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Nanosecond pulsed laser welding of high carbon steels

Alessandro Ascari *, Alessandro Fortunato

DIN – Industrial Engineering Department, University of Bologna, Viale Risorgimento 2, 40136-Bologna, Italy

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ABSTRACT

The present paper deals with the possibility to exploit low-cost, near infra-red, nanosecond pulsed laser sources in welding of high carbon content thin sheets. The exploitation of these very common sources allows to achieve sound weld beads with a good depth-to-width ratio and very small heat affected zones when the proper process parameters are involved. In particular the role of pulse frequency, pulse duration, peak power and welding speed on the characteristics of the weld beads is studied and the advantage of the application of short-pulse laser sources over traditional long-pulse or continuous wave one is assessed.

1. Introduction

High carbon steels are commonly used in modern mechanical industry due to their good mechanical properties and to their relatively low cost. Unfortunately, when dealing with welding processes, these materials must be set aside because of their very high crack susceptibility and more refined and expensive steels must be taken into consideration, such as HSLA, DP and TRIP ones, thanks to their lower carbon equivalent and similar, or even better, mechanical properties. In particular, when dealing with laser welding, these drawbacks can be emphasized due to the very high energy density and to the fast cooling characteristic of these joining processes, which tend to favor the formation of cracks and hardened zones, as mentioned in many well-known welding-related handbooks [1,2]. In laser welding, where energy density and cooling rates are very high, if compared to traditional arc one, and no filler material is used, the optimal source and the relating process parameters must be selected very carefully in order to achieve the optimum trade-off useful for obtaining a sound joint. In this direction Cam et al., Yoo et al. and Li et al. [3–5] pointed out that the feasibility of laser welding of low carbon-manganese and medium carbon thin sheets, underlining the importance of process parameters selection in getting a defect-free weld bead. The use of high carbon steels has extended also towards micro-components industry for the production of MEMS, mechanisms for watches, springs, and medical devices [6–9]: in this case the high specific heat input and low power density, characteristic of traditional arc welding, determines the almost complete inapplicability of these processes and paves the way for a reliable and effective application of laser-based ones. This application field, which is characterized by micro-scale thickness components, opens the welding scenario also to the application of low power short-pulse laser sources, making possible to exploit the benefits of the pulsed regime in order to accurately control the energy delivered to the material. Laser micro-welding is a process whose industrial interest increased dramatically in the last 10 years not only when dealing with steels but also with hard materials such as tungsten carbides for cutting tool technology, polymers for medical products and, under particular conditions, even ceramics, polymers, glass and diamonds, as reported by Masuzawa [10] and Haberstroh et al. [11]. In particular laser micro-welding of metals have been studied since 1995, when Olsen and Alting [12] presented the possibility to exploit pulsed millisecond Nd:YAG sources for joining AISI316 thin sheets. In this case the authors stressed on the fact that the good control of the heat input, due to the pulsed regime, could help in achieving very good weld beads even for thicknesses smaller than 1 mm. Glasmacher and Pucher [13] dealt with millisecond pulsed Nd:YAG laser welding of Fe–Ni and Cu–Ni alloys for electronic components, pointing out the first outlines for the application of laser in that particular manufacturing field. The first decade of the 2000s has been a very profitable period for the research in laser micro-welding. Schmidt and Otto [14] stressed on the application of millisecond pulsed Nd:YAG sources in manufacturing of electronic components demonstrating the weldability of AISI304 thin wires and copper alloy foils. Szymanski et al. [15] studied the effect of power modulation in Nd:YAG laser welding of less than 1 mm thick mild steel thin sheets. Klages et al. [16] proposed a novel technique named SHADOW® for the generation of circular micro-scale weld seams by means of a single laser pulse and they applied it on dissimilar AISI304-brass lap joints. Semak et al. [17] developed a combined simulation-experimental activity aimed at defining a numerical model for micro-welding. They demonstrated that, in order to achieve high penetration by means of key-hole formation, short pulse laser sources should be used. Chmelickova

* Corresponding author. Tel.: +39 051 2090494; fax: +39 051 2090484.
E-mail address: a.ascari@unibo.it (A. Ascari).

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Nomenclature

A_r	weld bead aspect ratio
D	weld bead penetration depth (μm)
E_s	specific energy (J/mm)
P	average power (W)
P_d	pulse duration (ns)
P_e	pulse energy (mJ)
P_l	pulses per unit length (1/mm)
P_p	peak power (kW/pulse)
P_{rr}	pulse repetition rate (kHz)
S	welding speed (mm/s)
W	weld bead width (μm)

