Revista Brasileira de Aplicações de Vácuo, v. 27, n. 1, 29-32, 2008.

LASER MICRO-WELDING OF THIN SHEETS USING NANOSECOND LASER PULSES

A.C. Oliveira[1*]; R. Riva[2]; M.S.F. Lima[2]; N.A.S. Rodrigues[2]
[1] CTA, *Instituto Tecnológico de Aeronáutica, 12.228-900, São José dos Campos, São Paulo, Brazil*
[2] CTA, *Instituto de Estudos Avançados, 12.231-970, São José dos Campos, São Paulo, Brazil*

Received: October 26, 2007; Revised: March 20, 2008

Keywords: laser microwelding, Cu-HyBrID laser, laser material processing

ABSTRACT

This work presents a new method for micro-welding thin sheets using a high repetition rate Cu-HyBrID laser emitting intense nanoseconds pulses. An experimental study of micro-welding process using short laser pulses was conducted on stainless steel (AISI 304) thin sheets with thickness of 100 µm. A theoretical model was developed to explain the role of the laser pulses emitted at high repetition rates on the micro-welding process. Although the intensity laser pulses exceed the threshold to perforate the thin sheets, the model results shown that the geometry of drilled hole can be controlled in a way that the vapor and liquid remains trapped and further condensate on the cavity inner wall allowing the welding of the sheets. In those controlled experimental conditions the thin sheets were welded using 20 watts of laser average power which is much lower than the power used in CW laser welding.

1. INTRODUCTION

Due to the very precise dimensional control and high energy concentration in a very small spot, laser micro-welding has been considered as an industrial valuable tool for joining thin or heat sensitive components. The main applications include electric and electronic components packaging, medical devices and clock parts [1].

The recent literature shows that laser micro-welding of thin sheets is commonly obtained using continuous wave (CW) or very long pulses (> 1ms) lasers which allows a thermal penetration depth comparable to the sheet thickness. Du and co-workers [2], for example, had developed a concept known as marginal lap welding in order to produce welds in 50-100 µm thick stainless steel foils using a 100 W CW Nd:YAG laser. Kleine and Watkins [3] used a CW Ytterbium fiber laser (single-mode, 100 W power) to achieve 0.4 mm deep penetration seam welds in stainless steel using 4 ms long pulses at a repetition rate of 200 Hz. Miyamoto and co-workers also reported results on ultra-fine keyhole welding of 80 µm thick stainless steel foils using a single mode Ytterbium fiber laser [4]. Funaka and Abe investigated welds of 100 µm thick INCONEL718 foil using a prototype micro welding system equipped with a 200 W class direct diode laser [5]. Naeem at GSI Lumonics [6] reported some of the welding results for 20-70 µm thick stainless steel sheets using 0.1 up to 20 ms laser pulses.

In a previous work, it had been shown, for the first time, the use of high repetition short pulsed laser to weld very thin metal foils [7]. Short pulses (~ 10's ns) are not commonly used in laser welding because limitation of the thermal penetration depth to less than 1 µm, which is more adequate to cutting and drilling processes [8,9]. However, an enhanced thermal penetration depth is obtained due to the accumulated energy when using high repetition rate (> 10 kHz), which partially overlap within the weld line. Consequently, the overall thermal penetration depth is determined by the superposition of several laser pulses, which depends of the welding speed and laser beam diameter. Considering the low average power used here (<20 W), the welding depth should be limited to few of micrometers. Therefore, conduction heat transfer alone cannot be used to explain the welding of thicker sheets (>100 µm). In this work it was proposed a model to explain the experimental observations in which thin sheets can be fully welded using a high repetition rate Cu-HyBrID laser emitting intense nanoseconds pulses. The results of the model are compared with the experiments data.

2. EXPERIMENTAL ARRANGEMENT

The Figure 1 shows a schematic diagram of the experimental arrangement to produce the micro-joining.

