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Laser beam welding: research state of the art on performance and measures*

by

Sudhin Chandran, R. Rajesh and M. Devanand**

Department of Mechanical Engineering,
Noorul Islam Centre for Higher Education, Kumaracoil, Tamilnadu, India
**corresponding author: udhinchandran@gmail.com

Abstract: Laser beam welding (LBW) is a remarkable method for combining dissimilar materials, primarily when the unique amalgamation of metals is necessary. LBW, owing to attractive features, namely: low heat input, high heat concentration, high power density and low distortion is one of the more advantageous methods for, e.g., welding and repair of aircraft and turbine engine elements, constructed from superalloy. In this paper, the literature is scrutinized on diverse techniques that are associated with laser welding systems. The review is provided of several dozen research articles, involving an appropriate analysis. Initially, the analysis depicts various schemes that are contributed in different articles. Subsequently, the analysis also focuses on various particular features such as laser beam width and type of laser, and it also considers the heat treatment analysis that is contained in each of the articles reviewed. Furthermore, the present paper provides a detailed study regarding the performance measures and maximum performance achievements regarding each contribution accounted for. Finally, it indicates the various research issues, which can be useful for the researchers to carry out further research on laser welding systems. Of particular interest to the Readers of this journal is the fact of ample application of modelling, identification, data processing, image processing and AI tools in the respective surveyed studies.

Keywords: laser welding; beam width; heat treatment; performance measures; maximum performance

1. Introduction

Modern industries, namely such as automotive, aeronautics, and power production require products with high performance, incorporating an enlarged count of functions and features, involving, in particular, recyclability and lightweight, while warranting effectiveness and flexibility (Lee et al., 2015; Dhivyasri et al.,

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2018; Dutra et al., 2014). As particular materials do not satisfy these requirements by themselves, it can be expected that an amalgamation of more materials might stand to the respective challenges. Joining methods are mainly deployed in fabricating customary and novel products (Prasad et al., 2018; Pelsmaeker et al., 2018; Hao et al., 2018). Laser beam welding (LBW) is very trendy in the industrialized manufacturing processes. Both solid state and fusion welding is exploited for numerous products and materials (Fadaeifard et al., 2016; Wang, 2014, 2017). Among various approaches, the use of laser achieved an important position as an autogenously blending source for joining metals (Zhang et al., 2018; Jiao et al., 2018; Liu et al., 2017; Kumaran and Das, 2018).

LBW (Kovacs, 2018; Oliveira et al., 2018) represents an appropriate approach, since it is essential to weld portions with very little width by HCLW (see notation table in the next section) with movement of laser beam (Casalino et al., 2017). In addition, it is a smart method for joining disparate materials, especially if unique amalgamation of metals is needed. While the laser performs in the key-hole form involving increased energy, such increased energy melts the crack and the neighboring substance (Lei et al., 2018; Soltani and Tayebi, 2018). In distinction to the erstwhile fusion methods, fiber LBW can be regarded as an enviable technology, owing to its high process speed and high energy input (Ai et al., 2018). Furthermore, it was established that the amalgamation with high energy density and high welding speed could limit the development of the IMC zone (Carvalho et al., 2018; Pourali et al., 2017; Mubiyai and Akinlabi, 2017).

In addition, LBW is exploited in production conditions for welding the dissimilar steels and dissimilar metals, with thickness related features, offered by KHLW and transmission or pulsed modes of laser welding. A technique to weld dissimilar metals (Evdokimov et al., 2018) was to adapt the laser beam to a metal, characterized by the lowest thermal conductivity. Anyhow, the thermal conductivity of dissimilar steels (Pouranvari and Abbasi, 2018; Xia and Jin, 2018; Lee and Chang, 2012) cannot vary so considerably as this can occur with the thermal conductivity of aluminium and titanium or copper and steel (Dinda et al., 2016; Di et al., 2017; Hekmatjou and Naffakh-Moosavy, 2018).

The present survey paper contains a review, regarding the diverse techniques that are associated with laser welding systems. A number of relevant research papers is considered and their content is analysed. Initially, the analysis portrays various schemes that are proposed and/or characterised in different papers. The analysis also concerns various concrete features such as laser beam width and type of laser, and provides also a perspective on the heat treatment in the framework of the approaches exploited in the particular papers. The structure of the paper is the following one. Section 2 describes the related works and the research carried out under the topic here considered. Section 3 contains the analysis related to laser types, heat treatment and performance measures for laser beam welding. Then, Section 4 reveals the research gaps and Section 5 concludes the paper.

Notation used in the paper

Acronyms	**Descriptions**
AEF	Additional electric field
Ar	Argon
CCD	Charge-coupled device
CDMS	Capacitance displacement measurement system
CLAM	China low activation martensite
CR	Cold rolled
CW	Continuous-wave
EBSD	Electron back-scattered diffraction
EBW	Electron beam welding
FEM	Finite-element method
FP	False positive
FPR	False positives rate
GB	Grain boundary
GMAW	Gas metal arc welding
HAZ	Heat affected zone
HCLW	Heat conduction laser welding
He	Helium
HSA	Homogenizing+solutionizing+aging
KF	Kalman filtering
KHLW	Keyhole laser welding
LBW	Laser beam welding
LHT	Laser heat treatment
LIBS	Laser-induced breakdown spectroscopy
LSP	Laser shock peening

Notation table ctd.

