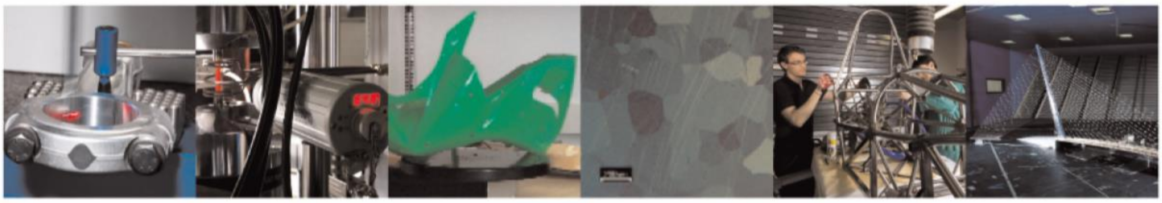

Hand-Held Laser Welding of AISI301LN for components with aesthetic requirements: Toward the integration of machine and human intelligence

Caprio L.; Borzoni G.; Previtali B.; Demir A. G.

DIPARTIMENTO DI MECCANICA ■ POLITECNICO DI MILANO
via G. La Masa, 1 ■ 20156 Milano ■ EMAIL (PEC): pecmecc@cert.polimi.it
http://www.mecc.polimi.it
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HAND-HELD LASER WELDING OF AISI301LN FOR COMPONENTS WITH AESTHETIC REQUIREMENTS: TOWARDS THE INTEGRATION OF MACHINE AND HUMAN INTELLIGENCE

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Leonardo Caprio[1], Giulio Borzoni[1], Barbara Previtali[1], Ali Gökhan Demir[1]

[1] Department of Mechanical Engineering, Politecnico di Milano, Via Giuseppe La Masa 1, Milano, Italy

Abstract

The use of Hand-Held Laser Welding (HHLW) systems in the industry has been rapidly growing in the recent years as alternative solution to conventional manual arc-based welding systems. The decreasing cost of fiber laser sources and optics has been a driving factor in enabling a wider use of HHLW systems, beyond the established advantages of the laser technology with respect to arc-based systems. While the industrial use of HHLW increases, the subject matter has been studied sparingly in the scientific literature. Due to the intrinsic flexibility of the technology, HHLW systems are highly appealing for joining relatively low thickness metals (≤2mm) in autogenous configuration in sectors where production lots present low batch and high variability. However, a critical aspect of HHLW is correlated to the operator skill, where welding velocities can vary within and between the welds affecting both their aesthetic and mechanical properties. Hence, the development of combined digital and physical approaches to support manual operations may be highly beneficial. The current study presents an open laboratory HHLW system designed for process development purposes. Beyond conventional manual welding operations, the welding torch could be arranged in different configurations. The system could be combined with a linear axis (enabling welding with stable velocity and inclination) or manually with the aid of a newly developed roller device designed to provide constant speed and inclination. Firstly, the process was benchmarked by joining in butt weld configuration 2 mm thick AISI301LN stainless steel sheets with the linear axis. Successively, four operators with different levels of training (rookie and professional) realized welds with the system in hand-held configuration and with the mechanical roller. The weld width variability was assessed as a direct indicator for aesthetic compliance whilst tensile tests allowed to determine the mechanical properties of the joint obtained with the different configurations.

Introduction

The concept of manipulating a device to manually orient a laser beam to perform the joining of metals was conceived no longer than 10 years after the first laser was born[1]. Nonetheless, since their first conception, hand-held laser devices for the processing of metals have found limited diffusion within the industrial community. Reasons may be found in the elevated costs of laser equipment (with respect to competing technologies) and to the requirements in terms of power levels and beam quality. Nonetheless, the always decreasing cost of solid-state laser systems led to the development of various hand-held devices. Puester *et al.* reported different uses of hand-held laser devices for different applications ranging from mould repairing, laser cutting during nuclear plant dismission, laser cleaning of dies and of facades[2]. In order to tackle the safety issues correlated to the use of such systems, the first international standard related to the use of hand-held laser processing devices was thus published (ISO 11553-2). Still, the industrial field has been employing limitedly hand-held devices for the joining of materials mainly due to the limited availability of laser sources with elevated brilliance and the costs associated with them. On the other hand, in the medical field, where power or energy levels required are more restrained, the use of hand-held laser devices has been surging since the mid-1980s [3,4].

In the case of industrial Hand-Held Laser Welding (HHLW) there are strong requirements in terms of laser delivery system, device compactness and energy power levels in order to achieve the required penetration depths and ease of use. Only the development of contemporary single module fiber laser sources with elevated brilliance and the significant cost reductions operated by the market in recent years, have enabled a new market of HHLW systems as an alternative to conventional arc welding processes[5]. Commercially available HHLW systems employ single module fiber laser sources with power levels between 1 and 2 kW launched into transport fibers with 50 µm core diameter. The spot diameter is in the range of a few hundreds of microns and components to achieve spatial beam oscillation are integrated in the beam delivery system in order to obtain apparent spots in the millimetre range. The use of such techniques is effective in improving the gap-bridging capabilities of the laser welding technology and possibly overcome misalignment issues[6,7]. Moreover, beneficial effects may be found in terms of the mechanical properties and crack susceptibility of the joints[8,9].

