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Determination of laser cutting process conditions using the preference selection index method

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ABSTRACT

Determination of adequate parameter settings for improvement of multiple quality and productivity characteristics at the same time is of great practical importance in laser cutting. This paper discusses the application of the preference selection index (PSI) method for discrete optimization of the CO_2 laser cutting of stainless steel. The main motivation for application of the PSI method is that it represents an almost unexplored multi-criteria decision making (MCDM) method, and moreover, this method does not require assessment of the considered criteria relative significances. After reviewing and comparing the existing approaches for determination of laser cutting parameter settings, the application of the PSI method was explained in detail. Experiment realization was conducted by using Taguchi's L_{27} orthogonal array. Roughness of the cut surface, heat affected zone (HAZ), kerf width and material removal rate (MRR) were considered as optimization criteria. The proposed methodology is found to be very useful in real manufacturing environment since it involves simple calculations which are easy to understand and implement. However, while applying the PSI method it was observed that it can not be useful in situations where there exist a large number of alternatives which have attribute values (performances) very close to those which are preferred.

1. Introduction

Laser cutting is one of the industry leading technologies for cutting a wide variety of materials. Compared to other alternative cutting technologies, laser cutting offers significant advantages and possibilities such as ability to cut complex geometries with tight tolerances, high cutting speeds, i.e. increased productivity, localized heat affected zone (HAZ), high quality, ease of automation, etc. [1–3]. Although initial capital investments of laser cutting technology are high, operational costs are low making this technology being economically competitive and cost effective.

In order to take full advantages and benefits that laser cutting technology offers one needs to carefully consider determination and selection of adequate process conditions, i.e. particular combination of the main parameter values. In general, the selection of parameter settings is mainly dependent on the composition of the workpiece material, workpiece thickness and desired performance characteristics related to cost, quality and productivity. However, the main difficulty is the fact that optimal combination of laser cutting parameter values for one performance characteristic is not even near optimal for other performance characteristics [4–7]. Therefore, determination of laser cutting process conditions for multi-performance (multi-criteria) optimization is of prime importance.

In the open literature and manufacturing practice one can identify four main approaches for determining of the most suitable laser cutting conditions for a given application: trial and error method, Taguchi method, continual optimization and discrete optimization. Trial and error method is one the most common approaches in real manufacturing environment. It assumes that process planners and engineers use acquired experience and recommendations from handbooks for selecting laser cutting parameter values. This subjective approach leads to the fact that selected values of laser cutting parameters vary from one case to another and are preferably conservative. Although this approach may be sufficient in most applications, it denies the possibility of using better (optimized) cutting conditions and ultimately it does not provide a basis for the full utilization of the laser cutting machine. It can be argued that, due to complexity and stochastic nature of laser cutting, even highly skilled process planners and engineers can hardly determine laser cutting process conditions with respect to several criteria.

Due to its simplicity and ease of implementation the application of the Taguchi method is the second most common approach in real

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manufacturing environment. The Taguchi method is a well-known, unique and powerful method for product/process quality improvement. In laser cutting, application of this method allows for identification of near optimal laser cutting process conditions making the process insensitive to noise factors such as environmental temperature, humidity or dust. High popularity of this method is due to fact that this approach does not require development of any mathematical model, thus can be readily applied in real manufacturing environment [4–6,8,9]. However, on the other hand, this approach permits only discrete optimization and if one need to consider multiple objectives, application of additional methods such as utility method, principal component analysis or principal component analysis is inevitable.

Determination of laser cutting process conditions based on continual optimization represents higher level approach. It consists of development of an empirical model of a laser cutting performance characteristic and application of an optimization method. Empirical mathematical models establish relationships between inputs (cutting parameters) and outputs (performance characteristics). To this aim regression analysis, artificial neural networks and genetic programming are predominantly being used [3,7,10–13]. Once developed, these mathematical models are used as objective functions which are optimized using an optimization method. Since laser cutting process optimization problems are complex, highly non-linear and multi-dimensional, meta-heuristic optimization methods have become a preferred trend for solving these types of optimization problems [2,7,12,14–16]. Integration of empirical models and optimization methods allows for continuous single and multi-criteria optimization of laser cutting process. Namely, laser cutting parameter values (independent variables) are defined in continual or integer domain and the goal is to determine the best solution (laser cutting process condition) which satisfies all previously set constraints and ranges of independent variables. Although providing better optimization solutions this approach is more time and computationally expensive and requires higher knowledge levels from design of experiments, mathematical model development, optimization theory as well as meta-heuristics.

