“Mircea cel Batran” Naval Academy Scientific Bulletin, Volume XIV – 2011 – Issue 2
Published by “Mircea cel Batran” Naval Academy Press, Constanta, Romania

ANALYSIS OF DYNAMIC ASPECTS OF STEEL PIECES MELTING IN LASER WELDING

Remus BOBOESCU[1]
[1] Ph.D., Professor, Polytechnic University Timişoara

***Abstract**. We analyze the conditions for obtaining molten zone for welds made with laser Nd: YAG on carbon steel plates 10mm thick. Power and welding speed are the main parameters that control the welding process. We analyze the effects of distance between the focal plane and the workpiece surface (defocusing). From the analysis of welds cross section the welding regime is identified by shape and area of molten zone. Dynamic aspects of the welding process are showed by solid waves on the weld surface and by crater at end of the welding process.*

Keywords laser welding, carbon steel, weld surface, solid waves, response surface

1. Introduction

Laser welds surface analysis shows interest in terms of physical phenomena occurring in the welding bath. At the welds surfaces appear where solid waves having a great regular in shape and sizes (height, width and curvature).Their appearance is explained by the melt movement welding bath. Waves on the surface of the welding bath are trapped in the solidification [1]. As remoteness from the formation point the wave period increase and becomes comparable to the solidification time. Production of solid waves is simultaneous with the over lifting of the weld. Accurate assessment of solid waves formation and their regularity is difficult. For weld solid waves are studied the two consequences of their presence. They are weld over lifting and weld surface roughness [2], [3].

The purpose of the paper is to present the characteristics of solid waves produced at weld surface. They come from catching molten material current in the solidification proces. Solid wave contour (wave length) characterizing the weld surface. It simultaneously shows the welding bath width and melt movement in welding bath. This paper studies compared solid wave contour length (wave length) and weld width.

2. Experimental procedure

The experiment consisted of fusion lines (welds) with the line length of 110mm on steel Dillimax500 plates with thickness 10 mm. An industrial laser machine Nd: YAG Trumph Haas 3006D was used. It emits radiation with wavelength λ = 1.06 μm and has a maximum power of 3kW. Irradiation was performed in continuous regime. Laser beam was transmitted through a fiber with 0.6 mm diameter. The focusing system assures the spot in focal point with 0.6 mm diameter. The focal distance of lens was 200 mm. As protective gas was argon with a flow rate of 20 l/min. On the 6 sheets of material with $100\times130\times10$ mm dimensions was made between 5 and 8 welds on each plate, total 37 welds.

The material used was steel Dillimax500 EN 10137. This is a fine grain steel with high elasticity limit elasticity. Chemical composition with the upper limit expressed as a percentage is given as follows:$C\leq 0.16, Si\leq 0.5, Mn\leq 0.1.6, P\leq 0.02, S\leq 0.01, Cr\leq 0.7, Ni\leq 1, Mo\leq 0.6, V+Nb\leq 0.08.$

Steel was made by tempering in water and return. Dillimax500 has a low carbon content and relatively low carbon equivalent index. Also it shows a low hardness in heat affected zone and therefore a low risk fracture at cold because inclusion of hydrogen and good tenacity. Experience shows that good characteristics are obtained in welded area if the parameters are chosen so that cooling times $t_{8/5}$ have value between 10 to 30 seconds.

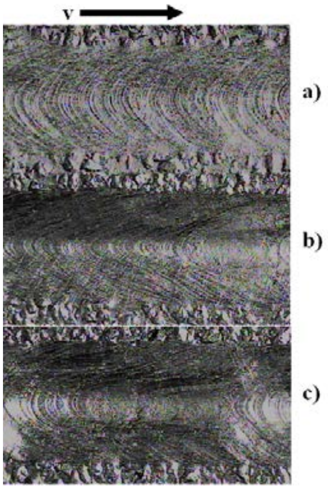

Fig. 1 Weld surface for welds made at laser power a) 1.5kW, b) 2.5kW, c) 3kW

Table 1. Values of parameters in experiment

Weld	Power		Speed		Defocusing	
	P[kW]	A[-]	v[m/min]	B [-]	δ [mm]	C [-]
1	1	-1	0.6	-1	0	-1
2	3	+1	0.6	-1	0	-1
3	1	-1	1.5	+1	0	-1
4	3	+1	1.5	+1	0	-1
5	1	-1	0.6	-1	-2	+1
6	3	+1	0.6	-1	-2	+1
7	1	-1	1.5	+1	-2	+1
8	3	+1	1.5	+1	-2	+1
9	2	0	1	0	-1	0
10	2	0	1	0	-1	0
$A = P-2$ [-], $B=-2.33+2.22v$ [-], $C=-1-\delta$ [-]						

Experiments were conducted after complete factorial plan or full factorial design type 2^3. It contains three variables with two levels to each one. Scheme using a combination of factors levels “one with each others” For statistical analysis is added a number experiments with values at mid-range level named as replies in the centre point of the experimental field. For the varied parameters values are expressed as dimensionless variables. Such for presented experiments varied parameters (or influence factors) are named laser power A [-], welding speed B[-] and defocusing C [-]. Their levels are designated by values +1 for the upper level and -1 for the lower level. Table 1 shows actual and coded values for made welds. Figure 1 shows the welds surfaces for increasing values of laser power. In Figure 2 are presented the vary parameters in experiments.

