"HENRI COANDA"
AIR FORCE ACADEMY
ROMANIA

"GENERAL M.R. STEFANIK"
ARMED FORCES ACADEMY
SLOVAK REPUBLIC

INTERNATIONAL CONFERENCE of SCIENTIFIC PAPER
AFASES 2012
Brasov, 24-26 May 2012

APLICATIONS OF FULL FACTORIAL DESIGN FOR LASER PROCESSING

Cristian MÎNZAT*, Remus BOBOESCU*

*Mechanical Faculty, University Politehnica, Timisoara, Romania,

Abstract: *We analyze the fusion lines fused applicable for laser welding of steels. A factorial experimental design type* 2^2 *in which were varied power and welding speed was applied to thick carbon steel plates. The laser beam focuses to the workpiece surface and at 2mm inside piece were used. The weld cross section weld depth and weld molten zone area were measured. Effects of power and welding speed were presented by Pareto charts. It was shown that the laser beam power has role in determining the material molten zone dimensions.*

Keywords: *laser welding, steel, Pareto chart, keyhole welding regime, melted area*

1. INTRODUCTION

Experimental modeling of laser welding of steels has been the subject of several studies. Olabi (2006)[1] conducted a study on CO_2 laser welding of steels with medium carbon content. As response function are considered the ratio of weld depth and width and depth of the weld and heat affected zone width. Benyounis and others (2005) [2] studied to optimize the laser welding with a CO_2 laser ,of steel with medium carbon content .As a influence factors are considered laser power, welding speed and focal point position, (defocusing distance). As the response function is take heat necessary for the process of welding, weld width, heat affected zone width and depth of weld. Anwara (2008)[3] presented a study on the laser welding of two different materials: steel AISI 316 stainless steel and low carbon steel AISI 1009 using a CO_2 laser with emission in continuous regime. The study led to the conclusion that laser power and welding speed are influence factors of significant influence on the welding bath. Benyounis (2008) [4] is studying the laser welding for stainless steel AISI304. Determined correlation function was the square type. ANOVA method was used for statistical analysis of variance and response surface method for the representation of results. The study described some conditions for the realization of the welding process.

This paper proposes a study on the weld cross section area which is melted in laser welding. On the weld cross section dimensions of molten zone are considered. Shape of melted area shows the welding regime, conduction welding or keyhole regime.

2. EXPERIMENTS

The experiment consisted in made lines of fusion (welds), 110 mm long, on Dillimax 500 steel plates with thickness of 10 mm (carbon steel, carbon content ≤ 0.16 %), figure 1. Was used a Nd: YAG Trumph Haas 3006D laser source with 3kW maximum power on a continuous wave regime CW. Laser beam was transmitted through a optical fiber with core diameter of 0.6 mm

The focus system made a focal spot with 0.6 mm diameter. Lens focal length was 200 mm. As protective gas argon was used with a flow rate of 20 l/min. Parameters varied in the experiments are presented in Figure 2.

Figure 1 Image the welds a) plate surface b) welds cross-section

In experiments was varied the laser power, welding speed and distance between focal plane and piece surface (defocusing or defocusing depth) figure 2. Welds were cut in the stable part of the weld near the place where welding process was stopped. Weld section was processed metallographic. Weld width, near the piece surface, and weld depth were examined using a microscope with precision of 0.01 mm. Melted area was measured directly by its footprint.. Defocusing values are considered negative if the laser beam focus inside the piece.

