# APPLICATIONS OF FULL FACTORIAL DESIGN EXPERIMENTS FOR LASER WELDING

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**Abstract:**. Laser welding using Nd: YAG laser with continuous emission is applied for a low alloyed steel. The study pursued molten areas characteristics in the material. On the weld cross section was measured weld width, weld depth and the weld molten zone. Their variation was analyzed with power and welding speed. A full factorial experimental design was applied for two particular values of the distance between focal plane and the workpiece surface (defocusing depth). It presents mathematical models, the ranking effects by Pareto charts, response surface method and the multiple ANOVA analysis of variance. It showed the main effect of laser power in determining the weld characteristics.

**Keywords:** *laser welding, Nd:YAG laser, full factorial design, laser beam defocusing, mathematical model.*

## 1. Introduction

Laser welding is widely applied machining of metals and in particular for steels. The laser beam is a concentrated heat source that allows for the intensity of the laser beam $10^4$-$10^7$W/cm$^2$ and for interaction time between laser radiation and the material $10^{-3}$-$10^{-2}$s obtaining molten zones. Melting material is used for welding. Several papers have presented the features of the steel melted zone for laser welding [1].

Main information about the weld characteristics are given of the weld cross section. On this are measured the weld width, weld depth and the weld molten zone area. Sectioning the welds in a stable area provides information about the ability to perform laser beam melting material. Applied the mathematical modeling for the molten zone of welds is useful for estimating the parameter values used in making welded joints. Type the full factorial experiment with the statistical method of ANOVA analysis of the multiple underlying several methods of statistical analysis in experimental research [2] [3].

This paper proposes a study on the laser welds made on the low alloy steel plates.

Apply a complete factorial experimental design type$2^2$ for two different experimental situations given by the focal plane position relative to the workpiece surface (Defocusing) for welds made using laser irradiation Nd: YAG under continuous regime. In experiments were varied laser power and welding speed.

## 2. Experiments

The experiment consisted in made lines of fusion (welds) ,110mm long, on Dillimax 500 steel plates with thickness of 10 mm (carbon steel, carbon content $\leq 0.16$ %), figure 1.

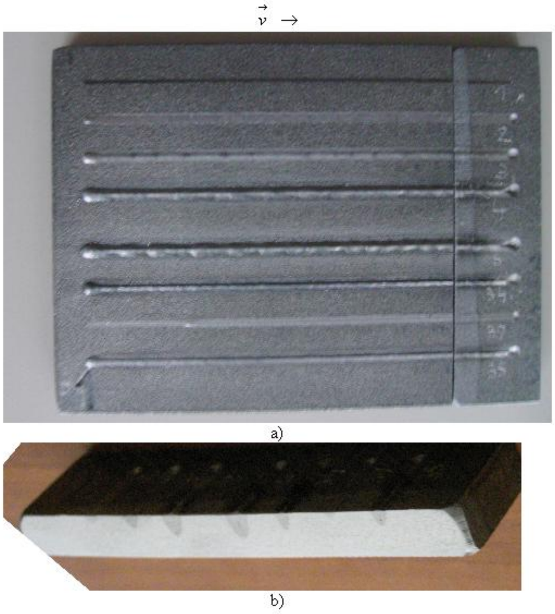

**Figure 1**: *Plate with welds a) Surface plate b) cross-sections through the plate*

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. Were used sheets of material with dimensions of $100 \times 130 \times 10$ mm for which were made between 5 and 8 welds, with a distance of over 10 mm between welds,.

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.

Parameters varied in the experiments are presentations in Figure 2. To focus within the piece defocusing values are considered negative.