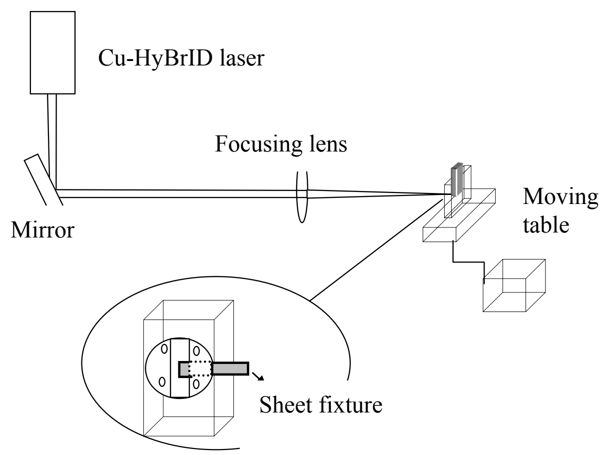


Figure 1 - Schematic diagram of the experimental arrangement to produce the micro-joining.

* alinecapella@ieav.cta.br

The material to be welded was a class 304 stainless steel 10x25 mm metal sheets of 0.1 mm thickness. The beam of a Cu-HyBrID laser [10] with pulses 30 ns long was focused to a 40 μm spot on to the sheets. Both, 512 nm and 578 nm laser emission lines, were used in the experiments with constant laser average power of 20 W and pulse repetition rate of 14 kHz. The metal foils were tightly clamped and fixed at a motorized translation stage which travel speed was varied from 1 to 5 mm/s. Metallographic analyses of the welded samples were carried out by optical microscopy of polished cross-sections after electrochemical etching using a 10% oxalic acid solution.

3. MODEL FOR WELDING WITH NANOSECOND PULSED LASERS

For high intensity laser beams (> 10^6 W/cm^2) with short laser pulses, the dominant physical process is the vaporization and most of the incident energy is used for drilling a small cavity on the sample surface.

Considering a Gaussian laser beam power profile described by $P_L(r) = P_0 \exp(-2(r/w_0)^2)$, where P_0 is the maximum power at radial position $r = 0$ and w_0 is the laser beam waist, the radial depth of drilled cavity can be estimated using a simple energy balance equation [7]:

$$d(r) = \frac{\varepsilon P_L(r) t_p}{A_L} \cdot \frac{1}{\rho \cdot (L_V + c_p (T_V - T_0))} \quad \textbf{(1)}$$

where P_L, t_p are respectively the power and pulse width of laser, A_L is the laser beam area, ε is the material emissivity at the laser wavelength, ρ is the material density, c_p is the specific heat, L_v is the latent heat of vaporization, and T_v and T_o are the vaporization and ambient temperatures, respectively. The cavity diameter can be estimated considering the radial position where the laser power heats the sample to the vaporization temperature T_V. In this way, the cavity profile follows the laser beam profile, truncated at the radial position defined by Tv, as presented in Figure 2.

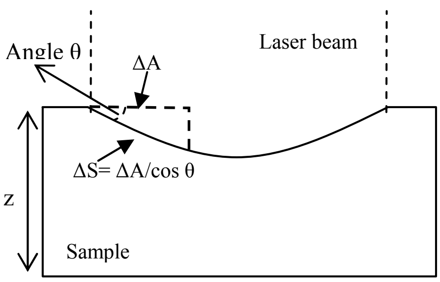


Figure 2 - Cavity geometry after one laser pulse applied.

For low traveling speeds and due to the laser high repetition rate used in welding experiments, several laser pulses will overlap, increasing the cavity depth. The number of overlapping pulses can be estimated by $N = (V/w_0)fp$, where V is the traveling speed and fp is the repetition rate. As shown in Figure 2, the area illuminated by the laser increases with the cavity depth and hence the effective laser beam intensity on the cavity surface decreases at each new laser pulse. The effective area to be used in equation (1) for the N-th laser pulses must be corrected taking into account the cavity angle θ formed in the prior pulse incident in the material, according to:

$$A_L{}^N = \frac{A_L^0}{\cos \theta^{N-1}} \quad \textbf{(2)}$$

where $A_L{}^0$ is the laser beam area for the first pulse. Figure 3 shows the radial cavity profile calculated by the model for different number of applied pulses.