et al. [18] explored the millisecond pulsed Nd:YAG of 0.5 mm thick foils of different materials: mild steel, stainless steel, brass, and aluminum alloys, stressing also on the actual role of the shielding gas. Gillner et al. [19] reviewed several laser-based micro-manufacturing techniques and they stressed on the possibility of exploiting pulsed lasers for both fusion welding and brazing. Nobuyuki et al. [20] investigated the applicability of continuous wave direct diode sources in welding of 50 and 100 μm AISI304 foils, achieving sound joints at relatively high welding speeds (18 m/min). Mys and Schmidt [21] dealt with dissimilar Al–Cu laser spot welding for micro-packaging. Kawahito et al. [22] studied millisecond pulsed Nd:YAG welding of titanium foils stressing on the role of adaptive controls for dealing with gap variability. Abe et al. [23] exploited a direct diode source with elliptical spot for lap welding of 5 μm thick AISI304 foils on 1 mm thick AISI304 sheets. Okamoto et al. [24] compared the applicability of millisecond pulsed Nd:YAG sources and high brightness single mode constant wave fiber ones in case of welding of 25 μm AISI304 foils. The paper involved also the use of a galvanometric scanner for the beam displacement, pointing out the benefits of that solution on process versatility. P'ng and Molian [25] were the first to present some results concerning the exploitation of short-pulse (nanosecond) Q-switched Nd:YAG sources. In that paper 60 μm thick AISI304 foils were lap-welded exploiting a 200–400 mJ energy-per-pulse and a pulse repetition rate equal to 10 Hz, demonstrating the potential of short pulse, high peak power, laser sources in micro-welding. Schmitt et al. [26] stressed on the importance of integrating high dynamics optical devices for the beam displacement and they introduced the benefits in superimposing a high frequency beam oscillation during the process for dealing with difficult-to-weld materials. Ventrella et al. [27] dealt with Nd:YAG pulsed laser lap welding of AISI316 100 μm thick foils at different values of the energy-per-pulse and they stressed on the importance of a good contact between the foils at the welding interface. Rohde et al. [28] stressed on the importance of pulse shape when welding high thermal conductivity materials, such as aluminum alloys, for achieving very narrow weld beads while maintaining small specific heat inputs. Isaev et al. [29], in a different direction from the previous authors, proposed a numerical model suitable for simulating laser welding of thin sheets, stressing on the importance of process simulation for an effective optimization of all the variables involved. Fortunato et al. [30] presented a preliminary feasibility assessment of nanosecond, high pulse repetition rate laser welding of high carbon steels, demonstrating the applicability in case of micro welding of laser sources whose typical application is confined to micro-milling and marking. In that case the laser source involved was characterized by a fixed pulse duration and a limited range for the pulse repetition rate.

On the basis of the above mentioned considerations the present paper deals with the possibility to exploit a modern low cost, 4–200 ns variable pulse duration, high pulse repetition rate, Q-switched fiber laser source in the realization of micro-scale weld beads on 0.7% carbon steel. By means of an experimental activity the optimum process parameters were defined for the achievement of deep penetration and crack-free weld beads. In particular, by fine-tuning the peak power, the pulse repetition rate, the pulse duration and the welding speed, a bead penetration as high as 230 μm was achieved and no appreciable heat affected zone was observed. These results underline that, when dealing with micro-welding, the proper exploitation of a short-pulsed laser source makes possible to extend autogenous fusion welding processes to difficult-to-weld materials such as high carbon steels. Moreover, when dealing with micro-scale pulsed laser welding, the high versatility of the galvanometric beam delivery system makes possible to deal with very high welding speeds, which contribute to lower the specific heat input of the process and to achieve very high production rates. By means of modern 3-axes galvanometric heads very complex 3D weld beads can be achieved on micro-scale mechanical components and, combining the intrinsic characteristics of short-pulse laser sources, very versatile manufacturing cells can be set up in which micro-cutting, welding, marking and engraving operations can be performed on a single workpiece positioning.

2. Experimental setup

The experimental setup exploited in the present activity was based on a IPG YLPM-1-4 × 200-20-20 Q-Switched laser source (see Fig. 1 and Table 1 for specific details) equipped with a Raylase SuperScan II-10 galvanometric scanning head and a Aerotech PRO115 3-axis linear motion system.

The experimental specimens were constituted by a 70 × 19 × 1.3 mm UNI C70 (AISI1070) plain carbon steel thin sheet in the quenched and tempered state, with a base micro hardness equal to 515 HV. The weld beads were carried out in a bead-on-plate configuration exploiting the maximum average power typical of the laser source (20 W) and considering the variation of four specific process parameters: peak power (P_p), pulse duration (P_d),

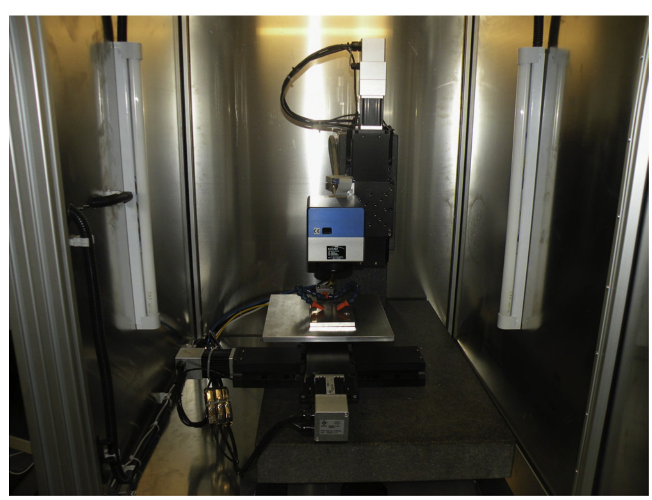

Fig. 1. Experimental equipment.