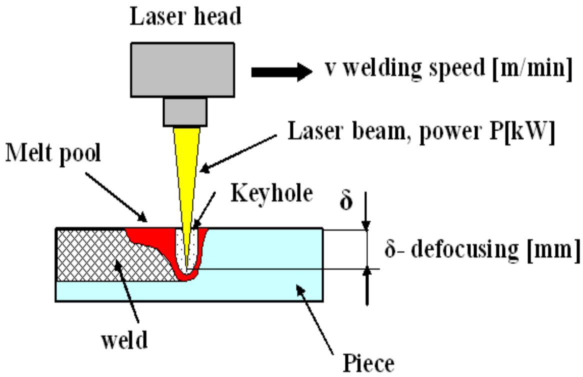

Figure 2 Scheme welding pool with varied parameters in welding process

In the experiments were varied power and welding speed. To statistically analyze the effects of parameters was necessary to introduce a dimensionless parameter values.Transformations between the two systems of parameters values are presented in table 1

The experimental plan is presented in Table 1 with actual values that coded for power and cutting speed.

Table 1: Varied parameters values in experiment

	Power		Speed	
weld	A[-]	P[kW]	B [-]	v[m/min]
1	-1	1	-1	0.6
2	+1	3	-1	0.6
3	-1	1	+1	1.5
4	+1	3	+1	1.5
5	0	2	0	1
6	0	2	0	1
$A = P - 2$ [-] $B = -2.33 + 2.22v$ [-]				

Analysis procedure consisted of presenting the results of the mathematical model, ANOVA table showing the correlation coefficients associated with the mathematical model, Pareto chart showing the hierarchy of effects and response surface is a graphic representation of mathematical model. For the mathematical model were presented two forms for real values laser power and welding speed and for coded system values. The first allows rapid application of formulas and the second allows direct analysis of the values of regression coefficients. Based on these values were achieved Pareto charts.Figure 3 shows the analysis weld scheme and analyzed sizes that characterizing the weld.

To study objective functions characterizing welds made were considered as parameters of the laser beam power and welding speed. Power is related to the laser beam intensity. Welding speed is related with the time of interaction between laser beam and material. These parameters were independent action. Defocus of the beam at piece surface changes the effects of the laser beam intensity and time of interaction in a way that can not be said before. The two levels of defocus present in the experimental plan will be called the focus to the piece surface and focus within the piece. Defocusing effect is considered high with the descent of laser beam focal plane within the piece.

Experimental data processing was performed using the Statgraphics program.
The analysis consisted of determining the polynomial mathematical models, making Pareto charts and statistical analysis using ANOVA method. For data analysis was considered only Pareto diagrams. Much of the information provided by other data processing is included in these figures. Pareto chart shows the contribution of each effect in determining the objective function (measured size). Associated positive sign for effect value indicates increases of objective function value. Negative sign for effect value indicates that this effect decreases the value of objective function.

Variation for objective function values will be discussed for situation where the parameter or effect increases. Pareto diagrams containing the interaction between laser beam power and welding speed are based on a quadratic model. Pareto diagrams without interaction are based on a linear mathematical model.

3. ANALYSIS WELD CROSS SECTION

Weld cross section analysis aim is to reveal the effects of parameter variations on the dimensions of the material melted area.
For the weld cross section the analyzed sizes are shown in Figure 4.

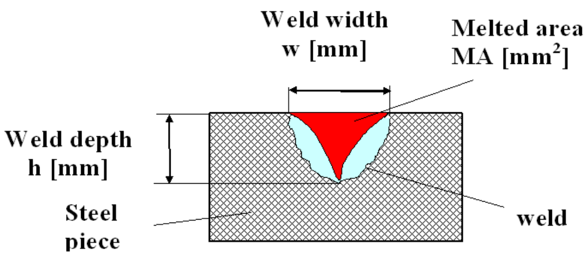

Figure 4 Weld cross-section with the considered sizes

On the weld cross section was measured near the surface of the weld the width w[mm], at the center of the weld the depth h [mm] and melted area MA [mm^2]. These measurements are shown in Figure 4.

The analysis will start with where the laser beam focusing was performed on the workpiece surface. In this case for a given power level the laser beam intensity at piece surface had maximum value. Laser beam spot size at the workpiece surface had minimal value.