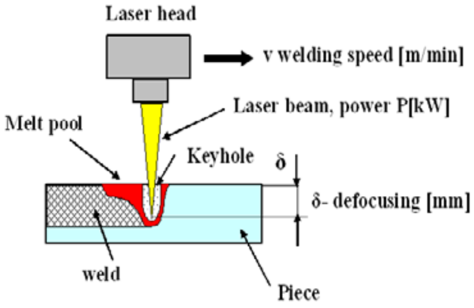

Figure2 Parameters varied in experimental tests

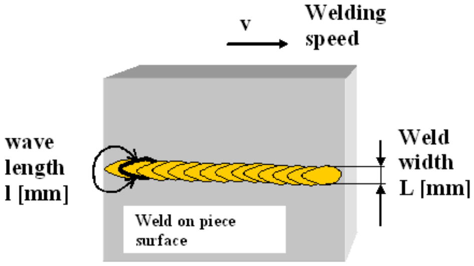

Figure 3 Sizes measured on the piece surface, weld width and wave length

In this paper the two sizes were analyzed characterizing the weld area. Its characterize transverse the weld. Weld width L [mm] directly characterize the weld width. Wave length l [mm] presents the length of solidification front. Wave length added to the weld width deflection deformation produced by melt flow. It was considered that the wave is characterized by this size, wave length; better than the distance between waves that is difficult to measure. Figure 3 shows the two sizes measured on the piece surface of the piece.

To measure the weld width and wave length were made three replicas for each measurement. To measure the wave length were used photographs of the weld surface with a magnification of 15X. Analysis of experimental results will be made below.

3. Comparison on the parameters effects on solid wave length and weld width

In the following will be analyzed the sizes to characterize weld surface changes relative to situation where defocusing was included as a parameter in full factorial experimental design type 2^3 and for situation where was considered two full factorial plans type 2^2 for the two levels of defocusing. For each of the situations discussed will analyze cases that consider the interaction between parameters and cases where the interaction between parameters is not considered. Will present mathematical polynomial models, statistical analysis ANOVA and Pareto diagrams. The main discussion will take place on Pareto diagrams. It presents the main issues of variations.

Polynomial mathematical models for wave length and weld width where it considers the interactions between parameters are presented in relations (1) and (2). They are accompanied by ANOVA statistical analysis method presented in Tables 2 and 3. Effects and interactions of these parameters are shown in Figure 4.

$$l = 3.461 + 1.58375A - 0.69375B - 0.02375C - 0.27375AB \text{ [mm]} \quad (1)$$
$$+ 0.22125AC + 0.25375BC + 0.16375ABC$$

$$L = 2.034 + 0.5825A - 0.64B + 0.0075C - 0.025AB + 0.2925AC - 0.3ABC \text{ [mm]} \quad (2)$$

Table 2 ANOVA table for solid wave lenght l with interactions

Effect	Sum of Squares	DF	Mean. Sq.	F-Ratio	P-val
A(power)	20.066	1	20.066	5.59	0.14
B(speed)	3.850	1	3.850	1.07	0.40
C(defocusing)	0.004	1	0.004	0.00	0.97
AB	0.599	1	0.599	0.17	0.72
AC	0.391	1	0.391	0.11	0.77
BC	0.515	1	0.515	0.14	0.74
ABC	0.214	1	0.214	0.06	0.83
Total error	7.181	2	3.590		
Total (corr)	32.822	9			
$R^2 = 0.78 \quad R^2(adj.for\ d.f.) = 0.015$					

Table 3 ANOVA table for weld width L with interactions

Effect	Sum of Squares	DF	Mean. Sq.	F-Ratio	P-val
A(power)	2.7144	1	2.7144	18.09	0.05
B(speed)	1.6928	1	1.6928	11.28	0.07
C(defocusing)	0.0004	1	0.0004	0.00	0.96
AB	0.0050	1	0.0050	0.03	0.87
AC	0.6844	1	0.6844	4.56	0.16
BC	0.0578	1	0.0578	0.39	0.60
ABC	0.7200	1	0.7200	4.80	0.15
Total error	0.3000	2			
Total (corr)	6.1750	9			
$R^2 = 0.95 \quad R^2(adj.for\ d.f.) = 0.78$					

