

STATE-OF-THE-ART OF MONITORING AND IMAGING OF LASER WELDING DEFECTS

P. Norman¹, H. Engström¹, A. F. H. Kaplan¹

¹Luleå University of Technology, Luleå, Sweden

Abstract

Several weld defects like lack of fusion, blow-out holes, pores, cracks or undercuts can occur during laser welding. They can be crucial for product failure. Due to its complexity the laser welding process and the origin of its defects are only partially understood. Both experimental observation and numerical simulation is difficult. Beside generally accepted knowledge on welding defects, to a limited extent high speed imaging, particularly by X-ray transmission, and mathematical modelling have generated some understanding. However, experimental observation suffers from the small size of the process zone, from its high dynamics and from the hot environment, while the physical process is too complex for complete simulations.

Besides avoiding welding defects through process understanding, detection is of importance in industrial production. It can be distinguished between pre-, in- and post-process inspection, and between on- and off-line. Off-line post inspection is often expensive. Today in-process monitoring is provided by photodiodes or cameras, but owing to the lack of understanding it is limited to empirical correlations between the appearance of a defect and signal changes.

The present review provides a survey on laser welding defects, on their experimental observation, on their theoretical treatment by modelling or simulation and on their detection by process monitoring. Despite large research efforts the understanding and detection of laser welding defects is still very limited and unsatisfactory, hindering industrial implementations. Further research will be needed to fully control this critical welding process and in turn to guarantee reliable production and safe product function.

Keywords: laser, welding, monitoring, imaging, defects

1. Introduction

The present paper provides a survey on relevant literature on laser welding defects, divided into microscopic post-process analysis of defects, mathematical modelling or numerical simulation of defect mechanisms, high speed imaging of the welding process and in-process monitoring of defects. The main focus is put on the last issue.

Motivation of the literature study is the current research project DATLAS that aims at improving commercial process monitoring systems (photodiode based) through better knowledge on the mechanisms causing the welding defects and monitoring signal changes. To succeed with this we have, together with eight companies, performed tests on different materials, joints and material thicknesses to accomplish a matrix correlating the weld defects to the sensor signal for these different setups. However, beside revealing empirical correlation rules, high speed imaging in cooperation with simulation of radiation emissions impinging on the sensor is planned in order to try to predict and explain the context between the physical mechanism of the dynamic welding process (in particular the defect origins) and dynamic signal changes. Therefore the larger picture of the above different topics is an important starting point. The main objective is to improve the judgement of the capabilities and limitations of the context defect-signal and of the signal meanings by better understanding.

Fig. 1 illustrates the connection between the laser welding process, defects and how they can be monitored. The laser technique bubble in Fig. 1 includes; cw/pw, keyhole/conduction and laser/hybrid type welding

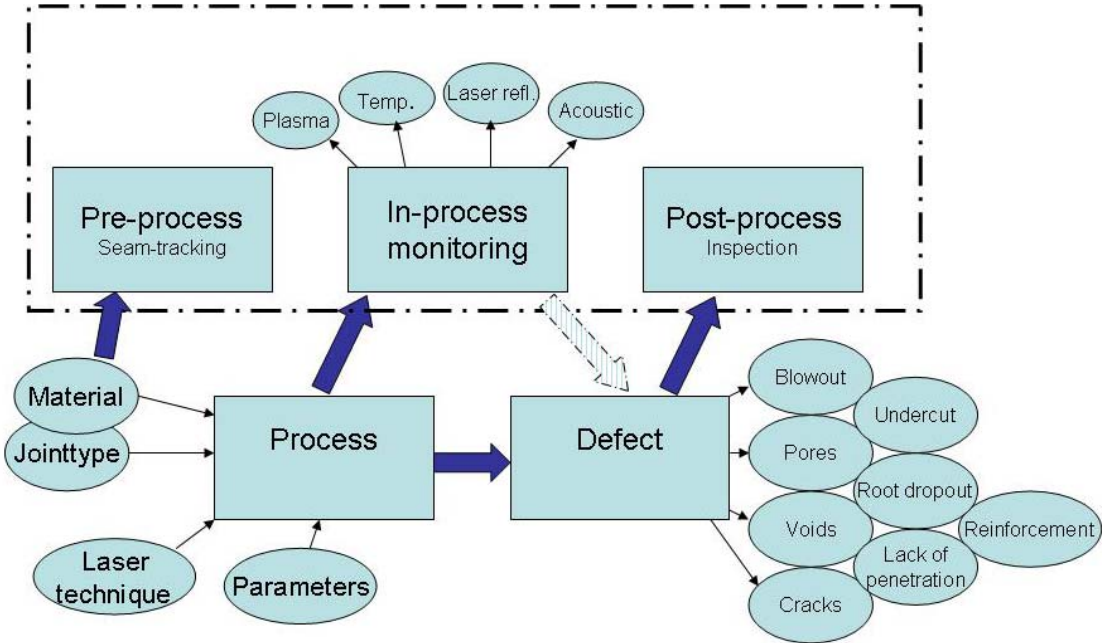


Fig. 1: Context process-defect and classification of process monitoring/inspection methods

The monitoring can be divided into three different types: (i) *pre-process*, arranged ahead of the welding zone like seam tracking devices for identifying the edge position; (ii) *in-process* monitoring, by on-line sensors observing the laser welding process. This can be done by using different sensors like photodiodes, cameras, pyrometers or acoustical sensors; (iii) *post-process* inspection is done after the welding zone after the weld has solidified, either during manufacturing with camera sensors or afterwards by visual inspection, microscopy or other inspection or testing methods.

