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SOFTWARE TOOL FOR THE LASER CUTTING PROCESS CONTROL – SOLVING REAL INDUSTRIAL CASE STUDIES

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Abstract. *Laser cutting is one of the leading non-conventional machining technologies with a wide spectrum of application in modern industry. It order to exploit a number of advantages that this technology offers for contour cutting of materials, it is necessary to carefully select laser cutting conditions for each given workpiece material, thickness and desired cut qualities. In other words, there is a need for process control of laser cutting. After a comprehensive analysis of the main laser cutting parameters and process performance characteristics, the application of the developed software tool "BRUTOMIZER" for off-line control of CO_2 laser cutting process of three different workpiece materials (mild steel, stainless steel and aluminum) is illustrated. Advantages and abilities of the developed software tool are also illustrated.*

Key Words: *CO_2 Laser Cutting, Process Control, Software Tool, Mild Steel, Stainless Steel, Aluminum, Cut Quality*

1. INTRODUCTION

The last decade has witnessed an increasing industrial use of contemporary materials with improved properties. Consequently, non-conventional machining technologies gain an ever increasing importance since in many concrete applications they represent the only possible, or at least, the only economically viable machining technology.

In a large number of non-conventional machining technologies that are widely used in modern industry the laser cutting stands out as a technology that offers a number of advantages such as: high productivity, high cut quality, low waste, ability to cut a wide range of materials, low operational costs when it comes to cutting speed, etc. [1, 2].

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However, effective application of the laser cutting technology requires excellent knowledge of the actual process as well as the determination of the most suitable laser cutting conditions for each purpose. In manufacturing companies it is a common practice for machine tool operators and/or process planning engineers to select laser cutting conditions based on their acquired knowledge and previous experience as well as machining handbooks. Although this is essentially a subjective approach, and selected laser cutting conditions are not even near optimal ones, in most cases this approach is sufficient [3]. As noted by Rao and Pawar [4], determination of the most acceptable machining conditions is essential as non-conventional machining technologies incur high initial investment, tooling, operating and maintenance costs. The situation is even more complex when attempting to satisfy multiple objectives (productivity, cut quality characteristics, cost, etc.), since the laser cutting conditions that are suitable for one performance characteristic may deteriorate other performance characteristics [5].

In the situations when there is a need to produce a large number of pieces, cut workpieces made of expensive materials, or to produce finished parts from the limited amount of available workpiece material, a comprehensive analysis and detailed process planning and control of the laser cutting process is necessary and preferred. In that sense, in order to ensure the achievement of the required processing quality, costs and productivity, it is necessary to quantify the relationships between the laser cutting process parameters and the process performance characteristics through mathematical modeling. On the basis of the established relationships it is possible to perform a detailed analysis of the effects of the process parameters on the process performance characteristics, identify near optimal values of the process parameters and control the actual laser cutting process.

From relevant literature one can observe that the selection of the laser cutting parameters on the basis of the established relationships between inputs and outputs is performed by formulation of a classical optimization problem with or without some constraints. Subsequently, an optimization method/algorithm is applied aiming to find extreme values of the objective function and corresponding laser cutting parameter values [6-9]. In contrast to the afore-mentioned approach this paper discusses the selection of the laser beam cutting parameter values based on the process control approach, i.e. situation when one needs to determine laser beam cutting parameter values so that the objective function has the target value, while, at the same time, other objective functions and possible constraints need to be taken into consideration. There are generally two approaches to the machining process control. One is adaptive control and the other is model-based simulation and control. The principal difference between these two approaches is that the adaptive control is a feedback method, whereas the model-based simulation and control is feed-forward in its characteristics [10]. The model-based simulation and control is basically an off-line strategy performed at the machining process planning stage, and its efficiency depends largely on the availability of accurate and reliable mathematical models [3].

In this paper a comprehensive analysis of the main laser cutting parameters and process performance characteristics shows the complexity of the laser cutting process, thus demonstrating the need for process control. Thereafter, the application of the developed software tool for off-line control of CO_2 laser cutting process is illustrated. Three real case studies dealing with CO_2 laser cutting of stainless steel, mild steel and aluminum alloy are considered.

