

## GENERAL CHARACTERIZATION OF LASER WELDS CROSS SECTIONS

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**Abstract:** Laser beam is able to melt metals hence its application in welding processes. It presents an experimental study on laser welding of carbon steel. The welds cross-section are characterized by weld width, weld depth and melt area. Laser power, welding speed and defocusing were varied. Has developed a unified account of the experimental conditions by introducing the interaction energy as a function of varied parameters. Were used the regression functions to present the variations. Showed the existence of logarithmic variation for main sizes characterizing the weld section. We studied the melt zone width at piece surface produced by static irradiation.

**Keywords:** laser keyhole welding, metal melting, defocusing, interaction energy

### 1. INTRODUCTION

Laser welding has many industrial applications. The melting process is carried out using a non-contact method between tool and workpiece. Many parameters are involved in welding process control. From them the major role have the parameters related to the material irradiation. They are average laser power, welding speed and laser spot size on piece surface. This is controlled by the defocusing (distance between focal plane and piece surface). Laser power and spot size determines the intensity of laser beam on the piece surface and welding speed determined during the interaction time. The analysis proposed in this paper uses the ratio of laser beam intensity and welding speed defining a size called interaction energy. This provides a uniform characterization of irradiation conditions.

Laser weld is characterized by features observed in the area melted and resolidificate on the weld cross-section. Main characteristics are weld width, weld depth and weld melt zone area. In interpreting experimental data were used for regression functions. This data processing shows the general changes that can be applied independent of experimental conditions have been carried out in this research.

Is given a general description of the laser capacity to melt the material and thus achieving welds.

More recent studies have been concerned with laser welding of steels [1, 2,

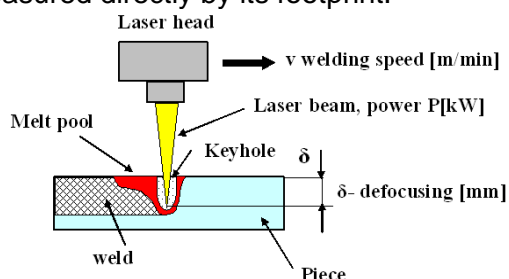
3]. Laser power, welding speed and defocusing are used as parameters in works [4, 5, 6]. For welds made weld width and weld depth were measured and expressed in terms of variations in laser power and welding speed [7, 8, 9].

This paper studies the variation weld width of weld depth and weld melted area on weld cross section with interaction energy. To highlight the keyhole welding regime was analyzed the relationship between weld width and weld depth. Introducing interaction energy allow for comparisons between melted width for fusion lines (welds) obtained and static irradiation on piece surface. For variations presented mathematical models are presented with regression functions.

### 2. EXPERIMENTAL PROCEDURE

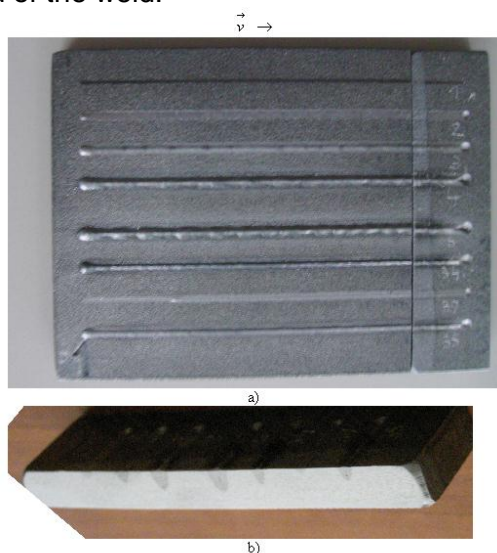
The experiment consisted in made lines of fusion (welds) ,110mm long , on Dillimax 500 steel plates with thickness of 10 mm (carbon steel, carbon content  $\leq 0.16\%$ ). Was used a Nd: YAG Triumph Haas 3006D laser source with 3kW maximum power on a continuous wave regime CW. Laser beam was transmitted 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 6 sheets of material with dimensions of 100×130×10mm 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 1. 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.