Classification of welding defects

Some important welding defects [1] and their physical origin are summarised in **Tab. 1**.

Table 1: Classification of laser welding defects and explanation of their physical cause

Defect	Explanation of the physical cause
Pore	Spherical gas bubble trapped by solidifying material
Void	Sharp edged volume caused by impurities or during resolidification
Blow-out	Caused by a near surface pore that opens and forms a crater
Crack H/C	Hot cracks are formed during solidifying in welded zone Cold cracks can form after welding, often in HAZ
Undercut	Not enough material in upper weld zone, depends on speed, power and gap
Root dropout	Too much molten material in lower weld zone
Penetration	Joint not completely penetrated, depends on oxidation, gas protection, contamination of gas or fluctuation of laser power
Lack of fusion	The laser misses the joint, partially or fully
Reinforcement	Too much material in upper weld zone, fluctuation of gap width

These defects have been under serious investigation because they cause large problems to companies. The weld has to achieve the mechanical properties under load conditions in order to maintain the function of the product. Weld failures weaken the material locally and can lead to fracture and in turn to catastrophic product failure. Therefore standardisation of welds and weld defects is essential, as well as their detection. All of the above defects are geometrical and therefore visible by the use of either ultrasound testing, X-ray or by looking at a cross section of the work-piece.

Process monitoring can support the detection of defect welds. However in lack of 100% reliability even such detection has only indicative nature. Some of the defects are easier to detect on-line during the process, others are very difficult to detect. A single sensor is the most robust setup for the industry, as simple but reliable systems are wanted.

2. Results from literature and discussion

This chapter reviews the state-of-art of microscopic post-analysis, mathematical modelling, process observation and process monitoring of welding defects.

2.1 Microscopic post-process analysis of welding defects

To be able to make accurate descriptions of errors occurring during welding several specimens has to be evaluated. This is done either done by destructive testing of the mechanical properties (tensile testing, impact testing, fatigue testing, etc.), by destructive microscopic testing when examining the welded surface and taking a cut out of the joint, or it can be done by non-destructive testing using ultrasound or X-ray methods to look “inside” the joint. A typical laser weld surface is shown in **Fig. 2(a)**. **Fig. 2(b)** shows a good weld after it has been grinded, polished and etched. **Fig. 2(c),(d)** shows a hot crack that is formed during resolidification of the weld. This type of crack can severely lower the strength of the joint.

Welding defects can become the origin for fracture. Under load conditions initially plastic deformation takes place, along with the development of a stress field. In particular sharp corners or edges and constraints can act as stress raisers where locally very high stresses occur. They can initiate crack formation at the microstructure level, e.g. between grains. From these micro-defects crack propagation takes place. If the stress cannot locally relax

sufficiently quickly, the fracture will propagate through the weld and workpiece thickness, leading to damage. Product dimensioning is usually based on defect free welds of certain shape and throat depth. The detection of welding defects is therefore essential, as it is a main cause for product failure.

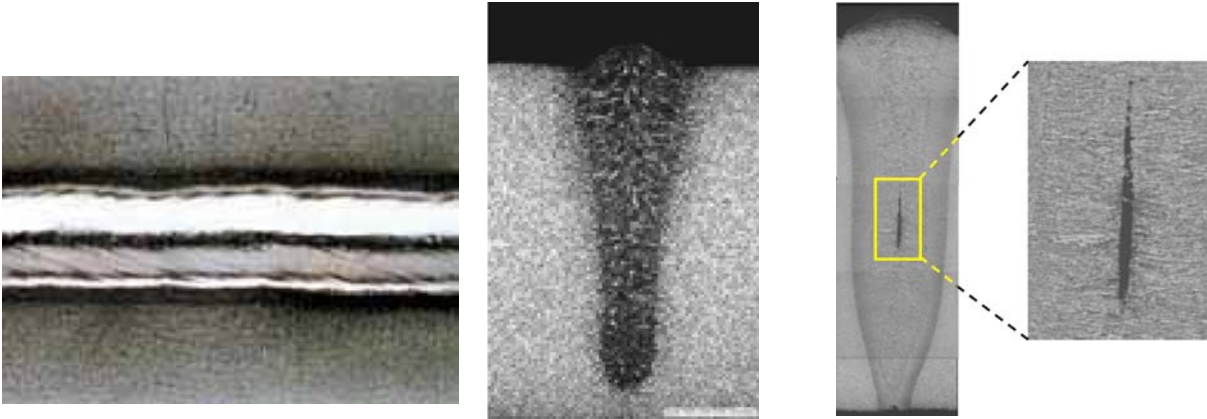


Fig. 2: (a) weld surface, (b) cross section for a good joint, (c),(d) hot crack

2.2 Modelling and simulation of laser welding defects

By mathematical modelling and simulation understanding on the physical welding process mechanisms can be achieved. Development of a model can be supported by experimental observation, from which theories can be derived. Matsunawa and Katayama [2] use an in-house developed X-ray imaging system together with a high speed camera to visualize the plasma and melt pool. With these tools they explain how the keyhole dynamics, liquid motion in the melt pool and the plasma affect the welding result, e.g. pore formation.

