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Monitoring and adaptive control of laser processes

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- Invited Paper -

Abstract

Monitoring of laser processes has been researched actively since the 1980's in several institutes around the world. The goal of process monitoring is to gather information on the process and to improve the understanding of the occurring phenomena, and to use the gathered data to create quality control methods and adaptive, closed loop control of the process. The methods used for laser process monitoring can be divided into optical and acoustic methods of which the optical methods are more common. Today, monitoring has been commercially applied to even the newest laser processes, e.g. additive manufacturing. For laser welding, the process monitoring has been developed even further and closed-loop systems have been demonstrated several years ago. The improvements in digital camera technology and data processing have resulted in development of systems that use feature recognition for determining certain features of the process. Monitoring systems have developed from simple systems using single sensors to a more sophisticated systems utilizing a multitude of different detectors and detection methods.

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Keywords: process monitoring; closed loop control; laser cladding; laser welding; directed energy deposition; powder bed fusion; laser additive manufacturing

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1. Introduction

Any manufacturing process requires monitoring, but depending on the dynamics of the process and the amount of parameters involved in fabrication, the significance of the monitoring increases. Also, as the parameter window of the process narrows, the monitoring becomes more important.

During laser material processing, the laser beam interacts with the material being processed. When the laser beam hits the material surface, it is absorbed, reflected, refracted, scattered or transmitted. These interactions result as heating, melting, vaporization or plasma formation. Depending on the process one or more of the mentioned phenomena may occur during the process.

All of these phenomena present themselves as emission that can be monitored with a variety of different methods. The emission can be divided into radiation, acoustic emission, and electromagnetic emission. According to Lott et al. (2011), the most frequently monitored types of radiation during laser material processing are back reflected laser radiation, plasma or metal vapour induced radiation and thermal radiation.

The aim of this article is to present an overview of non-contact monitoring methods that are used for in-process monitoring of such laser based processes as welding, cladding and additive manufacturing of metallic materials. The overview has been drawn up according to the articles written on monitoring and adaptive control (closed loop systems) of afore mentioned processes. Concerning this overview, it has not been considered important, whether the data analysis has been performed during the monitoring or only afterwards, i.e. off-line.

1.1. Aim of monitoring

Generally the object of monitoring is the improvement of reproducibility and assurance of reliability and quality of the process within a single manufacturing cycle and between several cycles. However, quality assurance and optimisation of the process are not the only aspect concerning monitoring of manufacturing process. The other significant uses for monitoring and monitored data are observing, experimenting, systematic gathering of information and understanding the process and related phenomena, and finally developing adaptability of the process.

Bi et al. (2013, p. 464) have noticed, that applications for monitoring and controlling the laser additive manufacturing process are quite rarely adopted in industry and the process is usually carried out without any monitoring and control. This is probably due to the fact that monitoring equipment is only rarely available for commercial laser additive manufacturing machines. As the manufacturing of a product may take several - even tens or hundreds - of hours, lack of information on the progress and uncertainty of the quality of the finished product may prevent the process from spreading in industry more widely. (Pavlov et al. 2010) As it is known, process monitoring and control are an essential way to reduce the amount of rejects, improve the process reproducibility and save costs.

Often in practical applications the procedure is based on trial and error, that is on empirical and experimental knowledge. According to Zeng (2012), experimental design methods are usually used to test the process parameter effects and predict the temperature using a database collected from experiment or simulation. A more systematic approach is to experiment one factor at a time, which is suitable for reproducible processes, but tends to fail if the result of the process depends on the parameters in a non-linear way.

The beforehand estimation and choice of manufacturing parameters is a difficult and time-consuming task. E.g. the relationship between process parameters and weld quality is complex and therefore in-process monitoring of the welding process is important to avoid time-consuming post-process analysis. (Haran et al. 1997) A recent trend is to create closed loop systems in which the process parameters are automatically controlled. However, creating such a system is not possible, unless the parameters and their effects on process and monitoring data are understood.

2. Monitoring methods for laser processing

Monitoring methods for laser processing are based on the utilization of the consequent physical phenomena that occur due to laser-material interactions. The principle of the operation may be acoustical, optical, electrical or thermal, and the methods are also often combined to improve the performance of monitoring (Vallejo 2013). The methods in this paper are divided into two groups, which are acoustical and optical methods. The thermal methods are included in optical methods. Electrical methods, such as capacitance monitoring, are excluded from this paper. As this article concentrates on monitoring of emissions that are formed during manufacturing, such pre-process or in-process monitoring methods as e.g. wire feed monitoring, laser power monitoring, seam tracking and beam analysis are excluded from this review.