**Fig.1. Experimental parameters for welds.**

One of the plates with welds made and welds cross-section are shown in Figure 2. For comparison with molten zones produced by static irradiation average weld width were measured using three measurements on the piece surface at the beginning, middle and end of the weld.



**Fig.2. Plate with welds a) Surface plate b) cross- sections through the plate**

### 3. APPROACH TO INTERPRETATION OF EXPERIMENTAL RESULTS

Intensity laser beam to piece surface is the ratio between the laser beam power and spot area on the piece surface. This area increases with the focus within the play or negative values for defocusing.

Laser spot diameter at piece surface variation with defocusing is given by an empirical relationship. Laser beam intensity to piece surface is given by the following:

$$I = \frac{4}{\pi} \frac{P}{D^2} = \frac{4}{\pi} \frac{P}{(0.12|\delta| + 0.6)^2} \text{ [W/cm}^2\text{]} \quad (1)$$

Interpretation of experimental results followed a uniform characterization of welds obtained. This was achieved by introduction a calculated size to take into account the variables laser power, welding speed and defocusing. Was introduced as “interaction energy”  $E_v$  [ $\text{J/cm}^3$ ].

Interaction energy is defined as the ratio of laser intensity on the piece surface and welding speed. Laser intensity has been determined by varying laser power and spot size on the piece surface. Laser spot size on piece is determined by the conditions of focusing expressed by defocusing.

Welding speed is a parameter that is adjusted directly. Interaction energy has no direct physical significance as the energy brought in a certain volume. Higher interaction energy values are justified by the small size of laser spot at piece surface. Interaction energy shows laser ability to produce thermal phenomena in the material. Thermal effect of laser beam is proportional to the laser intensity on the material surface and interaction time between laser radiation and material. This is inversely proportional to the welding speed. The size interaction energy ensures a complete definition of the conditions in which take place the laser irradiation of material.

$$E_v = \frac{I}{v} \left[ \frac{\text{J}}{\text{cm}^3} \right] \quad (2)$$

Sizes are analyzed in the paper are main sizes that characterize the weld, figure 3. They were measured on the weld cross-section. Obtain a uniform characterization of the welding process at a time. Weld width  $LS$  [mm] was measured in the near the piece surface. Depth  $h$  [mm] was measured at the center of the weld. Measurements were made with an accuracy of 0.1 mm. Over height of weld surface  $S_u$  [mm] was measured near the area where the section was made with a comparator with an accuracy of 0.01 mm.

Molten weld area was measured by translating footprint on graph paper. The study included changes in the ratio of weld

width and weld depth. This is also named shape ratio of the weld.

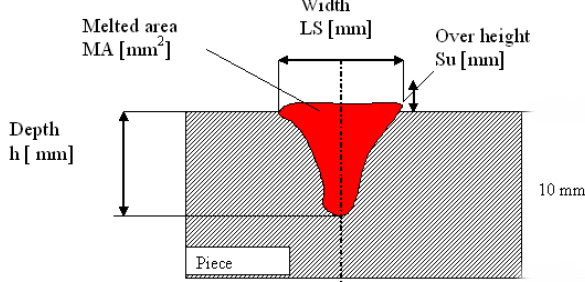


Fig.3. Scheme of weld cross-section with the measured sizes.

#### 4. VARIATIONS ANALYSIS

Figure 4 shows the variation of weld width LS [mm] with interaction energy. It notes that there is an increase in weld width with interaction energy. For small values of interaction energy this increase can be considered linear. General appearance of variation on the trial field show a logarithmic increase.