2. COMPLEXITY OF THE LASER CUTTING PROCESS

Laser cutting represents a cutting technology in which material removal is carried out by the focused beam movement across the surface of the material. The laser beam heat melts/vaporizes the workpiece throughout the thickness in a fraction of second, thus creating a cutting front [11]. The molten material is removed using a coaxial jet of a pressurized assist gas. In Fig. 1 the schematic of the CO_2 laser cutting process is given. Depending on the nature of the assist gas, it may also help in enhanced material removal through chemical reactions such as oxidation of the material. If high productivity is the main criterion, then oxygen-assisted melt shearing is the chosen cutting mechanism. Alternatively, if a high edge quality is more important, then a slower high pressure inert gas melt shearing mechanism is used [2].

In mild steel laser cutting the most frequently used is oxygen as assist gas, whereby due to the exothermic reaction, additional energy is provided and used in the cutting process. In the case of stainless steel, laser cutting is commonly realized using nitrogen as assist gas in order to achieve a cut of high quality. The main reason is that some oxides such as chromium oxide, which is normally created when cutting with oxygen, have a high viscosity and are difficult to be ejected from the cutting zone [1]. Aluminum can be cut with both oxygen and nitrogen as cutting gases, but the cutting speed with oxygen is not significantly higher than with nitrogen. This is because solid or viscous aluminum oxide forms a seal on the cut front preventing the oxygen from penetrating into the metal itself [12].

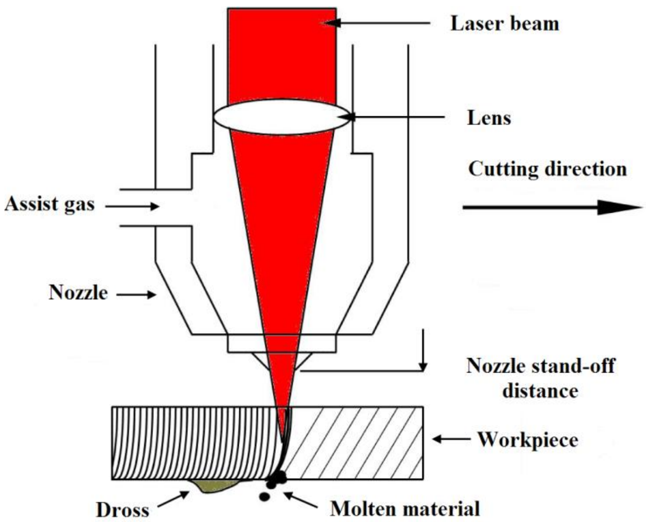

Fig. 1 Schematic diagram of CO_2 laser cutting

The laser cutting process is difficult to control due to the nature and complexity of the phenomena that occur in the interaction of the laser beam and the workpiece material (absorption of radiation, local heating, melting, evaporation, heat dissipation, removal of melted and vaporized material, etc.). In addition, as majority of the machining processes, the laser cutting process is a complex multi input multi output (MIMO) machining process in which a number of controllable and uncontrollable parameters (inputs) have an essential role in the process performance characteristics (outputs). Moreover, it is a diffuse process, as there are significant interactions between inputs, and has a stochastic behavior [13]. For successful realization of laser cutting for a given machining application it is necessary to consider a broad set of inputs, i.e. laser cutting parameters that directly determine laser cutting conditions as well as a set of outputs, i.e. laser cutting process performance characteristics (Fig. 2).