Acronyms	**Descriptions**
LTE	Local thermodynamic equilibrium
MZ	Mushy zone
NTS	Notched tensile strength
NZ	Nugget zone
PCA	Principal component analysis
PHT	Pre-heat treatment
PMZ	Partially melted zone
PWHT	Post welding heat treatments
RAFM	Reduced-activation ferritic-martensitic
RBFNN	Radial basis function neural network
SDSS	Super duplex stainless steel
SEM	Scanning electron microscope
SISO	Single-input-single-output
SLM	Selective laser welding
SVM	Support vector machine
TIG	Tungsten inert gas
TMAZ	Thermo-mechanically affected zone
TO	Transistor outline
TP	True positive
UTS	Ultimate tensile strength
WM	Weld metal
XRD	X-ray powder diffraction
Yb	Ytterbium

2. Literature review

2.1. Related work

In 2018, Leo, D'Ostuni and Casalino (2018) suggested a model that portrays the consequences of the PWHT carried out at 450 °C and 350 °C on different laser welds. The tensile and microstructure features of the suggested scheme at minimum temperature were also examined and, along with it, the tensile and hardness characteristics of the welds were also calculated and investigated. Casalino et al. (2017) generated different Ti6Al4V and AA6000 butt joints by moving a Yb LBW on the higher surface of the Ti sheet. In this study, groove research was performed, and dissimilar seam shapes and working circumstances were measured with respect to the mechanical and metallurgical performances.

Li et al. (2018) manufactured CLAM steel that was then analysed under diverse PWHT to accomplish a superior amalgamation of toughness and strength. Finally, the mechanical and microstructure characteristics of the joints were examined and confirmed. Oláh, Croitoru and Tierean (2018) adopted a technique, which attains an overall raise with thirty-four to ninety percent in the average resistance and hardness of the coatings, owing to the configuration of martensite. Moreover, LHT offered improved compatibility that has been verfied on the basis of simulation results.

Kuryntsev (2018) examined the impact of PHT of SLM on steel regarding CR steel. The results of mechanical tests and studies of generated welds were presented, and these results demonstrate that the PHT of SLM workpieces has an effect on the strength of welded joints. Rezaei and Naffakh-Moosavy (2018) implemented a technique, which intends to assess the achievements attained from the PHT on superalloy weldments. In addition, the outcomes of mathematical computations demonstrated that the thickness of diverse welding areas together with MZ, HAZ and PMZ have been considerably diminished. Jia et al. (2018) analyzed the impact of the PHT and LSP on the properties and microstructures of EBWed joints. In addition, the features of micro-hardness, microstructures, fracture morphology and tensile properties of samples were examined and the results have shown that the adopted scheme offers better outcomes when compared with the conventional schemes.

Liu et al. (2018) suggested a method, according to which EBW was exploited to connect RAFM steel to 316L steel. Moreover, mechanical and microstructure dissimilarity in the WM and HAZ throughout the PWHT was examined. Finally, the results obtained implied that the rigidity attained due to the adopted method decreased with the rise in temperature of PWHT. Li, Wang and Huang (2018) have been identifying the heat distribution and heat transfer capabilities during welding. In this study, simulations were carried out, and the obtained results demonstrated that the proposed scheme ensures better features when compared to other works. Zhang et al. (2018) presented a technique, which analyses the impacts of major welding constraints on certain tensile properties of the steel. In consequence of heat treatment, the entire joints demonstrate decreased ductility owing to the clear grain coarsening in the TMAZ and NZ.

Ahn et al. (2018) suggested a new technique to weld crack 2024 Al alloy by deploying fiber LBW. When superior welds were generated, micro-cracks that were minimum were noticed in welding substance as the constraints had a restricted impact on the susceptible composition. Saravanan, Raghukandan and Sivagurumanikandan (2017) discovered the welding ability of SDSS, by means of a pulsed Nd: YAG laser. The procedure was carried out by changing the speeds of welding and maintaining the erstwhile constraints unmoved, in order to vary the input of heat.

Forouzan, Vuorinen and Mücklich (2017) adopted a scheme for simulating the impact of various Q&P constraints subsequent to welding in the most significant region of HAZ. The diverse methods, including XRD, EBSD, and SEM were exploited to investigate the microelements of the structure and their properties along with toughness and tensile tests. Windmann et al. (2017) implemented a technique, by which the strength of HAZ was reduced to a great extent, on the basis of heat given at input. Accordingly, the least strength constantly is applied in the region with the maximum heat input that was found adjacent to the welding zone. Zhang et al. (2017) analyzed the microhardness and microstructure of laser fabricated alloys following PHT. In addition to that, the microstructure and temperature and mechanical characteristics of laser were also examined and compared with other conventional approaches.

Kumar, Mukherjee and Bandyopadhyay (2017) implemented a technique, where the intention of the novelty was twofold. First, the work intended to determine the consequences of the tensile characteristic of the welded joints. Subsequently, laser power, incident angle, tensile strength, and welding speed were examined by introducing a model in the form of a polynomial equation. The results of this study were confirmed by three experiments. Yu et al. (2016) studied the mechanical and microstructure characteristics of laser weld before and after PWHT was applied. The outcomes demonstrated that the tensile potency of the joints could be raised by 90 MPa. Thus, it was shown that the adopted scheme was able to improve (strengthen) the tensile characteristics of the joints. Li et al. (2016) considered the toughness and strength performance of T-250 steel, which was done by LBW with involvement of dissimilar techniques of three PWHT, i.e. A, SA and HSA. The results showed that a better mechanical power was attained, demonstrating the superiority of the adopted scheme.

Hsieh et al. (2016) implemented a technique, by which the NTS and microstructures of the different welds were examined in the as-welded and PWHT circumstances, and the outcomes were compared with Ti laser welds for the similar PWHT. Fadaeifard et al. (2016) presented a technique, by which the nanomechanical, mechanical and microstructure characteristics of the joint were assessed in PWHT by means of tensile tests. The final results obtained point out that PWHT offers better features in terms of mechanical characteristics of base metal. Kubiak et al. (2016) focussed on the numerical and arithmetically supported design of temperature throughout the hybrid welding course by means of electric arc and Yb: YAG laser in GMAW technique. The ultimate examination was carried out by considering the movement of liquid steel in the blending zone.