Figure 5 shows the effects of power and welding speed on weld width w for the laser beam focus on the workpiece surface. Note that the weld width increases with power and decreases with welding speed. Interaction between parameters is low and decreases the weld width.

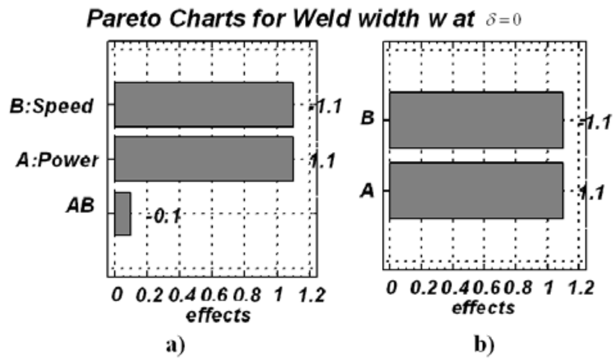

Figure 5 Pareto chart for weld width for focus at piece surface a) with interaction between the effects b) without interaction

Figure 6 presents the parameters effects on weld depth for focusing the laser beam to the workpiece surface. Note that the weld depth increases with power and decreases with welding speed. The power effect is much higher than the welding speed effect. We can say that the weld depth depends almost exclusively by power level.

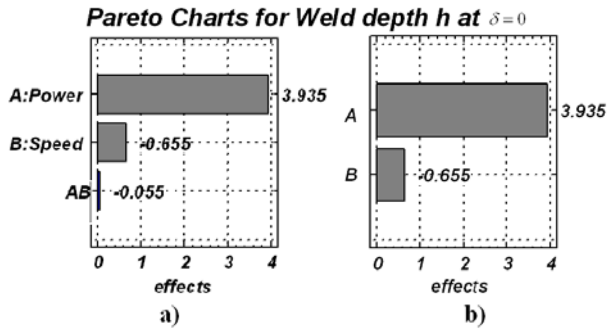

Figure 6 Pareto chart for weld depth for focus at piece surface a) with interaction between the effects b) without interaction

Figure 7 shows the effects of parameters for melted area on the cross section. It shows that melted area increases with power and decreases with welding speed. Power has the highest effect. Interaction between power and welding speed decreases melted area. The interaction effect is quite high compared with previous cases analyzed. So the overall effect of welding speed is close to the power effect.

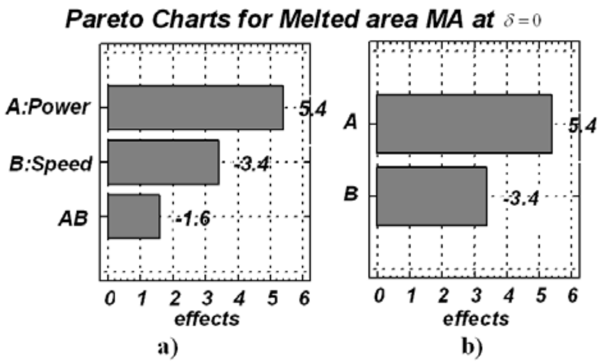

Figure 7 Pareto chart for melted area for focus at piece surface a) with interaction between the effects b) without interaction

Analysis of variance for focusing the laser beam to the workpiece surface showed that the higher effect belong to power. This is related to quantitative aspect for formation of melt. Increasing welding speed has a decreasing effect for molten zone. If we discuss strictly dimensional appearance of melt zone is observed that power and welding speed are equal but opposite sign contributions. The interaction effects between the parameters are small. This is due to the high intensity of laser beam which provides a good separation between the effects of power and welding speed.

Focus inside piece decreases the laser beam intensity on piece surface. This is achieved by increasing the laser beam spot size at the workpiece surface. In this situation laser beam propagates convergent in the keyhole. This will increase the energy absorbed in the keyhole.