Given their intrinsic characteristics, Hand-Held Laser Welding systems are apt for the welding of low thickness steel or stainless steel sheets (in the range of 1-3 mm). Their applicability for the processing of highly reflective materials has also been reported for low thickness sheets[5]. Although the use of HHLW systems has shown widespread adoption in the industry, such change has not been anticipated nor studied by the scientific literature. The only publication related to the topic, merely presents the architecture of such systems[10]. Even though there have been several publications in the field of laser safety of hand-held laser devices (culminated in the publication of the standard 11553-2), questions still remain relative to different technological aspects of the process[2,11,12].

The HHLW technology can be specifically competitive in the cases where manual arc welding processes are employed. With respect to electric arc-based processes, laser welding generally allows to achieve significantly higher welding speeds and lower distortions due to the higher energy density of the heat source[13]. Laser welding also provides a further competitive advantage with respect to conventional arc technologies in applications where the final aesthetic aspect of the joints is significant. As reported in literature, laser welding allows to obtain finer beads which thus require significantly lower post-processing efforts. The use of a HHLW system can thus provide benefits in the manufacturing both during production and during the successive post-processing steps. In terms of technological choice, another competitor to HHLW system may be found in laser systems with robotic manipulators or linear axis. Such systems can provide significantly greater accuracy at the expense of greater programming efforts and complicated fixturing systems in order to ensure low gap conditions. Advanced sensing solutions are available in the market and under study to provide intelligent process adaptations[14,15]. Nonetheless, the inherent flexibility to the real process conditions provided by human operators of HHLW system configures as an alternative solution in the case of low-batch productions with complex geometries.

A fundamental aspect of the Hand-Held Laser Welding process which thus requires greater attention is the influence that different operators introduce over the mechanical and aesthetic properties of welds. Clearly, the operator performing the welds may introduce significant variations to the operating conditions (for instance the laser welding speed and the inclination of the laser welding gun). Concurrently, such aspects may influence also the aesthetics of the weld beads. Considering that a shortage of more than 300,000 skilled welders has been foreseen by the American Welding Society[16], an analysis regarding the operator skill required to employ HHLW systems is of great significance as well as enhancing the process stability via the development of novel devices adaptable to existing systems.

The effects of different operators over quality related aspects of the welding process is of great significance as reported by Ji *et al.* [17]. Sïkstrom showed the variations in terms of process efficiency during Gas Tungsten Arc welding [18]. In the field of laser processing of metals, literature is sparse. Capello and Previtali analysed the operator influence during the laser cladding process showing that trained operators did not affect significantly the process outcome [19]. Bertrand *et al.* addressed the topic during the laser welding of FeNiCr wires for dental applications showing differences in terms of ultimate tensile strength [20].

From a general perspective, the HHLW process is of particular importance in laser based manufacturing processes as it changes the paradigm from a specialized high-cost operation towards an enabling digital and approachable tool in the workshop. With an increased usage of such systems, the benchmarking studies concerning their capabilities but also the safety issues should be tackled. On the other hand, the literature has not been developed yet around this theme as to authors' knowledge, no previous work has attempted to quantify any aspect of the HHLW process before.

The aim of the present work is hence to investigate the influence of operators with different training levels on the HHLW process and the possibility of introducing stabilizing devices on existing systems to aid the laser welding operations. An industrial Hand-Held Laser Welding device was adapted to a laboratory set up in order to flexibly configure it to perform both hand-held welds as well as mounted on a linear axis. Moreover, a novel mechanical roller system was developed that could be adapted to the laser welding torch as an intermediate solution between the hand-held and linear axis configuration (i.e. flexible workpiece adaptation yet providing a constant velocity and inclination). Thus, an experimental campaign characterizing the Hand-Held Laser Welding of 2 mm thick AISI301LN stainless steel was carried out. Four different operators performed the welding operations employing the HHLW system both with the roller device and the hand-held configurations. Two operators were professional welders with plurennial experience with arc welding systems whereas the other two welders were non-professionals. The welds were analysed both in terms of their mechanical and aesthetics.

Materials & method

Hand-held laser welding system

An open laboratory hand-held laser welding system was developed within the premises of SITEC – the Laboratory for Laser Applications of the Politecnico di Milano. A hand-held laser welding head (BWT15, Shenzhen Qilin Laser Application Technology, Shenzhen City, China) was adapted to a multi-mode fiber laser system with a maximum emission power of 3 kW (YLS-3000, IPG Photonics, Cambridge, MA, USA). In order to ensure correct delivery of the beam to the head from the 50 µm transport fiber, an in-house designed collimating unit with a QBH fiber adapter and 75 mm focal length was coupled to a beam reducer with a magnification factor of 1/3. The collimated laser beam is then focused onto the weld region by means of a focusing lens (f_{foc}=150 mm). Beam oscillation was obtained by two galvanometric mirrors positioned prior to the focusing unit. Figure 1 reports the optical path and main system components of the hand held laser welding head.