Keskitalo et al. (2015) considered the accumulation of an Ar gas shield for the improvements in tough, formable welds. PWHT and microscopic examination have led to recommendation that the reduced welding ductility generated in the absence of a gas shield would result in the existence of oxides in the welding metal. Neto et al. (2015) introduced a technique, which exploits LBW as an alternative welding process that was considered as a substitute to the conventional TIG welding. The hardness and tensile analyses were carried out, and the superiority of the adopted scheme was demonstrated. Ma et al. (2015) assessed the mechanical development and characteristics of Ni-dependent weld joint, analyzing the microhardness, microstructure characteristics, tensile features, and phase structure. Their results point out that, in the blending zone, three divisions are formed depending on the grain patterns.

Sheikhi, Ghaini and Assadi (2015) aimed at identification of the correlations observed in the welding process, and hence to formulate a principle for solidification cracking. Depending on the correlation measure and the corresponding interpretations of the results obtained, it was established that the adopted scheme offers better effects than the ones it was compared to. Köse and Kaçar (2014) implemented a technique, in which the welding ability of AISI 420 steel by CO2 laser beam welding scheme was examined. In addition, the impacts of PWHT on mechanical characteristics and microstructure properties were also investigated. Finally, it was established that PWHT satisfactorily enhanced the mechanical features of the welds. Kermanidis et al. (2014) introduced a methodology, by which the influence of corrosion on the fatigue behavior of 6156 AA LBW along with other various PWHT T8, was evaluated. The results obtained were compared to those resulting from other, conventional approaches.

Hsieh et al. (2014) suggested a new technique, in which the various attempts at welding welding of the Ti-6-4 to Ti-6-6-2 alloys were carried out with the CO_2 laser. In addition, the impact of PWHT on the NTS of the various welds was calculated, and the effects were assessed to feature better hardness. Yan et al. (2014) considered the impact of heat treatment on the mechanical reaction in LBW joints. In the framework of this study, the incidence of liquated GB was found to deteriorate the binding among the grains, which means that the HAZ would turn out to be the weakest region in the joint. Bendaoud et al. (2014) provided the mathematical analysis and models of a hybrid laser MIG welding. Accordingly, mathematical exploratory models were exploited to identify the heat constraints, so as to attain a possibly negligible disparity among the mathematical outcomes in diverse locations.

Serizawa et al. (2014) examined a a technique, involving butt-joint between the minimized activation ferrite steel and austenitic steel and, accordingly, the influence exerted by the position of LBW on its tensile characteristics after and before PWHT was investigated at room temperature. The ultimate results implied offering enhanced tensile strength by the proposed technique. Lü et al. (2018) developed the method for tracing the precision and speed of the weld seam. Obtaining of the weld image is a multifaceted process, and as a result, it is easily interrupted by noise. Therefore, precise techniques have to be exploited to process the images. In addition, the results of the proposed procedure were assessed and the assessment revealed the accurateness of feature extraction. Wang (2017) implemented a detection scheme based on the intensity allocation, realized with the use of the arc light in the confined image. Depending on this scheme, a proficient and robust model was implemented. Finally, the results obtained in this study confirmed that the implemented scheme was considerably better than the conventional models with respect to detection accuracy.

Schulte-Huxel, Kajari-Schröder and Brendel (2015) noted two different processes, based on the width of the irradiated layer. On considering Al layers, a melt-through of Al-layer was also noticed, and the simulation results suggested a better performance of the adopted model. Ernst et al. (2015) adopted the LBW procedure for the automatic association of a thin Si film with a detached stabilizing frame. In the framework of this study, the stresses were analyzed and accordingly, from the experimental results, the enhancement, resulting from the adopted scheme has been verified. You, Gao and Katayama (2015a) proposed a novel technique to carry out monitoring of laser welding process and welded fault diagnosis. The results, obtained from this investigation demonstrated that the feature vector, influencing the classification accurateness, can be established by means of PCA.

Further, You, Gao and Katayama (2015b) established a system, consisting of two visual sensors and two photodiode sensors for multi-signal mining. In this study, five welding characteristics were acquired and analyzed by an approach based on image processing and signal processing. Yet in 2014, You, Gao and Katayama (2014) had introduced a scheme meant to optimize the efficiency of industrial development regarding the welding process, a multi-sensing implement, supported by the use of SVM, was applied in the analysis, aiming at scrutinizing and recognizing weld faults. Resulting from the analysis, it was established that the developed SVM-based scheme was proficient in examining the faults occurring in the laser welding course of action. Also in 2014, Fang et al. (2014) suggested a prequalification of welding that includes consideration of the particulars such as the welding model, its requirements, and the results of the critical tests. It could be concluded from the obtained results that the welding deformation and quality were very close to the modeling requirements, which might be supportive for the improvements in the future.

Gao et al. (2013) introduced a scheme for seam tracking throughout high-power LBW. Accordingly, in the adopted scheme, KF was enhanced by the application of RBFNN. On evaluation in comparison with the conventional KF scheme, the real welding experiments reveal that the KF enhanced by the use of RBFNN was more effective in terms of tracking precision and reduction of interruptions caused by colored noise. Chen, Li and Liu (2012) established a method, which mainly focuses on the interactions, involving laser arc plasma in consideration of the consequences of application of an electric field. In the effect of the analysis, the AEF was found to raise the penetrability of laser welding.

