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

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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 to 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

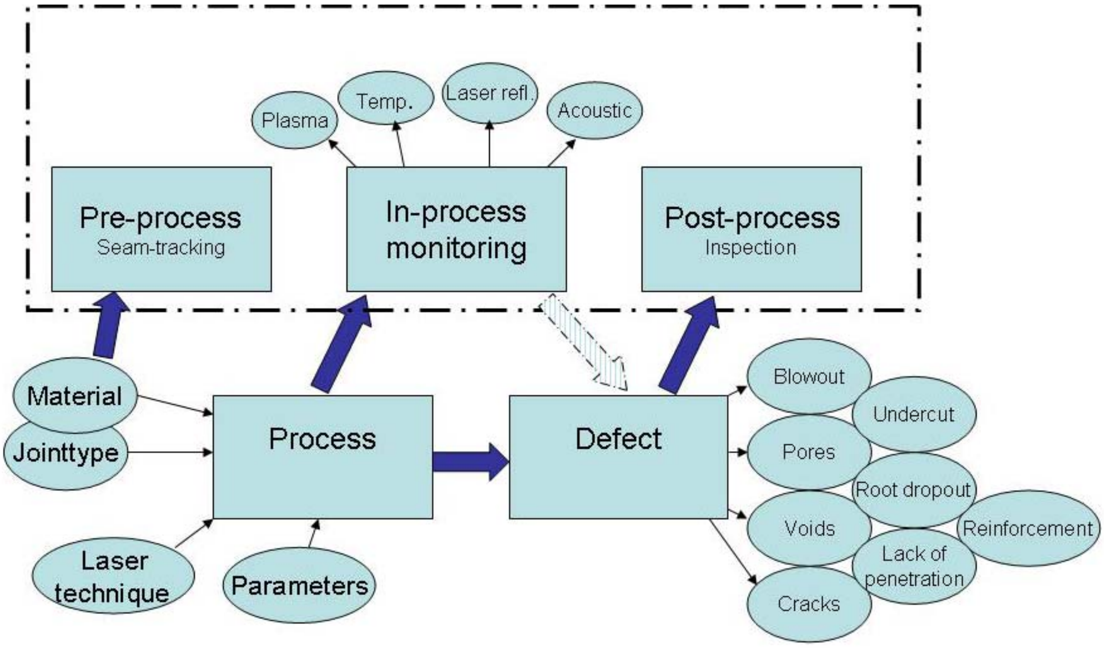


Fig. 1: *Context process-defect and classification of process monitoring/inspection methods*

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 Void	Spherical gas bubble trapped by solidifying material 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.

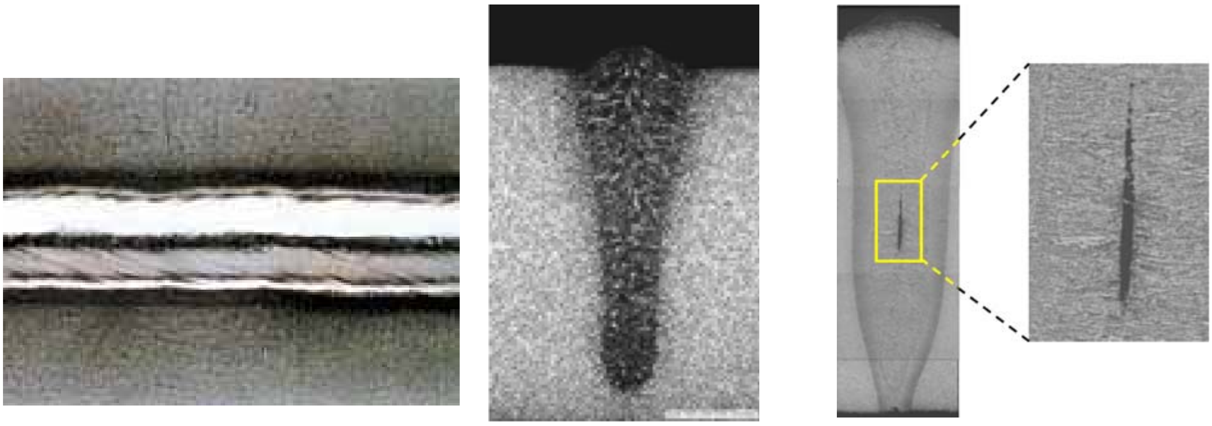


Fig. 2: ***(a)*** *weld surface,* ***(b)*** *cross section for a good joint,* ***(c),(d)*** *hot crack*

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**.