Figure 8 presents the parameters effects on the weld width w for laser beam focus t inside the piece. Note that the weld width with increases with power and decreases with welding speed. Interaction between power and welding speed decreases the weld width. This effect is relatively high compared with other effects listed Decreasing effect of weld width is given by the speed of welding and its interaction with power. Overall decreasing effect does not exceed the increasing effect given by power. It looks like there is a better control of weld width by power. This was not observed for focusing the laser beam to the workpiece surface.

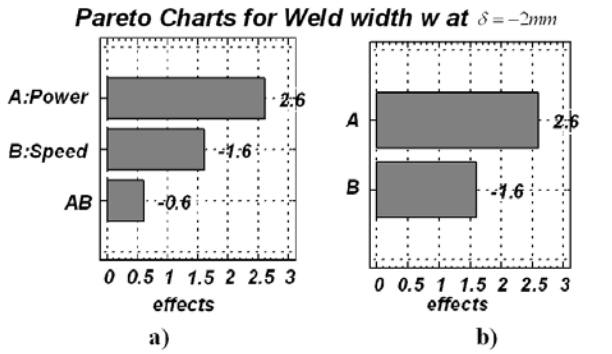

Figure 8 Pareto chart for weld width for focus within the piece a) with interaction between the effects b) without interaction

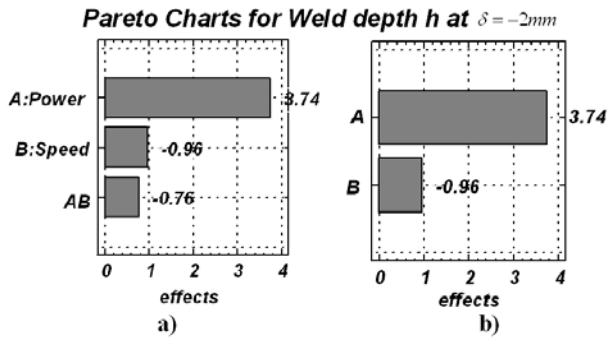

Figure 9 Pareto chart for weld depth for focus within the piece a) with interaction between the effects b) without interaction

Figure 9 presents the effects of welding parameters on weld depth for laser beam focusing the inside the piece. Weld depth greatly increase with power and decreases with welding speed. Interaction between power and welding speed decreases the weld depth. Decreasing effect on speed (through its effect and the interaction effect) is much higher than effect when focusing the laser beam on workpiece surface.

It is shown that variations with welding speed which change the interaction time between laser and material affect greater the weld depth focusing the laser beam welding inside piece than focusing at piece surface.

Figure 10 shows the effects of parameters for melted area on the weld cross section for laser beam focus within the piece. Note that melted area increases with power and decreases with welding speed. The first effect is the power effect and the second effect is the interaction between power and welding speed. Welding speed and the interaction between speed and power decreases the melted area.

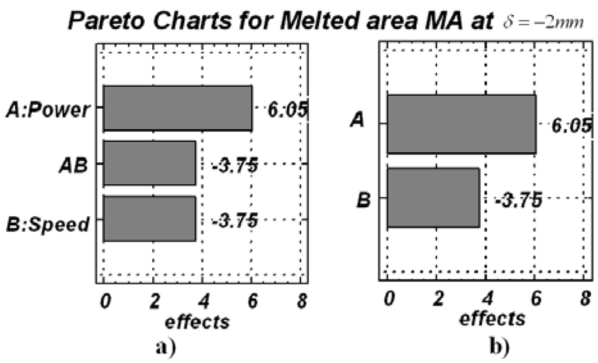

Figure 10 Pareto chart for melted area for focus within the piece a) with interaction between the effects b) without interaction

The two effects are almost equal.On the overall decreasing effect due to welding speed is greater than power effect. Thus appear that for melted area the role of interaction time between laser radiation and the material is higher.

For the laser beam focus the inside the piece was shown that there is an increased role of the interaction between power and welding speed. Weld width and weld depth depend on power as higher effect and both are expression for melt formation. Melted area has a significant dependence of welding speed. Low intensity causes heat loss in the material may have an increased role and decreases amount of melt.