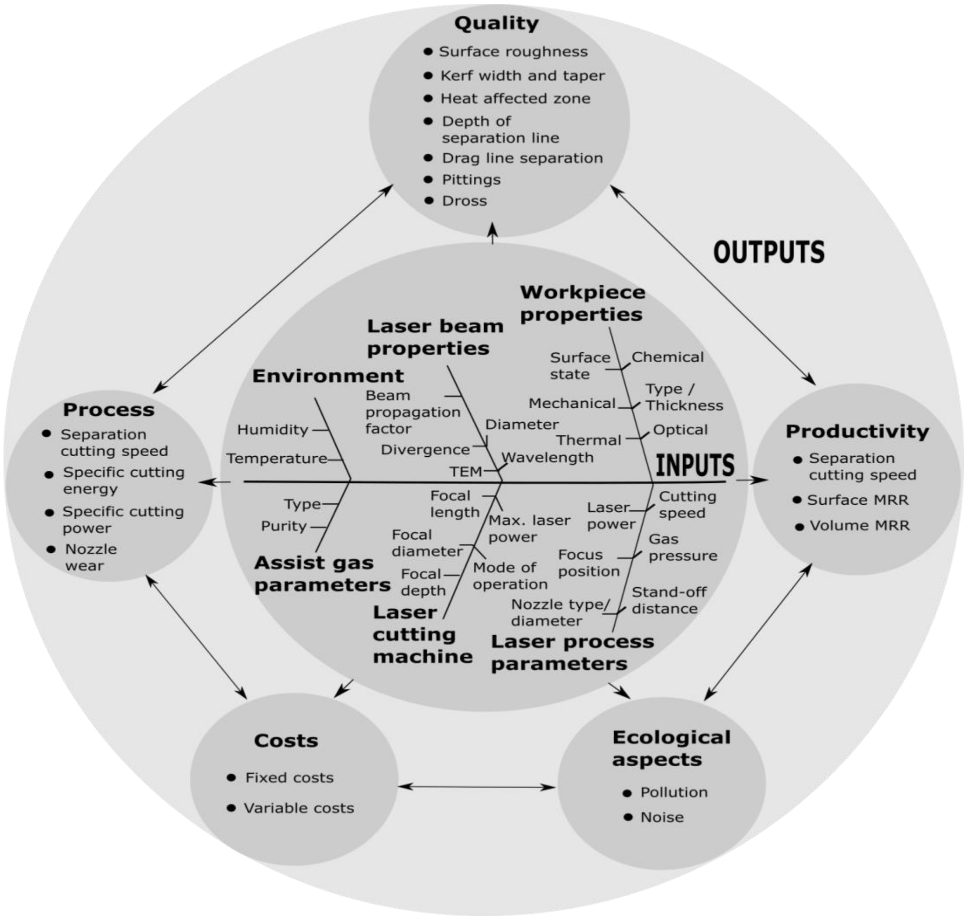

Fig. 2 Complexity of laser cutting process as MIMO machining process

As shown in Fig. 2, a set of inputs include parameters related to laser cutting machine, workpiece characteristics and laser process parameters. It should be noted that the set of laser process parameters consists of variable process parameters such as laser power, cutting speed and assist gas pressure, and constant process parameters such as focus position, type and purity of the assist gas, nozzle diameter and nozzle-workpiece standoff distance. In a real production environment, laser cutting machine operators usually consider afore-mentioned parameters as means of intermediate intervention for achieving desired effect during the laser cutting process.

As shown in Fig. 2 the laser cutting involves a number of process performance characteristics and it is difficult to perceive each of them for a given machining application. Moreover, it is important to notice that the process performance characteristics for a given machining application are in most cases interrelated, therefore there is a need to make certain trade-offs. For customers, quality performance characteristics and price are of the prime importance, while process and productivity performance characteristics as well as production costs are in the forefront for manufacturers. Ecological performance characteristics are closely related to different criteria defined by international environmental and ecological standards. In addition to energy, the assist gases consumed in the process and waste generated significantly contribute to the total environmental impact of the use stage of a laser cutting machine tool [14].

As clearly indicated in Fig. 2, a set of different parameters affect laser cutting process, wherein the character of the influence of certain parameter can be different taking into account interaction with other process parameters. Among others, laser power, cutting speed, assist gas pressure, focus position and characteristics of lasers and laser beam significantly affect the performance of the laser cutting process in terms of cut quality, productivity and efficiency for each workpiece material and thickness [1].