Up to date the laser welding process has been too complex to be fully simulated, but successful results in simulating parts of the process were achieved such as the work by Amara [3]. They model the keyhole and melt pool movement that is affected by the flow of metal vapour in Nd:YAG laser welding. Fabbro [4,5] simulates the movement of the melt pool, metal vapour plume and keyhole during Nd:YAG laser welding. This work is also supported by high speed imaging of the weld pool motions. The work presents explanations of the keyhole behaviour and how the melt pool and vapour are coupled. Jin [6] modelled the keyhole in 3D by taking pictures of the keyhole during welding in glass and from this data building the model. Thus partial progress was achieved, but still no complete prediction or description of the laser welding process, in particular of its context to welding defects has been achieved. A keyhole model with melt flow and drop calculation [3] is shown in **Fig. 3**.

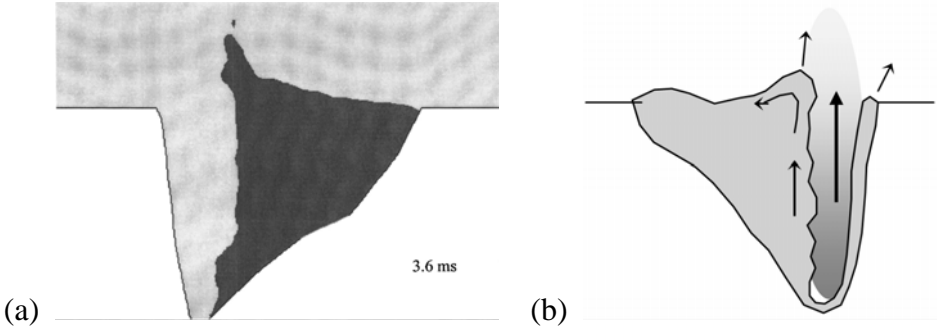


Fig. 3: (a) Simulation of the keyhole and melt pool flow, (b) explaining drop ejection [3]

A model for explaining pore formation during the keyhole collapse after the end of a laser pulse [7] is shown in Fig. 4, explaining that recondensation of the metal vapour after pulse termination sucks the surrounding Ar-shielding gas into the keyhole that closes to a cavity during the collapse. During contraction the cavity ends in a stable spherical bubble where the surface tension pressure is in balance with the trapped Ar gas volume. During resolidification the slowly rising bubble turns to a pore.

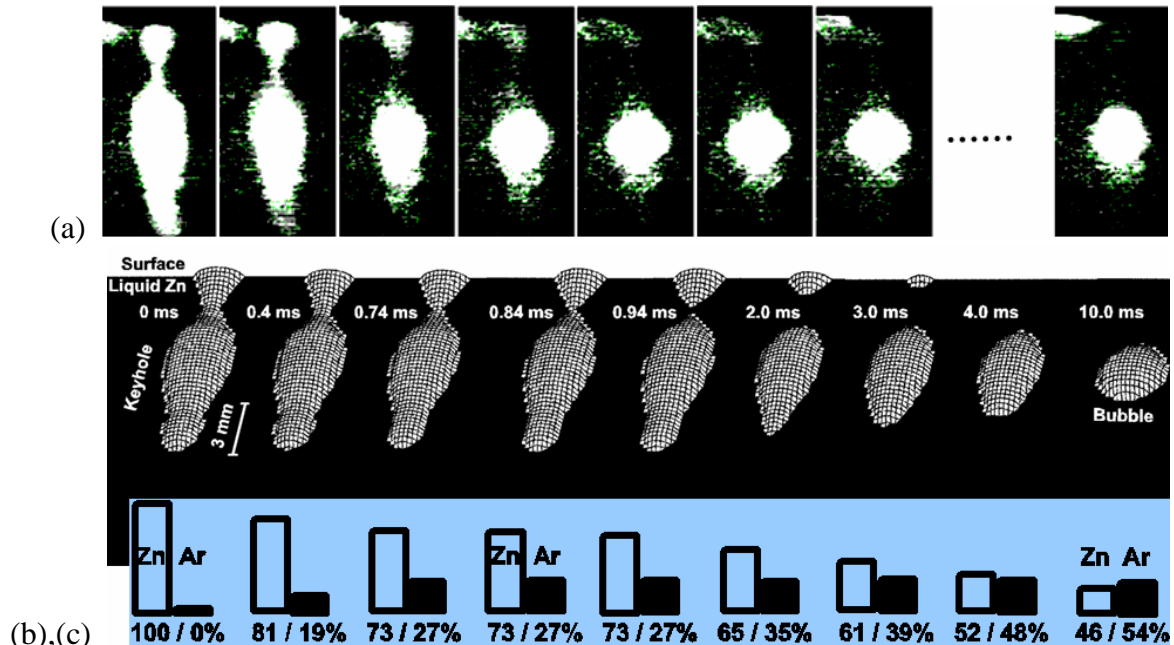


Fig. 4: Keyhole collapse towards a bubble after termination of a laser pulse: (a) time sequence of X-ray images of the keyhole (side view), (b) contraction predicted by the model, (c) calculated mixture of metal vapour (Zn) and shielding gas (Ar) in the keyhole/cavity [7]

Further models enable to calculate the metallurgical composition in the laser weld cross section, in particular the amount of martensite formation leading to hot cracking susceptibility for stainless steel [8]. For calculating the local fraction of martensite formed, several authors developed dendritic microstructure diffusion models. J. F. Gould [9] thermodynamically determined the critical cooling rate of martensite for Advanced High Strength Steel (AHSS). With modern sophisticated multi-scale modelling, e.g. at the grain size scale in cooperation with the macro-continuum scale, also the crack formation and propagation during load can be modelled to some extent [10],[11].