Gao, You and Katayama (2012) proposed seam tracking observation throughout fiber laser welding. In this study, the results of the welding experiments have established the efficiency of the introduced technique in terms of improvement of accurateness of weld recognition. Na et al. (2010) suggested a nonlinear SISO approach, which was implemented and verified for the diode laser welding process by means of the appropriate study data. Moreover, the results obtained demonstrated that the proposed method was proficient in predicting the weld pool's surface width. Song et al. (2009) implemented a group of strategies for the convenient modeling of lensed fiber for the pairing of lasers. The respective model was estimated experimentally, and the coupling effectiveness was found to be in 28%-72% free of horizontal misalignment damages.

Jager and Hamprecht (2009) established a method, meant to effectively make use of the features from face detection and to exploit appearance-dependent characteristics to identify the pertinent features of the traced images. The results, obtained from this study, revealed that the classification scheme, based on appearance features could perform better than the one based on geometric features. Jager, Humbert and Hamprecht (2008) adopted a classification technique to analyze the welding process series that were recorded mechanically for establishing the error measures. The results obtained demonstrated that the fabric particles can be tracked precisely. On a test data set, the novel scheme discovers all flawed welds with a little FPR and performs better than the formerly developed techniques. Fuerschbach (2008) proposed a scheme to improve the accuracy and to reduce the operational complication of the respective processes. In this work, logical equations were proposed, which serve for calculating the magnitude of the PWS, and also provide guidance for the optimal modeling of geometries and desired welding conditions.

Wang (2014) introduced a scheme, intended to deduce the P-GMAW weld pool geometry. The adopted scheme consists in precisely segmenting and recognizing the laser lines that are represented, and also image processing schemes were implemented to accomplish this definite task. The results of these investigations established the efficiency of the introduced scheme. Chen, Li and Liu (2014) analyzed the coupling discharge process among laser keyhole and arc plasma. Here, the adopted process proved to provide an outstanding connector between workpiece and arc plasma, resulting in an electron flow concentration. Wang et al. (2009) suggested a technique that analyzes the mechanical characteristics of the welded joints, and is meant to improve the quality of the welds. Bending experiments were carried out to compute the bending ductility of laser welded joints. Simulation was performed, due to whose results the fractural behavior of the adopted scheme has been verified. Hao and Liu (2009) established a method, by which the laser pulse on arc plasma was examined by analyzing the arc voltage, plasma shapes, and plasma spectra. The interdependences obtained allowed for raising the output power of arc plasma, and therefore the welding dispersion was improved. Liu and Jiang (2011) suggested a technique, by which the consequence of applying adhesive on arc behavior was analyzed throughout the laser-TIG hybrid welding process. For comparison, the laser-TIG hybrid welding without consideration of adhesiveness was performed under similar situations. The final results demonstrated that the adopted methodology offered improved features, involving a rigorous jet of metal vapour.

Liu and Hao (2010) established a method, in which the weld joints and Mg alloy were welded by exploiting low-power LBW method. Within the framework of this study, the triggering and controlling of TIG arc and pulsed laser were modeled so as to ensure the superiority of welding in pulsed laser welding process. Tan et al. (2008) aimed at representing the behavior of laser-welded joint between Kovar base metal and Ni200 weld clip in conditions of different mechanical loadings. The fatigue proportions, obtained in this study, demonstrate that the adopted scheme has reduced the probability that fatigue breakdown would ever happen for joints created by exploiting such sorts of weldings. Hsu et al. (2006) suggested a coupled thermal-elasto-plasticity design of a FEM testing to estimate the PWS and the TO-Can module. The results obtained provide the evidence for the improved properties of the proposed scheme.

Tseng and Sung (2005) introduced a scheme, in which a reflector positioned close to the fiber during laser welding was exploited to find out the shift along the Y-axis. The fiber images, obtained by means of the CCD camera, could be deformed every now and then, and hence digital image processing was exploited to rectify the images that were deformed. Anabitarte et al. (2012) established a sensor system dependent on a LIBS -provided characteristic to identify and differentiate aluminum remains in the welding region, without the need of damaging the sample prior to the welding process. In this work, a spectral model, based on SVM was exploited as a classifier, meant to recognize respective areas automatically, featuring the existence of aluminum. In 2010, Liu et al. (2010) have introduced a quantitative PWS improvement by deploying a CDMS in butterfly-type package. On performing an accurate evaluation of the PWS deploying CDMS, it was now feasible to manufacture better module packages by the adopted scheme.

Liu et al. (2008) suggested and analyzed electron density and electron temperature of local arc plasma, which were obtained, correspondingly, from the Stark broadening mechanism and the Boltzmann plot method. In this context, the LTE and its characteristics were also provided by the adopted method. Hao and Song (2009) established a scheme, in which the characteristics of interactions of hybrid laser with the Mg alloy were obtained, and the differentiation between them were examined. The results obtained in the study are described, demonstrating the superiority of the presented technique. Reisgen et al. (2010) suggested a scheme, which is based on the consideration of impacts from the types of shielding gas and flow rates on LBW. The gases, considered in the context of shielding involve Ar, He, and various mixtures of Ar and He. The results obtained showed the improvement of performance due to the proposed scheme.

Pekkarinen and Kujanpää (2010) developed and presented a method that consists in finding out the microstructural variations occurring in duplex and ferritic stainless steels, while input heat is regulated by welding conditions. In this study, variations in weld characteristics were identified and analyzed by means of optical techniques. Grünenwald et al. (2010) considered laser welding of steel substances for the manufacturing of pipes. In the course of investigations, X70 and X65 steel plates, having thicknesses of 14 mm and 9.5 mm, were welded with the highest laser power of 8 kW. The procedure adopted was found to offer better results when compared with other approaches considered. Kurosaki and Satoh (2010) introduced a scheme that operates a novel fiber LBW technique for manufacturing plastics, aided by a solid heat sink translucent to the laser beam for avoiding any thermal break on the surface. According to this scheme, production of harmful gas, owing to plastic decomposition, was prevented. Kägeler and Schmidt (2010) suggested a method, by which the welding procedure in zinc-coated steel sheets was implemented. The performance and geometry of capillary and weld pool were evaluated from the attained camera images, and the outcomes have shown better improvements in frequency and time domain.