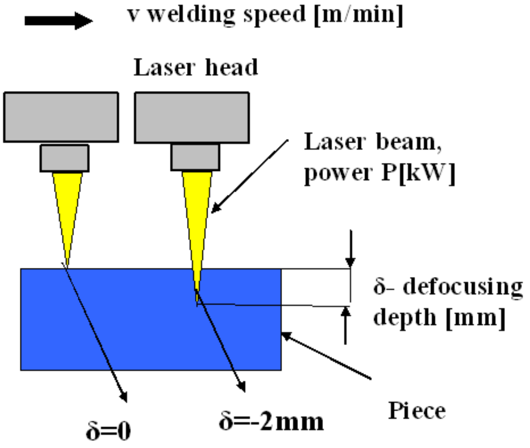

**Figure 2:** *Parameters varied in the experiments*

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 are based on real-coded relationships following:

$$A = P - 2 \text{ [-]} \quad (1)$$

$$B = -2.33 + 2.22v \text{ [-]} \quad (2)$$

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

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.

**Table 1:** *Varied parameters in the experiment*

| | power | | speed | | defocusing |
|---|---|---|---|---|---|
| weld | A[-] | P[kW] | B [-] | v[m/min] | $\delta$[mm] |
| 1 | -1 | 1 | -1 | 0.6 | 0 |
| 2 | +1 | 3 | -1 | 0.6 | |
| 3 | -1 | 1 | +1 | 1.5 | |
| 4 | +1 | 3 | +1 | 1.5 | |
| 5 | -1 | 1 | -1 | 0.6 | -2 |
| 6 | +1 | 3 | -1 | 0,6 | |
| 7 | -1 | 1 | +1 | 1.5 | |
| 8 | +1 | 3 | +1 | 1.5 | |
| 9 | 0 | 2 | 0 | 1 | -1 |
| 10 | 0 | 2 | 0 | 1 | |

Based on these values were achieved Pareto charts.

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 3.

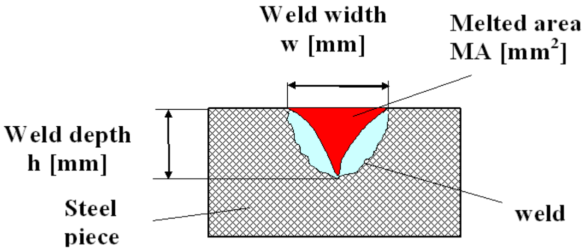

**Figure3:** *Weld cross-section with the considered sizes*

## 3. Effects of welding process parameters

The varied parameters laser power, welding speeds and defocusing have the following effects on molten zone dimensions:

- Laser power. Increasing the laser power produce increase the intensity on piece surface therefore melted material amount increases. From a certain value, intensity not too high melting material amount, favours material vaporization.
- Welding speed. Increasing welding speed decrease the interaction (time) between laser radiation and material. If the interaction time is less then the molten zone dimensions are smaller.
- Defocusing. Defocusing by lowering the focal

plane within piece produce lower intensity at piece surface by increasing laser spot area at piece surface and from same issue will increase interaction time between laser and material.
Focus within piece associated with the presence of keyhole in welding bath will increase the spread of radiation in keyhole and coupling of laser radiation and material. Defocusing may thus have different effects on melting material. You can not predetermine a clear trend of increasing or decreasing the molten zone. Defocusing effects will be analyzed based on experimental results.

## 4. Weld width

For the weld width at defocusing $\delta = 0$ polynomial mathematic model is given by relations (3) (4). Statistical analysis of variation is given in Table 2.

$$w = 0.7348 + 0.4335P - 0.999v - 0.111Pv \tag{3}$$

$$w = 2.8833 + 0.55A - 0.55B - 0.05AB \tag{4}$$

**Table 2**: *ANOVA table for weld width w at* $\delta = 0$

| Effect | Sum of Squares | DF | Mean.Sq. | f-Ratio | P-val |
|---|---|---|---|---|---|
| A(power) | 1.21 | 1 | 1.21 | 132 | 0.00 |
| B( speed) | 1.21 | 1 | 1.21 | 132 | 0.00 |
| AB | 0.01 | 1 | 0.01 | 1.09 | 0.40 |
| Total error | 0.018 | 2 | 0.09 | | |
| Total (corr) | 2.448 | 5 | | | |
| $R^2 = 0.992$ | | | $R^2(adj.for\,d.f) = 0.981$ | | |

Pareto diagram on Figure 4 shows that the weld width increases with power and decreases with welding speed. The two parameters are equal but opposite sign effects on weld width. The interaction between power and welding speed has an effect on the decrease weld width. The mathematical model presented is statistically significant data for the effects of speed and power.