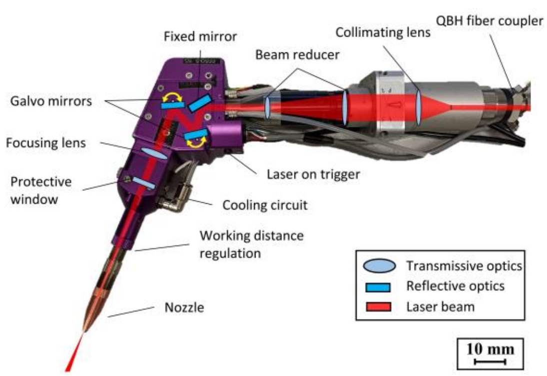

Figure 1. Optical path of the hand-held laser welding head

Given the flexible nature of the system developed, the hand-held laser welding system could be adapted on a linear axis with an external laser emission trigger (as exemplified in the scheme of Figure 2 (b)). The linear axis provided motion to the material to be welded whilst the welding was maintained stationary by means of a dedicated fixturing system. Hence, this configuration enables the testing of the process in controlled conditions in terms of welding speed and beam inclination.

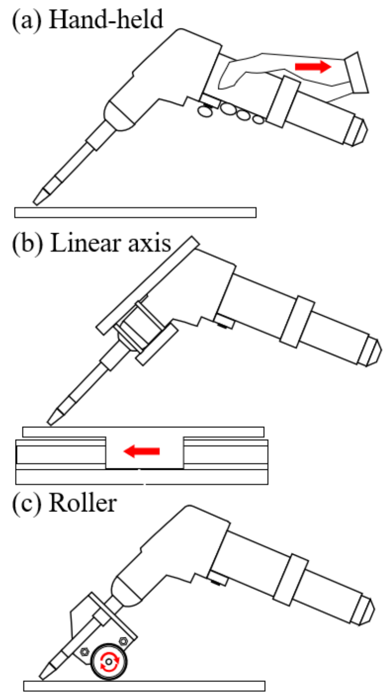

Figure 2. Schematic representation of the possible configurations of the flexible HHLW system developed (a) hand-held, (b) linear axis and (c) roller

Moreover, a mechanical roller device was realised to provide an aid to the welder during the process (schematically shown in Figure 2 (c)). The roller device provides a two-point contact on the welding material. The first point of contact is always the nozzle to ensure the safety potential-free contact to enable the laser emission. Secondly, a circular wheel actuated by a stepper motor acts as a towing mechanism. The roller device was calibrated in order to provide a 45° inclination with respect to the welding material and different levels of welding speed which could be commanded by means of the rotational speed of the motor. This system hence facilitates maintaining a fixed inclination angle and a constant welding speed. Figure 2 schematically shows the different configurations possible of the HHLW system ranging from the conventional hand-held operations to the linear axis and roller device conditions. The main system specifications of the in-house developed HHLW are defined in Table 1.

Table 1. Overall specifications of the HHLW system employed in the present work

Specification	Value
Max. laser power, P_{max} (W)	2000
Emission wavelength, λ (nm)	1070
Beam quality factor, M^2	9.1
Fiber diameter, d_{f0} (µm)	50
Collimator focal length, f_{col} (mm)	75
Beam reduction factor, m	1/3
Focus lens focal length, f_{foc} (mm)	150
Beam waist diameter, d_0 (µm)	300
Wobble amplitude, *WA* (mm)	0 – 5
Configuration	Linear axis; Hand-held; Roller

Safety procedures

The hand-held laser welding system developed in the present work was classified as a Class 4 laser product according to standard EN 60825-1. Hence, personal protective equipment is required to avoid exceeding the maximum permissible exposure levels. In the present work, laser protective eyewear for the emission wavelength with a rating of DLB7 was selected in accordance to standard EN-207. Users of the system were provided with working gloves and suits in order to protect against spatter ejections.

The system was located within a laser welding cell (certified in accordance to EN 60825-4) thus defining the laser controlled area. Once the operator is within the laser welding cell, a laser interlock circuit must be activated in order to enable the laser emission and personal protective equipment must be worn by the operator. A further safety mechanism implemented is provided by the need of a potential free contact between the nozzle and the material being welded. Clamping equipment allows the welder to connect the workpiece to the electronic controller of the system whereas the other contact is provided by the nozzle of the welding torch. Once the potential free contact is performed, the welder can activate the laser emission via a trigger button (indicated in Figure 1).

Material & joint geometry

2 mm thick sheets of AISI301LN stainless steel were employed as weld material. The joint geometry under examination in the present work is the butt-weld condition. The material and joint geometry under investigation are considered representative of conditions typically employed for the manufacturing of hand-held laser welded aesthetic components.

Table 2. Nominal chemical composition of AISI301LN

Elem	Fe	Ni	Cr	C	Si	N	P	S	Mn
wt%	Bal	6 - 8	16 -18	≤0.03	≤1	0.07-0.2	≤0.045	0.03	≤2

Experimental design

An experimental campaign was designed in order to assess the influence of different operators and the mechanical roller device over both the mechanical and aesthetic properties of the joints (butt welds of 2 mm thick AISI301LN stainless steel). Four different operators performed the welds. Two of the operators (n°1 and n°2) are students of the MSc in Mechanical Engineering who received basic training with the HHLW system and thus were classified as “Rookie”. Two of the operators (n°3 and n°4) were experienced professionals who habitually employ either arc welding or HHLW systems, accordingly classified as “Professional”. Laser welding parameters were selected with the aid of the experienced operators via a preliminary experimental campaign on the linear axis to provide a compromise between weld bead penetration depth, width and aesthetic appearance for the manufacturing of aesthetic components. Results of this campaign are not reported for brevity.