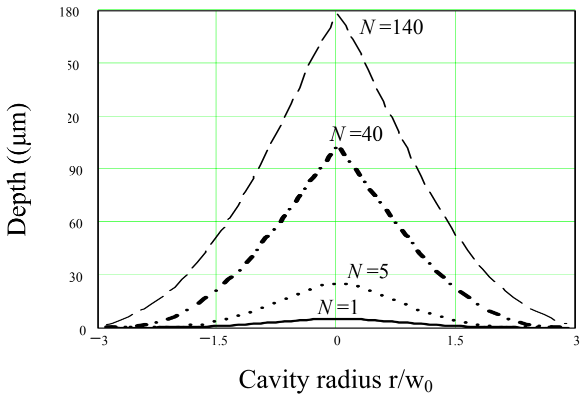


Figure 3 - Cavity profile as a function of number of laser pulses.

The importance of the cavity morphology on the welding process can be explained with three different situations, as shown in Figure 4.

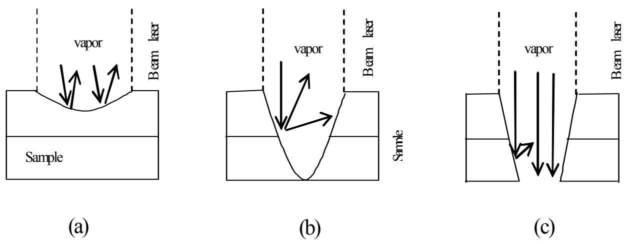


Figure 4 - Schematic diagram of the cavity geometry as a function of number *N* of overlapping pulses (a) small *N*, (b) moderate *N* and (c) large *N*.

The main features of these situations are:

(a) a small number of laser pulses is applied on the material surface. In this situation, the cavity depth is small and the vapor and few liquid are ejected outside of the cavity.
(b) a controlled amount of laser pulses is applied on the material surface, generating a very concave cavity that ends on the bottom surface (blind hole) of the sheet. In this case, the

vapor (and liquid) is trapped in the internal surface of the hole, redistributing the energy of the laser beam to the whole extension of the cavity during the time between pulses. This condition is very similar to the keyhole welding processing obtained with CW or long laser pulses [11], excepted that in our case the welding width is of the same order of the laser beam diameter. On keyhole welding, the welding width is of the same order of the thermal diffusion length.

(c) A very large number of laser pulses are applied to the sample, creating a deep cavity in the material. Here, the vapor and liquid are flushed down through the open hole, causing drilling (or cutting) of the sheets.

4. RESULTS AND DISCUSSION

Welding experiments were conducted maintaining a constant average laser power and varying the welding speed of the sample. For welding speeds lower than 1 mm/s both sheets were cut off. At welding speeds higher than 3 mm/s the sheets could be easily put apart, showing a shallow cavity only in the upper sheet. The best results were obtained with welding speeds from 1 up to 3 mm/s. Optical microscopy of the transverse sections of the samples within this range of welding speeds are presented in Figure 5.