Response surface in Figure 5 shows the variation of weld width with power and welding speed at defocusing $\delta = 0$.It is noted that on the experimental field weld width increases with power and decreases with speed. Maximum values for the weld width are obtained at the highest power and lowest speed. Lower values of weld width are not recommended because they are associated with low weld depth.

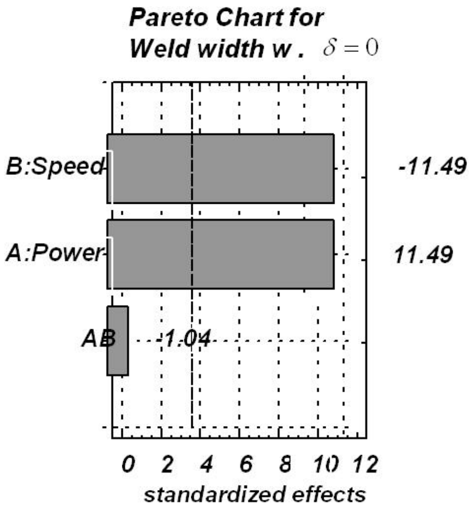

**Figure 4**: *Pareto Chart for weld width at* $\delta = 0$

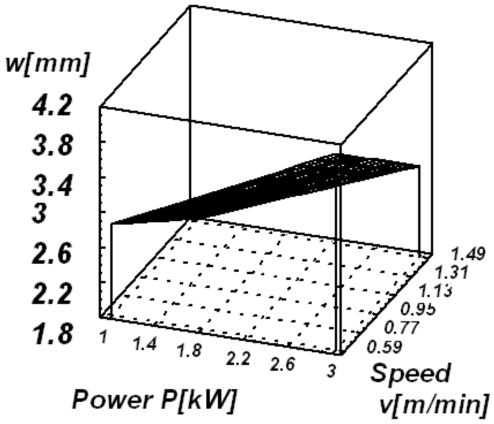

**Figure 5**: *Response surface for weld width at* $\delta = 0$

For the weld width at defocusing $\delta = -2mm$ mathematic model is given by polynomial equations (5) (6).Statistical analysis of variation is given in Table 3. Pareto chart in Figure 6 shows that the weld width increase with power and decreases with welding speed. Both effects are statistically significant. Power effect is greater than the welding speed. Interaction between the welding speed and power decreases the width of the weld.

$$w = 0.5826 + 1.999P - 0.444v - 0.666Pv \tag{5}$$

$$w = 2.7166 + 1.3 \cdot A - 0.8B - 0.3 \cdot AB \tag{6}$$

**Table 3:** *ANOVA table for weld width w at* $\delta = -2mm$

| Effect | Sum of Squares | DF | Mean. Sq. | f-Ratio | P-val |
|---|---|---|---|---|---|
| A(power) | 6.76 | 1 | 6.76 | 80.32 | 0.01 |
| B( speed) | 2.56 | 1 | 2.56 | 30.42 | 0.03 |
| AB | 0.36 | 1 | 0.36 | 4.28 | 0.17 |
| Total error | 0.168 | 2 | 0.84 | | |
| Total (corr) | 9.848 | 5 | | | |
| $R^2 = 0.98$ | | | $R^2(adj.for\,d.f) = 0.95$ | | |

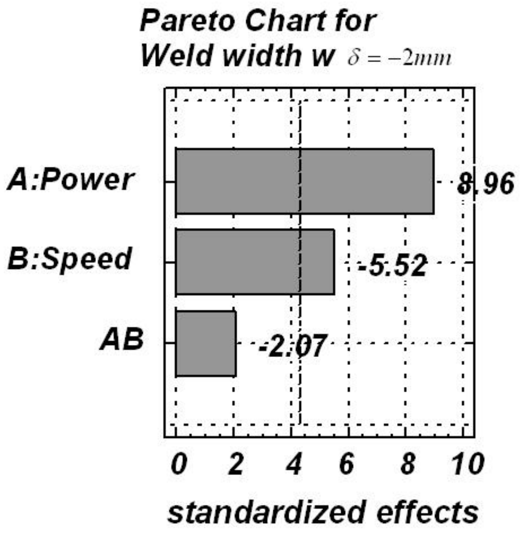

**Figure 6**: *Pareto Chart for weld width at* $\delta = -2mm$

Response surface in Figure 7 shows the variation of weld width with power and speed at defocusing $\delta = -2\,mm$. It is noted that on the experimental field weld width increase with power and decreases with speed. The variations of weld width are low at low power and high welding speeds. It looks like that under weak irradiation weld width may be associated with the laser beam spot on the workpiece surface.