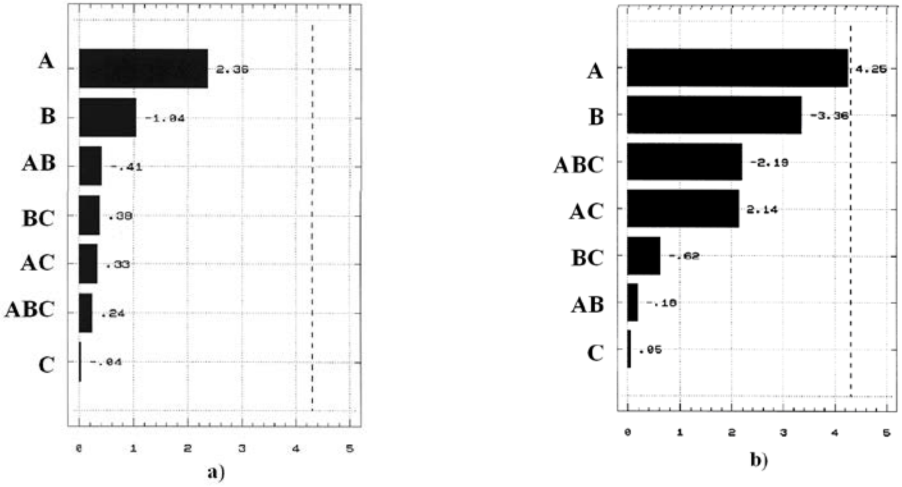

Figure 4 Pareto standardized chart for a) solid wave lenght l, b) weld width

Figure 4 shows the effects on the solid wave length and weld width. Wave length decreases with increasing power and welding speed. Second order interaction effects are closer. Interactions involving defocusing increases wave length. Defocusing has the lowest effect, it is weaker than the interaction of the three parameters. For all effects parameters and interactions the wave length presented no statistical significance.

For weld width is observed that it increases with power and decreases with welding speed. The interaction between power and welding speed is as the following effect after parameters efects. It is close but opposite sign of the with interaction between power and defocusing. Defocusing effect is the last effect. The effect of power is close to statistical significance. From the two Pareto charts is noted that defocus and defocus interaction with power increase melted zone dimensions.

Mathematical models in case where defocus effects were excluded, but its value was considered on the piece surface $\delta = 0$ are given by relations (3) and (4).

$$l = 3.61833 + 1.3625A - 0.9475.B - 0.4375AB \text{ [mm]} \tag{3}$$

$$L = 2.08667 + 0.29A - 0.375.B + 0.275AB \text{ [mm]} \tag{4}$$

Statistical analysis of variations by ANOVA method and to mathematical models equations (3) and (4) is given in Tables 4 and 5.

Figure 5 presents Pareto diagrams for solid wave length and weld width where the laser beam focus is made on the surface of the workpiece, $\delta = 0$.

Table 4 ANOVA table for solid wave length l with interactions at $\delta = 0$

Effect	Sum of Squares	DF	Mean. Sq.	F-Ratio	P-val
A(power)	7.425	1	7.425	2.18	0.27
B(speed)	3.591	1	3.591	1.05	0.41
AB	0.765	1	0.765	0.22	0.68
Total error	6.814	2	4.407		
Total (corr)	18.59	5			
$R^2 = 0.16$			$R^2(adj.for\,d.f.) = 0.08$		

Table 5 ANOVA table for weld width L with interactions at $\delta = 0$

Effect	Sum of Squares	DF	Mean. Sq.	F-Ratio	P-val
A(power)	0.336	1	0.336	2.60	0.24
B(speed)	0.562	1	0.562	4.34	0.17
AB	0.302	1	0.302	2.34	0.26
Total error	0.258	2	0.129		
Total (corr)	1.460	5			
$R^2 = 0.82$		$R^2(adj.for\,d.f.) = 0.55$			

It shows that the wave length increases with power and decreases with welding speed. The interaction between power and speed decreases wave length. It shows that the overall effect of decreasing with the welding speed is higher. For weld width is noted that the welding speed has the highest effect.

The effect of interaction between power and speed is much greater for weld width than for the wave length. On the overall effect of increasing with the power is much higher than decreasing effect the given by welding speed. For both size, wave length and weld width, effects presented not reach statistical significance threshold.