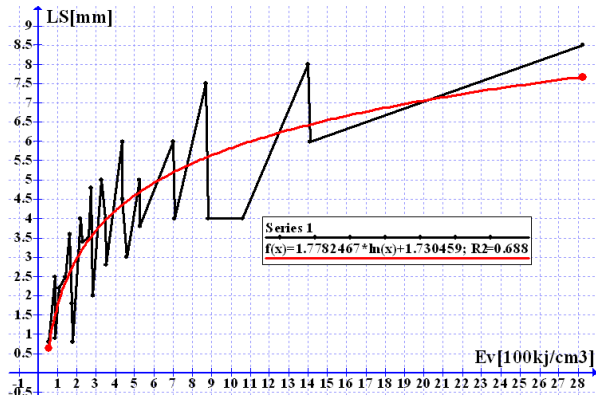


Fig.4. Weld width depending on the interaction energy

Logarithmic type of change shows that the weld width tends to reach a limit. This is due to laser capacity limitation to melt the material. There is a relatively high scattering of data around the regression curve. This is shown and the regression coefficient.

Figure 5 shows the variation for weld depth with interaction energy. On the experimental field was obtained a logarithmic increase. This shows that the penetration of the melting front in material is limited. At low interaction energies are strong variations due to changing focus conditions. The existence of the same type variations for weld width and weld depth show the validity, in the principle, for uniform propagation in material in a hemispherical symmetry of the melting front. Correlation coefficient indicates the

degree of confidence for this model. Moderate level of correlation coefficient leaves possibility of stronger increase for weld depth compared to the weld width. his trend is very pronounced for keyhole welding regime.

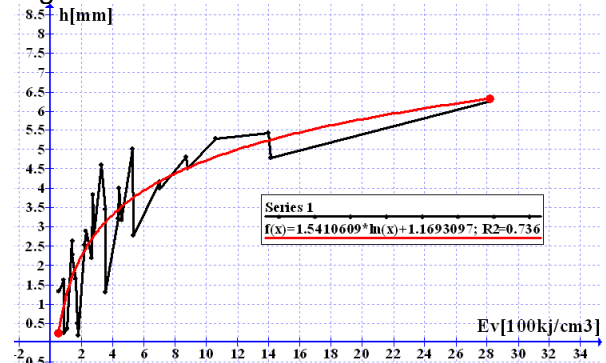


Fig.5. Weld depth depending on the interaction energy

Figure 6 shows the variation of weld shape ratio F with interaction energy. Over unity values of F ratio indicates conduction welding regime and subunit values of F ratio looks to keyhole welding regime. F ratio shows a logarithmic decrease. F ratio values for the field trial shows that the with interaction energy increase is obtained keyhole welding regime. Low values of interaction energy favors the appearance of conduction welding regime and high values of interaction energy produce a unit values for ratio F. Keyhole welding regime is obtained for moderate values of interaction energy. Low correlation coefficient indicates that F ratio values are very sensitive to the focusing condition.

Figure 7 shows the variation of the weld melted area with interaction energy. This presents a logarithmic increase more pronounced than that observed for the weld depth and weld width.

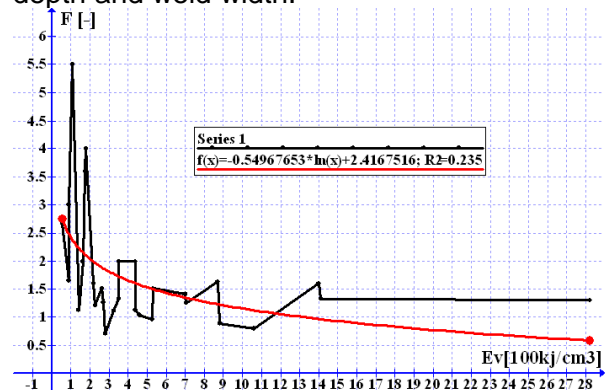
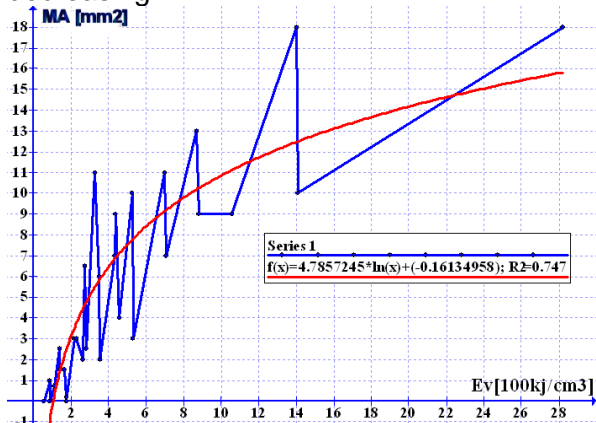