Thus the focus within the piece can produce acceptable weld width even if using low power or high values of welding speed.

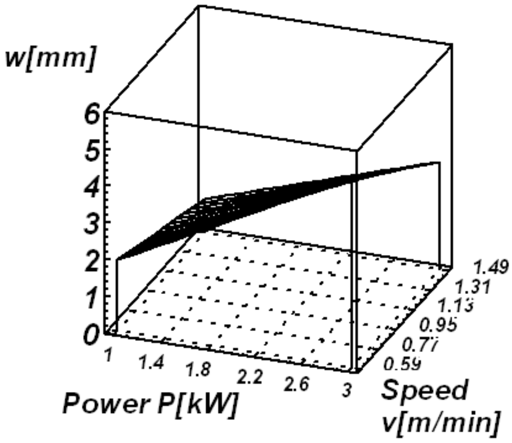

**Figure 7**:*Response surface for weld width at* $\delta = -2mm$

The variation observed previously shown that the weld width becomes more dependent on power for the laser beam focus within the piece.

Interaction effect between laser power and welding speed increases weld width. It is associated with dynamic phenomena occurring in the weld pool that influence laser radiation absorption.

## 5. Weld depth

For the weld depth at defocusing $\delta = 0$ polynomial mathematical model is given by equations (7) (8).Statistical analysis of variation is given in Table 4. Pareto chart in Figure 8 indicates that the weld depth increases with power and decreases with welding speed. Effect of power is much greater than the effect of welding speed. The interaction between power and speed has a small role and does not present statistical significance.

$$h = -1.566625 + 1.903425P - 0.60495v - 0.06105Pv \qquad (7)$$

$$h = 3 + 1.9675A - 0.3275B - 0.0275AB \qquad (8)$$

**Table 4:** *ANOVA table for weld depth h at* $\delta = 0$

| Effect | Sum of Squares | DF | Mean. Sq. | f-Ratio | P-val |
|---|---|---|---|---|---|
| A(power) | 15.484 | 1 | 15.484 | 1161 | 0.00 |
| B( speed) | 0.429 | 1 | 0.429 | 32.19 | 0.02 |
| AB | 0.003 | 1 | 0.003 | 0.23 | 0.68 |
| Total error | 0.026 | 2 | 0.013 | | |
| Total (corr.) | 5.942 | 5 | | | |
| $R^2 = 0.998$ | $R^2(adj.for\,d.f.) = 0.995$ | | | | |

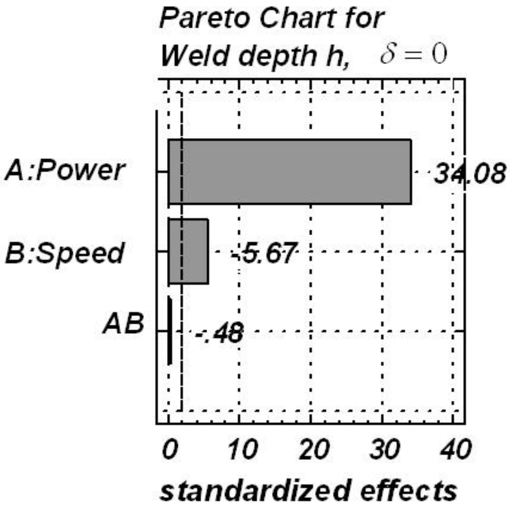

**Figure 8**: *Pareto Chart for weld depth at* $\delta = 0$

Response surface in Figure 9 shows the variation of weld depth with power and speed at defocusing $\delta = 0$. It is noted that on the experimental field weld depth increases sharply with the power and almost no variation with welding speed. Welds with high depth presents keyhole welding regime.