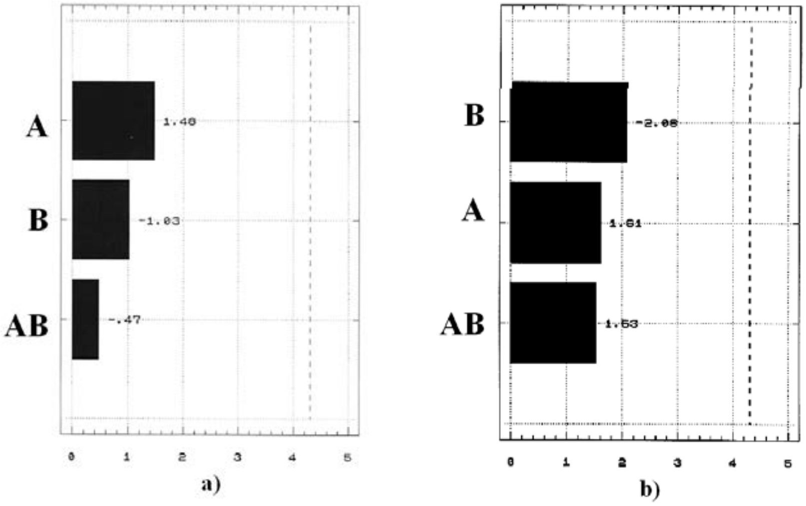

Figure 5 Pareto standardized chart for a) solid wave lenght l, b) weld width, at $\delta = 0$

Mathematical models for case where where laser beam was focus whitin the piece $\delta = -2mm$ are presented in the relations (5) and (6). Statistical analysis is presented in tables 6 and 7. Pareto diagrams for solid wave length and weld width are shown in Figure 6.

$$l = 3.64 + 1.885.A - 0.36.B - 0.03.AB \text{ [mm]} \quad (5)$$

$$L = 2.09667 + 0.875.A - 0.545.B - 0.325.AB \text{ [mm]} \quad (6)$$

Table 4 ANOVA table for solid wave lenght l with interactions at $\delta = -2mm$

Effect	Sum of Squares	DF	Mean. Sq.	F-Ratio	P-val
A(power)	14.212	1	14.212	4.23	0.17
B(speed)	0.518	1	0.518	0.15	0.73
AB	0.003	1	0.003	0.00	0.97
Total error	6.725	2	3.362		
Total (corr)	21.460	5			
$R^2 = 0.68 \quad R^2(adj. for\, d.f.) = 0.21$					

Table 5 ANOVA table for weld width L with interactions at $\delta = -2mm$

Effect	Sum of Squares	DF	Mean. Sq.	F-Ratio	P-val
A(power)	3.0625	1	3.0625	25.35	0.03
B(speed)	1.1881	1	1.1881	9.83	0.08
AB	0.4225	1	0.4225	3.50	0.20
Total error	0.2416	2	0.1208		
Total (corr)	4.9147	5			
$R^2 = 0.95 \quad R^2(adj. for\, d.f.) = 0.87$					

In figure 6 for the wave length is observed that it increases with power and decreases with welding speed. The main dependence is given by the effect of power. Presented effects have not statistically significance. For weld width is noted that it increases with power. Welding speed and the effect of interaction decrease the weld width. On the overall effect of increasing with power is greater than the decrease effect with welding speed.

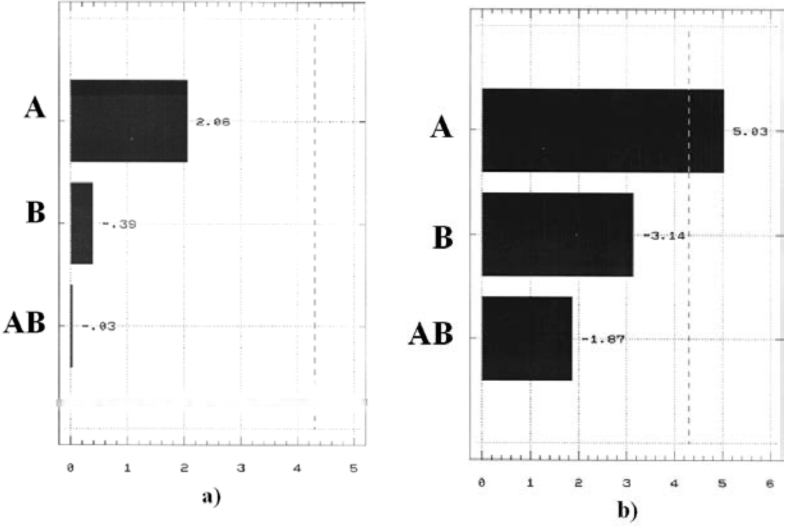

Figure 6 Pareto standardized chart for a) solid wave lenght l,
b) weld width, at $\delta = -2mm$

Wave length and weld width are sizes that characterize melted zone at piece surface. If a size is dependent on a single parameter can say that there is better control over that quantity. Parameter which in this situation is the power. It was shown that the wave length is more dependent by than the weld width.Welding process instability occurs when the contrary effects of power and speed to are close. Has been shown that increase the stability of welding process takes place to laser beam focus in the piece depth. It was shown that for two analyzed sizes, sodid wave lehght and weld width, defocusing effect is the same type as power effect. Defocusing effect is manifested through interactions in which it participates. Wave length is a size for which the variations are stronger than for the weld width. Instability is shown by the lack of statistical significance for solid wave length effects. For the weld width statistical significance is reached for the whole experiment and focus within the piece.