(a)

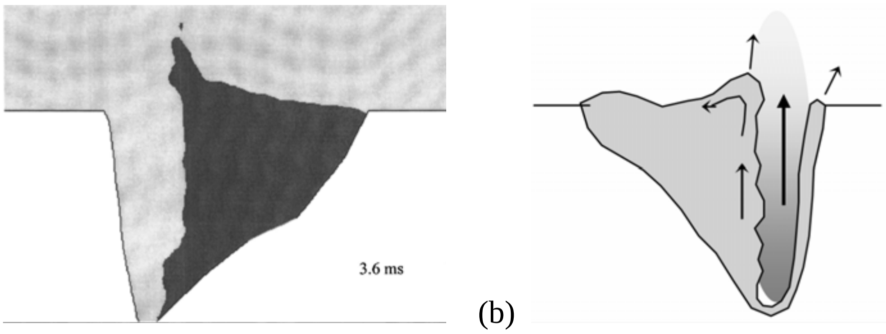
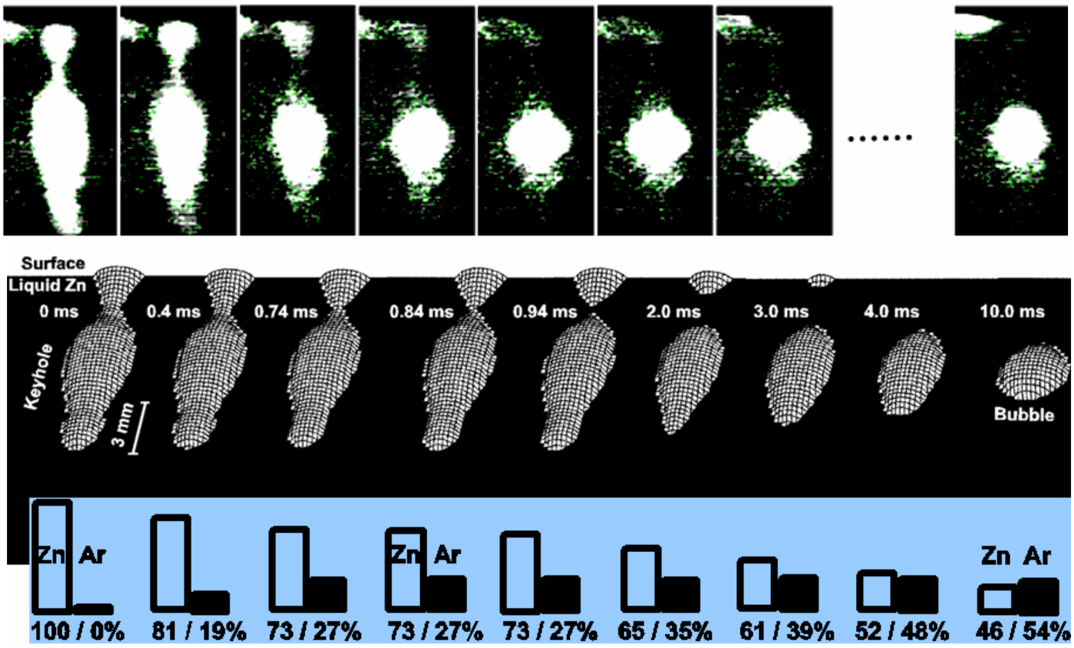


Fig. 3: ***(a)*** *Simulation of the keyhole and melt pool flow,* ***(b)*** *explaining drop ejection [3]*

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.