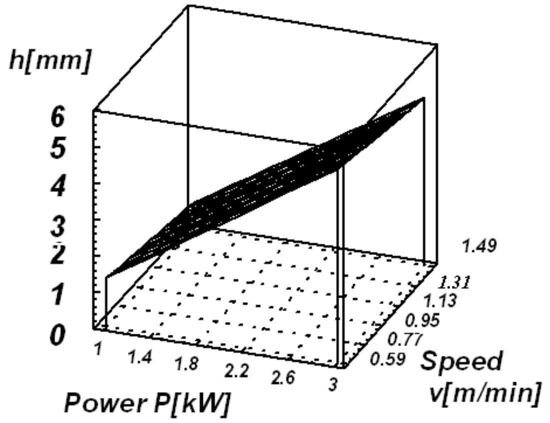

**Figure 9**:*Response surface for weld depth at* $\delta = 0$

For weld depth at defocusing $\delta = -2mm$ polynomial mathematical model is given by equations (9) (10). Statistical analysis of variation is given in Table 5. Pareto chart in Figure 10 shows that the weld depth increases sharply with power. Power effect is statistically significant. Weld depth and decreases the interaction between welding speed and power. The two effects mentioned above are close.

They are not given by the mathematical model with statistical significance. It looks like that for the focus inside piece the effect of power becomes important. Dynamic phenomena occurring in the weld pool becomes more intense, which is reflected in the increasing role of the interaction between power and welding speed.

$$h = -1.8541 + 2.7554P + 0.6216v - 0.8436Pv \qquad (9)$$

$$h = 2.5383 + 1.87 \cdot A - 0.48 \cdot B - 0.38 \cdot A \cdot B \qquad (10)$$

**Table 5:***ANOVA table for weld depth h at* $\delta = -2mm$

| Effect | Sum of Squares | DF | Mean. Sq. | F-Ratio | P-val |
|---|---|---|---|---|---|
| A(power) | 13.987 | 1 | 13.987 | 31.96 | 0.02 |
| B(speed) | 0.921 | 1 | 0.921 | 2.11 | 0.28 |
| AB | 0.577 | 1 | 0.577 | 1.32 | 0.36 |
| Total error | 0.875 | 2 | 0.437 | | |
| Total (corr.) | 16.362 | 5 | | | |
| $R^2 = 0.94$ | | | $R^2 (adj. for\ d.f.) = 0.86$ | | |

Response surface in Figure 11 shows the variation of weld depth with power and speed at defocusing $\delta = -2mm$. It is noted that on the experimental field there is a weld depth increase with power. At high power has been a slight decrease in the weld depth with welding speed. Effect of welding speed is obvious by reducing the increase with power at high welding speeds.