4. Defocusing effects analysis for the weld cross section

Complete analysis of the melted zone for made welds considers two important aspects weld cross section zone and weld surface. Measured sizes are presented in Figures 7 and 8.

Weld cross section shows the characteristics of molten zone. For weld cross section have studied defocusing variations, this are presented as response surfaces. Its are based on linear polynomial models. Response surfaces shows the type of variation on the experimental field.

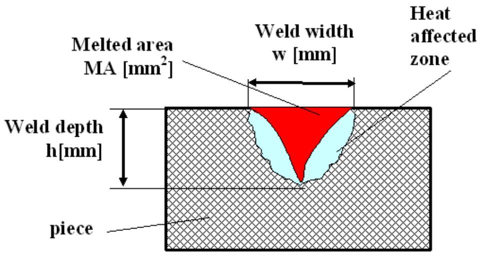

Figure 7 Sizes measured on weld cross section

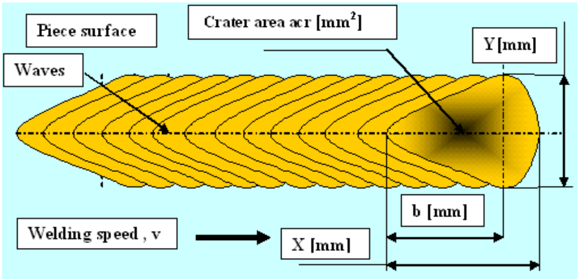

Figure 8 Sizes measured on the weld surface

Figure 9 presents the response surface for weld width w. It is noted that on the experimental field weld width increases with power and varies little with defocusing. Defocusing effects are small at high power. We recommend using high power levels regardless of defocusing values.

Figure 10 shows the response surface for weld width w variation with welding speed and defocusing. It is noted that the weld width decreases with welding speed. Defocusing produces a slight decrease for weld width on the experimental field. We recommend using low welding speeds. For this variation caused by defocus not have meaning.

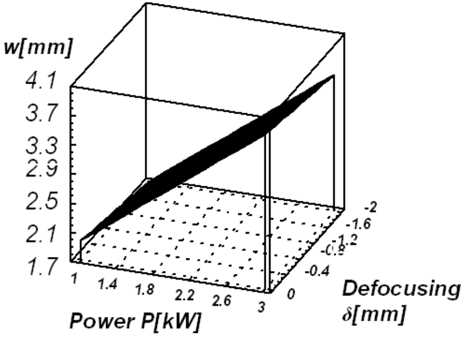

Figure 9 Reponse surface for weld width with power and defocusing

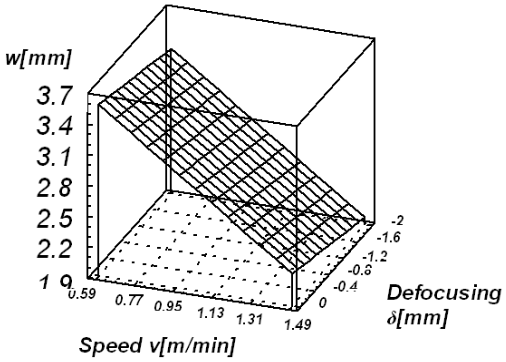

Figure 10 Reponse surface for weld width with speed and defocusing

Figure 11 presents variations for weld depth with power and defocusing. On the experimental field weld depth increases sharply with power. It is noted that defocusing does not produce produce variations on the weld depth. We recommend a high level of power to get welds penetrated in the material.

Figure 12 shows variation of the weld depth with welding speed and defocusing. Defocusing decreases weld depth. Defocusing effect is substantial relative to the welding speed effect. To obtain profound welds is recommended welding laser beam focus on the piece surface and low values for welding speed.