2.1. Optical methods

Deduced from the amount of the written articles, optical methods are used most frequently for monitoring of laser processing. The optical sensing systems are classified in the literature differently depending on the writer. Kenny (2005) divides light detectors as quantum detectors and thermal detectors. This classification bases on the operating method of the detectors. According to Bollig et al. (2005), sensors can be divided into three groups which are diode-based sensors, camera based sensors and light stripe systems. Boillot et al. (1985) classifies the optical systems either active (using external illumination) or passive (without external illumination). Passive systems can be further divided into reflective or emissive systems. A classification that is made by several authors, is a division into spatially resolved (vision systems, e.g. CCD and CMOS cameras), spatially integrated (photodiodes) (Lott et al. 2011) or spectrally resolved (spectrometers) methods/techniques. (Vallejo 2013) Infrared cameras and also pyrometers, which Vallejo (2013) groups into thermal methods, are classified as optical methods in this paper.

The advantages of the optical approach are non-contact operation, versatility and the availability of a large amount of information from the spatial as well as the spectral features of the optical output. (Boillot et al. 1985) Voelkel and Mazumder (1990) justify the use of visual methods by explaining the usefulness of them. However, Köhler et al. (2013) point out that a variety of non-contact temperature monitoring methods lack accuracy due to gas or dust that attenuate the temperature signal in the optical path. In addition to that, optical methods provide only limited information on the material surface structure and therefore additional illumination is required for capturing the surface structure and the melt pool shape. (Lott et al. 2011) As additional illumination does not belong to the core of this article, but it is essentially part of optical monitoring, the subject is discussed briefly.

Active illumination can be arranged by spectrally narrow lamps (Norman et al. 2007) or by laser. External illumination has been arranged e.g. by an array of UV light emitting diodes during laser metal deposition of tool steel H13 (Barua et al. 2011), by green laser (Kong et al. 2012; Kim and Ahn 2012) or by fiber-coupled infrared laser diode during CO_2 laser welding (Palanco et al. 2001 and Salminen 2002). Voelkel and Mazumder (1990) studied the effects of both focused and diffused argon-ion laser beam as illumination during CCD video camera monitoring of CO_2 laser created melt pool. The aim of illumination was to reduce high contrast and the effects of obscuring plasma and specular surface of the melt pool. Voelkel and Mazumder (1990) noticed that passive illumination was entirely insufficient for capturing details of the melt pool and that the melt pool illuminated with only the focused laser beam appeared very dark in figures. The diffuse light alone revealed more details on the area of the melt pool, but the best results were received with the combination of the focused and diffused laser light.

2.2. Acoustic methods

Acoustic sensing techniques could be applied to processes that involve melting, vaporisation, plasma generation and keyhole formation (Li 2002), but also for monitoring e.g. air pressure from the coaxial gas jet, rapid phase change (Lee et al. 2014) and crack propagation (Wang et al. 2008) could be monitored with acoustic sensing techniques.

Acoustic emission involves a sensor which converts process sounds into electrical output to a measurable variable (Shao and Yan 2005). Earlier acoustic emission related to laser processing was collected with sensors attached to work piece. This procedure was though considered problematic (Jon 1985) and therefore non-contact sensing of acoustic emission was considered as more convenient.

2.3. Combining the methods

Combining methods may mean combining different optical monitoring methods or combining acoustic and optical monitoring methods. Combining different optical methods for monitoring laser processes is nowadays a common procedure, but acoustic and optical methods are rarely combined for monitoring, although such a combination might produce interesting data on monitored target.

Lewis and Dixon (1985) used a test setup with a microphone and a photomultiplier for monitoring of plasma behaviour during CO_2 laser welding process. Similar setup was used by Farson et al. (1998), who combined a microphone with two photodiodes. The photodiodes measured wavelengths from 300 to 1000 nm from the top and bottom side of the weld, while the microphone measured the airborne sounds from the welding process. In best cases, the signals showed a clear correlation, which could be also used to determine certain features of the process, e.g. penetration depth. Khosroshahi et al. (2010) utilized a slightly different approach in pulsed CO_2 laser welding. Their setup, which was used for determining the plasma plume profile, consisted of a microphone with a CCD camera.