2.2. Chronological review

A rough chronological statistic of the surveyed works is given by the histogram of Fig.1. It should be stated, at the outset, that studies published before 2005 have not been taken into consideration in the framework of this review, since the aim was to assess the state of the art rather than the historical developments.

Against the background of Fig. 1 let us note the actual numbers of studies surveyed. And thus, for the period from 2005 to 2010 nineteen contributions have been included, while for the subsequent period of 2011 to 2015 – as many as twenty-three contributions. Then, for the years 2016 and 2017 thirteen contributions have been accounted for, and, finally, the papers that have been published in the years 2018 constitute eleven contributions accounted for here.

Altogether, then, we see a per annum increase from 3.33 in the years 2005-2010, to 4.6 in the years 2011-2015, then to 6.5 in the years 2016-2017, and, finally, 11 in the year 2018. Although this is, of course, the effect of the choice made by us, it reflects, at the same time, the increase in interest in the subject matter taken up here.

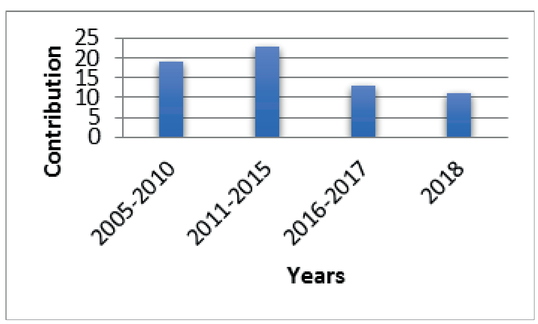

Figure 1: Chronological shares of contributions surveyed

3. Laser types, heat treatment and performance measures for laser beam welding statistics

3.1. Width of the laser beam welding analysed

The statistics, concerning the various widths of the laser beam welding that are considered in the papers surveyed are given by Fig. 2. Concerning the width of the welding laser beam, the widths from 8 mm to 50 mm were considered in forty-nine papers, then, the widths of the welding laser beam ranging from

50 mm to 100 mm were taken into consideration in six papers, and finally, the widths of the welding laser beam ranging from 100 mm to 200 mm were accounted for in three papers.

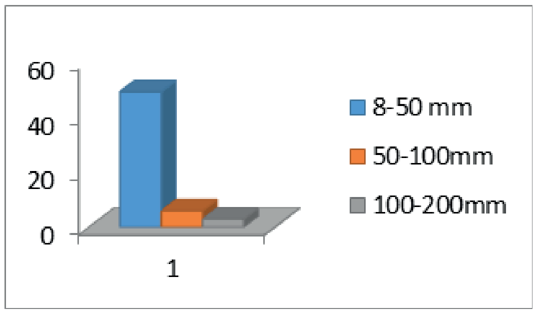

Figure 2: The widths of the welding laser beam welding on material in the adopted schemes surveyed

This highly biased distribution of publications suggests not only the actual distribution of the technologies used, but also, supposedly, the assumed usefulness of the procedures.

3.2. Performance analysis

The performance analysis, carried out in the studies surveyed, is summarised in the ample Table 1. It can be read, in particular, from this table, that UTS has been adopted by Leo, D'Ostuni and Casalino (2018), Li et al. (2018), Kumar, Mukherjee and Bandyopadhyay (2017), Yu et al. (2016), Li et al. (2016), Fadaeifard et al. (2016), Ma et al. (2015), and Köse and Kaçar (2014), i.e. by 12.3% of the entire set of contributions considered.

Then, concerning welding speed, this aspect was taken up in Rezaei and Naffakh-Moosavy (2018), Jia et al. (2018), Liu et al. (2018), Li, Wang and Huang (2018), Zhang et al. (2018), Ahn et al. (2018), Saravanan, Raghukandan and Sivagurumanikandan (2017), Windmann et al. (2017), Zhang et al. (2017), Kumar, Mukherjee and Bandyopadhyay (2017), Li et al. (2016), Hsieh et al. (2016), Fadaeifard et al. (2016), Keskitalo et al. (2015), Neto et al. (2015), Sheiki, Ghaini and Assadi (2015), Hsieh et al. (2014), Bendaoud et al. (2014), Serizawa et al. (2014), Lü et al. (2018), Wang (2017), You, Gao and Katayama (2012, 2015b), Fang et al. (2014), Gao et al. (2013), Chen, Li and Liu (2012, 2014), Na et al. (2010), Wang et al. (2009), Hao and Liu (2009), Liu and Jiang (2011), Liu and Hao (2010), Hao and Song (2009), Reisgen et al. (2010), Pekkarinen and Kujanpää (2010), and Grünenwald et al. (2010), meaning 56.9% of all of the contributions here accounted for.