2.3 High speed imaging of laser welding defects

For observing the process in the simplest way a standard video camera can be used. However it has a very limited spatial resolution, giving poor image quality, and a limited frame rate and exposure time that has the consequence that it will not be able to accurately reproduce an image of the high intensity laser welding. Several companies [12-15] have therefore developed different cameras that can observe the process. The cameras range from being able to reproduce an area of 1280x1024 pixels at 600 frames per second to about the same area but at 5000 frames per second. With lower resolution the frame rate can be as high as 30000. What also sets the price of the equipment is the dynamic range of the camera. It ranges from 8bit to 12bit from these companies. Today the price ranges from 25000USD to 90000USD.

There are also even more expensive cameras with higher frame rate and higher resolution but these are not of interest for the industry nor for researchers within laser welding as they probably won't contribute with any deeper knowledge.

To better see the melt pool and keyhole a high brightness illumination is required, by at the same time extracting through filters the broad bright spectrum of the weld zone, particularly of the plasma plume above the keyhole. Such filtering even succeeds for hybrid (laser+arc) welding [16], where even stronger plasma disturbs the observation. Such illumination can be achieved by spectrally narrow lamps but also by using a laser. As the laser gives a well defined light it is simple to use filters on it to get a better image quality, although it is possible to achieve very good quality using only halogen lamps as done by Fabbro et al [4], where they look at stabilizing the melt pool with a gas jet, as shown in Fig. 5(a),(b).

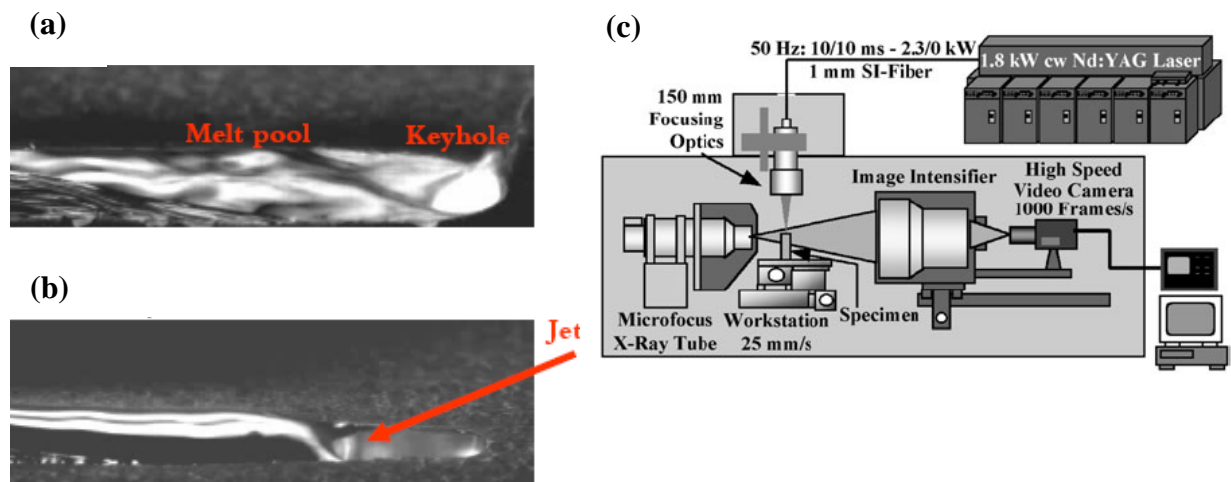


Figure 5: High speed imaging of the top side of the melt pool and keyhole [4]: (a) weld pool waves, (b) calmed weld through an additional gas jet directed to the keyhole rear side. (c) Example of a set-up for X-ray high speed imaging [7]

As shown in Fig. 4(a), X-ray illumination of a (narrow piece of) weld from the side enables even high speed imaging of the keyhole and pores. A typical experimental set-up [7] is shown in Fig. 5(c). By the addition of tracer particles, e.g. carbides with high melting point, a contrast can be achieved that permits X-ray tracing of the particle trajectories corresponding to the flow inside the melt pool. By adding Sn, having a low melting point, it quickly dissolves in the weld pool and gives a contrast on the vertical weld pool shape during X-ray high speed imaging [2].

2.4 In-process monitoring of laser welding defects

Several monitoring techniques can be applied, as shown in Fig. 1. In our research work we will use the in-process method as this enables on-line inspection capabilities to information in the welding process zone. This way of monitoring is used by several researchers because it gives most information about the process in a robust, simple manner when looking for defects, thus it also has high industrial potential.

2.4.1 State-of-the-art of monitoring

Tab. 2 provides a survey on publications on in-process process monitoring of laser welding, with corresponding classifications.