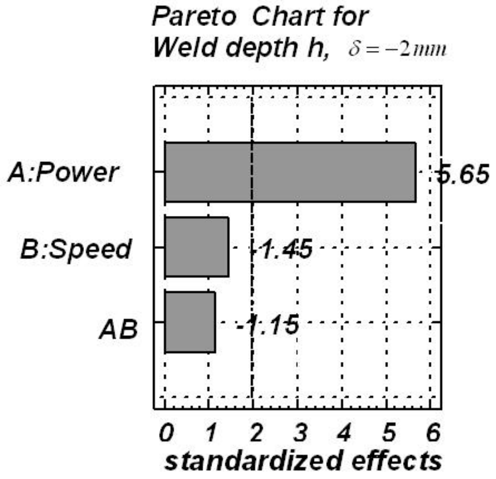

**Figure 10**:*Pareto Chart for weld depth at* $\delta = -2mm$

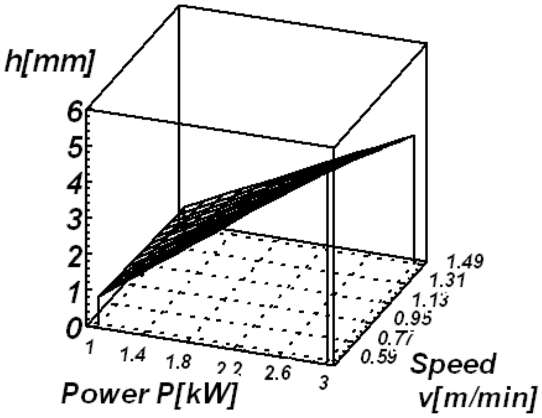

**Figure 11**:*Response surface for weld depth at* $\delta = -2mm$

Effects on weld depth analysis show that it depends strongly on the power in both cases of defocusing depth. Focusing inside the piece increases the welding speed effects due to increased contribution of dynamic phenomena in the weld pool. They are very sensitive to variations in time of interaction between laser radiation and material controlled by the welding speed.

## 6. Melted area at the weld cross section

For melted area mathematic polynomial model at defocusing $\delta = 0$ is given by equations (11) (12). Statistical analysis is presented in Table 6. Pareto chart in Figure 12 shows that the melted area increases with power and decreases with welding speed. The interaction between power and speed decreases melted area. Power is the only effect that has statistical significance. Contribution of welding speed by its effect and by its interaction with power is lower than power effect.. But the effect of welding speed is close to power effect. It looks like that for the melted area on weld cross section are important both laser beam intensity at workpiece surface and interaction time between laser radiation and material.

$$MA = -1.7664 + 0.836P - 0.222v - 1.776Pv \quad (11)$$

$$MA = 3.866 + 2.7A - 1.7B - 0.8\ AB \quad (12)$$

**Table 6**: *ANOVA table for melted area MA at* $\delta = 0$

| Effect | Sum of Squares | DF | Mean. Sq. | f-Ratio | P-val |
|---|---|---|---|---|---|
| A(power) | 29.160 | 1 | 29.160 | 28.40 | 0.03 |
| B( speed) | 11.560 | 1 | 11.560 | 11.26 | 0.07 |
| AB | 2.560 | 1 | 2.560 | 2.49 | 0.25 |
| Total error | 2.053 | 2 | 1.026 | | |
| Total(corr.) | 45.333 | 5 | | | |
| $R^2 = 0.95$ | $R^2(adj.for\,d.f) = 0.88$ | | | | |

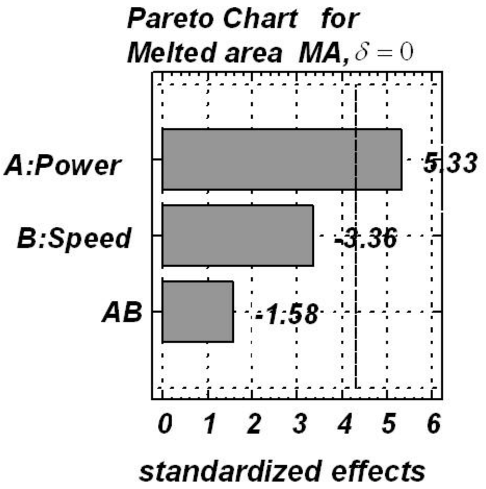

**Figure 12**: *Pareto Chart for melted area at* $\delta = 0$

Response surface in Figure 13 shows the variation of cross section area of the molten weld welding power and speed at defocusing $\delta = 0$. High values for melted area are recommended for joint the two pieces in laser welding. It is noted that the melted area increases with the power and decreases with welding speed. The decrease with speed is lower at the low power than the high power. This shows the role of interaction between power and speed. Highest values of the melted area are obtained at maximum power and welding speed on the experimental field.

For melted area mathematic model polynomial at defocusing $\delta = -2mm$ is given by equations (13) (14). Statistical analysis is presented in Table 7.Pareto chart in Figure 14 show that the melted area on the weld cross section increases with power. Power is the only effect that is statistically significant.