(a)



(b),(c)

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).**

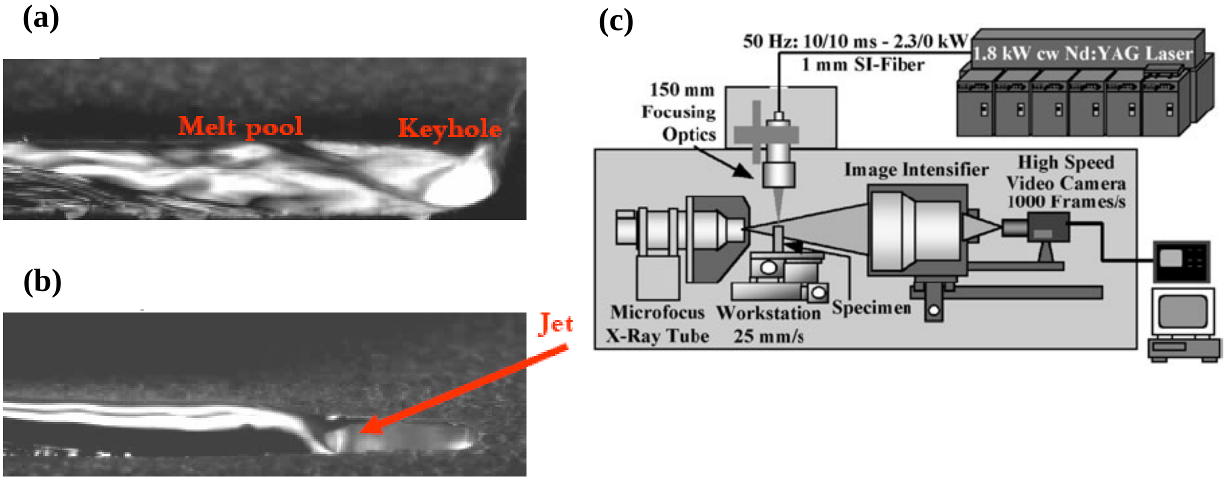


***Figure 5**: High speed imaging of the top side of the melt pool and keyhole [4]: **(a)** weld pool waves, **(b)** calmed weld through an additional gas jet directed to the keyhole rear side. **(c)**Example of a set-up for X-ray high speed imaging [7]*

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	Technoque	Power	Material	Thickness	Joint type	Defect	Inspection type	Monitoring sensor	Control loop
			CO2/ Nd-YAG	cw/ pw	kW		mm					
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=Continous 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 CO_2 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 sensoring 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)**.

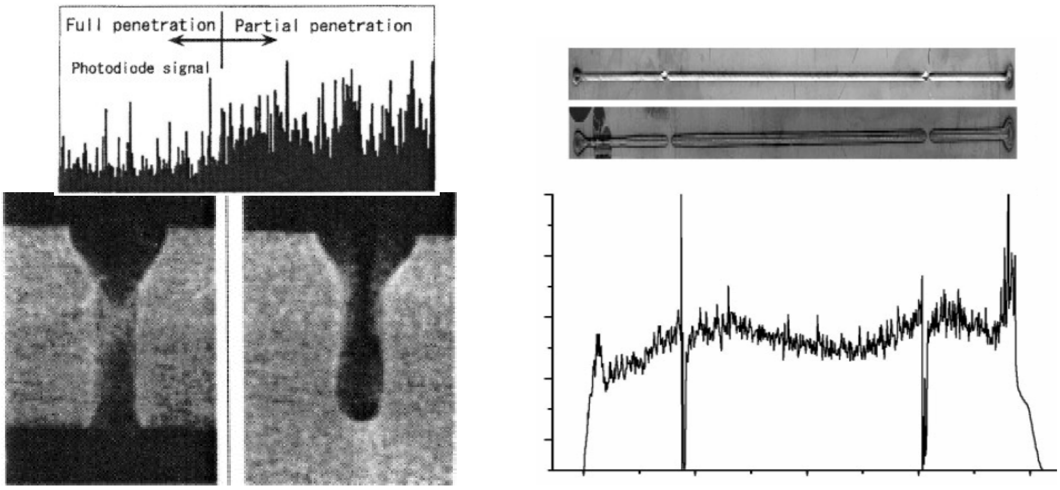


Fig. 6: ***(a)*** *Photodiode signal detecting full vs. partial weld penetration [26];* ***(b)*** *pyrometer signal detecting laser weld interruptions [36]*

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 know. 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.

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