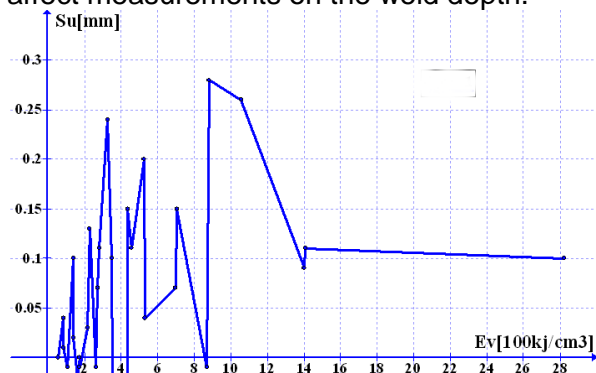
Fig.6. Ratio F (weld width to the weld depth) depending on the interaction energy.

Obtain a better approximation of the values by regression function. Through this kind of increase indicates that the ability to obtain a melt using the laser is limited. On the other hand it shows that there is a mutual compensation between the weld width and weld depth values. It looks like there where the weld depth is increasing the weld width decreasing.



**Fig.7. Melted area depending on the interaction energy**

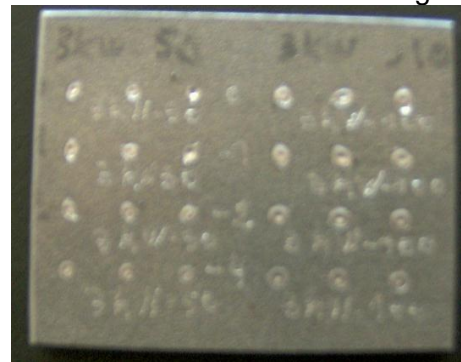
Figure 8 shows the variation weld over height with interaction energy. This indicates a relative increase of weld over height with interaction energy. The values for weld over height are small. There is some negative values, welds are below the surface of workpiece. In these cases the material vaporization was strong. Maximum weld over height obtained can be associated with moderate values for interaction energy. In these cases increased the amount of melt and its movement. But not achieved a balance with the conditions for obtaining vaporization. Weld over height size is very sensitive to conditions of focus and the interaction between laser power and welding speed. Weld over height low values did not affect measurements on the weld depth.



**Fig.8. Weld over height depending on the interaction energy**

#### 4. COMPARISON WITH STATIC IRRADIATION

Static irradiations of piece were made at maximum power available of 3kW were considered two values of pulse time 50 ms and 100 ms. Defocusing was varied by focusing laser beam from the piece surface to its interior part. Three replicates were performed for each test. For melted zone at the piece surface axis was measured Was performed an average of results for the three replicates performed. Plate that has been made static irradiation is shown in Figure 9.



**Fig.9. Plate which static irradiations**

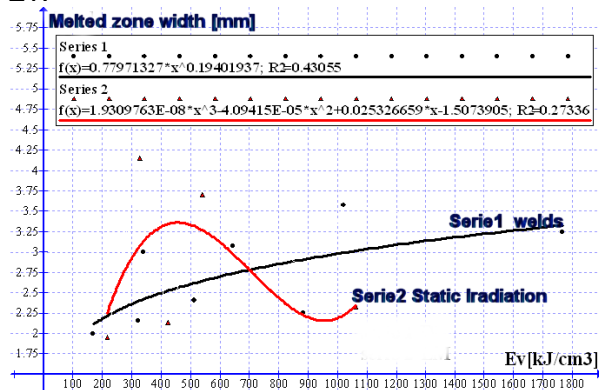
For static irradiation, made on the same material as the welds, the molten zone axis was measured. This was obtained as a result of two measurements one for maximum axis and the other for the minimum axis, the mean value was considered to melt zone axis (table 1). For each irradiation conditions three replicas (a, b, c) were made. We calculated average axis corresponding to the three replicas.