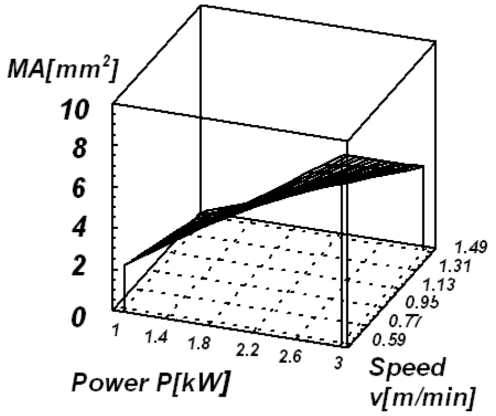

**Figure13**:*Response surface for weld melted area* $\delta = 0$

Welding speed and the interaction between power and welding speed lower melting area. The two effects are equal. It is noted that the overall cumulative effect of decreased melted area with speed and with interaction between speed and power is greater than the effect of increasing the power given. It looks like the melted area is heavily dependent on the time of interaction between laser radiation and material.

$$MA = -6.93545 + 7.39375P + \quad (13)$$
$$+ 4.16250v - 4.1625\ Pv$$

$$MA = 3.4843 + 3.025A - 1.875B - 1.875AB \quad (14)$$

**Table 7:**ANOVA table for melted area MA at $\delta = -2mm$

| Effect | Sum of Squares | DF | Mean. Sq. | F-Ratio | P-val |
|---|---|---|---|---|---|
| A(power) | 36.602 | 1 | 36.602 | 26.14 | 0.01 |
| B( speed) | 14.062 | 1 | 14.062 | 10.04 | 0.04 |
| AB | 14.062 | 1 | 14.062 | 10.04 | 0.04 |
| Total error | 2.80 | 2 | 1.4 | | |
| Total (corr) | 67.528 | 5 | | | |
| $R^2 = 0.95$ | $R^2(adj.for\,d.f.) = 0.89$ | | | | |

Response surface in Figure 16 shows the variation in area melted on weld cross-section at defocusing $\delta = -2mm$.It is noted that on the experimental field melted area increases with the power and decreases with welding speed. The decrease with welding speed is stronger at high power. Increasing with power is greater at low welding speeds. It looks like the importance of interaction between power and speed. Maximum values for the melted area are obtained at maximum power and minimum welding speed. At low power and high welding speeds there is a domain with small variations for melted area.

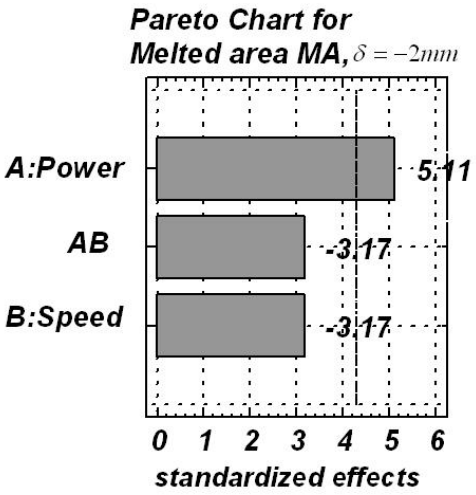

**Figure15**:*Pareto Chart for melted area at* $\delta = -2mm$

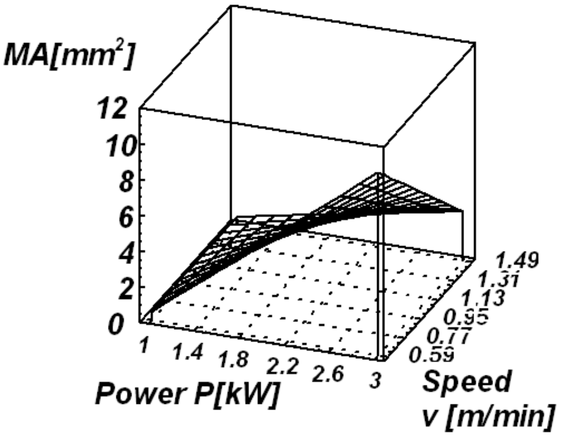

**Figure16**:*Response surface for weld melted area* $\delta = -2mm$

Focusing within piece shows as additional elements for the weld cross section melted area increased the welding speed contribution. This is accomplished through both its effect and its interaction with power. It is noted that the effect of welding speed on melted area is stronger than the effects of welding speed on weld width and weld depth.