4. ANALYSIS OF THE DYNAMIC ASPECT FOR WELDING PROCESS

Issues related to welding regime and melt movement can be identified in the variation of measured quantities on weld surface and weld cross section. Analyzed sizes are presented in Figure 11.

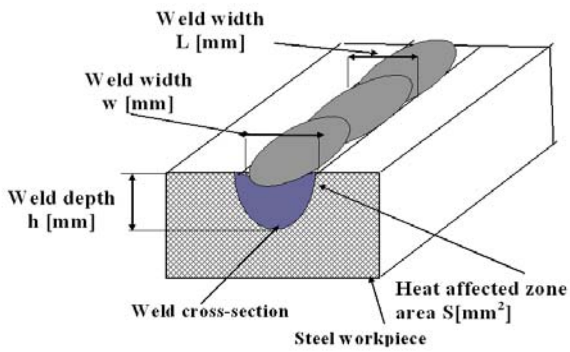

Figure 11 Scheme of weld with measured sizes

The paper analyzed variations the following sizes: weld width, shape ratio of weld cross section and the heat affected zone area on the weld cross section.

Weld width L[mm] was obtained as a result of three measurements on the weld surface at the beginning, middle and end of the welding process.The weld width characterized in general the weld and it is independent of the area in this cross section in weld was performed.

F ratio (w/h) is the ratio beetwen weld width and weld depth on the weld cross section. This ratiois associated with the welding regime characterization.Values of F ratio below unity shows keyhole welding regime.

A heat affected zone area S[mm^2] was measured on the weld cross section. It is given by the isothermal line of transformation metal structure which is well below the melting temperature. Area heat affected zone containing molten zone area. Heat affected area can be measured with greater accuracy than the area of molten zone.

Figure 12 shows the effects of parameter variations on weld width L when laser beam was focusing the to the workpiece surface. Note that the weld width decreases with welding speed and increases with power. Welding speed has the first effect. This is almost equal to the effect of the interaction between power and welding speed. It is shown that the laser beam focus on the workpiece surface may produce instability for weld width depending on the varied parameters values.

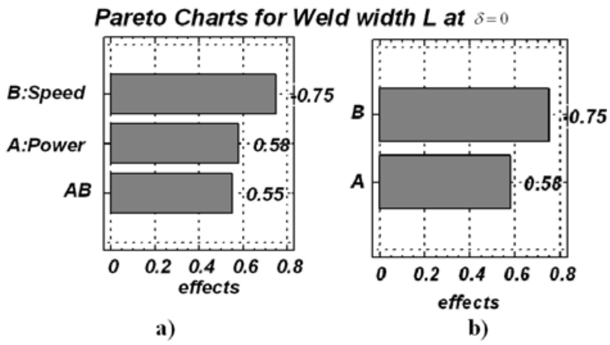

Figure 12 Pareto chart for weld width for focus at piece surface a) with interaction between the effects b) without interaction

Figure 13 shows the Pareto chart for ratio F for focusing the laser beam to the workpiece surface. Note that ratio F decreases with power and have a slight increase with welding speed. Interaction between power and speed decreases ratio F. This is the second effect. A decrease in the F ratio means transition from conduction welding regime to keyhole welding regime. This occurs for high values of laser beam intensity to the workpiece surface. Interaction sign indicates that the interaction effect acts as the effect of power favors keyhole welding regime. It will facilitate the secondary absorption of laser radiation in keyhole.

