60
ID	Internal hole diameter)mm(	10	20	30

For selecting the appropriate array, the required number of degrees of freedom should be calculated. According to Table 3, each of the four factors (P, bd, V and ID) must be examined at three levels. Based on the discussion provided in [20], each factor has 2 degrees of freedom. Therefore, degrees of freedom for all 4 factors are 8. As suggested by [20], degrees of freedom of Orthogonal Taguchi array should not be less than the test total degrees of freedom. In the current problem, due to the number of performed simulations, the required time for each simulation and the reference recommendations, suggestions array is L9 which is from Taguchi group.

Based on L9 array, the variable values in designed experiments are illustrated in Table 4. It should be mentioned that the number of laser scanning occurrences in all nine tests is intended to be 5.

Table 4. Design of experiment of laser forming process of hole's edge according to L9

ID(mm)	Bd(mm)	V(mm/s)	P(w)	Test number
10	2.4	40	200	1
20	2.8	50	200	2
30	3.5	60	200	3
30	2.8	40	300	4
10	3.5	50	300	5
20	2.4	60	300	6
20	3.5	40	400	7
30	2.4	50	400	8
10	2.8	60	400	9

For each of the scanning radiuses given in table 5, 9 finite elements tests of table 4 are simulated in two stages (thermal stage and mechanical analysis stage). Then all outputs that are important in the process of creating the final design of the bend (the collar shape) are extracted. These outputs include maximum temperature obtained on the sheet, collar deflection of the edge and each circular scanning radius on the sheet. In other words, for each radial combination, 18 simulations have been conducted and for each test 54 quality characteristics (temperature and deflection) has been extracted. The average time consumed for each series of simulations and data extraction was 216 hours. To sum up, the total time spent to collecting data according to the election L9 array was about 3240 hours. If the number of levels increased by one, L27 array must be used which will increase the time of simulation and extracting by three times.

Table 5. various combinations of the scan radiuses

Single radial combination	2-radial combination	3-radial combination
1	1,2	1,2,3
2	1,3	1,2,4
3	1,4	1,3,4
4	2,3	2,3,4
	2,4	
	3,4	

The collected data is used to create the laser forming simulating using regression algorithm via MATLAB software. According to the comparison between estimation models in [21], linear estimation model is the most appropriate model for estimating deflections, assuming independence deflections for each scanning radius. It has the lowest error in deflection calculations in compared to other models. This type of modeling has offered three data classification for single, two and three radial estimations. Related equations are shown in Table 6.

Table 6. linear estimator model for every single beam scanning deflection with independence assumption

Number of used radius	Estimation deflection equation by regression	The average absolute error
Single radius	(-0.0005 * power + 0.0032 * speed - 0.0416*beam diameter- 0.2522*hole diameter + 0.044 * R + 0.3021 * NOS +10.6385) /10000	5.14E-5
2 radial	(0.0018 * power - 0.0143 * speed - 0.0223 * beam diameter -0.1983 * hole diameter + 0.0454 * R1 -0.0886 * R2 + 0.1821 * NOS +11.7753)/10000	5.4E-5
3 radial	(-0.0004 * power +0.0055 * speed + 0.0972 * beam diameter -0.2942 * hole diameter +0.0626 * R1 + 0.021 * R2 -0.0032 * R3 + 0.1852 * NOS + 11.2277)/10000	5.4E-5

4. Multi objective optimization

4.1 Optimization problem

Figure 7 is a cross-sectional slice (the axis has passed the final Flange) around the collar. In the ideal case the two-dimensional profiles which cross each other over the three-dimensional object, has fixed curvature that is rotated around the axis of perforated sheets.