The reference welding condition identified on the linear axis consisted in a weld speed of v= 1 m/min whilst the emission power was maintained at P= 1350 W. The process gas to shield the weld region was Nitrogen and the focal position of the beam was positioned in the middle of the weld thickness (h_f=-1 mm). Beam oscillation geometry was a linear trajectory transverse to the welding direction whilst the wobbling amplitude (*WA*) and frequency (*WF*) of the oscillation were fixed respectively at 0.3 mm and 51 Hz. The welds performed with the linear axis were considered as the reference condition in terms of mechanical and aesthetic properties.

Hand-Held Laser Welding was performed by the welders under controlled conditions with the system presented in the previous sections using both the hand-held and roller configuration. The welding parameters were maintained constant to the condition with the linear axis configuration. Regarding the welding speed, welders aimed at a target value of 1 m/min. Figure 3 shows the operators conducting the experimental campaign.

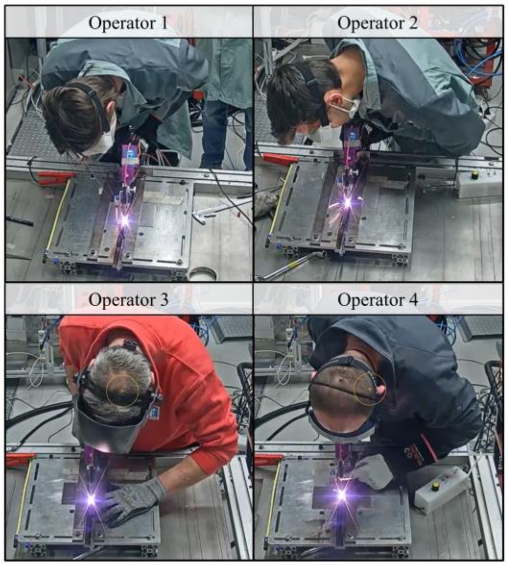

Figure 3. Operators 1 to 4 performing the welds of the experimental plan

Each welding condition was replicated 5 times and successively analysed in terms of the aesthetic and mechanical properties (in accordance with the procedures reported in the characterization section).

Table 3. Fixed and variable factors of the experimental campaign

Fixed factors	
Process gas	Nitrogen
Material	AISI310LN
Joint configuration	Butt weld
Sheet thickness, t (mm)	2
Laser power, P (W)	1350
Wobble shape	Line
Wobble amplitude, WA (mm)	0.3
Wobble frequency, WF (Hz)	51
Focal position, h_f (mm)	-1
Replicates, n	5
Variable factors	
System configuration	Hand-held; Roller
Operator	1; 2; 3; 4

Table 3 reports the overall experimental design. The results regarding the aesthetics and mechanical properties were analysed using Analysis of Variance (ANOVA) in order to establish the statistical significance of the factors (with a statistical significance level of α=0.05).

Characterization

The aesthetic properties and their variation with respect to the reference axis conditions were evaluated by means of macro-photography of the top profile of the weld bead. The photographs were taken on a calibrated photography set with a 17-55 mm objective on a Nikon D3500 (Nikon, Chiyoda, Japan).

The macro-photographs were analysed using an image processing algorithm which following binarization allowed to extract the profile weld width. The welds were thus characterised in terms of the average weld bead width $\mu(w)$ and its variability represented by the standard deviation of the width profile $\sigma(w)$. Figure 4 (a) shows an example of a macro-photograph of a weld beam profile and in Figure 4 (b) and (c) the profile identified with a schematic representation of $\mu(w)$ and $\sigma(w)$.

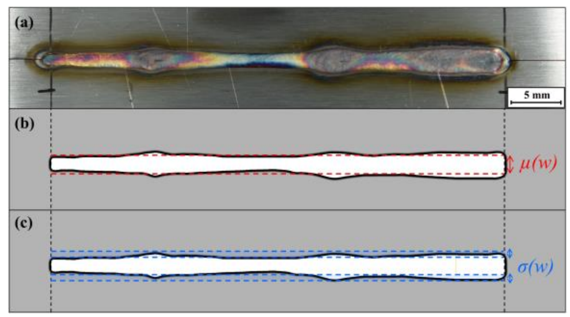

Figure 4. (a) Macro-photography of the weld bead and (b) and (c) weld profile identified via image processing algorithm and schematic representation of the average width $\mu(w)$ and standard deviation $\sigma(w)$.

Tensile testing of the laser welded samples was conducted on a universal testing machine with 100kN maximum force in accordance with the ISO 4136 standard (Alliance RT 100, MTS, Eden Praire, MN, USA). From each welded sample, 3 tensile specimens were taken with nominal width of 12 mm, 2 mm thickness and length of 160 mm. Each sample was analyzed with a strain gauge in order to obtain the stress-strain curves during the test. An average ultimate tensile stress (UTS) for each weld track was thus measured.

In order to expose the sub-surface geometry of the weld bead, the jointed samples were cut transversally to the feed direction. The cross-sections were prepared for metallographic analysis through polishing and chemical etching. The etching solution consisted in 1 ml of nitric acid 65% concentration, 1 ml of chloridic acid 37% concentration and 1 ml of water. Optical microscopy images after etching were obtained with an Ergolux 200 system (Leitz, Grand Rapids, MI, USA).