Further, power was considered in the studies by Kuryntsev (2018), Rezaei and Naffakh-Moosavy (2018), Ahn et al. (2018), Saravanan, Raghukandan and Sivagurumanikandan (2017), Forouzan, Vuorinen and Mücklich (2017), Zhang et al. (2017), Hsieh et al. (2016), Kubiak et al. (2016), Keskitalo et al. (2015), Neto et al. (2015), Sheikhi, Ghaini and Assadi (2015), Hsieh et al. (2014), Yan et al. (2014), Bendaoud et al. (2014), Serizawa et al. (2014), Lü et al. (2018), You, Gao and Katayama (2014, 2015a,b), Fang et al. (2014), Gao et al. (2013), Wang et al. (2009), Hao and Liu (2009), Liu and Jiang (2011), Liu and Hao (2010), Hao and Song (2009), Reisgen et al. (2010), Pekkarinen and Kujanpää (2010), and Grünenwald et al. (2010). This, in more detailed distinction, amounts to the measurement of temperature being accounted in 32.3% of the contributions surveyed, and the welding energy being measured and analyzed in 13.84% of the the papers considered. Further, voltage was taken into account by 12.31% of the whole sample considered, while current was measured in 16.92% of the papers in this sample. Then, wavelength was measured by 10.76% of the papers surveyed and frequency was measured in 13.84% of them.

Finally, length was analyzed in 1.53% of the papers surveyed and the spot size was measured in 10.77% of them, while elongation was measured in 3.07% of the entire set of contributions accounted for.

3.3. Maximum performance measures reported

The maximum performance values attained among the studies here reported for each of the indicators analysed are given in Table 2.

Thus, the UTS attained by Li et al. (2016) was the highest, equalling 1350.6 MPa, while the value of the welding speed, reported in Zhang et al. (2018) was the highest, being equal 500 mm/min. Then, maximum hardness, equal 500 HV, was reported by Hsieh et al. (2016), while the maximum power, equal 270.7 kW, appeared in Rezaei and Naffakh-Moosavy (2018).

The highest temperature, namely 538 ^{o}C, was reported again by Hsieh et al. (2016). The highest welding energy (23 J/mm) was shown in Keskitalo et al. (2015). The highest values of voltage and current, 23.6 V and 312 A, respectively, were reported by Grünenwald et al. (2010). The maximum wavelength of 1030 nm was reported in Kägeler and Schmidt (2010), while the highest frequency, equal 78 Hz, appeared in Hao and Liu (2009).

Reference	UTS	Welding speed	Hard-ness	Power	Tempe-rature	Welding energy	Voltage	Current	Wave-length	Fre-quency	Length	Spot size	Elon-gation
Ahn et al. (2018)		✓		✓									
Anabitarte et al. (2012)													
Bendaoud et al. (2014)		✓		✓	✓								
Casalino et al. (2017)						✓							✓
Chen, Li & Liu (2012)		✓				✓		✓					
Chen & Liu (2014)		✓			✓								
Ernst et al. (2015)					✓	✓							
Fadaeifard et al. (2016)	✓	✓			✓								
Fang et al. (2014)		✓		✓			✓	✓					
Forouzan, Vuorinen & Mücklich (2017)				✓	✓								
Fuerschbach (2008)					✓								
Gao et al. (2013)		✓		✓								✓	
Gao, You & Katayama (2012)		✓										✓	
Grünenwald et al. (2010)		✓					✓	✓					
Hao & Liu (2009)		✓			✓		✓			✓			
Hao & Song (2009)		✓		✓				✓		✓			
Hsieh et al. (2014)		✓		✓	✓								
Hsieh et al. (2016)		✓	✓	✓	✓								
Hsu et al. (2006)				✓								✓	
Jager & Hamprecht (2009)													
Jager, Humbert & Hamprecht (2008)													
Jia et al. (2018)		✓				✓			✓				
Kägeler & Schmidt (2010)				✓					✓	✓			
Kermanidis et al. (2014)			✓										

Keskitalo et al. (2015)		✓		✓		✓							
Köse & Kaçar (2014)	✓				✓								✓
Kubiak et al. (2016)				✓			✓						
Kumar, Mukherjee & Bandyopadhyay (2017)	✓	✓		✓									
Kurosaki & Satoh (2010)				✓	✓				✓				
Kuryntsev (2018)			✓	✓	✓								
Leo, D'Ostuni & Casalino (2018	✓									✓	✓		
Li et al. (2016)	✓	✓		✓									
Li et al. (2018)	✓		✓			✓							
Li, Wang & Huang (2018)		✓										✓	
Liu et al. (2008)				✓	✓					✓			
Liu et al. (2010)				✓									
Liu et al. (2018)		✓	✓		✓			✓					
Liu & Hao (2010)		✓		✓				✓		✓			
Liu & Jiang (2011)		✓							✓				
Lü et al. (2018)		✓		✓									
Ma et al. (2015)	✓					✓							
Na et al. (2010)		✓		✓				✓	✓				
Neto et al. (2015)		✓		✓			✓	✓					
Oláh, Croitoru & Tiercan (2018)												✓	
Pekkarinen & Kujanpää (2010)		✓		✓									
Reisgen et al. (2010)		✓											

Rezaei & Naffakh-Moosavy (2018)		✓		✓	✓								
Saravanan, Raghukandan & Sivagurumanikandan (2017)		✓		✓									
Schulte-Huxel, Kajari-Schröder (2015)					✓								
Serizawa et al. (2014)		✓		✓								✓	
Sheikhi, Ghaini & Assadi (2015)		✓		✓	✓	✓	✓						
Song et al. (2009)				✓				✓					
Tan et al. (2008)					✓		✓					✓	
Tseng & Sung (2005)				✓									
Wang (2014)							✓	✓					
Wang (2017)		✓						✓					
Wang et al. (2009)		✓		✓	✓								
Windmann et al. (2017)		✓			✓	✓							
Yan et al. (2014)				✓					✓				
You, Gao & Katayama (2014)				✓					✓				
You, Gao & Katayama (2015a)				✓						✓			
You, Gao & Katayama (2015b)		✓		✓						✓			
Yu et al. (2016)	✓			✓	✓					✓			
Zhang et al. (2017)		✓		✓									
Zhang et al. (2018)		✓	✓										

Further, the biggest length and spot size, equal, respectively, 100 mm and 3 mm, were reported in Leo, D'Ostuni and Casalino (2018). The biggest elongation, equal 23%, appeared in Köse and Kaçar (2014), while the highest robot head speed was reported in Oláh, Croitoru and Tierean (2018), and it was equal 1000 mm/min.