Table 2: Survey on publications on in-process monitoring and corresponding classification

No.	Author	Country	Laser system		Power kW	Material	Thickness mm	Joint type	Defect	Inspection type	Monitoring sensor	Control loop
			CO2/ Nd-YAG	cw/ pw								
17	C. Bagger	DK	1	3	1,5	5	,5 1,25 2 3	13	25	27	31	+
18	A. Ghasempoor	Can	1	3	8	6	5	11	17,18,20,24	27	31-34	
19	H. K. Tönshoff	D	1, 16	3	6	6	10	12	20, 25	27	29-30	
20	H.B. Chen	UK	1	3	2 5	6	0,6 1 6	11	25	27	30	
21	A. Sun	US	1	3	1,1 7,4	6	0,91 1,2	13	25	27	30, 34	
22	Y. Kawahito	Jpn	2	4	0,05	5	0,1 1	15	24		29,31-32	+
23	B.N. Bad'yanov	Rus	2		1,4	6	0,5	13	25	27	29-32	
24	P.G. Sanders	US	1, 2	3, 4	6 1,6	5,6		14		27	30-31	
25	K. Kamimuki	Jpn	2		6	6,7	10	14	20,21,22,25	27	31	
26	K. Kamimuki	Jpn	2		3,5	6	6 10	11, 14	18, 20, 25	27	32, 34	
27	D. Travis	UK	2, 16		3	6		14			31, 33	
28	S. Postma	Ned	2		2	6	0,7	11	25		30-31	+
29	J. Petereit	D	1, 2						25	26-28	29-31	
30	M. Kogel-Hollacher	D						11		26-28	29	
31	J. Beersiek	D	1, 2									
32	F. Bardin	UK	2		4 2,5	8, 10		14	25	27	29, 31	+
33	M. Doubenskaia	F	2	3, 4	2					27	31	
34	M. Doubenskaia	F	2	4	3	6,7				27	31	
35	M. Doubenskaia	F	2	3	2	9	0,7 1	13	24	27	31	
36	Ph. Bertrand	F	2	3	3	6,7		11		27	31	
37	V.M. Weerasinghe	UK	1	3	2	6		11		27	30,32,34	
38	H. Gu	Can	1		1,7	6	1	11, 13	25	27	34	
39	D.P. Hand	UK	2	3	2	6	1	11, 13	25	27	30	+
40	S.-H. Baik	Kor	2	4	1	6	1	11		27	31	
41	L. Li	UK	1		2	6	5			27	34	
42	L. Li	UK	1	3, 4	1,5 5	5,6,8,9	2 0,22 1,5	11,13,15	25	27	30	
43	B. Kessler	D	1, 2	3					17,19,24,25	26-28	29-33	+
44	W. Wiesemann	D	1, 2							26-28		+
45	J. Shao	UK	1, 2						17, 19, 25	26-28	29-34	

TABLE LEGEND

Laser type	Material	Joint	Defect	Inspection type	Sensor
1=CO ₂	5= Al-alloy	11=Butt joint	17=Blow-out	26=Pre-Process	29=CMOS-Camera
2=Nd:YAG	6= Low C-steel	12=T-Joint	18=Void	27=In-Process	30=Plasma/ph.diode
3=Continuous wave (cw)	7= Stainless steel	13=Lap Joint	19=Crack Hot/C.	28=Post-Process	31=T / photodiode
4=Pulsed wave (pw)	8= Titanium alloy	14=Bead on plate	20=Pores		32=Laser reflect./p.d.
16=Hybrid welding (MIG)	9= Zn-coated steel	15=Spot weld	21=Undercut		33=Voltage / current
	10=Inconel		22=Reinforcement		34=Acoustic / mic.
			23=Root drop-out		
			24=Lack of fusion		
			25=Lack of penetration		

2.4.2 Scope of published experiments

The experiments in **Tab. 2** comprise both CO₂ and Nd:YAG lasers in cw and pw mode. Materials are not only standard steel and different alloys as Inconel and stainless steel but also aluminium alloys and zinc coated steel. The thicknesses of these materials vary from 0,1mm to 10mm. Also the joint types are different, including Butt-, T-, Lap-joint, simplified Bead on plate welds and spot welding. All defects shown in **Tab. 1** are monitored with sensors like cameras, photodiodes and acoustic emission sensors.

2.4.3 Monitoring techniques

Photodiode sensor: To be able to observe a process, a sensor is needed. For laser welding as a high temperature process with accompanying thermal emissions optical sensors are favoured, in contrast to e.g. machining as a vibration governed process where acoustic and vibration sensors are preferred.

Such sensor set-up typically consists of an optical fibre collecting process emissions and guiding them to the photodiode which converts it into a time dependent voltage signal, which will be amplified and digitalized by an A/D-converter. A DSP or a computer carries out signal analysis, enabling to create threshold rules that distinguish between defect and no defect. Important is that the thermal emissions from the process contain a lot of information on the process dynamics, like melt pool motion, however in a non-trivial indirect manner.

While cameras are suitable for visualisation and for sophisticated measurement of e.g. the melt pool or keyhole dimensions, one or several photodiodes are powerful for simpler, industry robust monitoring of the process. The signal integrates the emitted information from the process and is thus more difficult to interpret, requiring empirical correlations with welding defects or theoretical understanding of the process, which is limited today. Many researchers studied this type of sensor successfully [17-23]. Bagger and Olsen [17] placed a single photodiode under the weld zone. The system successfully controlled the power of the laser to achieve full penetration in sheets of variable thicknesses. Using single diodes is also realised by Sanders [24], but they have gone a step further by using the signal to detect part misalignment and surface contamination. Ghasempoor [18] used three diodes, one for UV, one for IR and one for visible light. By using this setup they have detected lack of fusion and also in some cases porosity.