The average speed of the welding process v_{avg} was measured calculating the ratio between the effective length of the weld l_{weld} and the welding time t_{weld} as formulated in the following equation:

$$v_{avg} = \frac{l_{weld}}{t_{weld}} \quad (1)$$

l_{weld} was measured via an optical coordinate measurement machine (Quick Vision ELF, Mitutoyo, Takatsu-ku, Kawasaki, Japan) whereas t_{weld} was retrieved by means of the laser emission signal triggered by the operators which was recorded via an oscilloscope (Tektronix TDS5034B, Beaverton, OR, USA).

Results

Aesthetic properties

A first qualitative assessment of the HHLW process could be conducted by observing the welds via macro photographs (shown in Figure 5). The welds realized with the linear axis had the most aesthetically pleasing result given the consistency in terms of weld bead width. The joints performed in the hand-held configuration on the other hand show a greater variability in terms of weld width and a difference with respect to the reference value obtained with the linear axis, whilst the roller device appears to improve the aesthetics.

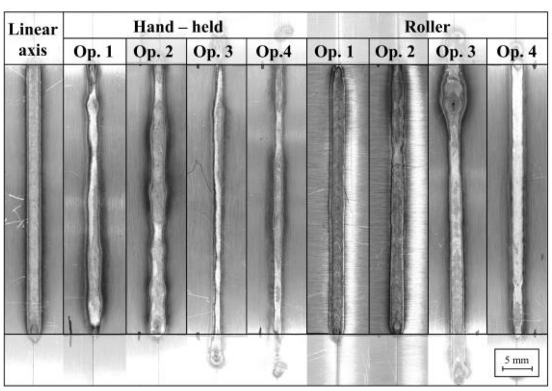

Figure 5. Representative macro photography of the welded samples for each of the configurations and operators of the experimental campaign

The image analysis algorithm allowed to extract both the average value of the width profile $\mu(w)$ and its standard deviation $\sigma(w)$ from the macro-photographs (respectively reported graphically in Figure 6 (a) and (b)). The average width values in both hand-held and roller configurations find good correspondence with the reference set by the linear axis. In terms of aesthetics of a weld it is generally preferable to maintain constant weld bead, whilst the average weld bead width might rather be correlated to the mechanical properties of the joint.

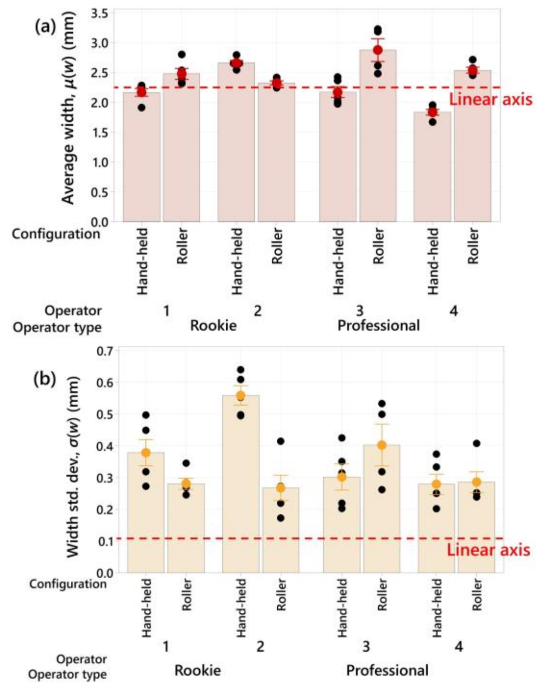

Figure 6. (a) Average value of weld bead width $\mu(w)$ and standard deviation $\sigma(w)$ in the different conditions of the experimental campaign. Error bars report the standard error.

In terms of uniformity of the weld bead, represented by the standard deviation of the width profile $\sigma(w)$, the roller appears to promote a reduction in terms of variability. On the other hand, the operator skill appears to be an influential factor since the professional welders exhibit lower values of $\sigma(w)$. The only data points which have a different trend belong to Operator n°3 in the roller configuration. This is actually consistent with the fact that operator n°3 found the roller to actually reduce the mobility of the welding torch and thus more complicated to employ the roller device.

ANOVA analysis was conducted on the weld bead width variability $\sigma(w)$. The results are reported in Table 4. In this case, the operator was found to be a significant factor in agreement with the expectation that skilled operators possess a greater dexterity with respect to non-trained operators. The data points of Figure 6 indicate that in the case of operators 1, 2 and 4 the roller was effective in reducing the width variability whereas in the case of operator 3, $\sigma(w)$ increased due to the aforementioned issues that the operator had in employing the device. This is in accordance with the results of the ANOVA analysis which indicates that the interaction between operator and configuration is significant.

Table 4. Analysis of Variance for the standard deviation of the bead width $\sigma(w)$

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Operator	3	0.0521	0.0173	3.37	0.031
Configuration	1	0.0312	0.0312	6.05	0.020
Operat*Config	3	0.1342	0.0447	8.67	0.000
Error	31	0.1599	0.00516		
Total	38	0.3815			
Model summary					
S	**R^2**	**R^2_{adj}**	**R^2_{pred}**		
0.0718	58.08%	48.62%	32.62%		

Mechanical properties

The tensile stress-strain curves of each specimen for the different combinations are reported in Figure 7. The welds performed with the linear axis appear to have a lower variability with respect to the other conditions in terms of both elongation at break and ultimate tensile stress (UTS). Observing Figure 7, it is also possible to denote that welds performed with the roller device appear to yield lower mechanical properties with respect to those performed without the aid of the roller device.