**Table 1. Values for molten zone axis**

Defocusing $\delta$ [mm]	Laser power 3kW Pulse time 50ms			
	Axis [mm]			
	a	b	c	average
0	2.5	2.25	2	2.25
-1	2.25	2.5	2.5	2.41
-2	2.5	2	2	2.16
-4	2	2	2	2
	Laser power 3kW Pulse time 50ms			
	Axis [mm]			
	a	b	c	average
0	3.5	3	3.25	3.25
-1	3.75	3.5	3.5	3.58
-2	3.25	3	3	3.08
-4	3	3	3	3

For static irradiation was considered an arbitrary irradiation rate by ratio of laser spot diameter on the piece surface and the pulse time. From this static irradiation conditions can be characterized with interaction energy and like welds (fusion lines). The figure compares molten zone axis obtained in static irradiation with average weld width.

Figure 10 shows that for static irradiation zones melt with values are still higher than values for the welds at low interaction energy  $E_v$ .



**Fig.10. Comparison of variation for weld width and molten zone axis obtained from irradiation static with interaction energy**

These show the development of melt phase on the piece surface. At high values of interaction energy  $E_v$  molten zone width decreases due to increase vaporization. Overall it shows that getting melted by irradiation areas still show a situation where obtaining fusion is not stabilized, in contrast to how it happens in obtaining lines of fusion (welds).

Static irradiations on the piece surface showed that of the craters (in melted zone) obtained at 50 ms exposure time are lower than those obtained for the 100 ms under the same defocusing conditions. Craters obtained by focusing on the piece surface are elongated (oval), there is differences in crater shape and orientation between the three replicates performed under the same conditions of exposure and the defocusing. By lowering focal point within piece the craters size decrease. The three replicates made for each experimental condition became increasingly more similar in shape and size with focusing in the piece. Thus lowering the focal point when provides good reproducibility of the melt process.

For each radiation conditions is a decrease in molten zone according with focusing within the piece. Largest axes are

obtained from defocusing -1. Changes in the size (relative) of the molten zone are not significant which shows that molten zone sizes depend mainly on the regime of irradiation (power and time) and not the focal point position (defocusing).

It is noted that increasing interaction time leads to higher significantly higher melt areas, regardless of defocusing. It notes that between replicas is better similarity with in-depth focus. This was observed for welds 5, 15, 25, named in the experimental plan, made under the same experimental conditions with lowering the focal point. If the first two welds showed irregular shapes (elevation), then for the last weld its have disappeared.

Molten zone axis values were compared with average weld width, taking as a criterion only interaction times. For time 50 ms was considered average weld width value 2.33 mm for weld 5 and for time 100ms average weld width 4.15 mm for weld 25. These can be compared with values of table 1. By comparison concludes that the melted zone is larger for welds than for static irradiation.

## 6. CONCLUSIONS

Introducing interaction energy made it possible to account for defocusing parameter with power and welding speed for the general description of the irradiation conditions. Usually only the power and welding speed are taken into account by their report called linear energy.

Analysis of variation sizes that characterize the melted area on weld cross-section by the interaction energy showed advantages. Thus for all analyzed sizes weld width, weld depth and melted area were obtained logarithmic changes. This showed that the obtained melted with laser beam irradiation can be characterized by one type of variation.

The type of regression function was shown that molten zone dimensions are limited by increasing interaction energy. Regression functions that characterize the variation with interaction energy considers a large number of experimental points. This can make general predictions on the values of parameters even if the effect of each parameter in part is not presented accurately.

Static irradiation showed that molten zone dimensions are determined by pulse time.

Equivalence conditions between the situation of static irradiations and fusion lines (welds) showed close values for melt zone width. Showed the importance of stabilizing irradiation effect for welds. Account all the radiation condition by introducing the interaction energy allows better comparisons between welding and static irradiation than those where it is considered only time interaction.

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