The photodiode can also be combined with other sensing techniques like voltage and current signals in hybrid welding, where Tönshoff [19] detected lack of fusion and porosity defects. Observing hybrid welding by photodiodes has been done by Travis [27] showing that a simple and cheap system can be effectively used. Different sensor combinations were tried by Sun [21] who demonstrated the use of acoustic sensors for monitoring of both structure and airborne sound emissions. These were combined with UV and IR sensors to detect if the weld had penetrated fully or not. If access to the process zone is difficult, fibre optics can be employed, later splitting the signal to different sensors. This way of measuring has been shown by Chen [20]. A combination of a variety of sensors provided good insight in the process as Bad'yanov [23] has done by using IR, UV and temperature diodes together with a pyrometer and a CCD camera. They accomplished a suitable mathematical approximation of the signals and consequently lowered the signal computation efforts. The photodiode is successfully used in heavy industry when welding thick plates [18, 26]. **Fig. 6(a)** shows the correlation between the photodiode signal and full or partial weld penetration, respectively.

Visualisation of the weld pool is performed by CMOS-cameras, requiring less signal interpretation, rather image evaluation processing, which is more straightforward. Several authors studied the setup with photodiode and camera. Kawahito et al have come a long way by introducing adaptive control to a laser spot welding [22]. Several system manufacturers developed mature systems on the market, i.e. Weldwatcher [28], Fraunhofer ILT CPC [29], Precitec [30] and Prometec [31]. Single pictures can be isolated from the camera, correlating to different situations during welding. This is studied by Bardin [32], monitoring the penetration depth in real time with a photodiode and analysing the pictures from the camera to be able to control the penetration depth.

Pyrometer sensor: The process can also be monitored by using a pyrometer as shown by Doubenskaia [33-35] and Bertrand [36]. They use the pyrometer to monitor the surface temperature for different setups like laser cladding [33], not for monitoring of defects but for optimisation of cladding parameters. In [34] a pyrometer monitors the surface temperature profile during a laser pulse, e.g. to control how the melt is formed to avoid thermal decomposition of sensitive materials. The pyrometer can also be used to monitor weld quality during welding of zinc coated steels. This can be realised as the quality of these welds are connected to the joint gap, and the gap gives different temperatures depending on its size [35]. Bertrand [36] uses a pyrometer to detect fusion defects and lack of shielding gas, as well as variable speed and gap misalignment, see **Fig. 6(b)**.

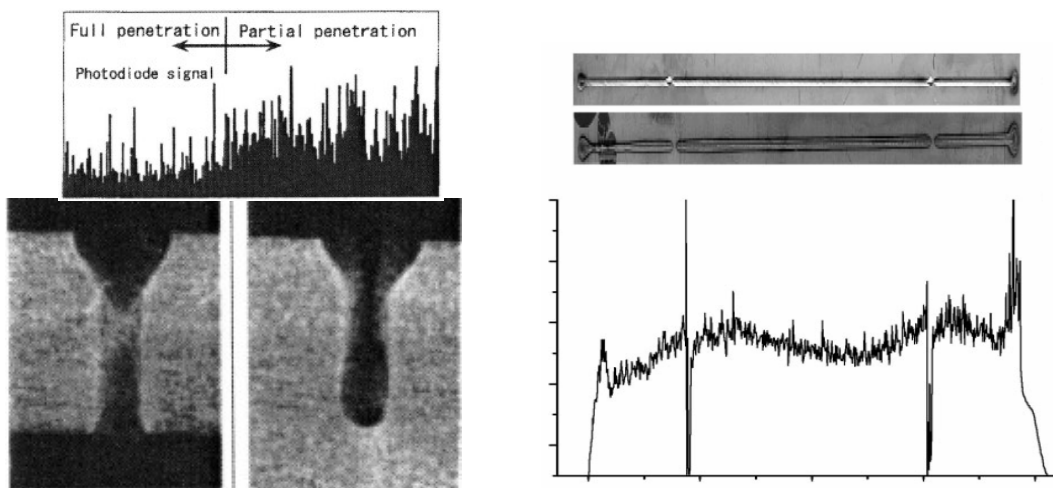


Fig. 6: (a) Photodiode signal detecting full vs. partial weld penetration [26]; (b) pyrometer signal detecting laser weld interruptions [36]

Other sensors: Less usual monitoring techniques are studied by several authors [37-42]. Earlier, Weerasinghe [37] and Gu [38] used acoustic emission sensors to monitor the lack of penetration or the penetration depth. Li [41] compared two different ways of monitoring with acoustic emission sensors.

Hand [39] looks at the plasma radiation reflected through the cladding layer of the optic fibre that guides the laser beam. They successfully detect focus errors and shield gas interruption during welding. A similar way of monitoring using the fibre delivery system is presented by Baik et al [40], however they use so-called chromatic filtering to detect power variations and focus shifts. They measure the thermal radiation of the melt pool at different wavelengths and then identify mathematical correlations to calculate the focus shift and power variation. Another way of monitoring the welding process is to measure the plasma charge. Li [42] measures the charge between the nozzle and the work-piece during keyhole welding, enabling to detect keyhole failure, penetration depth, weld perforation, crater formation, weld humping, gap and beam position shift.

The defects, monitoring techniques and ways of controlling the process of welding were summarized in different ways. Kessler [43] describes pre-, in and post-process monitoring, different defects and how to effectively monitor them using two different methods. Wiesemann [44] makes an in-depth look at process monitoring for many different laser techniques. He describes what sensors to use with different methods. Shao and Yan [45] survey on-line monitoring techniques for laser welding, classifying the sensors into acoustic, optic and other types.