The afore-mentioned performance characteristics in laser cutting can be viewed as technological and techno-economic objective functions, which, for a given machining application, are to be met to the greatest extent.

3. Developed Software Tool

Desktop application “BRUTOMIZER” is a software tool developed for mathematical models optimization and off-line model-based simulation and control. The off-line control is based on exhaustive iterative search of input values combinations and corresponding mathematical model outputs. Input parameters of developed software tool are the following: a discrete set of possible input values, mathematical model for off-line control and arbitrary number of constraints. Both regression and artificial neural network (ANN) models are supported. “BRUTOMIZER” is able to determine the input values that correspond to the user-defined output with desired accuracy, and at the same time satisfy given constraints. As there can be many viable solutions in the case of off-line control, the developed software tool enables exploitation of solutions hyperspace starting from the smallest values as well as starting from the highest values of input parameters.

Main benefits of using developed software tool "BRUTOMIZER" are the following:

- user is able to define limits and search step for each input variable, according to the appropriate machine tool limitations,
- by using exhaustive iterative search algorithm, optimality of obtained solutions in given discrete search space is guaranteed,
- although brute force algorithm is used, the use of multiple processor cores enables very efficient application of the developed software tool even to very complex problems, and,
- intuitive user interface.

Developed software tool "BRUTOMIZER" is publicly available at http://www.virtuode.com/?page=SoftwareSolutions. A screenshot of the main window is shown in Fig. 3. In this window the user can set input parameters for both optimization and off-line control. A screenshot of the window for off-line control is given in Fig. 4.

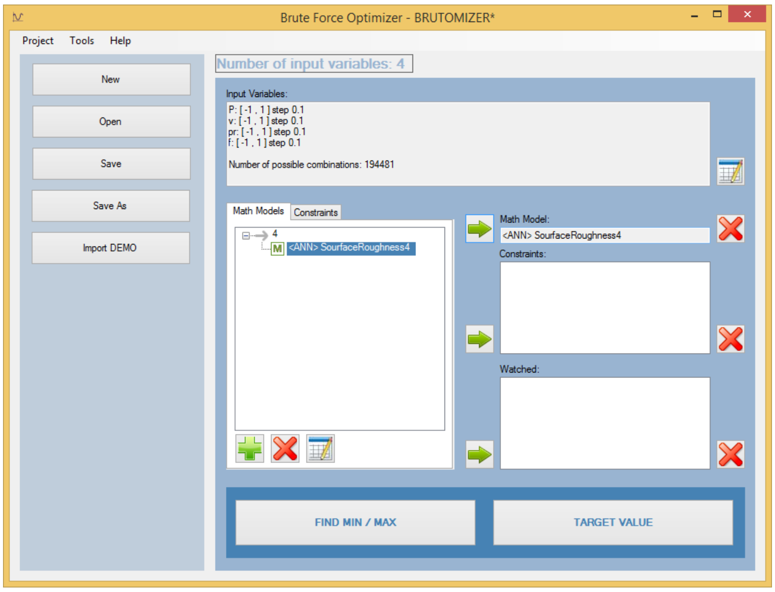

Fig. 3 Main window of the developed software tool "BRUTOMIZER"