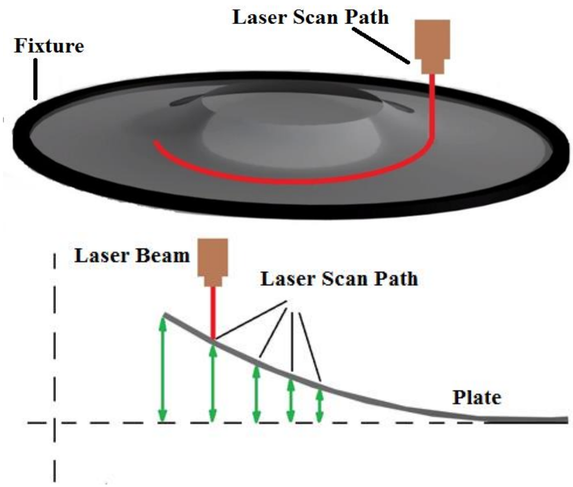

Fig. 7. Deflection to four independent positions on deflection edge of plate

The purpose of the optimization problem is finding appropriate deflection and situations for laser scanning, to model the deflection function and cross-sectional shape of the sheet as much as possible close to the goal deflection. Parameters to achieve the desired curvature user profiles and specify the necessary improvements are: laser power, scanning velocity, beam diameter, and the number of scans per radius for all of the paths. Applying each scan in circular path will cause a deflection in margins, alone. Since, the deflection caused by single scanning is often smaller than required deflection, it is necessary to repeat the scanning with the same parameters on the identical path. According to the results of Golabi and et al. research [10] it was shown that exposure to other circular scans on other further paths causing deflection as well. Therefore, in addition to the number of scanning paths, the radius of circular scan paths is also considered as an optimization variable. The number of radiuses (NOR) represents the optimal number of scans which is selected between 1, 2 and 3. If NOR is set to 1, R1 expresses the corresponding radius for the single path and 2 other radiuses are neglected. Similarly, if the NOR is set to 2, R1 and R2 are used for two scan paths, respectively and R3 is discarded. In the case that NOR is selected to be 3, all of the three radiuses are meaningful. Therefore, the optimization is designed so that the optimal solution suggests the scanning strategy in addition to laser forming process parameters. In other words, this algorithm specifies both the number and diameters of scanning paths.

According to the given description, the 8 input variables and 5 output variables are presented in Table 7. In this study due to the high number of studied variables (beam power, beam speed, beam diameter, radial position of scan path, the hole diameter and number of laser beam passes) and in order to increase the accuracy of the outputs only 3 specific hole diameters have been studied. Therefore, the optimization problem is considered and solved for three hole diameter values of 10, 20 and 30, respectively.

Table 7. the variables of problem and related ranges

	Name	Explanation
Input variables	P	Laser power
	V	Scan velocity
	bd	Beam diameter
	NOS	The Number of scans per radius
	NOR	The Number of Radiuses
	R1	First Radius
	R2	Second Radius
	R3	Third Radius

The optimization is constrained so that the values of variables must be in acceptable ranges. The range of values that is searched to identify optimum values are presented in Table 8, for different hole diameters.

4.2. Objective functions

After selecting the appropriate model, the desired objective function should be chosen. The most important challenge in practical use of laser is determining the optimum conditions in terms of energy consumption and the obtained error. Therefore, the selected objective functions can be related to geometry and energy consumption.

Table 8. the acceptable range of variables

Hole diameter (mm)	Power (W)	Scan velocity (mm/s)	Beam diameter (mm)	Number of scans	Radius range (mm)	Number of radius
10	[200 400]	[40 60]	[2.4 3.5]	[1 5]	[5.5 10]	[1 3]
20	[200 400]	[40 60]	[2.4 3.5]	[1 5]	[11 20]	[1 3]
30	[200 400]	[40 60]	[2.4 3.5]	[1 5]	[16.5 30]	[1 3]

The defined objective functions are as follows:

1- Reaching the desired deflection on the edge (minimalizing the error between estimated and desired deflection values). The following equation shows this objective, where *ED* is estimated deflection by regression model and *DD* is the desired deflection.

$$error = \left| ED(P, V, bd, R1, R2, R3, NOS) - DD \right|$$

2- Energy minimization. The Energy consumption is calculated from the following equation.

$$E = 2\pi \times \sum \mathrm{NoS} \times \frac{\mathrm{PR}}{\mathrm{V}}$$

Where P is the amount of power, V is laser beam speed, NoS is number of scanning and R is the radius of laser beam path.

