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APPLICATION OF THE MONTE CARLO METHOD FOR LASER CUTTING OPTIMIZATION

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ABSTRACT: In this paper an experimental based artificial neural network (ANN) model was designed to model the surface roughness obtained in CO_2 laser nitrogen cutting of stainless steel considering laser power, cutting speed, assist gas pressure and focus position as input variables. To obtain experimental data, laser cutting experiment was planned and conducted according to the Taguchi's L_{27} orthogonal array. ANN training was performed by using the Levenberg-Marquardt algorithm. In addition to modeling, the second goal of this paper was to determine laser cutting conditions which minimize surface roughness. In contrast to previous studies, where for optimization purposes ANNs were usually integrated with meta-heuristic algorithms, the aim of this paper was to show the methodology of the Monte Carlo method and its applicability to optimization of ANN models.

KEY WORDS: Monte Carlo method, optimization, CO_2 laser cutting, artificial neural networks

1 INTRODUCTION

Laser cutting is today the most common industrial application of the laser. Laser cutting of a workpiece is achieved by focusing the high intensity laser beam onto the surface of the workpiece to melt the kerf volume and an coaxial jet of assist gas blows the melt out of the cut kerf.

There are numerous significant advantages of the laser cutting considering cut quality characteristics and process characteristics. Numerous advantages along with technological improvements in laser machines, made laser cutting technology more prevalent in today's production systems [1]. Laser cutting is a multi-parameter problem and hence sometimes difficult to understand regarding the interrelationship between all the parameters [2]. To obtain desired laser cutting performance, the principal parameters of laser cutting such as laser power, cutting speed, assist gas type and pressure, focus position are to be carefully considered for each material and workpiece thickness. Researchers worldwide are focused on laser cutting process modeling and optimization to improve the process in terms of cut quality, productivity and costs [3]. To that purpose different methodologies were employed, such as analytical, numerical, semi-empirical and in recent years approaches based on artificial intelligence. Theoretical predictions of the laser cut quality are very complicated, requiring complex and sophisticated modeling approaches due to the great variety of parameters involved [4], and are limited in their ability to model detail in real-world problems [2].

In situations where mathematical formulas and prior knowledge of the functional relationships between process parameters is unknown, artificial intelligence based techniques are especially suitable. Artificial neural networks (ANNs) are one of the most used artificial intelligence tools for process modelling. Numerous research attempts based on ANNs for modeling and optimization of laser cutting process have proven its powerful modeling capabilities. Compared to multiple regression analysis (MRA), ANN based modeling is more complex since numerous decisions related to ANN architectural and training parameters had to be made. However, ANNs, which are based on matrix-vector multiplications combined with nonlinear (activation) functions, offer better modeling ability for complex processes with many non-linearities and interactions such as laser cutting and outperforms MRA [5]. Do determine optimal laser cutting conditions ANNs are coupled with an optimization algorithm, in most cases metaheuristic algorithms such as genetic algorithm (GA), particle swarm optimization (PSO) algorithm and simulated annealing (SA) algorithm.

The present paper has three objectives: (i) to obtain a mathematical model based on ANN technique for prediction of the surface roughness obtained in CO2 laser cutting process, (ii) to investigate applicability of Monte Carlo method for optimization of mathematical models based on ANNs, and (iii) identify near optimal laser cutting conditions to minimize surface roughness by integrating ANN model and Monte Carlo method.

2 MONTE CARLO METHOD

Many numerical problems in science, engineering, finance, and statistics are solved nowadays through Monte Carlo methods, that is, through random experiments on a computer [6]. Monte Carlo is in fact a class of methods now widely used in computer simulations [7]. The „classical" Monte Carlo is used as an uncertainty analysis of a deterministic calculation because it yields a distribution describing the probability of alternative possible values about the nominal (designed) point [8]. The idea of the Monte Carlo calculation is much older than the computer. The name Monte Carlo is relatively recent, and is connected to famous casinos in Monaco. It was coined by Nicolas Metropolis in 1949 under the name "statistical sampling". Since the pioneer studies in 1940s and 1950s, especially the work by Ulam, von Newmann, and Metropolis, it has been applied in almost all area of simulations, from Ising model to financial market, from molecular dynamics to engineering, and from the routing of the Internet to climate simulations [7].

Monte Carlo methods are used for a long time, but only in the last few decades, the methods have gained the status of fully rounded numerical methods. As for obtaining a reasonably accurate assessment, calculation of large number of special cases are needed, as well as appropriate statistical analysis, the effective application of the Monte Carlo methods begins with the emergence of fast computers.

At the heart of any Monte Carlo method is a random number generator: a procedure that produces an infinite stream: $U_1, U_2, U_3, \ldots \overset{iid}{\sim} Dist$ of random variables that are independent and identically distributed (iid) according to some probability distribution Dist. When this distribution is the uniform distribution (have equal probability in the interval from 0 to 1), that is $Dist = U(0,1)$, the generator is said to be uniform random number generator [6]. Uniform distribution has wide application in various problems in engineering modeling and optimization.