## 7. Discussion

Mathematical modeling using full factorial design showed high values of correlation coefficients and statistical significance was obtained for sizes analyzed with power effect.

For weld width and weld depth the focus within the piece led to an increase in power effect.

For melted area on weld cross-section variation was contrary effect, namely increased speed effect. It looks like that lower intensity laser beam to the workpiece surface by focusing the laser beam inside piece lowers laser beam intensity to the workpiece surface. The intensity is mainly controlled by power. So considered sizes are more sensitive to changes in power. Fused area is related to the total amount of melt obtained after irradiation. At defocusing $\delta = -2mm$ the laser beam heat source is inside the Keyhole at its front wall. Keyhole front wall angle depends on the welding speed.

Strong inclination of the keyhole front wall of the laser radiation encourage reflection outside keyhole. This reduces the coupling between laser radiation and the material thus obtained decreases the amount of melt. The mathematical models presented are useful in determining the size of area that can be melted by laser beam. The deep welds are in keyhole regime. Molten zone should be sufficient to melt the pieces and filler material used in welding.

Mathematical modeling presented in this paper can be used to determine the characteristics of welds in concrete terms the imposition of restrictions related to carrying out the welding. For deep weld the weld width must be high. Focusing the laser beam inside the piece from the start ensures high values for weld width due to the increased the size of laser beam spot on the workpiece surface. Experiments have shown that inside piece weld width decreases in comparison with the weld at the surface but a certain amount is kept relatively constant with depth in the material.

The high level of power ensures an appropriate weld width both of the weld surface and inside the piece.

Increasing the depth of the weld is given by power level. The high level of power produce welds in keyhole regime. Getting the welds under keyhole regime is strongly associated with the formation of pores in the material. Increasing power and decreasing the welding speed leads to a situation in which many pores are produced in welds. Low welding speed produce significant heat affected zone. Appears important to control the laser beam intensity at the workpiece surface by changing the defocus. Decrease laser beam intensity independent of power provides a moderate keyhole welding regime is useful for reducing porosity in the weld.

For melted area is recommended the maximal values in all cases. This can be achieved by increasing power and decreasing welding speed.

Be sure that it is not excessive variations do not produce enlarged pores and heat affected zones.

## 8. Conclusions

This paper has analyzed the characteristics of a cross section through the weld associated with a period in which the welding process showed maximum stability. The effects of power and welding speed are considered for two situations for the laser beam focus relative to the workpiece surface.To control variation in the welding process by power and welding speed mathematical modeling associated with experimental research has shown the following:

-Power is the main effect on the characteristics of the weld. We recommend a high level of power.

-In relation to central point of a factorial experiment is recommended to increase power and lower welding speed without reaching the extreme values for both parameters.

- It is recommended to focus the laser beam inside the piece to achieve a moderate keyhole welding regime that is associated with reduced porosity.
- Modeling of the melted zone of the weld cross section will be useful for the design of welded joints.

The paper presents several ways of presenting the measured sizes. The mathematical model, Pareto diagram and response surface shows the same variation. Each of them has a different utility.

From the technological point of view these types of representations can be used to determine the objective function values that characterize the welds for data values of welding parameters power, welding speed and defocusing. It can address the inverse problem required to determine the values of parameters power, welding speed , defocusing to obtain employment objective functions, melted area, weld width, weld depth within certain limits. For this problem is to use utility of response surfaces. Response surface is a function of grade 2.Applications of response surface in optimization of this type, refers to the determine of maximum and minimum extremes on the experimental field from response surface figure. Thus the presentation of multiple mathematical models for the same experimental situation is useful**.**

For laser machining processes defocusing is an important parameter. Defocusing can be varied continuously but that it may be the range is narrow because much lower intensity of laser beam to the workpiece surface compromise the welding process. Small variations in defocus make that its effect can not be seized. Experimental situation presented in the paper is a case in which defocusing variations are obtained without excessive lowering laser beam intensity to the workpiece surface.

Using mathematical modeling and statistical analysis of the changes is a powerful tool for understanding the causes of variations for analyzed sizes and control the welding process.

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