3. Conclusions

The detection or suppression of laser welding defects is essential for successful welding applications. A series of different welding defects can be distinguished. Their physical origin is often only partially understood. According to the here presented survey, high speed imaging and mathematical modelling are powerful methods for improved understanding. Nevertheless, according to the complexity of the process, only part of the underlying mechanisms could be revealed until now. Also mathematical modelling of the resulting fracture mechanisms has been conducted.

In-process monitoring of light or acoustic emissions by different sensors enables access to information on the process dynamics in context with the generation of welding defects. Cameras provide images of the top weld pool and keyhole geometry, while photodiode sensors and pyrometers provide more abstract, as information-integrated, but industrially more powerful monitoring. Today mainly empirical correlations between sensor signals and defects led to suitable industrial applications, while there is still a strong need for better understanding of the context process-signal and in turn for more systematic monitoring.

4. Acknowledgements

The authors are grateful to VINNOVA – The Swedish Innovation Agency (project DATLAS, no. 27744-2, project HYBRIGHT, no. 27382-2, and project LOST, no. 2006-00563), to the Kempe Foundation and to the Research Council of Norrbotten for funding the research.

5. References

1. -, Swedish standard, SS-EN ISO 13919-1, p. 27 (1996)
2. A. Matsunawa, S. Katayama, **Understanding physical mechanisms in laser welding for construction of mathematical models**, Welding in the World, Le Soudage Dans Le Monde, v 46, n SPEC, p 27-38 (2002)
3. E. H. Amara, R. Fabbro, F. Hamadi, **Modeling of the melted bath movement induced by the vapour flow in deep penetration laser welding**, Journal of Laser Applications, v 18, n 1, p 2-11 (2006)
4. R. Fabbro, S. Slimani, I. Doudet, F. Coste, F. Briand, **Experimental study of the dynamical coupling between the induced vapour plume and the melt pool for Nd:YAG CW laser welding**, J. Phys. D: Applied Physics, v 39, n 2, p 394-400 (2006)
5. R. Fabbro, S. Slimani, F. Coste, F. Briand, **Study of keyhole behaviour for full penetration Nd:YAG CW laser welding**, Journal of Physics D: Applied Physics, v 38, n 12, p 1881-7 (2005)
6. X. Jin, P. Berger, T. Graf, **Multiple reflections and Fresnel absorption in an actual 3D keyhole during deep penetration laser welding**, Journal of Physics D: Applied Physics, v 39, n 21, p 4703-12 (2006)
7. A. F. H. Kaplan, M. Mizutani, S. Katayama and A. Matsunawa, **Unbounded keyhole collapse and bubble formation during pulsed laser interaction with liquid zinc**, Journal of Physics D: Applied Physics, v 35, p 1218-1228 (2002)

8. K. Nishimoto, H. Mori, **Hot cracking susceptibility in laser weld metal of high nitrogen stainless steel**, *Sci. Techn. Adv. Mat.*, v 5, p. 231-240 (2004)
9. J. F. Gould, S. P. Khurana, T. Li: **Predictions of microstructures when welding automotive advanced high strength steel**, *Weld. J.*, v 85, p 111s-116s (2006)
10. S. Hao, W. K. Liu, B. Moran, F. Vernerey, G. B. Olson, **Multi-scale constitutive model and computational framework for the design of ultra-high strength high toughness steels**, *Comput. Meth. Appl. Mech. Eng.*, v 193, p 1865-1908 (2004)
11. U. Prah, S. Papaefthymiou, V. Uthaisansuk, W. Bleck, J. Sietsma, S. van der Zwaag, **Micromechanics-based modelling of properties and failure of multiphase steels**, *Comp. Mat. Sci.*, v 39, p 17-22 (2007)
12. www.redlake.com
13. www.pco.de
14. www.dantecmt.com
15. www.photron.com
16. A. Fellman, A. Salminen, V. Kujanpää, **A study of the effects of parameters on filler material movements and weld quality in CO₂-laser-MAG hybrid welding**, (NOLAMP10 2005), Luleå, p343-354, (2005)
17. C. Bagger, F. O. Olsen, **Laser welding closed-loop power control**, *Journal of Laser Applications*, v 15, n 1, p 19-24 (2003)
18. A. Ghasempoor, P. Wild, M. Auger, R. Mueller, **Automatic detection of lack of fusion defects in CO₂ laser gear welding**, *J. Laser Appl.*, v 15, n 2, p 77-83 (2003)
19. H. K. Tönshoff, K. Körber, T. Hesse, M. Stallmach, **Increased performance and flexibility of process monitoring for deep penetration laser welding**, ICALEO 2002. 21st Intl. Congress on App. of Lasers and Electro-Optics, p 1105-13 Vol.2 (2002)
20. H.B. Chen, L. Li, D.J. Brookfield, W.M. Steen, **Multi-frequency fibre optic sensors for in-process laser welding quality monitoring**, *NDT&E International*, v 26, n 2, April 1993, p 67-73 (1993)
21. A. Sun, Elijah Kannatey-Asibu, Jr., **Monitoring of laser weld penetration using sensor fusion**, *Journal of Laser Applications*, v 14, n 2, p 114-21 (2002)
22. Y. Kawahito, Seiji Katayama, **In-process monitoring and control for stable production of sound welds in laser microspot lap welding of aluminium alloy**, *Journal of Laser Applications*, v 17, n 1, p 30-37 (2005)
23. B.N. Bad'yanov, A.A. Elizarov, **Application of the step by step approximation method for the computer control of laser welding processes**, *Measurement Techniques*, v 46, n 2, p 162-5 (2003)
24. P. G. Sanders, J. S. Keske, K. H. Leong, G. Kornecki, **Real-time monitoring of laser beam welding using infrared weld emissions**, *J. Laser Appl.*, v 10, p 205-11 (1998)
25. K. Kamimuki, T. Inoue, K. Yasuda, M. Muro, T. Nakabayashi, A. Matsunawa, **Prevention of welding defect by side gas flow and its monitoring method in continous wave Nd:YAG laser welding**, *J. Laser Appl.*, v 14, n 3, p 136-145 (2002)
26. K. Kamimuki, T. Inoue, K. Yasuda, M. Muro, T. Nakabayashi, A. Matsunawa, **Behaviour of monitoring signals during detection of welding defects in YAG laser welding. Study of monitoring technology for YAG laser welding**, *Q. Journal of the Japan Welding Society*, v 20, n 3, August, 2002, p 369-377 (2002)
27. D. Travis, G. Dearden, K. G. Watkins, E.W. Reutzler, R.P. Martukanitz, J.F. Tressler, **Sensing for monitoring of the laser GMAW Hybrid welding process**, ICALEO 2004. 23rd International Congress on Applications of Lasers and Electro-Optics, (2004)