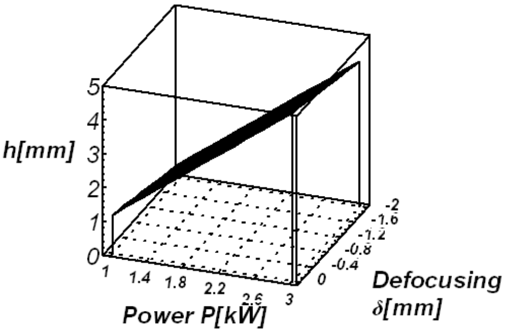

Figure 11 Reponse surface for weld depth with power and defocusing

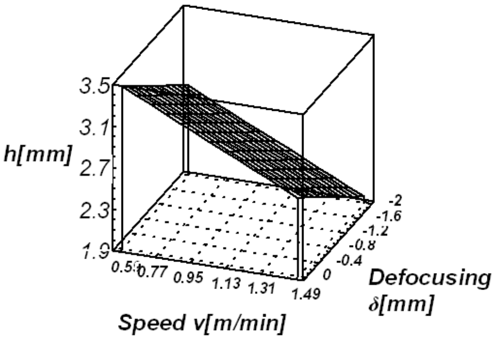

Figure 12 Reponse surface for weld depth with speed and defocusing

F ratio (weld width / weld depth, w/h) is a quantity that characterizes the weld cross section. An oblong shape to weld cross section is specific to keyhole welding regime. This is shown by subunit values for the ratio F. Figure 13 presents the variation ratio F with power and defocusing. It is noted that on the experimental F ratio decreases with power. Defocusing produces a slight increase in the ratio F. The laser beam focus within the piece is basically unfavorable obtain keyhole welding regime. At low values of power conduction welding regime and the high values of power is achieved keyhole welding regime. Figure 14 presents the variation of ratio F with welding speed and defocusing. It is noted that on the experimental field F ratio values increase with speed and defocusing. Both sizes have an adverse effect on keyhole welding regime. It is noted that on the experimental field defocusing effect is stronger than welding speed effect.

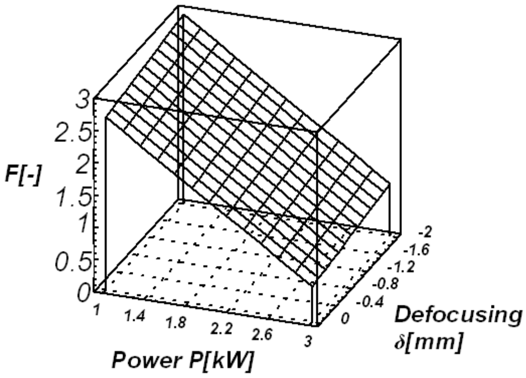

Figure 13 Reponse surface for ratio F power with and defocusing

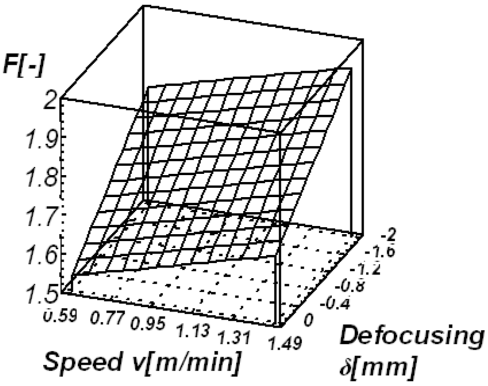

Figure 14 Reponse surface for ratio F with speed and defocusing

The melted area on the weld cross section is the size that best expresses the amount of melt produced during the welding process. Figure 15 presents variation of melted area with power and defocusing.

It is noted that on the experimental field melted area increases with power. Defocusing does not produce variations on the melted area. To obtain an extended molten material areas are recommended high power values. Figure 16 presents the response surface for melted area variations with welding speed and defocusing. On the experimental melted area decreases with welding speed and defocusing. Decrease with defocusing is small compared to that with the welding speed.

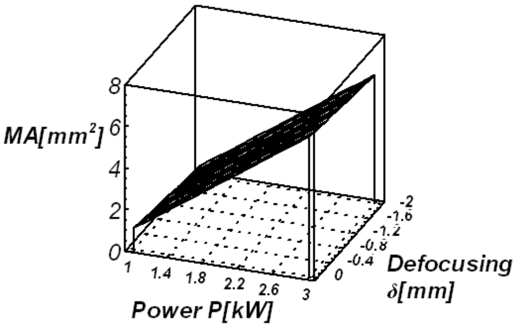

Figure 15 Reponse surface for melted area with power and defocusing

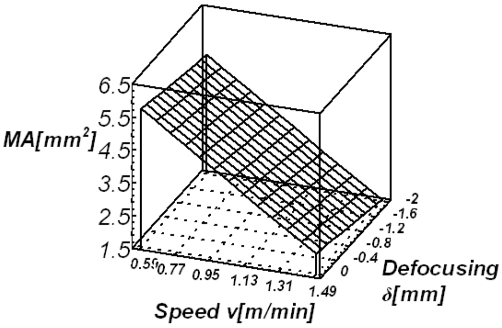

Figure 16 Reponse surface for melted area with speed and defocusing

Using relatively low welding speeds provide cross section melted areas of weld sufficient for making welded joints. It is noted that on the melted area defocus effects are small. Defocus has a similar effect of decreasing with welding speed effect.