4.3. Multi-objective genetic algorithm

In a multi-objective optimization problem, several objective functions must be optimized, simultaneously. Usually in these problems, there is a tradeoff between objectives. For example, by increasing the amount of one objective, another will be decreased. The simplest method for solving multi-objective optimization problem is to combine the objectives into a new single objective. This method produces only one optimal solution and the objectives neutralize the effect of each other. Furthermore, finding the optimum weights to combine the objectives is itself a challenging issue. Therefore, we employed multi-objective genetic algorithm for solving the multi-objective optimization problem, which optimize all objectives simultaneously. Moreover, genetic algorithm is used to solve the optimization in order to handle the high dimensionality of the problem.

Multi-objective genetic algorithm is an algorithm that gives a set of optimal solutions for an optimization problem with several objective functions. Due to the evolutionary nature of this algorithm and its population-based design, it can provide a set of optimum solutions, efficiently.

One of the most frequently used and powerful algorithms for solving multi-objective optimization is NSGAII. Its Purpose is to find the optimal set of points that do not dominant each other and have enough diversity. This set is called Pareto set. If x and y are two solutions to a problem, we say x dominant y if,

a) x is not worse than y in any objectives

b) x is strictly better than y at least in one of the objectives

In this case, it can be claimed that x is better than y according to optimization objectives.

Crowding distance is used in order to calculate the difference between the points of Pareto set. The overall process of NSGAII is similar to standard genetic algorithms. Algorithm steps are as follows:

1. Create an initial population randomly
2. Calculate the objective values for the population individuals
3. Sort the population based on best fitness values
4. Calculate the crowding distance
5. Select parents based on best fitness values and crowding distance in comparison with other solutions
6. Apply genetic operators, including recombination and mutation to produce children
7. Select the population of the next generation: including the selection of the appropriate solutions among the previous population and the generated children.
8. Return to step 2 until satisfying the stopping criteria

Two controlling parameters should be set for applying the algorithm for optimization. The first parameter is the percentage of participation in the Pareto, which indicates that what portion of the population should be included in the Pareto. Its value in this study is set to 0.5. The second parameter is crowding distance that controls the diversity in the Pareto. This value can be calculated either in phenotype or genotype spaces. In this study, it is based on phenotype. The size of population has been considered 200. The initial genetic algorithm population includes chromosomes that are random values for power, speed, beam diameter and number of each scan. The value of each variable is generated randomly in its valid interval. Stop criteria for NSGAII algorithm are:
1- The maximum number of generations exceeds, which in this paper is set on 200 times of the number of variables, which is suggested by [22].
2- The average distance of the chromosomes in Pareto becomes less than a threshold which is set to 0.001.
Other genetic parameters are described in Table 9.

Table 9. GA parameters

Population size	Number of generations	Recombination probability	Selection method	Number of stall generations
1000	60	0.8	Uniform	50

4.4 Optimization results

Table 10, 11 and 12 represent the laser forming parameters in order to create a collar with 0.9mm of deflection according to parametric limitation which shown in Table 8 and to minimize the energy consumption. In these tables, some samples chromosomes of Pareto set achieved by NSGAII are reported.