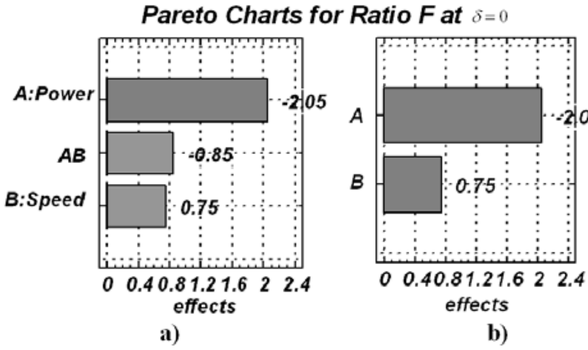

Figure 13 Pareto chart for ratio F for focus at piece surface a) with interaction between the effects b) without interaction

In Figure 14 shows Pareto diagram for the heat affected zone area on the weld cross section for laser beam focusing to the workpiece surface. It noted that heat affected zone area increases with power and decreases with welding speed. Decreasing effect of welding speed is higher than the increasing effect of power. The two effects have close values. This shows that the variation of parameters which also can produce instability in the material heat affected zone.

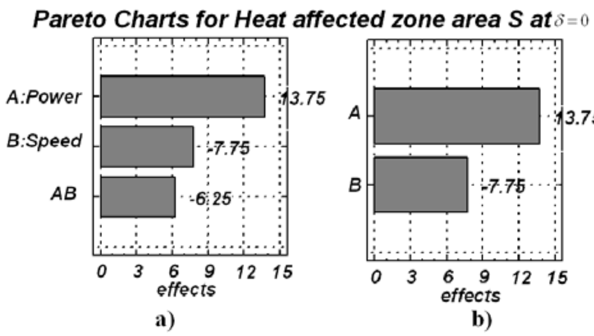

Figure 14 Pareto chart for heat affected zone area for focus at piece surface a) with interaction between the effects b) without interaction

Analyzed sizes show that with increased power is obtained keyhole welding regime. Focusing the laser beam to the workpiece surface is a source of instability for weld presented both by the weld width and heat affected zone area.

Figure 15 presents Pareto diagram for weld width L for focus within the piece. Note that the weld width increases with power and decreases with welding speed. Interaction decreases the weld width. On the overall increasing effect of power and decreasing effect of welding speed are close.

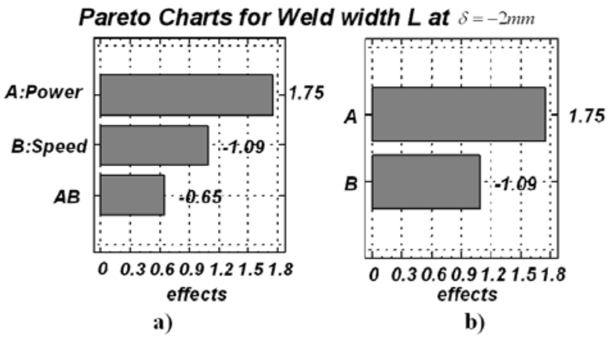

Figure 15 Pareto chart for weld width for within the piece a) with interaction between the effects b) without interaction

Figure 16 shows Pareto diagram for F ratio where the laser beam focus is achieved within the piece. Note that F ratio decreases with power and with welding speed. Interaction between power and welding speed increase ratio F. Interaction effect is close to welding speed effect. The speed effect shows that in the situation by decreasing the interaction time between laser beam and material there is propagation of melting front inside the workpiece and not in the sides of the weld bath.

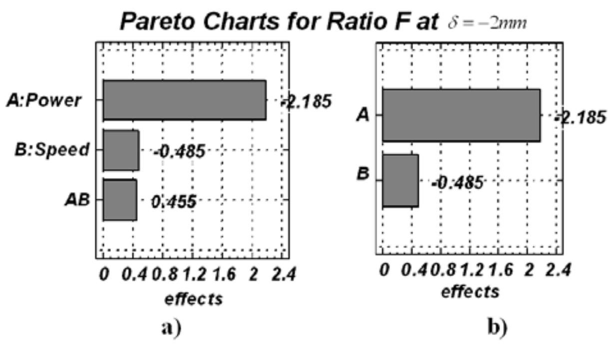

Figure 16 Pareto chart for ratio F for focus within the piece a) with interaction between the effects b) without interaction

For focus the laser beam inside the piece laser beam spot on piece surface is greater. Keyhole cavity is large and favors the emergence of multiple reflections of laser radiation.