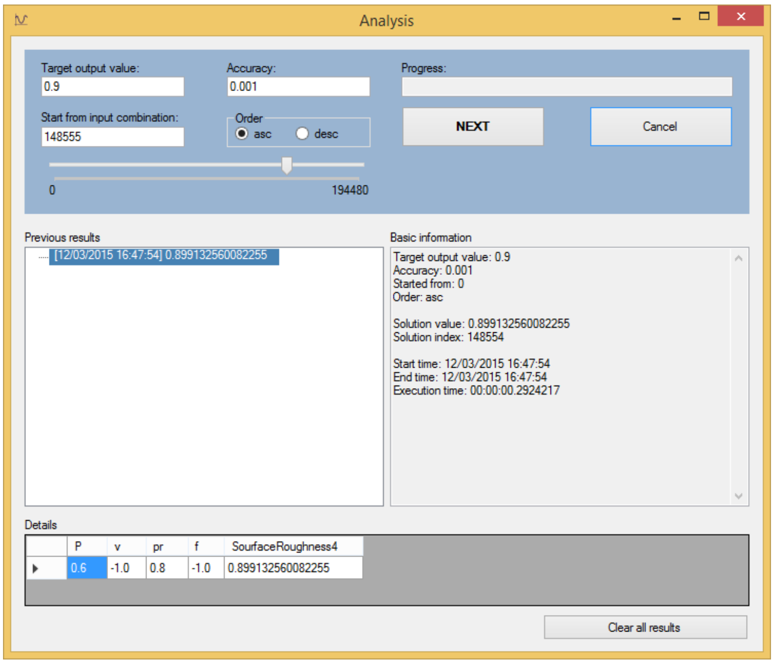

Fig. 4 Window for off-line control of the developed software tool "BRUTOMIZER"

4. CASE STUDIES

The application of the developed software prototype is demonstrated considering experimental data and developed mathematical models from previous investigations [1, 15, 16]. Three case studies have been considered, that is CO_2 laser cutting of stainless steel, mild steel and aluminum.

It should be noted that prerequisites for the application of the developed software prototype for off-line control of CO_2 laser cutting process are: planning and realization of experimental investigation of CO_2 laser cutting process and development of mathematical relationships between process parameters (inputs) and different performance characteristics (outputs). Case studies considered, used experimental plans, and details regarding developed mathematical models for the purpose of control of CO_2 laser cutting process are given in Table 1.

Table 1 Control of CO_2 laser cutting process: details of case studies

	Workpiece material	Experimental design	Mathematical model for control
Case study 1	stainless steel	Taguchi L_{27}	ANN
Case study 2	mild steel	Taguchi L_{25}	regression
Case study 3	aluminum	full factorial design	regression

In all the considered case studies, search step for each laser cutting parameter is set to 0.01. The search step defines the number of possible values for each parameter inside the parameter limits which are defined in experimental design.

4.1. CO_2 laser cutting of stainless steel - Case study 1

Consider the following situation in job shop manufacturing using CO_2 laser cutting technology. On the basis of technical drawing, manufacturing engineers in production planning need to determine laser cutting conditions for a large batch cutting. The main requirement is to obtain surface roughness of the cut edge of R_a=1.6 μm. It should be noted that an extremely high quality cut surface can be produced at the cost of higher production costs. CO_2 laser cutting is to be done on workpieces with thickness of 3 mm made of stainless steel by using nitrogen as assist gas.

Experimental investigation of CO_2 laser cutting process was performed by using Taguchi's L_{27} experimental design using different combinations of laser cutting parameters around the laser cutting conditions as recommended by manufacturer or as usually used. In the experiment four laser cutting parameters such as laser power (P), cutting speed v (m/min), assist gas pressure (p) and focus position (f) were varied at three levels in the following ranges: P=1.6-2 kW, v=2-3 m/min, p=0.9-1.2 MPa, and f=-2.5-2 mm [1]. Using the obtained experimental data, different ANN mathematical models were developed to establish relationships between laser cutting parameters and different performance characteristics. Mean absolute percentage error between experimentally measured values of surface roughness and ANN model predicted was about 8.5 %. This ANN model was then incorporated in the developed software prototype. On the basis of ANN mathematical models, which are valid for the covered experimental hyperspace, the software prototype can generate a set of potential solutions which satisfy the aforementioned requirement.

Based on the given target values for surface roughness and the desired accuracy, Δ, (maximum difference between the desired and calculated values of surface roughness) the software prototype can determine appropriate values of the laser cutting parameters. As explained previously, the software prototype can determine these values by two options: (1) starting from the smallest values of inputs i.e. laser cutting parameter values, and (2) starting from the highest values of inputs. Which option will be selected in the software prototype depends on the nature of the problem being solved and some other techno-technological aspects. The values of laser cutting parameters that satisfy the condition that surface roughness of the cut edge is R_a=1.6 μm are given in Table 2.