It should be noted that for a certain deflection, laser forming conditions are not unique, it is correct that these conditions produce a deflection on collar but other objectives have produced different values. In Pareto optimization there is no preferences among objectives, therefore in this case the user can choose his proper laser forming conditions between optimum conditions for which no objective is dominated by others. It is up to user to prefer matching with the curvature function of the collar or minimizing the energy consumption according to the application. Since a limited number of population of genetic algorithm according to the performance of this algorithm may not accurately lined on Pareto optimal, therefore the conditions of laser forming with same deflected collar monitored again and if the objective function is dominant, those conditions will be deleted. Figure 8, Figure 9 and Figure 10, are the corresponding Pareto curves of table 10, 11 and 12 which illustrate the relation between energy, and matching error in Pareto points.

Table 10. Laser forming conditions to form the edge of the 10 mm hole and 0.9 deflection

Number of radius	Scan radius(mm)	Num. scans	Beam Diameter(mm)	Scan speed(mm/s)	Power(W)	Error	Energy
1	5.8073	2	2.42	59.89	203	3.46E-06	2.47E+02
1	5.5163	2	2.42	59.88	202	4.72E-06	2.35E+02
1	8.1838	1	2.44	59.91	203	2.33E-05	1.75E+02
1	8.1556	1	2.43	59.94	203	2.34E-05	1.74E+02

Table 11. Laser Forming conditions to form the edge of the 20 mm hole and 0.9 deflection

Number of scan Radius	Scan radius (mm)	Num. of scans	Beam diameter(mm)	Scan speed(mm/s)	Power (W)	Error	Energy
2	19.89,11.06	1	2.92	44.64	243	1.35E-04	1.06E+03
2	19.78,11.01	5	2.64	54.29	216	8.04E-05	3.86E+03
1	11.04267	1	3.25	55.87	205	2.68E-04	2.55E+02
2	19.90,11.03	5	2.45	42.03	323	4.29E-05	7.47E+03
2	19.89,11.09	5	2.62	43.25	294	5.07E-05	6.63E+03
1	11.36395	2	2.86	54.89	205	2.35E-04	5.36E+02

Table 12. Laser forming conditions to form the edge of the 30 mm hole and 0.9 deflection

Number of scan radius	Scan raduis (mm)	Num. scans	Beam diameter(mm)	Scan speed(mm/s)	Power(W)	Error	Energy
2	22.6962, 16.5975	2	2.76	46.31	272	3.48E-04	2.90E+03
1	17.6764	2	2.86	54.28	205	4.59E-04	8.39E+02
2	22.7991, 16.6097	2	2.73	45.26	345	3.33E-04	3.78E+03
1	16.8326	1	2.73	53.99	203	4.93E-04	3.98E+02
1	19.1001	2	2.78	53.95	207	4.53E-04	9.23E+02