5. Defocusing effects analysis for welds surfaces

More sizes characterize weld surface. Weld width is a visible feature of the weld. For weld width there is issues for weld design and utility for weld joint. For conduction welding regime is an excessive increase of weld width. For moderately keyhole welding regime a increase of weld width is associated with a increase in weld depth. In this case a high weld width is associated with a higher weld depth. For strong keyhole welding regime there is a excess increase of weld depth in relation to the weld width.

Figure 17 presents response surface for weld width L depending to the power and defocus. It is noted that on the experimental field weld width increases with power. Defocusing produces almost no variations. For welds obtained to have a width to be correlated with sufficient depth are recommended for high values of power but not the highest possible.

Figure 18 presents the variation weld width L with welding speed and defocusing. It is noted that on the experimental field weld width decreases strongly with welding speed. Defocusing does not produce significant variations. It is recommended to avoid excessive increase of welding speed.

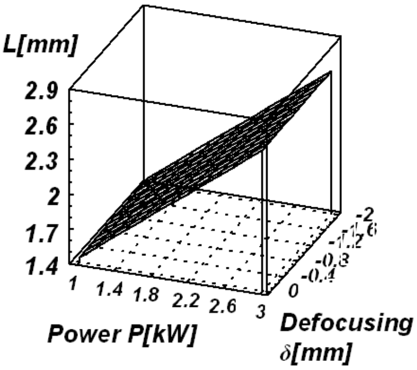

Figure 17 Reponse surface for weld width with power and defocusing

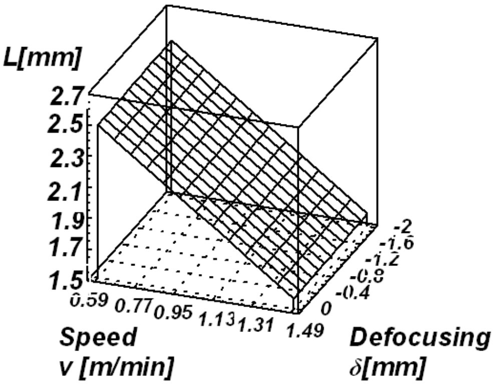

Figure 18 Reponse surface for weld width with speed and defocusing

Crater is obtained at the end of the welding process shown in solidified form a trace of the weld pool. Crater is obtained as the cumulative effects of vaporization and melts movement. Crater surface may be associated with the weld pool surface.

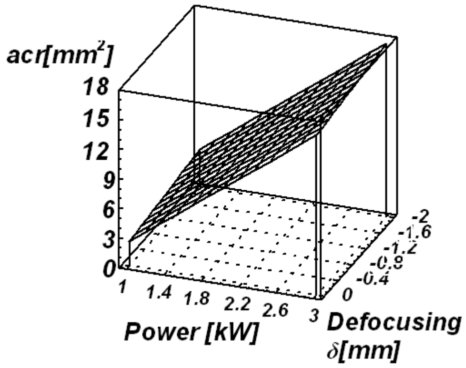

Figure 19 Reponse surface for crater area with power and defocusing

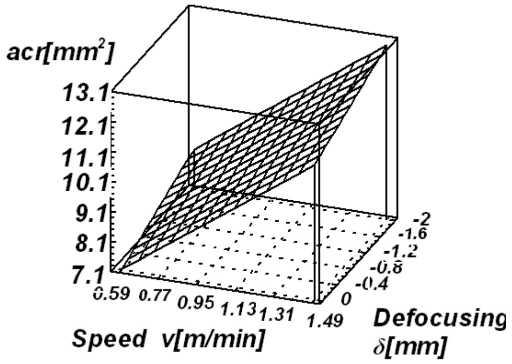

Figure 20 Reponse surface for crater area with speed and defocusing

Figure 19 presents variation of the crater area with power and welding speed. It is noted that on the experimental field crater area increases with power. Defocusing does not produce significant variations. Crater area increases with defocusing. It looks like the sizes of the weld pool are mainly dependent on power. Lowering the focal plane below the piece surface increases the laser beam spot size on the piece surface. This will increase the size of the weld pool.

Figure 20 presents variation of the crater area with welding speed and defocusing. It is noted that on the experimental field the crater area increases with welding speed and with defocus (to piece inside). Defocusing effect is more obvious in this case than the one in which power varies. Increase of crater area with speed welding is explained by melt movement. At height welding speeds the weld pool area will increase by melting with lowering the vaporization that takes place at low welding speeds. Another important indicator is given by the crater is the crater elongation. There were three forms of it: round, oval and elongated teardrop-shaped.