Monte Carlo is not only used for estimation but also for optimization purposes. The optimization based on Monte Carlo methods can be useful for solving optimization problems with many local optima and complicated constraints, possibly involving a mix of continuous and discrete variables [6]. In order to enhance the accuracy of the method, the multistage approach may be applied in which the stochastic computations are repeated by diminishing the region of search.

The basic steps in the implementation of Monte Carlo method for solving engineering problems may be as follows: (i) generation of the pseudo-random numbers considering the limitations of input variables, (ii) estimation of the dependent variable(s) (objective function(s)), (iii) performing a large number of iterations, and (iv) analysis of the obtained results.

3 EXPERIMENTAL DESIGN AND SETUP

To reduce time and the number of experimental trials, yet to efficiently cover the experimental space, a design matrix was constructed in accordance with the standard L27 (313) Taguchi's orthogonal array. In the experiment, four laser cutting parameters were varied at three levels:

- laser power, P (kW): 1.6, 1.8, 2
- cutting speed, v (m/min): 2, 2.5, 3
- assist gas pressure, p (MPa): 0.9, 1, 1.2
- focus position, f (mm): –2.5, –1.5, –0.5

The values range for each parameter was chosen such that full cut for each parameter levels combination is achieved and by considering manufacturer's recommendation for parameter settings.

The cuts were performed on 3 mm thick AISI 304 stainless steel sheet using the nitrogen with purity of 99.95% as assist gas. More details about laser cutting system are listed in Table 1.

Table 1. Experimental details

Laser cutting system	Bystronic, ByVention 3015 maximum output power of 2.2 kW; operating in continuous wave mode; CO_2 laser beam profile in the TEM_{00}
Lens focal length	127 mm
Nozzle	diameter of 2 mm (HK20)
Assist gas	Nitrogen (purity of 99.95 %)
Workpiece material	AISI 304 stainless steel

Surface roughness was selected as laser cut quality characteristics. Surface roughness on the cut edge was measured in terms of the average surface roughness (Ra) using Surftest SJ-301 (Mitutoyo) profilometer. Each measurement was taken along the cut at approximately the middle of the thickness and the measurements were repeated three times to obtain averaged values.

4 MONTE CARLO OPTIMIZATION RESULTS

To establish mathematical relationships between laser cutting parameters (laser power, cutting speed, assist gas pressure and focus position) and the output parameter-response i.e. surface roughness, multilayer perceptron type ANN with one hidden layer was selected. The 4-4-1 ANN model for predicting surface roughness was trained using the Levenberg-Marquardt algorithm with experimental data , previously divided into training and testing dataset. For the purpose of training, all experimental data was normalized to interval [–1,1]. The ANN model showed average percentage errors less than 10 % on both training and testing datasets.

To obtain near optimal laser cutting conditions, ANN surface roughness model was optimized using the Monte Carlo method. Although, many optimization algorithms may provide acceptable solutions (or even better solutions), Monte Carlo method was here applied due to its simplicity. The goal of the optimization process is to determine the near optimal laser cutting parameter values (laser power - Popt, cutting speed - vopt, assist gas pressure - popt and focus position - fopt) in order to ensure that the Ra is bellow 1.6 µm, which satisfies the real requirement in practice. For CO2 laser inert cutting of AISI 304 stainless steel, optimization problem can be formulated as follows:

$$\begin{aligned} &\text{Determine } P_{opt}, v_{opt}, p_{opt}, f_{opt} \\ &\text{to minimize } R_a < 1.6\mu\text{m} \\ &\text{subject to}: 1.6\text{kW} \le P \le 2\text{kW}, \\ &\qquad 2\text{m/min} \le v \le 3\text{m/min}, \\ &\qquad 0.9\text{MPa} \le p \le 1.2\text{MPa}, \\ &\qquad -2.5\text{mm} \le f \le -0.5\text{mm} \end{aligned} \quad (1)$$

For calculating Ra, the mathematical function based on ANN was used. To obtain near optimal laser cutting parameter values, two-step Monte Carlo optimization approach was implemented. In the first step, 500 estimations of Ra were calculated and ranked. Subsequently, five best solutions with minimal Ra along with corresponding values of independent variables (Popt, vopt, popt and fopt) were identified. The optimization results from the first step are given in Table 2.

Table 2. Optimization results after first step

Optimization result	P_{opt}	v_{opt}	p_{opt}	f_{opt}	R_a
	normalized values				µm
1	0.953	–0.09	–0.48	0.417	1.656
2	0.89	0.937	0.88	0.972	1.673
3	0	–0.855	–0.566	0.879	1.649
4	**0.96**	**–0.129**	**–0.996**	**0.993**	**1.549**
5	0.969	0.219	–0.254	0.745	1.626

Note, since the ANN model was developed in terms of normalized values, the appropriate values of laser cutting parameters are at this stage given in the same format. From the analysis of the results given in Table 2, it can be observed that very different laser cutting conditions corresponds to best five identified optimization results. In other words, similar surface roughness values can be obtained by using drastically different laser cutting conditions. For example, focusing the laser beam near to the sheet surface and using high laser power, cutting speed and assist gas pressure (optimization result 2) produces similar surface finish as in the case of focusing the laser beam deeper into the bulk of material while using high laser power, intermediate level of cutting speed, and lower assist gas pressure (optimization result 1). However, as in the present case, to goal is to obtain surface roughness bellow 1.6 microns, the optimization result 4 is considered as acceptable, and was set as initial solution for the the second stage of the Monte Carlo optimization approach.