3. Sensors and detectors in monitoring for laser materials processing

Various types of sensors and detectors are used for measuring the emission generated from the monitored object/target. Some sensors can be used for detecting different types of emission, and often different filtering methods are used to isolate the certain type of emission. One example of this is described by Hu and Kovacevic (2003), who used a high pass filter with a CCD-camera to attain images of the melt pool during a directed energy deposition process. Following sections present the typical optical and acoustical sensors that are used for monitoring laser materials processing.

3.1. Photodiodes

Photodiodes are semiconductors, which convert light into current or voltage. They can be easily integrated into different types of setups and therefore they are commonly used in laser materials processing. They can be used to determine light intensities, and commonly they have a quick response time, which is useful in monitoring of laser materials processing. (Birtalan 2009)

Photodiodes can be used for different wavelengths ranges and they are used in many different systems, e.g. pyrometers, which can be used to remotely determine temperatures of up to thousands of degrees of centigrade. (Culshaw 2014). Typically silicon photodiodes are used for UV and visible wavelengths and indium-gallium-arsenide (InGaAs) photodiodes for visible and IR wavelengths. (Hamamatsu) The wavelength range that the photodiode perceives is often intentionally limited by optical filtering. There are also commercially available process monitoring systems which utilize photodiodes, e.g. Laser Welding Monitor by Precitec, and Plasma Monitor PM 7000 by Prometec.

3.2. Spectrometers

According to Al-Azzawi (2006) and Wolfe (2001), spectrometers are analytical instruments that are used to measure intensities of wavelengths from an observed spectrum. Spectrometers can be described according to their sensitivity, geometric and path configurations and how well they resolve lines. Khater (2013) describes a spectrometer as a monochromator with its exit slit replaced by a multichannel detector interface.

Spectral measurements cover a wide frequency range from gamma rays to microwaves, but the most commercial spectrometers are applied in the ultraviolet and infrared regions (Tan 2013). For laser material processing, the monitored range typically covers ultraviolet and visible wavelengths which are commonly measured with a spectrometer which uses grating or prism technique.

3.3. CCD and CMOS cameras

In the early days of process monitoring, e.g. Locke et al. (1972) as well as Lewis and Dixon (1985) observed the CO_2 laser welding process with film cameras. During the 1990's film cameras were replaced with more usable digital cameras. According to Nakamura (2006), image sensors are semiconductor devices that convert optical image to electronic signals. Charged coupled device (CCD) and complementary metal oxide semiconductor (CMOS) image sensors are currently the most common sensor types used in digital cameras. The most crucial difference between these two sensor types is that with CMOS sensors, some active circuits can be integrated into the pixel structure. By using a suitable optical filtering, both camera types can be used at near-infrared wavelengths. (Habibi, 2014)

3.4. Acoustic emission measurement

According to Vallejo (2013) microphones are used for measuring airborne acoustic emission and piezoelectric detectors are used to detect acoustic emission in solid structures. According to Rasmussen (2014), condenser microphones are most commonly used as measurement microphones. They are constructed of a capacitor, which changes its capacitance according to changes in the measured sound field. The capacitance change can be registered as a change in the output voltage of the microphone.

Safari et al. (2014) describes piezoelectricity as the ability of certain materials to develop electric charge that is proportional to a direct applied mechanical stress. According to Pedersen (2014), ceramic piezoelectric transducers are the most commonly used sensors for detecting e.g. ultrasonic frequencies in structures.

3.5. Pyrometers

According to Barela and Chrzanowski (2000), pyrometers can be classified by the number of spectral bands of the detection system. They can be divided into single-, dual- or multiband systems, which are either passive or active. Passive systems consist of only a receiver and active system consist of a radiation source that co-operates with a receiver. For active system, the measurement procedure has two steps. In the first step, the object emissivity is determined and the second step, the object temperature is determined on the basis of the measured power of the radiation emitted by the object. The distinction between passive or active pyrometers is not usually made in the literature.

Although a dual- or multi-wavelength pyrometer seems to be commonly used non-contact temperature measurement method nowadays, final conclusions on its superiority over monochromatic pyrometer cannot be made due to lack of consistency in experimental reports, as Duvaut (2008) points out. There are no consistent results in studies that prove that a multi-wavelength pyrometer gives more accurate results every time compared to a monochromatic pyrometer.