Of the yield strengths, reported in the papers reviewed, the highest – equal 283 MPa – appeared, along with the biggest crystallite size, 34.6 nm, in Ma et al. (2015). The biggest Gaussian radius, equal 35 μm, was reported by Schulte-Huxel, Kajari-Schröder and Brendel (2015).

The highest FP rate (2.7%) appeared in Jager, Humbert and Hamprecht (2008). The biggest nozzle diameter, equal 6 mm, was reported by Reisgen et al. (2010), while the highest TP rate (0.5%) – by Jager and Hamprecht (2009). The highest value of the error, namely 1.18%, appeared in Kumar, Mukherjee and Bandyopadhyay (2017).

3.4. Analysis of heat treatment

The papers considered in this review of laser welding technology state of the art include certain works, in which heat treatment was applied and also works, in which nonheat treatment procedures appear. The proportion between these two groups of approaches is illustrated in Fig. 3, showing that some 60% of papers presents the approaches including heat treatment, while the rest, i.e. roughly 40%, presents the approaches without heat treatment.

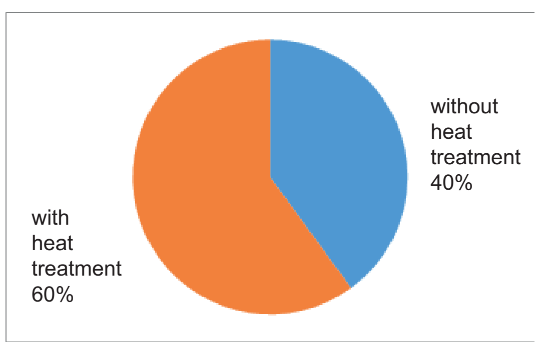

Figure 3: Illustration of the proportion between papers, presenting technologies with respect to heat treatment in the surveyed laser beam welding studies

Table 1: The maximum performance measures reported in the papers surveyed

Performance measures	**Maximum value**	**Reference**
UTS	1350.6 MPa	Li et al. (2016)
Welding speed	500 mm/min	Zhang et al. (2018)
Hardness	500 HV	Hsieh et al. (2016)
Power	270.7 kW	Rezaei and Naffakh-Moosavy (2018)
Temperature	538 textdegree C	Hsieh et al. (2016)
Welding energy	23 J/mm	Keskitalo et al. (2015)
Voltage	23.6 V	Grünenwald et al. (2010)
Current	312 A	Grünenwald et al. (2010)
Wavelength	1030 nm	Kägeler and Schmidt (2010)
Frequency	78 Hz	Hao and Liu (2009)
Length	100 mm	Leo, D'Ostuni and Casalino (2018)
Spot size	3 mm	Leo, D'Ostuni and Casalino (2018)
Elongation	23 %	Köse and Kaçar (2014)
Robot head speed	1000 mm/min	Oláh, Croitoru and Tierean (2018)
Yield strength	283 MPa	Ma et al. (2015)
Crystallite size	34.6 nm	Ma et al. (2015)
Gaussian radius	35 μm	Schulte-Huxel, Kajari-Schröder and Brendel (2015)
False positive rate	2.7%	Jager, Humbert and Hamprecht (2008)
Nozzle diameter	6 mm	Reisgen et al. (2010)
True positive rates	0.5%	Jager and Hamprecht (2009)
Error	1.18%	Kumar, Mukherjee and Bandyopadhyay (2017)

3.5. Laser types

The various types of lasers included in the works here surveyed are summarised in Table 3.

Thus, Yb Fiber Laser beam was used by Leo, D'Ostuni and Casalino (2018), Forouzan, Vuorinen and Mücklich (2017), Neto et al. (2015), Yan et al. (2014), as well as by Kägeler and Schmidt (2010). Then, Nd: YAG laser was applied by Li et al. (2018), Oláh, Croitoru and Tierean (2018), Rezaei and Naffakh-Moosavy (2018), Windmann et al. (2017), Kumar, Mukherjee and Bandyopadhyay (2017), Ma et al. (2015), Chen, Li and Liu (2014), Liu and Jiang (2011), Anabitarte et al. (2012), and Reisgen et al. (2010).

Next, Yag laser welding was performed in the studies reported by Kuryntsev (2018), Saravanan, Raghukandan and Sivagurumanikandan (2017), Hao and Liu (2009), Liu and Hao (2010), Liu et al. (2008), and Kurosaki and Satoh (2010). Further, fiber laser was applied in the studies, reported by Ahn et al. (2018), Li et al. (2016), Gao, You and Katayama (2012), Pekkarinen and Kujanpää (2010), and by Grünenwald et al. (2010). Also Pulsed Nd: YAG laser was useed, namely in Zhang et al. (2017). Moreover, 5 kW CO_2 laser was applied in Hsieh et al. (2014 and 2016), Yb:YAG laser was made use of by Kubiak et al. (2016), and Lakshaminarayanan laser welding was adopted in Keskitalo et al. (2015).