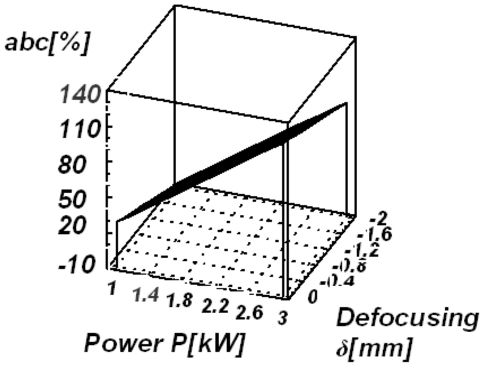

Figure 21 Reponse surface for circularity deviation with power and defocusing

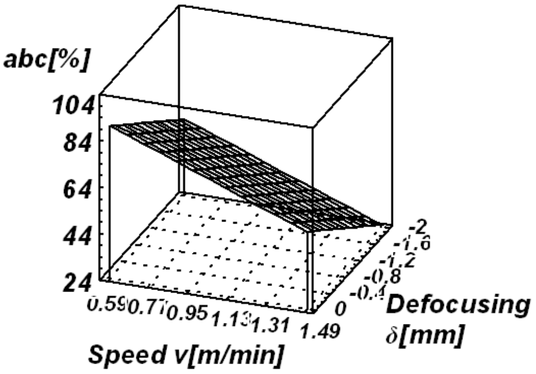

Figure 22 Reponse surface for circularity deviation with speed and defocusing

Deviation from circularity was determined by comparing the transverse and longitudinal dimensions of the crater. Crater elongation was measured from the center of the crater at the back of it (opposite direction of welding speed).

The front of the crater was considered semi-circular shape with radius r[mm]. Elongation was compared with the radius of circular part of the crater.

Crater size (X axis in the direction of welding, transverse axis Y and elongation b) and its area was measured indirectly using images of the crater, figure 2. Crater depth was measured using a comparator. Weld width, crater dimensions X, Y, b, crater area and the crater depth are measured sizes. Deviation from circular and crater volume are calculated sizes. They are given by the following relations:

- for deviations from circularity:

$$abc = \frac{b - r_{med}}{r_{med}} \, [\%] \qquad (7)$$

where: $r_{med} = \frac{1}{2}\left(\frac{Y}{2} + X - b\right)$ [mm] (8)

Figure 21 presents response surface for deviation from circularity with power and defocusing. It is noted that on the experimental field deviation from circularity increases with power. Increasing the crater deformation with power was associated with transition from conduction welding regime to keyhole welding regime, as the weld cross section is deformed by decreasing ratio F.

Figure 22 presents response surface for deviation from circularity with welding speed and defocusing. It shows that on the experimental field deviation from the circulation decreases with welding speed and defocusing. Decrease with welding speed is explained by overall lower size of the weld pool at increase of welding speed. Decrease with defocusing is explained by increased laser spot size on the piece surface that will lead to a circular shape of the crater.

6. Conclusions

This paper presents an analysis of the molten area in material that occurs in laser welding. A factorial experimental plan type 2^3 was performed. It was followed by analyzing the effect of melt dynamics by compared the solid wave length and the weld width. Defocusing effect was followed throughout the experiment and separately for each level of defocus. It's analyzed the effects of power and welding speed. It was shown that laser beam focus within the piece presents a situation in which welding process is stable. Wave length is a quantity that is more sensitive to instabilities of the welding process than the weld width. Response surface method was used for sizes characterizing weld cross section.

Defocusing effect was showed out in relation to the welding speed. Defocusing does not produce significant variations relative to the effect of power. Defocus does not produce significant variations relative to the melt zone area. For crater obtained at the end of welding showed that defocus produce the same type of effects as the welding speed and power does not influence the effects. On the overall it was found that power increasing the melted zone and a welding speed decreases melted zone. Increasing dependence on power with reduce dependence of welding speed leads to a stable welding process. Sizes analyzed on weld cross section are important for achieving technological welded joints. Sizes measured on the weld surface are important for dynamic phenomena in welding pool.

REFERENCES

[1] N. Rykalin, A Uglov, A Kokora *Laser Machining and Welding* Mir Publishers 1978.

[2] Cheolhee Kim, Junghak Kim, Hyunsik Lim, Jeonghan Kim *Investigation of laser remote welding using disc laser* Journal of materials processing technology 201 (2008) p:521–525

[3] Yih-Fong Tzeng *Effects of operating parameters on surface quality for the pulsed laser welding of zinc-coated steel,* Journal of Materials Processing Technology 100 (2000) p:163-170