Generally the use of pyrometers is considered problematic, because thermal measurement with pyrometers is linked with emissivity. For accurate temperature measurement the emissivity of the measurand has to be known or estimated. The estimation of the emissivity is complex especially in those cases, when the emissivity varies rapidly.

3.6. Infrared cameras

CCD and CMOS cameras are not suitable for detecting mid- and long wave infrared radiation, and therefore specific infrared cameras are needed. According to Gade and Moeslund (2013), infrared cameras can be separated into two different categories: cameras with cooled and uncooled detectors, of which uncooled detectors are more commonly used for process monitoring purposes due to their compact size and affordable price. Uncooled detectors can be divided into two basic types, which are ferroelectric detectors or microbolometers. The most common type is a vanadium oxide (VOx) microbolometer, which allows a relatively high spatial resolution and higher sensitivity compared to ferroelectric detectors. As the common glass material, e.g. fused silica, has a very low transmittance of IR-radiation, special materials are needed for the optics of IR-cameras. Germanium is the material commonly used for this purpose. However, the high price of germanium can reduce the availability of different optics for IR-cameras.

4. Closed loop systems

If the real-time monitoring signal is not used for controlling the processing parameters (e.g. power, speed, powder feed rate), the monitoring system is called an open-loop system. The problem concerning open-loop systems is that they do not prevent defects, but instead they only create signal from which the defects can be noticed. For quality and process reliability assurance purposes the interest towards closed loop manufacturing systems and adaptive processes has increased in recent years.

The lack of established quality control or closed loop systems has been the problem e.g. for laser welding (Blug et al. 2011), laser cladding (Hofman et al. 2012) and although at the moment e.g. the machines by SLM Solutions are equipped with a thermal sensor that is used for monitoring the temperature of the melt pool during manufacturing, the data is not being used for adapting the process parameters accordingly.

For laser welding, the closed loop control is typically achieved by optically monitoring either the back reflected laser radiation or plasma plume emission. Huegel et al. (1999) studied the former method during Nd:YAG laser welding of aluminium alloys and were able to show that the amount of back reflected laser radiation correlates with the weld quality. They also found out that back reflected radiation can be used for closed loop control of the weld penetration depth by altering the focal point position. The latter approach has been researched by Gu and Duley (1998). Their setup used two photodiodes, which measured the plasma emitted UV radiation to maintain correct focal point position during CO_2 laser welding of mild steel sheets.

5. Monitoring during laser materials processing

The main aspects that are linked with optical or acoustical monitoring of laser welding, cladding, directed energy deposition or powder bed fusion process are gathered into tables 1, 2, 3 and 4. The first table is dedicated for powder bed fusion processes. Due to the similarity of the processes, laser cladding and directed energy deposition are combined into the second table. The third table is on laser welding with CO_2 laser and the fourth on laser welding with solid state laser.

It is a common procedure to monitor all mentioned laser processes with optical methods as can be seen from the tables 1, 2, 3 and 4. Acoustical methods are only rarely applied for monitoring, although the use of acoustic methods could be useful e.g. for monitoring crack initiation and propagation during manufacturing of materials that are crack susceptible.

During powder bed fusion, the most commonly monitored targets are melt pool temperature and the thermal distribution over the melt pool area (table 1). The images produced by infrared cameras are used for analysing the width, length and shape or stability of the melt pool. Common CCD and CMOS cameras are utilized for studying e.g. balling phenomenon. With a high pass filter CCD and CMOS cameras can be used for IR imaging, which combined with feature recognition can be used as a basis for closed loop controlling.

Table 1. PBF-process monitoring with optical methods. **Method**: A=Acoustical, O=Optical. **Sensor type**: CCD=CCD-camera, CCD(NIR)=CCD camera filtered for near infrared wavelengths, CMOS (NIR)=CMOS camera filtered for near infrared wavelengths, HSC=Unspecified high speed camera, IRC=IR Camera, P=Photodiode, PM=Pyrometer, S=Spectrometer. **AI**=Active illumination. **Material**: CoCr=cobalt-chromium alloy, Cu=copper, Fe alloy=steel alloy, Ni-alloy=nickel alloy SS=stainless steel, Ti=titanium, W=tungsten,. **Target**: MP=melt pool, P=plume, WP=work piece (larger area than the melt pool).