Table 2 Control of CO_2 laser cutting process of stainless steel

Option	P [kW]	v [m/min]	p [MPa]	f [mm]	R_a [μm]
1	1.83	2	0.9	–0.5	1.600
2	2	2.83	1.18	–0.5	1.601
desired accuracy, Δ=0.001					

If, for some reason, the total gas consumption is not so important, the laser cutting process should be realized using laser cutting conditions as determined by option 2, since a higher cutting speed ensures higher productivity. Otherwise, the laser cutting condition as determined by option 1 are recommended.

4.2. CO_2 laser cutting of mild steel - Case study 2

In the laser cutting process there are often situations when one needs to simultaneously satisfy a number of criteria, i.e. performance characteristics such as surface roughness, kerf taper angle, kerf width, material removal rate (MRR), heat affected zone, cost, dross, etc. For example, when determining laser cutting conditions that will ensure that the desired surface roughness is achieved, one can take other criteria into account, such as kerf width (K_w). The application of the developed software tool for control of CO_2 laser cutting process in these situations is illustrated in the following case study. CO_2 laser cutting is to be done on workpieces with thickness of 2 mm made of mild steel by using oxygen as assist gas.

In an experimental investigation of CO_2 laser cutting process Taguchi's L_{25} experimental design was applied, using different combinations of laser cutting parameters around the laser cutting conditions as recommended by manufacturer. In the experiment three laser cutting parameters such as laser power (P), cutting speed v (m/min) and assist gas pressure (p) were varied at five levels in the following ranges: P=0.7-1.5 kW, v=3-7 m/min and p=0.3-0.7 MPa [15]. Using the obtained experimental data, two mathematical models for the prediction of R_a and K_w in the form of regression equations were determined as:

$$R_a = -1.704 + 1.495 \cdot v + 5 \cdot P - 1.13 \cdot p - 0.72 \cdot v \cdot P + 0.091 \cdot v \cdot p + 0.842 \cdot P \cdot p - 0.136 \cdot v^2 - 2.495 \cdot P^2 \quad (1)$$

$$K_w = 0.306 + 0.00097 \cdot v - 0.576 \cdot P + 0.0894 \cdot p - 0.011 \cdot v^2 + 0.379 \cdot P^2 + 0.00286 \cdot p^2 - 0.0331 \cdot v \cdot P - 0.01976 \cdot v \cdot p \quad (2)$$

Mean absolute percentage errors between experimentally measured values of surface roughness and kerf width and model predicted values of surface roughness and kerf width were about 5 and 6 %.

Let us consider that it is necessary to determine such values of the laser cutting parameters so as to obtain surface roughness of the cut edge of R_a=1.6 μm and kerf width less that 0.25 mm (K_w<0.25 mm). Ten laser cutting conditions, i.e. laser cutting parameter value combinations, as determined by options 1 and 2 of the developed software tool are given in Table 3.

Table 3 Control of CO_2 laser cutting process of mild steel

Option	P [kW]	v [m/min]	p [MPa]	R_a [μm]	K_w [mm]
1	0.75	3	3	1.607	0.230
	0.75	3	3.05	1.5957	0.232
	0.8	3	3.4	1.6086	0.245
	0.8	3	3.45	1.5995	0.247
	0.8	3	3.5	1.5903	0.250
2	1.15	7	6	1.6032	0.232
	1.05	7	5.85	1.5922	0.231
	1	7	5.85	1.6036	0.233
	0.95	7	5.85	1.6026	0.236
	0.9	7	5.9	1.6024	0.241
desired accuracy, Δ=0.001					

From Table 3 it can be observed that for a constant cutting speed there exist a number of different combinations of laser power and assist gas pressure which satisfy given set of conditions. As in the previous case study, one can observe that higher productivity implies higher gas consumption, but also more laser power.