Figure 17 presents Pareto diagram for heat affected zone area for laser beam focus the inside the piece. It shows that the area S increases with power and decreases with welding speed. Interaction between power and welding speed decreases the area S On the overall decreasing effect given by welding speed is less than the increasing effect of the power.

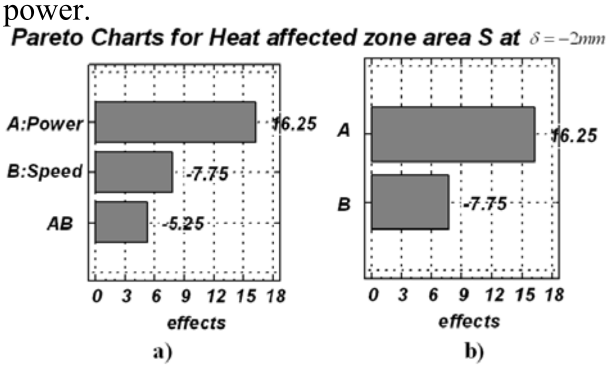

Figure 17 Pareto chart for heat affected zone area for focus within the piece a) with interaction between the effects b) without interaction

If compared with the focus on the workpiece surface shown an increase in power effect. This means increased control over the area S and reduces instability of welding process.

5. CONCLUSIONS

The paper analyzed several quantities that characterize laser welds made on steel plates. Thus the weld width w, weld depth h and molten area MA on the weld cross section show characteristics of material melting. Weld width L, the ratio F and heat affected zone area on the weld cross section can be correlated with the dynamic aspects of laser welding process. Pareto diagrams showed the effects of power and welding speed. Its considered two particular cases to focus the laser beam, focusing on the piece surface and focus within the piece. Its showed the following:

- Power and welding speed are the main parameters that characterize the material melting and welding process.
- The highest effect on melted area belong to power
- Pentru zona topită există întotdeauna o balanță între efectul de creştere al puterii şi cel de scădere al vitezei de sudare.
- For the melting area there is always a balance between the increasing of power and decreasing effect of welding speed.

Close values for increasing and decreasing effects are considered to be a source of instability. This has influence in parameters setting for welding process.

-Laser-beam focus within the piece provides a better control on the characteristics of molten zone by setting the power.

-The dynamic aspect of the welding process was shown by the transition from conduction welding regime to keyhole welding regime with increasing power. Showed that variations in weld width L measured at different points of weld are high than for the weld width w measured near the weld cross -section.

-Variations obtained for sizes with similar definitions (weld width w, weld width L and area melted MA, heat-affected zone area) are the same type. It looks like that type of variation can be generalized and general characteristics of the welding process are presented.

-It is recommended to consider the interaction between parameters. Presentation for each analyzed size two Pareto diagrams showed that for this type of analysis considering the effects of interactions are important.

REFERENCES

1. A.G. Olabi , G. Casalino b, K.Y. Benyounis, M.S.J. Hashmi,An ANN and Taguchi algorithms integrated approach tothe optimization of CO2 laser welding, *Advances in Engineering Software* 37 (2006) p:643–648
2. K.Y. Benyounis , A.G. Olabi, M.S.J. Hashmi “Optimizing the laser-welded butt joints of medium carbon steel using RSM” *Journal of Materials Processing Technology* 164–165 (2005) pp.986–989.
3. E.M. Anawa, A.G. Olabi Using Taguchi method to optimize welding pool of dissimilarlaser-welded components *Optics & Laser Technology* 40 (2008) p:379–388.
4. K.Y. Benyounis, A.G. Olabi, M.S.J. Hashmi, Multi-response optimization of CO2 laser-welding process of austenitic stainless steel *Optics & Laser Technology* 40 (2008) pp.76–87.