Method	Sensor type	AI	Closed loop	Laser	Operation mode	Material	Target	Reference
O	IRC	-	-	Nd:YAG	CW	Ti	WP	Kolossov et al. (2004)
O	CMOS (NIR), P	-	-	Nd:YAG	CW	Fe alloy	MP	Rombouts et al. (2006)
O	PM	-	-	Fiber	CW	-	MP	Furumoto et al. (2009)
O	HSC, P	-	-	-	-	-	-	Berumen et al. (2010)
O	CMOS (NIR), P	-	Yes	Fiber	CW	-	MP	Craeghs et al. (2010)
O	CCD, PM	-	-	Fiber	CW	Ti	MP	Chivel and Smurov (2010)
O	PM	-	-	Fiber	CW	SS	MP	Pavlov et al. (2010)
O	CMOS (NIR), P	-	-	-	-	-	MP	Craeghs et al. (2011)

Method	Sensor type	AI	Closed loop	Laser	Operation mode	Material	Target	Reference
O	CCD (NIR), PM	-	-	Fiber	CW	Cu, CoCr, W	MP	Chivel and Smurov (2011)
O	CMOS, P	-	-	Fiber	CW	-	MP	Craeghs et al. (2012)
O	CMOS	Yes		Fiber	CW	Alloy steel	WP	Furumoto et al. (2012)
O	IRC	-	-	Fiber	CW	SS	WP	Dadbakhsh et al. (2012)
O	IRC	-	-	Fiber	CW	Ni-alloy	WP	Krauss et al. (2012)
O	CCD, PM, S	Yes	-	Fiber	CW	SS	MP	Hirvimäki et al.(2013)
O	CCD, PM	-	-	Fiber	CW	Cu, CoCr, SS	MP	Chivel (2013)
O	CCD, PM	Yes	-	Fiber	CW	SS	WP	Islam et al. (2013)
O	CMOS, PM	-	-	Fiber	CW	-	MP	Furumoto et al. (2013)
O	CCD	-	-	Fiber	CW	Ti	MP	Yadroitsev et al. (2014)

Table 2. Process monitoring with laser cladding and directed energy deposition (DED) processes. **Method**: A=Acoustical, O=Optical. **Sensor type**: AES=Acoustic emission sensor, CCD=CCD-camera, CCD(NIR)=CCD camera filtered for near infrared wavelengths, IRC=IR Camera, P=Photodiode, PM=Pyrometer. **AI**=Active illumination. **Material**: Brz=bronze, Fe alloy=steel alloy, MMC=metal matrix composite, MS= mild or low carbon steel, Ni-alloy=nickel alloy, SS=stainless steel, Stellite=cobolt alloy, Ti=titanium alloy, Tool steel=tool steel,. **Target**: MP=melt pool, WP=work piece (larger area than the melt pool).

Method	Sensor type	AI	Closed loop	Process	Laser	Operation mode	Material	Target	Reference
O	PM	-	-	Cladding	CO_2	CW	MS, Stellite	WP	Smurov et al. (1994)
O	CCD	-	-	Cladding	Nd:YAG	CW	-	-	Meriaudeau et al. (1997)
O	CCD(NIR)	-	-	DED	Nd:YAG	CW	MS, Tool steel	MP	Hu and Kovacevic (2003)
O	PM	-	-	Cladding	CO_2	CW	MS, Brz, Stellite	MP	Jendrzejewski et al. (2004)
O	PM	-	-	Cladding	Nd:YAG	CW/P	MMC	-	Doubenskaia et al. (2006)
O	CCD, P, PM	-	-	Cladding	Nd:YAG	CW	MS	MP	Bi et al. (2006)
O	PM	-	-	DED	CO_2	CW	SS	MP, WP	Hua et al. (2008)
A	AES	-	-	Cladding	CO_2	CW	MS	WP	Wang et al. (2008)
O	CMOS	Yes	-	DED	Diode	CW	SS	MP	Barua et al. (2011)
O	PM	-	-	DED	CO_2	CW	SS	WP	Yu et al. (2010)
O	PM	-	-	DED	Diode	CW	MS, Tool steel	-	Tang and Landers (2010)
O	IRC, PM	-	-	Cladding	CO_2	CW	MMC, MS	MP	Pavlov et al. (2011)
O	CCD(NIR), IRC, PM	Yes	-	Cladding	CO_2	CW	Ti, MS	MP, WP	Smurov et al. (2012)
O	CMOS	-	-	DED	Fiber	CW	Ti	-	Heralic et al. (2012)
O	CCD	-	Yes	DED	Fiber	CW	Ti	MP	Yu et al. (2012)
O	CCD	Yes	-	Cladding	Fiber	CW	MS, SS	MP	Pekkarinen et al. (2012)
O	IRC, PM	-	-	Cladding	CO_2	CW	MS, Ti	MP	Smurov et al. (2013)
O	IRC	-	-	Cladding	Nd:YAG	CW	Ti	MP	Doubenskaia et al. (2013)
O	PM	-	Yes	DED	Nd:YAG	CW	MS, SS, Ni-alloy	MP	Bi et al. (2013)
O	CMOS, PM	-	Yes	Cladding	Nd:YAG	CW	MS, SS, Stellite	WP	Köhler et al. (2013)