28. S. Postma, R.G.K.M. Arts, **Penetration control in laser welding of sheet metal**, Journal of Laser Applications, v 14, n 4, p 210-214 (2002)
29. J. Petereit, P. Abels, S. Kaierle, C. Kratzsch, E.W. Kreutz, **Failure recognition and online process control in laser beam welding**, ICALEO 2002. 21st International Congress on Applications of Lasers and Electro-Optics, pt. 4, p 2501-9 Vol.4 (2002)
30. M. Kogel-Hollacher, T. Nicolay, A. Kattwinkel, M. G. Muller, J. Muller, **On-line process monitoring in laser material processing-techniques for the industrial environment**, (PICALO 2004), LMP-SC, p 1-4, (2004)
31. J. Beersiek, **New aspects of monitoring with a CMOS camera for laser materials processing**, (ICALEO 2002), pt. 2, p 1181-90 Vol.2 (2002)
32. F. Bardin, A. Cobo, J. M. Lopez-Higuera, O. Collin, P. Aubry, T. Dubois, M. Högström, P. Nylén, P. Jonsson, J. D. C. Jones, D. P. Hand, **Optical techniques for real time penetration monitoring for laser welding**, Applied Optics, v 44, n 19, p 3869-76 (2005)
33. M. Doubenskaia, Ph. Bertrand, I. Smurov, **Optical monitoring of Nd:YAG laser cladding**, Thin Solid Films, v 453-454, p 477-85 (2004)
34. M. Doubenskaia, I. Smurov, **Surface temperature evolution in pulsed laser action of millisecond range**, Appl. Surf. Sci., v 252, n 13 SPEC. ISS., p 4472-4476 (2006)
35. M. Doubenskaia, Ph. Bertrand, H. Pinon, I. Smurov, **On-Line monitoring of Nd-YAG laser lap welding of Zn-coated steel sheets by pyrometer**, Proc. BTLA 2006, St. Petersburg (RUS), p 203-209, (2006)
36. Ph. Bertrand, I. Smurov, D. Grevey, **Application of near infrared pyrometry for continuous ND:YAG laser welding of stainless steel**, Applied Surface Science, v 168, n 1-4, p 182-185 (2000)
37. V.M. Weerasinghe, J.N. Kamalu, R.D. Hibberd, W.M. Steen, **Acoustic signals from laser back reflection**, Optics and Laser Technology, v 22, n 6, p 381-6 (1990)
38. H.P. Gu, W.W. Duley, **A statistical approach to acoustic monitoring of laser welding**, Journal of Physics D: Applied Physics, v 29, n 3, p 556-560 (1996)
39. D.P. Hand, C. Peters, J.D.C. Jones, **Nd:YAG laser welding process monitoring by non-intrusive optical detection in the fibre optic delivery system**, Measurement Science & Technology, v 6, n 9, p 1389-1394 (1995)
40. S.-H. Baik, M.-S. Kim, S.-K. Park, **Process monitoring of laser welding using chromatic filtering of thermal radiation**, Meas. Sci. Technol., v 11, n 12, p 1772-7 (2000)
41. L. Li, **A comparative study of ultrasonic emission characteristics in laser processing**, Applied Surface Science, v 186, n 1-4, p 604-610 (2002)
42. L. Li, D. J. Brookfield, W. M. Steen, **Plasma charge sensor for in-process, non-contact monitoring of the laser welding process**, Measurement Science & Technology, v 7, n 4, p 615-626 (1996)
43. B. Kessler, **Online quality control in high power laser welding**, White paper, Precitec KG, Germany, 2003
44. W. Wiesemann, **Process monitoring and closed loop control**, Landholt-Börnstein – Group VIII Advanced Materials and Technologies, v 1C, Springer Berlin Heidelberg, XVIII, p 243-275, ISBN 978-3-540-00105-8, (2004)
45. J. Shao, Y. Yan, **Review of techniques for on-line monitoring and inspection of laser welding**, Journal of Physics: Conference Series, v 15, n 1, p 101-7 (2005)