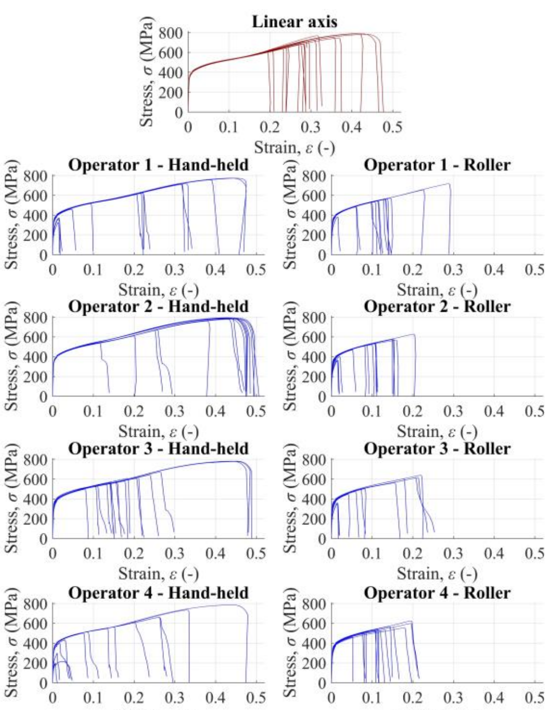

Figure 7. Stress σ against strain ε curves for the different conditions of the experimental design

Figure 8 reports graphically the values of Ultimate Tensile Stress for the different conditions thus confirming the trends depicted by the stress-strain curves. Observing the data, there appears to be a clear reduction in terms of the mechanical properties of the welds when moving from the hand-held configuration towards the roller condition.

In terms of dexterity of the welder, operator 2 appears to have provided the strongest welds. The data trends of Figure 8 indicate that the combined effect of the factors might play an important role in determining the mechanical properties of the welds. In order to establish the statistical significance of the different factors, the data was analysed by means of ANOVA (results reported in Table 5).

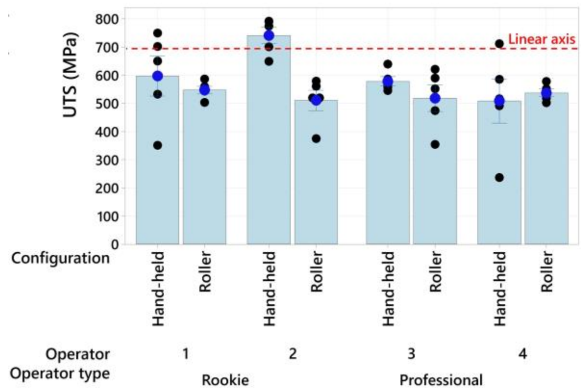

Figure 8. Ultimate tensile strength in the different conditions of the experimental campaign. Single data points in black, average value in blue. Error bars are one standard error from the mean.

Interestingly, the operator results as a non-significant factor (P-value>α) which thus indicates that no statistical difference could be asserted between the professional and rookie operators. On the other hand, the roller is responsible for lower mechanical properties in accordance with the trends visible in Figure 8.

Table 5. Analysis of Variance for the Ultimate Tensile Stress

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Operator	3	36035	12012	1.61	0.207
Configuration	1	87055	87055	11.68	0.002
Operat*Config	3	61229	20410	2.74	0.060
Error	31	231036	7453		
Total	38	419379			
Model summary					
S	**R^2**	**R^2_{adj}**	**R^2_{pred}**		
86.3294	44.91%	32.47%	12.41%		

Metallographic cross-sections

Representative cross-sections of the weld beads obtained in the different conditions tested may be viewed in Figure 9. The weld bead shapes indicate a single melt pool characterized by a deeper penetration in the centre and a wider seam at the top. The apparent linear spot achieved via the beam oscillation is expected to generate the bead shape. It can be expected that the keyhole penetration is effective in the central part of the oscillation, while the sides are closer to a conduction mode heating. Partial penetration is achieved in the majority of conditions which however is satisfactory for aesthetic or sealing applications of manufacts produced with this material.

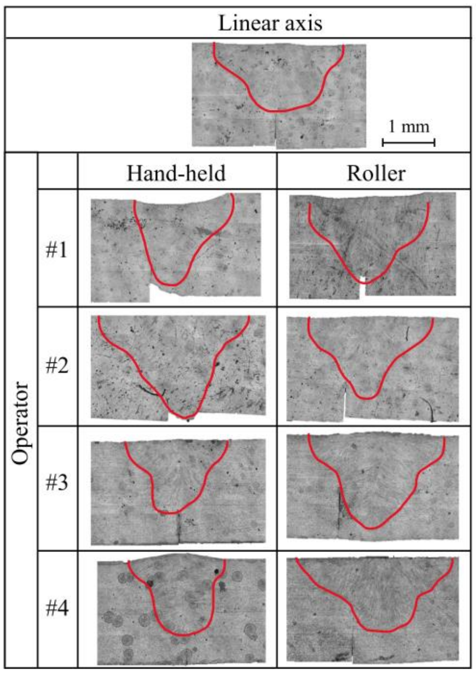

Figure 9. Representative metallographic cross-sections of the weld bead obtained in the reference conditions with the linear axis and in the different conditions of the experimental campaign