4.3. CO_2 laser cutting of aluminum - Case study 3

Laser cutting of aluminum and its alloys with CO_2 lasers is considered difficult because of high reflectivity and thermal conductivity of aluminum alloys. In essence it represents a specific laser cutting process since performance characteristics (outputs) are highly sensitive to the laser cutting parameters and their interactions. Moreover, the same performance characteristics can be obtained by a number of different combinations of laser cutting parameter values [16]. The application of the developed software tool for control of CO_2 laser cutting process in these situations is illustrated in the following case study. CO_2 laser cutting is to be done on workpieces with thickness of 3 mm made of aluminum alloy by using nitrogen as assist gas.

For the purpose of experimental investigation of CO_2 laser cutting process, a 3^3 full factorial experimental design using different combinations of laser cutting parameters was applied. In the experiment three laser cutting parameters such as laser power (P), cutting speed v (m/min) and assist gas pressure (p) were varied at three levels in the following ranges: P=3-4 kW, v=3-3.5 m/min and p=0.6-1 MPa [16]. Using the obtained experimental data, the mathematical model for the prediction of kerf width (K_w) in the form of regression equation was determined as:

$$K_w = -0.81791 + 1.5983 \cdot P + 0.32929 \cdot p - 1.72637 \cdot v - 0.23837 \cdot P^2 - 0.00612 \cdot p^2 + 0.36 \cdot v^2 + 0.01072 \cdot P \cdot p + 0.00622 \cdot P \cdot v - 0.07778 \cdot p \cdot v \quad (3)$$

Mean absolute percentage error between experimentally measured values of kerf width and model predicted values of kerf width was about 5 %.

Let us consider that it is necessary to determine the values of laser cutting parameters so as to obtain and kerf width less than 0.5 mm (K_w<0.5 mm) while maximizing material removal rate (MRR). Higher MRR is always preferred, particularly in large batch production. MRR can be calculated as the product of cutting speed, workpiece thickness and kerf width.

Different cutting conditions, i.e. laser cutting parameter value combinations, as determined by options 1 and 2 of the software tool are given in Table 4.

Table 4 Control of CO_2 laser cutting process of aluminum

Option	P [kW]	p [MPa]	v [m/min]	K_w [mm]	MRR [mm^3/min]
1	3	6	3.1	0.499	4640.7
	3	6	3.11	0.499	4655.67
	3	6	3.12	0.5	4680
	3	6.05	3	0.499	4491
	3	6.05	3.01	0.499	4505.97
2	3	6.05	3.09	0.5	4635
	3	6.05	3.08	0.5	4620
	3	6.05	3.07	0.5	4605
	3	6.05	3.06	0.499	4580.82
	3	6.05	3.05	0.499	4565.85
desired accuracy, Δ=0.001					

As can be observed from Table 4, among different combinations of laser cutting parameter values that produce almost the same kerf width, the third combination of the laser cutting parameter settings as determined by option 1 stands out and ensures the maximal MRR.

5. Conclusion

Complexity of the laser cutting process imposes the need to control the process in order to fulfill product specifications, improve materials processing and decrease processing costs. In this paper, the application of developed software tool "BRUTOMIZER" for off-line control of CO_2 laser cutting process is illustrated. Three real industrial case studies were considered showing a number of advantages of using developed software tool for CO_2 laser cutting process control. Among others, the most important are guaranteed optimality of the selected laser cutting conditions, ability to consider machine tool limitations in terms of allowed laser cutting parameter values and ability to obtain a set of solutions. Particular advantage of the developed software tool is its ability to be used as a laser cutting technological processor which can be further upgraded by incorporating new mathematical models which describe various CO_2 laser cutting processes.

As the presented approach for selection of process parameters values allows consideration of machine tool limitations and specific constraints, future research will be directed towards the application of developed software tool for off-line control of other machining processes. Also, the application of the developed software tool for solving machining multi-objective optimization problems with a number of constraints of equality and/or inequality type will be investigated.

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