For cladding or directed energy deposition the monitoring targets are typically melt pool or work piece (see table 2). The majority of studies written on laser welding (either with CO_2 laser or solid state laser) concentrate on monitoring plasma or melt pool as can be seen from the tables 3 and 4. Other aspects that also are monitored during laser welding are keyhole, back-reflected radiation, spatter or work piece. Work piece refers in this case to a larger monitored area, not merely the area of melt pool.

Laser cladding and directed energy deposition processes are often monitored with thermal imagers or pyrometers (table 2), which are usually used for determining the temperature of work piece or melt pool. The thermal monitoring during cladding is considered important, because it has been noticed that the quality of the clad can be recognized from the measured temperature signal. (Bi et al. 2006) For melt pool shape monitoring during cladding or directed energy deposition processes it is a common practice to use thermal imagers, see e.g. Smurov et al. (2012) or Hu and Kovacevic (2003).

Table 3. Monitoring of CO_2 laser welding process. **Method**: A=Acoustical, O=Optical. **Sensor type**: AES=Acoustic emission sensor, CCD=CCD-camera, FC=Film camera, HSC=Unspecified high speed camera, IRC=IR Camera, P=Photodiode, PM=Pyrometer, S=Spectrometer, X-ray=X-ray videography. **AI**=Active illumination. **Material**: Al=aluminium or its alloy, Cu=copper or its alloy, HSLA=high strength low alloy steel, Mg=magnesium or its alloy, MS=mild or low carbon steel, SS=stainless steel, Ti = titanium alloy **Target:** BR=back reflected laser radiation, K=Keyhole, MP=Melt pool, P=Plume, S=Spatter, WP=Work piece.

Method	Sensor type	AI	Closed loop	Operation mode	Material	Target	Reference
O	FC	-	-	CW	SS	WP	Locke et al. (1972)
A, O	AES, FC	-	-	CW	SS, Al	P	Lewis and Dixon (1984)
O	P	-	-	CW	-	P	Dowden et al. (1992)
O	PM	-	-	CW	MS	WP	Smurov et al. (1994)
O	P	-	Yes	Pulsed	-	P	Tönshoff et al. (1995)
O	S	-	-	CW	SS	P	Szymanski et al. (1997)
A, O	AES, P	-	-	CW	MS	MP, P	Farson et al. (1998)
O	P	-	-	CW	MS, AL, Mg	P	Sanders et al. (1998)
O	P	-	Yes	CW	MS	P	Gu and Duley (1998)
O	P	-	Yes	CW	Al	BR	Huegel et al. (1999)
O	PM	-	-	CW	MS	WP	Lankalapalli et al. (1999)
O	CCD	-	Yes	CW	MS	P	Dahmen et al. (1999)
O	S	-	-	CW	MS	P	Ferrara et al. (2000)
O	CCD, S	Yes	-	CW	Al	P	Palanco et al. (2001)
O	S	-	-	CW	SS	P	Ancona et al. (2001)
A	AES	-	-	-	MS	K, P	Li (2002)
O	S	-	-	CW	SS	P	Bruncko et al. (2002)
O	P	-	-	CW	MS	P	Sun et al. (2002)
A	AES	-	-	CW	MS	P, WP	Sun et al. (2002)
O	CCD, X-ray	-	-	CW	MS	K	Abels et al. (2003)
O	P	-	-	CW	MS, HSLA	MP, P	Ghasempoor et al. (2003)
O	S	-	-	CW	SS	P	Bruncko et al. (2003)
O	P, S	-	-	CW	SS	P	Hoffman and Szymański (2004)
O	S	-	-	CW	Al	P	Sibillano et al.(2005)
O	S	-	-	CW	Al	P	Sibillano et al. (2006)
O	S	-	-	CW	Al	P	Sibillano et al. (2007)
O	S	-	-	CW	Al	P	Lober and Mazumder (2007)
O	HSC, P	Yes	-	CW	Alloy steels	K, MP	Norman et al. (2009)
O	CCD	-	-	CW	MS	P	Li et al.(2009)
O	S	-	-	-	Al	P	Sibillano et al. (2009)
O	CCD	-	-	CW	MS	S	Fennander et al.(2009)
A, O	AES, CCD	-	-	Pulsed	SS	P	Khosroshahi et al.(2010)
O	P, S	-	Yes	CW	SS	P	Konuk et al. (2011)
O	S	-	-	CW	SS	P	Sibillano et al. (2012)