The cross-sections show that there is a high variability in the hand-held operations with respect to the linear axis. The variability in the cross-sectional geometry is clearly correlated to the $\sigma(w)$ parameter analysed previously. As a matter of fact, the reduced variability in terms of weld bead width could be correlated to a lower scatter in terms of mechanical properties between replicates (as in the case of the linear axis and mechanical roller device). Furthermore, the metallographic cross-sections provide a possible insight regarding the motivation behind the lower mechanical properties obtainable with the mechanical roller device. The centerline of the weld bead in the case of the roller conditions is slightly decentered with respect to the contact line between the two metal sheets. This implies an effectively smaller resistant cross-section due to the v-shaped geometry of the weld beads. This effect might be induced by the lower manipulability of the welding torch when the roller device is employed and leads to misalignments which are more difficult to correct.

Welding speed

The average welding speeds achieved in the different configurations are reported in Figure 10.

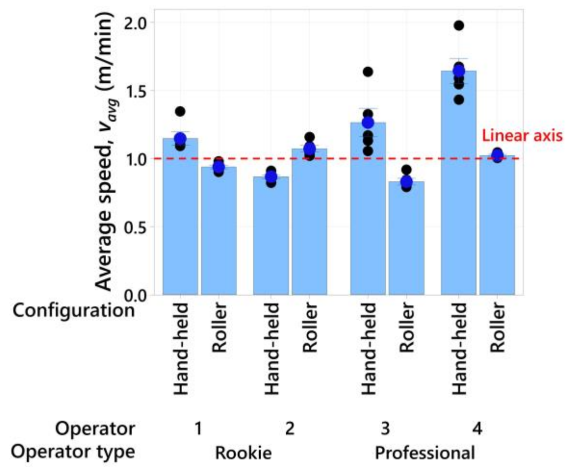

Figure 10. Average welding speed in the different conditions. Error bars report the standard error.

Interestingly enough, the rookie operators were more consistent with respect to the target velocity of the linear axis. On the other hand, the professional welders, when employing the system in hand-held configuration, performed at higher average velocities. Unfortunately, an instantaneous measurement of the velocity could not be obtained with the hardware currently available but it may certainly provide an interesting insight also in relation to the mechanical and aesthetic properties of the welds. The roller device enabled a smaller dispersion in terms of the average welding speed and consistently a smaller error with respect to the target velocity. This effect may be beneficial over the mechanical properties in terms of variability in between welds. As a matter of fact, in terms of Ultimate Tensile Stress, a smaller variation could be observed when the roller device was employed. Still, this aspect requires further attention in future investigations.

Discussion

The results presented in the current work show that operators have a non-significant effect over the mechanical properties of hand-held laser welds. On the other hand, in terms of the aesthetics of the welds (represented by the $\sigma(w)$ parameter), operator experience remains a significant parameter and the roller device developed can aid in reducing the variability. Still, the linear axis outperforms the hand-held laser welding equipment both in terms of aesthetic and mechanical properties.

From the perspective of moving towards enhanced cyber-physical systems reducing the operator influence over the process, the introduction of the mechanical device promoted beneficial effects in terms of aesthetics. Accordingly, the possibility of introducing further device sensorization is also envisaged by the authors of the present work. For instance, the introduction of an accelerometer and gyroscope may provide absolute inclination information of the welding torch. However, issues related to the encumbrance of the roller device reduce its effectiveness and may even be correlated to the reduction in terms of mechanical properties due to misalignment issues. Still, depending on the final application of the technology such reduction in terms of mechanical properties may be considered to be acceptable.

The information retrieved through the present research are of great importance from a technological perspective since they can aid end-users perform the appropriate choice of laser welding equipment in accordance with their production requirements. The fact that operator skill is non-significant in determining the ultimate tensile stress of the joints implies that the technology may potentially beneficial to overcome the shortage of skilled workers announced by the America Welding Society[16]. On the other hand, it must be taken into account that a HHLW system is a class 4 laser equipment thus appropriate operator training must still be provided alongside with an appropriate working environment. Moreover, it is important to consider that the current results were obtained on a specific material and joint configuration. Further work is required in order to determine if such conclusions may be generalized.

Conclusions

The present work explored the influence of operators during the hand-held laser welding process and the possibility of introducing a mechanical roller as a support to the welding operations. The main conclusions of the work may be summarized as follows:

- Motorized actuators are capable of performing joints with greater mechanical properties and reduced variability in terms of weld bead width with respect to HHLW systems.

- Operator training and experience does do not have a significant influence over the mechanical properties of the joints. On the other hand, skilled workers are capable of obtaining welds with lower weld bead width variability

- The mechanical roller device developed in the present work allowed an improvement in the aesthetics of the welds although a reduction in the mechanical properties of the joints was also recorded. A smaller variability in terms of weld speed was also promoted by the roller device which may also be a proxy of a reduction of the variability in terms of mechanical properties of the joints.