Finally, the problem of determining of laser cutting process conditions can be viewed as a multi-criteria decision making (MCDM) problem in which a particular cutting conditions represents an alternative while performance characteristics represent criteria upon which alternatives are assessed [17]. Although there is a number of mathematically relatively simple MCDM methods for assessment and ranking of alternatives, determination of laser cutting process conditions by using MCDM methods still do not have wide application in practice. Given that there is a finite number of pre-known alternatives (laser cutting process conditions) this type of multi-criteria optimization problems are referred as discrete.

The previously discussed four main approaches are predominantly used in manufacturing practice for determination of laser cutting process conditions. In practice the selection of a given approach is dependent on the particular application. Thus, if there is a need for large batch laser cutting on expensive work materials, the application of continual optimization may the right choice. On the other hand, in situations where waste and possible post-processing imply negligible financial losses, one can select other more simple approaches. Each approach has some advantages, disadvantages and limitations. Although does not provide even near optimal laser cutting process conditions, trial and error method can provide satisfactory results without the need of domain expert knowledge. On the other hand, formulation and solving of multi-criteria continual optimization problems can provide optimal laser cutting process conditions, however, this approach requires a considerable knowledge level of laser cutting, DOE, mathematical modeling, optimization and AI methods. Finally, if time is a limiting factor one can consider discrete optimization approach, whether Taguchi or MCDM methods. Comparison of existing approaches for determination of laser cutting process conditions with respect to different criteria is given in Table 1.

Table 1
Comparison of the existing approaches for determination of laser cutting process conditions.

	Trial and error	Taguchi method	Continual optimization	Discrete optimization
Computationally expense	–	small	high	small
Implementation time	permanent	fast	average	fast
Quality of determined solution	low	good	high	good
Practical suitability	high	very high	very high	average
Requirements of particular knowledge	–	some	high	some
Possibility to handle a number of criteria	none	good	good	very good
Requirements of using specialized software	–	none	yes	none

2. Application methodology

The application methodology for determination of laser cutting process conditions with the use of the PSI method can be summarized in the six following steps: problem definition, pre-analysis, laser cutting experimental investigation, data acquisition, formulation of decision matrix and application of the PSI method.

Problem definition implies determination of the objectives (customer requirements and manufacturers preferences) regarding desired cut quality, productivity and cost.

The goal of pre-analysis step is identification of main laser cutting parameters that predominantly influence the objective functions, i.e. laser cutting performance characteristics (surface roughness, kerf width, HAZ, MRR, etc.). Therefore, the laser cutting performance characteristics can be regarded as criteria for evaluation of laser cuts. To this aim in this stage one can perform one factor at a time (OFAT) experimental trials or conduct screening experimental designs such as Plackett-Burman designs.

Once the main laser cutting parameters are singled out, experimental trials with different laser cutting parameter values combinations are to be carried out. The laser cutting parameters are to be varied in a range considering manufacturing practices so that wider experimental hyperspace is covered while ensuring that full laser cut is obtained in each combination. To ensure minimal resource use and time saving experimentation one could apply Taguchi's orthogonal arrays, Box-Behnken designs, composite designs, fractional factorial designs, etc.

Data acquisition refers to measurement/calculation of quality and performance characteristics that are obtained in each experimental trial, i.e. for each laser cutting parameter values combination.

After collection of experimental data one needs to formulate decision matrix based on experimental data for each experimental trial, i.e. combination of laser cutting parameter values with respect to all considered criteria (performance characteristics). Each row in the decision matrix represents one alternative (specific laser cutting process condition), and each column represents one criterion.

The final step is the application of the PSI method for deriving the decision rule upon which the most suitable laser cutting process condition can be determined. The goal of the application of any MCDM method is to determine aggregate function, so-called decision