Table 4. Monitoring of solid state laser welding process. **Method**: A=Acoustical, O=Optical. **Sensor type**: AES=Acoustic emission sensor, CCD=CCD-camera, CCD(NIR)=CCD camera filtered for near infrared wavelengths, CMOS= CMOS-camera, HI=Holographic interferometry, HSC=Unspecified high speed camera, IRC=IR-Camera, P=Photodiode, PM=Pyrometer, S=Spectrometer. **AI**=Active illumination. **Material**: Al=aluminium or its alloy, Cu=copper or its alloy, Mg=magnesium or its alloy, MS=mild or low carbon steel, Ni-alloy=nickel alloy, SS=stainless steel, Ti=titanium alloy **Target:** BR=back reflected laser radiation, K=keyhole, MP=melt pool, P=plume, S=spatter, WP=work piece

Method	Sensor type	AI	Closed loop	Laser	Operation mode	Material	Target	Reference
A	AES, PMT	-	-	Nd:YAG	Pulsed	SS, Al	P	Dixon and Lewis (1985)
O	S	-	-	Nd:YAG	CW	SS	P	Collur and DebRoy (1989)
O	S	-	-	Nd:YAG	Pulsed	SS, Al	WP	Cremers et al. (1991)
O	S	-	-	Nd:YAG	Pulsed	SS	P	Lacroix et al. (1996)
O	P	-	Yes	Nd:YAG	CW	MS, Al, SS, Ti	-	Haran et al. (1997)
O	S	-	-	Nd:YAG	CW	SS, Ti	P	Fox et al. (1998)
O	P	-	Yes	Nd:YAG	CW	Al	BR	Huegel et al. (1999)
O	P	-	-	Nd:YAG	Pulsed	MS	MP, P	Ricciardi et al. (1999)
O	P	-	-	Nd:YAG	Pulsed	MS, Al, Mg	P	Sanders et al. (1998)
O	P	-	-	Nd:YAG	Pulsed	-	-	Lim (1999)
O	PM	-	-	Nd:YAG	CW	SS	MP, WP	Bertrand et al. (2000)
O	HI, P	-	-	Nd:YAG	Pulsed	SS	P	Baik et al. (2001)
O	HI, P	-	-	Nd:YAG	Pulsed	SS	P	Kang et al. (2001)
O	P	-	Yes	Nd:YAG	CW	MS	BR, P	Postma et al. (2002)
O	CMOS, PM	-	Yes	Nd:YAG	CW	Ti, Ni-alloy	BR, MP	Bardin et al. (2005)
O	CMOS	-	-	Nd:YAG	CW	Al	MP	Bardin et al. (2005/II)
O	S	-	-	Nd:YAG	Pulsed	MS	P	Sabbaghzadeh et al. (2007)
O	P, S	-	-	Fiber	CW	Ti	P	Colombo and Previtali (2010)
O	PM	-	Yes	Nd:YAG	Pulsed	Cu	MP	Stehr et al. (2010)
O	P, S	-	Yes	Disk	CW	SS	P	Konuk et al. (2011)
O	P	-	-	Nd:YAG	CW	MS	BR, P, WP	Olsson et al. (2011)
O	CMOS	-	Yes	Fiber	CW	SS	MP	Gao et al. (2012)
O	CCD, S	-	-	Fiber	CW	MS	MP, P	Kong et al. (2012)
O	S	-	-	Fiber	CW	SS	P	Sibillano et al. (2012)
O	S	-	-	Nd:YAG	Pulsed	SS	P	Sebestova et al. (2012)
O	CCD, CCD(NIR), P	-	-	Disk	CW	SS	K, MP, P, WP	You et al. (2013/II)
O	HSC	-	-	Disk	-	MS	P	Brock et al.(2013)
O	HSC	-	-	Disk	CW	SS	P, S	You et al. (2013/I)
O	CMOS, S	-	-	Fiber	-	Cu	BR, MP, P	Oezmert et al. (2013)
O	HSC	Yes	-	Fiber	CW	SS	K, MP, P, S	Zhang et al.(2013)
O	CCD, CCD(NIR)	-	-	Disk	-	SS	S	You et al.(2014)
O	CCD, S	Yes	-	Fiber	CW	Mg	P	Harooni et al.(2014)
A	AES	-	-	Nd:YAG	CW	SS	WP	Lee et al. (2014)