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References

[1] G. Nath, Hand-held laser welding of metals using fibre optics, Opt. Laser Technol. 6 (1974) 233–235.
[2] T. Puester, O. Berend, M. Drygalla, O. Meier, A. Ostendorf, M. Brose, Safety requirements for hand-held laser processing devices — Current status of ISO 11553-2, in: ILSC 2005 Conf. Proc., 2005: pp. 260–268.
[3] J.A. Dixon, Current laser applications in general surgery, Ann. Surg. 207 (1988) 355–372.
[4] J.A.S. Carruth, Lasers in medicine and surgery, J. Med. Eng. Technol. 8 (1984) 161–167.
[5] IPG Photonics hand-held laser welding system, (n.d.). https://lasersystems.ipgphotonics.com/products/Handheld-Systems/Handheld-Laser-Welding-and-Cleaning-System#nav-103-capabilities (accessed June 8, 2022).
[6] V. Schultz, T. Seefeld, F. Vollertsen, Gap bridging ability in laser beam welding of thin

aluminum sheets, Phys. Procedia. 56 (2014) 545–553.
[7] D.M. Boldrin, M. Colopi, S. D'Arcangelo, L. Caprio, A. Gökhan, B. Previtali, High speed videography of gap bridging with beam oscillation and wire feeding during the laser welding of stainless steel and aluminum alloys, in: Lasers Manuf. Conf. 2021, 2021.
[8] L. Wang, M. Gao, C. Zhang, X. Zeng, Effect of beam oscillating pattern on weld characterization of laser welding of AA6061-T6 aluminum alloy, Mater. Des. 108 (2016) 707–717.
[9] C. Hagenlocher, M. Sommer, F. Fetzer, R. Weber, T. Graf, Optimization of the solidification conditions by means of beam oscillation during laser beam welding of aluminum, Mater. Des. 160 (2018) 1178–1185.
[10] Y. Xin, Y. Huang, S. Gao, S. Li, S. Han, Development and Application of Hand-held Laser Welding System Development and Application of Hand-held Laser Welding System, J. Phys. Conf. Ser. 1650 (2020) 022087.
[11] T. Puester, O. Meier, A. Ostendorf, H. Beier, D. Wenzel, Qualification of personal protective equipment for the use of hand-held laser processing devices, Int. Laser Saf. Conf. World's Lead. Conf. Laser Safety, ILSC 2007. 91 (2007) 91–100.
[12] T. Puester, J. Walter, M. Hustedt, V. Wesling, Technical safety measures for the safe use of hand-held laser processing devices, J. Laser Appl. 24 (2012) 052004.
[13] S. Kou, Welding metallurgy, 2003.
[14] A. Rout, B.B.V.L. Deepak, B.B. Biswal, Advances in weld seam tracking techniques for robotic welding: A review, Robot. Comput. Integr. Manuf. 56 (2019) 12–37.
[15] T. Lei, Y. Rong, H. Wang, Y. Huang, M. Li, A review of vision-aided robotic welding, Comput. Ind. 123 (2020) 103326.
[16] AWS workforce data, (n.d.). https://weldingworkforcedata.com/ (accessed June 8, 2022).
[17] W. Ji, Y. Li, S.M. AbouRizk, Integrated data-driven approach for analyzing pipe welding operator-quality performance, Autom. Constr. 106 (2019) 102814.
[18] F. Sikström, Operator bias in the estimation of arc efficiency in gas tungsten arc welding, Soldag. e Insp. 20 (2015) 128–133.
[19] E. Capello, B. Previtali, The influence of operator skills , process parameters and materials on clad shape in repair using laser cladding by wire, 174 (2006) 223–232.
[20] C. Bertrand, Y. Le Petitcorps, L. Albingre, V. Dupuis, Optimization of operator and physical parameters for laser welding of dental materials, Br. Dent. J. 196 (2004) 413–418.

Meet the authors

Leonardo Caprio is assistant professor at the Department of Mechanical Engineering of the Politecnico di Milano. His research activities focus on the development of laser-based processes for the e-Mobility sector and Industry 4.0. His research activity has been awarded with a 2nd place at the "Student Paper Award" at ICALEO 2017 and 1st place at ICALEO 2020 and the prize Edoardo Capello "Giovane Ricercatore" at the XV AITeM conference in 2022.

Giulio Borzoni was born in 1997 in Italy and graduated in 2022 with a MSc in Mechanical Engineering with specialization in Production Systems from the Politecnico di Milano. The master thesis was focused on hand-held laser welding process. Currently he is investigating the role of spatial and temporal beam shaping in laser welding at the Sitec —Laboratory for Laser Applications of the Department of Mechanical Engineering of the Politecnico di Milano.

Barbara Previtali in 2016 was appointed as Full Professor in the Mechanical Engineering Department, Politecnico di Milano. She leads the Sitec — Laboratory for Laser Applications and PromozioneL@ser with AITeM, which collects Italian laser users in industry and academia. Her current research interests include modeling, optimization and control of laser processes in their application in various fields. On these research subjects, she has authored or coauthored over 100 papers in refereed international journals and international conferences and two international patents

Ali Gökhan Demir completed his PhD in Mechanical Engineering at the Politecnico di Milano in collaboration with the University of Cambridge in 2014. He has been an Associate Professor with the Department of Mechanical Engineering, Politecnico di Milano, since 2021. He leads LaserEMobility section of AITeM dedicated to the development of laser processes for eV manufacturing. His research interests include laser-based manufacturing processes with an emphasis to the light-material interaction mechanism in temporal, spatial and wavelength domains.