In the second step, the stochastic computations are repeated for 100 times by modifying the range around the near optimal solution (for each laser cutting parameter) obtained in the previous step. The modified ranges for the laser cutting parameters were as follows: P (0.9÷1), v (–0.24÷0) and f (0.9÷1). The value for the assist gas pressure (p) was to –1, because the identified value in the previous step was fairly close to the upper limit (–0.996). The Monte Carlo optimization results are given in Fig. 1.

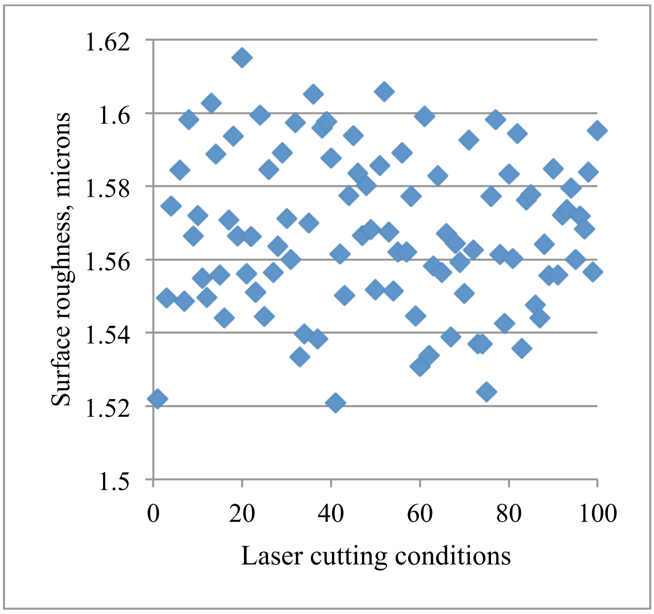

Figure 1. Monte Carlo simulation runs in the second step

Each point in the graph corresponds to a particular input laser cutting parameter settings. As seen from Fig. 1, in most cases, the identified laser cutting conditions satisfy constrain that surface roughness is bellow 1.6 microns. As in the first step, five best solutions with minimal Ra along with corresponding values of P, v, p and f were identified (Table 3).

Table 3. Optimization results after second step

Optimization result	*P*	*v*	*p*	*f*	R_a
	normalized values				μm
1	0.952	−0.234	−1	0.985	1.529
2	0.989	−0.169	−1	0.987	1.532
3	1	−0.224	−1	0.964	1.525
4	0.983	−0.205	−1	0.978	1.528
5	**0.995**	**−0.158**	**−1**	**0.977**	**1.536**

Generally, from Figure 1 and Table 3 one can choose many different solutions. In this paper, optimization result 5 was considered as acceptable near optimal solution. This solution was chosen considering material removal rate which is the function of cutting speed. The near optimal laser cutting conditions in terms of natural values are as follows: laser power Popt=2 kW, vopt=2.4 m/min, popt=0.9 MPa and fopt=−0.52 mm. These results were obtained using the inverse equation for the data normalized in the [−1, 1] range. Here it should be noted that obtained optimization result is not unique, i.e. there may exist some different laser cutting conditions that would achieve similar results in terms of surface roughness.

In CO2 inert laser cutting it is well known that a higher assist gas pressure ensures a greater drag force which can remove the molten material more effectively, making the machined surface smoother. From the optimization results one can see that high surface quality can be obtained also with low assist gas pressure. The explanation for this phenomenon may be considering the interaction effect of laser power and focus position. Namely, focusing the laser beam inside the workpiece, but nearer to the top surface, while using high laser power which means that the rate of melting is higher, produces a wider kerf such that coaxial nitrogen jet expel and blow away the molten melt more efficiently.

5 CONCLUSIONS

In this paper ANN surface roughness prediction model in terms of laser power, cutting speed, assist gas pressure, and focus position as input model parameters was developed. The experimental data obtained were used to train the ANN using the Levenberg-Marquardt algorithm. Based on the constructed ANN model, the surface roughness was optimized using Monte Carlo stochastic method. The obtained near optimal solution corresponds to the following operating conditions: P = 2 kW, v = 2.4 m/min, p = 0.9 MPa, and f = −0.52 mm. Although Monte Carlo method does not optimize objective functions globally, it yields optimization results that are acceptable in a simple and fast procedure. In the case when optimization results are not acceptable or are not achievable, considering techno/technological limitations, the optimizations steps are to be repeated. Also, in order to increase the probability of finding a set of acceptable near optimal solutions, a number of stochastic computations can be increased.

The authors of this paper showed the methodology of the Monte Carlo method and its possibility of use for optimization of ANN machining process models on the laser cutting case study. It was proved that it offers a simple, fast and effective method for determining of the near optimal process parameter settings. The methodology presented in this paper might be utilized for any ANN, for each ANN application

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