Further, pulsed laser welding appeared in Sheikhi, Ghaini and Assadi (2015), while CO_2 laser in Köse and Kaçar (2014) and in Wang et al. (2009). Similarly, TRUDISK 6002 Yb:YAG laser, Single pulse layer, and disk laser welding techniques were applied in Bendaoud et al. (2014), Schulte-Huxel, Kajari-Schröder and Brendel (2015), and in You, Gao and Katayama (2015b), respectively. Also, CW fiber laser, single pulsed YAG laser, diode laser and semiconductor laser were used in the studies reported, respectively, by Fang et al. (2014), Gao et al. (2013), Chen, Li and Liu (2012), Na et al. (2010), and by Song et al. (2009). Then, the HeNe laser, Nd:YAG laser, and LWS-500 YAG pulsed laser were applied by Fuerschbach (2008), Tan et al. (2008), and Hao and Song (2009), respectively. Finally, the Butterfly-Type laser was used in the study reported by Hsu et al. (2006), Tseng and Sung (2005), and by Liu et al. (2010).

4. Research problems and challenges

Laser welding is a guaranteed joining method, owing to its important advantages, namely: density, high energy, speed, narrow HAZ, low distortion, and deep penetration. The unification of dissimilar materials, particularly Al/Ti, Al/Mg, and Mg/Ti, is a very demanding task, even with LBW, owing to great

Table 2: Types of lasers used in the studies surveyed

Laser Types	References
Yb Fiber Laser beam	Leo, D'Ostuni & Casalino (2018), Forouzan, Vuorinen & Mücklich (2017), Neto et al. (2015), Yan et al. (2014), Kägeler & Schmidt (2010)
Nd: YAG laser	Li et al. (2018), Oláh, Croitoru & Tierean (2018), Rezaei & Naffakh-Moosavy (2018), Windmann et al. (2017), Kumar, Mukherjee & Bandyopadhyay (2017), Ma et al. (2015), Chen, Li & Liu (2014), Liu & Jiang (2011), Anabitarte et al. (2012), Reisgen et al. (2010)
Yag laser welding	Kuryntsev (2018), Saravanan, Raghukandan & Sivagurumanikandan (2017), Hao & Liu (2009), Liu & Hao (2010), Liu et al. (2008), Kurosaki & Satoh (2010)
Fiber laser	Ahn et al. (2018), Li et al. (2016), Gao, You & Katayama (2012), Pekkarinen & Kujanpää (2010), Grünenwald et al. (2010)
Pulsed Nd: YAG laser	Zhang et al. (2017)
5 kW CO_2 laser	Hsieh et al. (2014 and 2016)
Yb:YAG laser	Kubiak et al. (2016)
Lakshaminarayanan laser welds	Keskitalo et al. (2015)
Pulsed laser welding	Sheikhi, Ghaini & Assadi (2015)
CO_2 laser	Köse & Kaçar (2014), Wang et al. (2009)
TRUDISK 6002 Yb:YAG laser	Bendaoud et al. (2014), Tan et al. (2008)
Single pulse layer	Schulte-Huxel, Kajari-Schröder & Brendel (2015)
disk laser	You, Gao and Katayama (2015b)
4 kW IPG fiber laser	Fang et al. (2014)
CW fiber laser	Gao et al. (2013)
Single pulsed YAG laser	Chen, Li & Liu (2012)
Semi conductor laser	Na et al. (2010), Song et al. (2009)
HeNe laser	Fuerschbach (2008)
LWS-500 YAG pulsed laser	Hao & Song (2009)
Butterfly-Type Laser	Hsu et al. (2006), Tseng & Sung (2005), Liu et al. (2010)

dissimilarities in metallurgical and physical features, including melting point, crystal structure, coefficient of linear thermal expansion, and thermal conductivity. Due to such variations, brittle and hard IMCs are often created at the interface, thus damaging the required or expected behavior of the joints.

The LBW systems have better power density than plasma welding or GTAW systems. The heat in a laser system focuses on such a small spot that it generates a keyhole weld that usually broadens through the whole thickness of the substance and has a slim HAZ. A rising number of pipe and tube production processes move away from the traditional plasma and GTAW welding to LBW in view of the fact that this would offer advanced welding rates, stronger welds, as well as narrower and deeper keyholes.

However, there exists a trade-off to the benefits of LBW systems, i.e. the associated requirement to develop the monitoring of the seam location and edge presentation gains in importance. Similarly as in plasma welding and GTAW, the seam location and strip edge presentation relative to the weld head have to be regulated to reduce faults like edge wave, mismatch, seam wandering and edge gap. Since a laser beam spot is almost ten percent the volume of a plasma arc or GTAW, achieving such effective control is much more complex in LBW. As a result, the increased rate of application of dissimilar LBW-welded light alloys is accompanied with a challenge to comprehend the involved difficulties entirely and to improve the process by means of enhancing the joining performance and joint mechanism. As there are only few papers on LBM using Ti/Al materials, there is a large future scope for the upcoming research regarding the development of LBM.

5. Conclusion

Welding is very well accepted in the manufacturing industries. Both solid state and fusion welding is being exploited for numerous products and materials. Amongst several fusion welding methods, the laser has achieved an important position as an autogenous fusing method for combining metals. Laser beam welding is more advanced than other welding techniques, especially regarding the welding of Ti alloys, owing to its high operational flexibility and beam density. Throughout the welding process, the mechanical performance of weld beads can vary considerably and as a result, tempering might be advantageous, enhancing the ductility of the weldment and raising overall hardness. Here, the literature considers the diverse techniques associated with laser welding systems. Hence, in this paper:

- we reviewed a number of research papers and stated the significant aspects of respective analyses;

- then, we concentrated on diverse specific features namely, laser beam width and type of laser, examining also the heat treatment analysis that was described in each paper;
- in addition, this paper offers a comprehensive study concerning the performance measures and maximum performance achievements among the studies here considered;
- finally, the study points out the research issues that could be useful for the researchers in carrying out further research on laser welding systems that are mainly based on welding of Ti/Al materials.

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