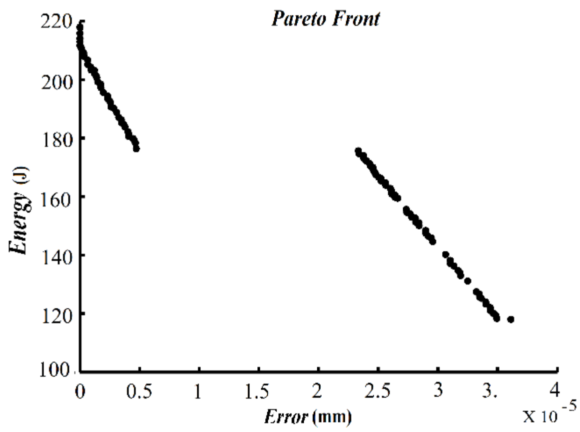

Fig. 8. Pareto diagram of 10 mm hole diameter – ratio of energy to error

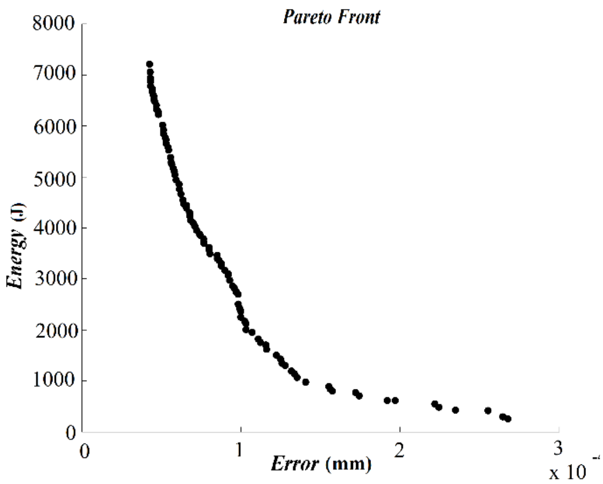

Fig. 9. Pareto diagram of 20 mm hole diameter – ratio of energy to error

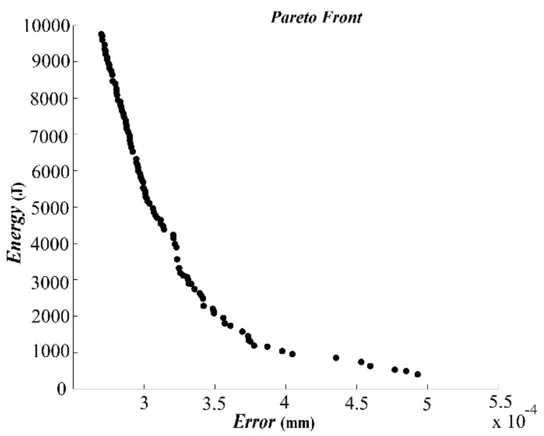

Fig. 10. Pareto diagram of 30 mm hole diameter – ratio of energy to error

In the above chart, sudden increase in error rate to the energy is due to the suggestion of using 2 scans over 1 scan which caused the error rate to suddenly increase. In Figure 9 and Figure 10, for each amount of errors the corresponding energy is illustrated. Although a number of different tests have examined in Pareto charts and data in order to present results for various number of strategies and scans, results showed no significant difference, which has caused by the philosophy of the problem. The algorithm is seeking conditions which has optimum energy and error. So, for example, if in different strategy conditions it does not provide different recommendations, this does not mean that there are no data, but this presented data have advantages compared to other strategies. For example, in the provided charts to achieve desired deflection of 0.9 mm in a perforated sheet with a 30mm diameter and 0.00033 of error, it requires 3780J energy, two scans in 16.6mm and 22.8mm radiuses and 45mm/s beam movement speed.

5. Discussion and conclusion

In this research, the multi-objective optimization problem is defined for laser forming process in circular path. The optimization variables include laser parameters as well as the number and radiuses of scanning paths. The objective functions are considered to be energy and error between specified and estimated deflections. The deflection due to the laser parameters are estimated using linear regression model. The optimization is performed using NSGAII algorithm and is subject to some linear constraints for parameter ranges. Based on the results, in order to achieve the lowest error rate, the amount of energy required for forming should increase. Furthermore, the accuracy of created deflection decrease by increasing in the hole internal diameter, due to the control conditions on the edge. Also, up to 10 times of the amount of energy is required to form the edge. In other words, the amount of energy needed for holes with different diameters in the same errors is different. It was also founded there are a large number of models in order to achieve to a desired deflection that according to the user's choice desirable errors and energy criteria can be selected.

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References:

[1] Y. Shi, Z. Yao, H. Shen, J. Hu, "Research on the mechanisms of laser forming for the metal plate", Int J Mach Tool Manu, Vol. 46, pp. 1689–1697, 2006.
[2] P. J. Cheng, S. C. Lin, "Using neural networks to predict bending angle of sheet metal formed by laser", Int J Mach Tool Manu, Vol. 40, No. 8, pp. 1185-1197, 6//, 2000.
[3] D.-J. Chen, Y.-B. Xiang, S.-C. Wu, M.-Q. Li, "Application of fuzzy neural network to laser bending process of sheet metal", Mater. Sci. Technol., Vol. 18, No. 6, pp. 677-680, 2002.
[4] H. Shimizu, "A heating process algorithm for metal forming by a moving heat source", Ph.d Thesis, Massachusetts Institute of Technology, 1997.
[5] J. G. Cheng, Y. L. Yao, "Process synthesis of laser forming by genetic algorithm", Int J Mach Tool Manu, Vol. 44, No. 15, pp. 1619-1628, 2004.
[6] M. Hoseinpour Gollo, H. Moslemi Naeini, G. H. Liaghat, S. Jelvani, "Theoretical and Experimental Study of the Effects of Process Parameters on Bending Angle in Laser Bending process", MME, Vol. 10, No. No.3, pp. 67-86, 2010. (In Persian)
[7] A. Gisario, M. Barletta, C. Conti, S. Guarino, "Springback control in sheet metal bending by laser-assisted bending: Experimental analysis, empirical and neural network modelling", Optics and Lasers in Engineering, Vol. 49, No. 12, pp. 1372-1383, 2011.
[8] K. Maji, D. K. Pratihar, A. Nath, "Analysis and synthesis of laser forming process using neural networks and neuro-fuzzy inference system", Soft Comput, pp. 1-17, 2013.
[9] A. H. Roohi, H. Moslemi Naeini, M. Hoseinpour, "Effects of process parameters on bending magnitude in laser forming and determine an equation to predict bending angle", MME, Vol. 14, No. 8, pp. 75-82, 2014. (In Persian)
[10] R. T. Esfahani, S. i. Golabi , "An investigation on the deflection estimator models in laser forming of the full circular paths", jcrs010, Vol. 2, No. 2, pp. 8, 2014.
[11] H. Shen, Z. Yao, Y. Shi, J. Hu, "The simulation of temperature field in the laser forming of steel plates", IJMIC, Vol. 2, No. 3, pp. 241-249, 2007.
[12] N. Alberti, L. Fratini, F. Micari, "Numerical simulation of the laser bending process by a coupled thermal mechanical analysis", LANE , Vol. 94,pp 327-336, 1994.
[13] Y.-C. Hsiao, H. Shimizu, L. Firth, W. Maher, K. Masubuchi, "Finite element modeling of laser forming", ICALEO'97: Laser Materials Processing Conference., Vol. 83, 1997.
[14] Abaqus 6.10 Analysis User's Manual, in: Eds., 2010.
[15] M. Safari, M. Ebrahimi, "Numerical Investigation of Laser Bending of Perforated Sheets" MME , 2016, Vol. 9, No. 2, 2016-07-27, 2016.
[16] L. Zhang, E. Reutzel, P. Michaleris, "Finite element modeling discretization requirements for the laser forming process", *IJMS*, Vol. 46, No. 4, pp. 623-637, 2004.
[17] G. Yu, K. Masubuchi, T. Maekawa, N. Patrikalakis, "FEM simulation of laser forming of metal plates", J Manuf Sci e-t Asme, Vol. 123, No. 3, pp. 405-410, 2001.
[18] l. Zhang, "Nonlinear FE analysis wtih application to laser forming and welding" Ph.D. Thesis,Pensilvania university pp. 214, 2005.
[19] R. Tarkesh Esfahani, S. i. Golabi, Z. Zojaji, "Optimization of finite element model of laser forming in circular path using genetic algorithms and ANFIS", Soft Comput, Vol. 20, No. 5, pp. 2031-2045, 2016.

[20] F. M. R. Niroumand M.R, "New optimization method"first ed, pp. 132: Isfahan university of technology, 1388. (In Persian)

[21] R. T. Esfahani, S. i. Golabi, "Evaluation techniques for laser forming collar on the flat sheets", Ph.D. Thesis, kashan university, 1393. (In Persian)

[22] Global Optimization Toolbox User's Guide, pp. 100-115: The MathWorks, Inc., 2012.