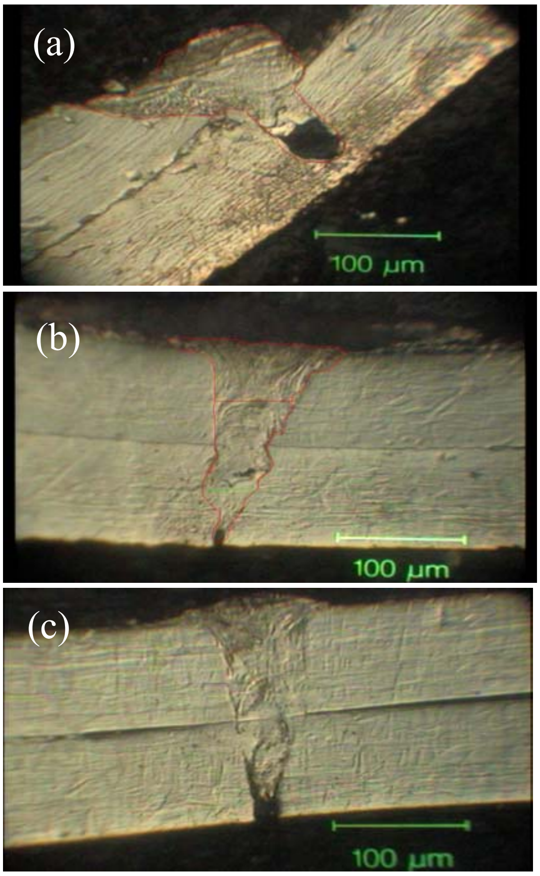


Figure 5 - Transverse sections of the samples obtained using the CuHyBrID laser with average power of 20 watts: (a) 1 mm/s, (b) 2 mm/s and (c) 3 mm/s.

With 1 mm/s (Figure 5-a), a weld bead was formed in the whole sample irradiated by the beam, although the upper sheet has been completely cut after the interaction with the laser. In the welding speeds between 2 and 3 mm/s (Figures 5-b and 5-c), the results obtained were approximately the same. As observed, the sample presents a weld bead in the region exposed to the laser.

The observed welding transverse profile is very similar to those calculated by the previous model as can be seen on Figure 6, where it was taking into account the number of overlapping pulses for each welding speed. The dashed line in Figure 6 indicates the thickness of the two clamped sheets. For the welding speed of 2 and 3 mm/s, the theoretical hole shape is conical and its depth approaches to the sample thickness (200 µm), and the width of the cavity the bottom sheet is quite small. The same did not happen in the case where the welding speed was of 1 mm/s, since the cavity depth exceeds the sample thickness and its bottom width is relatively larger than the previous ones. In this later case, the vaporized material can escape by the open hole.

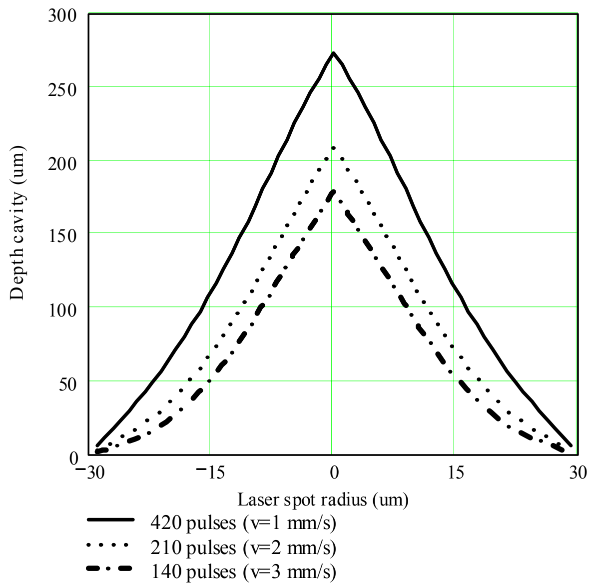


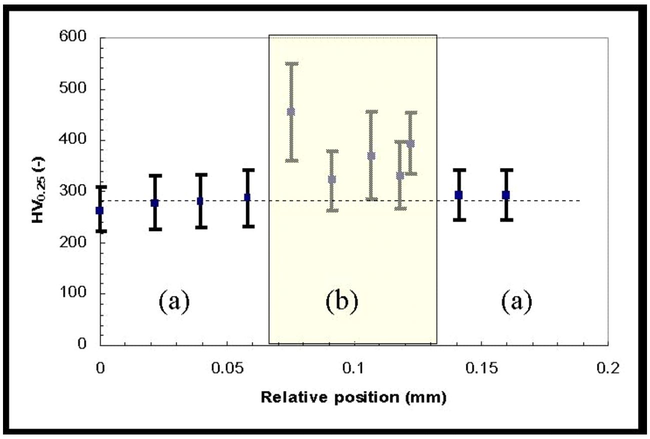
Figure 6 - Theoretical cavity profile for welding speeds of 1 mm/s, 2 mm/s and 3 mm/s.