Although plasma can be monitored either with optical or acoustical methods, the optical methods are evidently (see tables 3 and 4) more often applied for monitoring plasma-emitted radiation. The methods for monitoring and evaluating the electromagnetic emission generated during the material-laser beam-interaction are most commonly photodiode-based (Sibillano et al. 2012), but spectroscopy is also often applied for evaluating the laser plasma. (Colombo and Previtali 2010) However, nowadays it is a common practice to combine these methods with other methods, e.g. with CCD or CMOS camera. It is more common to combine at least two different sensors for monitoring solid state laser welding, but for CO_2 laser welding such a procedure is more rarely applied.

Monitoring of plasma-emitted radiation is considered important, because optical emission in the UV-visible and near-infrared ranges can give information on plume characteristics as composition, electron temperature, electron density and absorption coefficient. It has also been noticed that plasma instabilities correlate with the weld defects. (Ancona et al. 2001) Also the correlation between back reflected radiation and the weld penetration has been noticed that therefore back reflected radiation is considered as an important target for monitoring.

According to the reviewed articles, spectrometers are not used for closed loop systems. Instead, photodiodes and high-speed cameras are most commonly used for that purpose. E.g. Bardin et al. (2005/I) have compiled a system which utilized multiple photodiodes and a CMOS camera to monitor the keyhole behaviour. Based on the image information, a closed loop control for laser power with LabVIEW software was constructed. The focal point control is based on the emissions from the melt pool. These emissions are split into three different ranges – UV-visible, back reflected laser radiation and IR radiation – and each of these is measured with a separate photodiode. A signal related to the deviation from the optimum focal point is generated by subtracting the UV-visible signal from the IR signal. This calculated signal is then used as the control signal for the focal point translation stage.

Due to a large number of different non-contact monitoring methods only some of them can be listed on the previously presented tables. Other methods that have been used on monitoring of keyhole during laser welding are e.g. X-ray (Vänskä et al. 2013) or Cellular-Neural-Network-camera (Abt et al. 2011). Barua et al. (2014) have used SLR-camera (single-lens reflex) on monitoring temperature and defects during laser metal deposition of stainless steel.

6. Concluding remarks

The radiation emitted by the plasma or metal vapor plume during laser materials processing correlates with the process quality in laser welding. Also the melt pool behavior provides feasible information in laser welding, powder bed fusion and also directed energy deposition and laser cladding processes. The methods used for monitoring laser processes are usually optical methods, not acoustic methods. The problem of acoustic methods is that airborne acoustic emission can be subjected to disturbances and thus considered unreliable. On the other hand, structure borne acoustic emission monitoring could provide more reliable results.

Closed loop systems have developed from systems that utilize a simple sensor (e.g. photodiode), to systems that make use of more complicated detectors (e.g. camera systems with feature recognition). Such systems can be utilized e.g. for measuring changes in keyhole shape and size, which in turn can be used for controlling laser power and focal point position. Another application of feature recognition is the detection of melt pool shape, which can be useful in laser welding but also with cladding, directed energy deposition and powder bed fusion processes.

Laser welding has been the most monitored of the processes discussed in this paper due to its numerous industrial applications. As the number of different studies on laser welding monitoring is large, the overview on this subject in this paper has to be considered limited. The review in this paper is based mostly on peer-reviewed research articles, but as the aim of many research processes is to develop a system that could be commercialized, the applied patents would be another source of data. This applies to other processes than laser welding as well.

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