It can be concluded that the better energy coupling for welding occurs when the cavity depth approaches to the sample thickness, i.e. in the welding speeds of 2 and 3 mm/s.

The welding microstructure could be better observed in Figure 7-a. The grain boundaries are better defined inside and outside the welding. Dendritic growth could be also verified in some regions of Figure 7-a, obeying the heat flux direction. The grains inside the welding were relatively coarse for a pulsed laser welding, since pulse heat produces more equiaxial grain distribution. Usually equiaxed grains should not be pronounced to the heat transfer direction. These observations are typical of a continuous cooling welding such as that produced by CW-lasers. Therefore, the material response to the high repetition laser power is comparable to a very efficient CW-laser welding.

The microhardness was obtained using Vicker's tester with an applied charge of 0.25 N. Figure 7-b presents the results of the regions (a) outside and (b) inside the welding. The average microhardness values inside and outside the welding were 370±50 $HV_{0.25}$ and 280±10 $HV_{0.25}$, respectively. The welded material was slightly hardened in comparison to the base material. However, the hardening was not sufficiently high to deteriorate material properties such as toughness. The measured microhardnesses inside the weld bead showed wider scattering than in the base material due to the microstructural refinement and non-equilibrium phase transformations in the melted zone.

(a)



(b)

Figure 7 - (a) Transverse section at the top of welding. (b)Results of microhardness tests for regions (a) outside and (b) inside the weld.

5. CONCLUSIONS

A theoretical model was developed in order to explain the interaction of short laser pulses at high repetition rates on the micro-welding process. Model results indicated that however the high intensity of laser pulses exceed the threshold to perforate the thin sheets, it is possible to control the cavity geometry by the number of applied pulses in such a way that the liquid and vapor remains trapped and further condensate in the cavity, allowing the welding of the sheets. In those controlled experimental conditions the thin sheets were welded using 20 W of laser average power which is much lower than the power used on traditional methods.

ACKNOWLEDGEMENTS

One of the authors (A.C.O.) thanks CAPES (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior, Brazil) for the financial support.

REFERÊNCIAS

1. DEARDEN, G., Proceedings of the Third International WLT Conference on Lasers in Manufacturing, Munich, Germany, 2005, p.615.
2. DU, J.; LONGOBARDI, J.; LATHAM, W.P.; KAR, A., *Journal of Laser Applications* 14 (2002) 4.
3. .KLEINE, K.F.; WATKINS, K.G., Proceedings of Third International WLT – Conference on Lasers in Manufacturing, Munich, Germany, 2005, p. 637.
4. MIYAMOTO, I.; PARK, S.; OOIE, T., *LMP Section A* 203 (2003).
5. FUNAKA, Y.; ABE, N., Proceedings of the Third International WLT – Conference on Lasers in Manufacturing, Munich, Germany, 2005, p.625.
6. NAEEM, M.; COLLINS, P., Proceedings of the Third International WLT – Conference on Lasers in Manufacturing, Munich, Germany, 2005, p.643.
7. OLIVEIRA A.C., *Microssoldagem de chapas finas utilizando um laser de Cu-HBr*. Dissertação de Mestrado (2006). Instituto Tecnológico de Aeronáutica, São José dos Campos (SP).
8. SANTOS, C.L., *Determinação dos Parâmetros Ótimos de Operação de um Laser de Cu-HBr*. Dissertação de Mestrado (1999). Instituto Tecnológico de Aeronáutica, São José dos Campos (SP).
9. LUFT, A.; FRANZ, U.; EMSERMANN, A.; KASPAR, J., *Applied Physics A* 63 (1996) 93.
10. RIVA, R.; WATANUKI, J.T.; RODRIGUES, N.A.S.; SCWAB, C., Proceedings of the V Workshop on Separation Phenomena in Liquids and Gases, Fox do Iguaçu, Brasil, 1996, p.253.
11. DULEY, W.W. *Laser Welding*, Wiley Inter-Science, 1998.