2.8 Process monitoring and closed-loop control

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2.8.1 Introduction

It is a well known paradigm of modern production strategy to accomplish product quality by safely mastered process technologies rather than by off-line inspection of the production lot. Mastering any sophisticated process technology commonly relies on more or less sophisticated on-line monitoring or closed-loop process control means. While monitoring systems will immediately create failure messages in case of detected not allowed process irregularities, closed-loop control systems are designed to continue the process by applying appropriate feedback actions in order to instantaneously compensate the beginning decrease of process quality. Monitoring means are also being used in scientific environments to gain a better understanding of the interaction process of the laser radiation and the material.

Laser material treatment basically is a thermal process taking place in the interaction zone where the laser radiation is hitting the workpiece. The treatment process can be considered as a complexly coupled system of subprocesses like laser energy deposition, energy transformation and dissipation by temperature increase and heat conduction, material phase transition, flow dynamics of the liquid and gaseous phases, and radiation emission. By properly adjusting the strength of the interaction process and by simultaneously applying suitable solid, liquid or gaseous assist materials, directed or diffuse, pressured or not, the workpiece can be cut, drilled, welded, soldered, bent, partially ablated, sintered, or surface-treated.

Up to now the majority of the standard industrial laser material treatment machines, mainly used for cutting and marking, are operating without process monitoring means with up times close to 100 %. Obviously this is due to the high level of the machines' reliability. Standardly a big number of machine parameters like supply voltages, laser output power, cooling system and structure temperatures, stand-off distance of the cutting-head nozzle, etc. is closed-loop controlled. Within the scope of this chapter this is not regarded as process surveillance. In case of machine malfunctions most machine suppliers are capable of checking or even adjusting the relevant machine parameters remotely via telemetry.

However, there exist a few more issues being relevant to the treatment performance. For example, there are some important properties of the laser beam like, e.g., focal beam diameter or focal energy density distribution which cannot be monitored directly during the process. They may vary unnoticed since they are strongly influenced by barely detectable minor deformations of the beam shaping and guiding mirrors and lenses. The deformations – though occurring quite infrequently – result from thermal expansion in case there is an increased laser power absorption caused by damages or uncleanness of the optical surfaces.

In total, process-related machine parameters like beam parameters or feed speed as well as parameters characterizing the assist material and workpiece condition are called process input parameters. They determine the performance and conditions of the interaction process which in turn is characterized by a multitude of intrinsic process parameters like energy input efficiency, liquid and gaseous phase dynamics, temperature gradient in the workpiece near the interaction zone, etc.

Furthermore, there are workpiece features like thermal conductivity, reflectivity, melting and vaporization temperature, viscosity of the molten material, chemical reactivity, etc., which define important boundary conditions for the design of laser treatment processes and for the adjustment of the machine parameters. Quality problems may arise, if one or more of the workpiece parameters vary across the processing track. Such variations can be caused by internal chemical or structural irregularities. Also, workpiece surface irregularities like uncleanness or shape distortions may occur.

Finally, stochastically occurring short-term process-inherent disturbances like, e.g., plasma or particle shielding or strong laser radiation reflections from highly reflecting liquid parts of the workpiece into the laser resonator may severely deteriorate the treatment process.

Fortunately, there is a certain margin for the parameters to fluctuate in without seriously affecting the quality of the treatment result. The range of permissible variations for all relevant process parameters is called process window. The width of that multi-dimensional window of course is depending on the specific kind of treatment and on the required degree of quality.

Permanently meeting the process window during long production time periods is a critical issue for a growing number of innovative treatment applications. Even for standard applications there will be a growing demand for the documentation and evidence of regular treatment conditions due to the increasing importance of international quality standards. This is calling for an increased use of process-surveillance methods, too.

In the following sections the basics of laser-treatment surveillance methods are outlined and some examples are given which characterize the state of the art of the scientific activities and industrial applications. Finally, an attempt is made to foresee future developments.

2.8.2 Basics of process monitoring and closed-loop control

2.8.2.1 General

On-line process surveillance has to be based on monitoring some significant indicator(s) for the instantaneous condition of the laser-beam interaction zone and/or adjacent areas, since the reactions within that region are determining the quality of the laser treatment. Evidently, process monitoring means have to operate contactless since there must be no disturbing influence on the interaction zone. Fortunately, this requirement creates no problem because laser material treatment is accompanied by a variety of remotely observable treatment phenomena: depending on its temperature and shape the interaction zone is emitting more or less strong electromagnetic radiation and, during some types of treatment, acoustic radiation also. Gaseous and sometimes liquid workpiece material carrying electrical charge and emitting electromagnetic radiation may be ejected, and backscattering of laser power from the interaction zone may occur to some extend. All these process output phenomena carry some potential to be used as indicators of the process condition and, implicitly, of the treatment quality.

The process output phenomena are quantitatively characterized by process output parameters which can be measured by suitable sensors. The sensor signals are carrying more or less hidden information on the condition of the process and, hence, the treatment result. As a simple example, the detection of the optical radiation emission of a workpiece being surface-treated for hardening allows a fair estimation of the temperature of the emitting part of the surface. The temperature in turn is indicating the depth of hardening if the interaction time is kept constant.

Obviously, the design of process-surveillance systems has to be adapted to the particular application. This first of all includes the identification of the most suitable output parameter that has to be monitored. In the following, process output parameters which can be used for quality control are called quality indicators. Furthermore, a suitable signal assessment method has to be prepared.

As part of the assessment, filed information on the influence of all possibly occurring conditions of the process on the treatment result and on the selected quality indicator has to be used in some automatic mode. This information has to be gained by thorough research, if not already available, and has to be stored in real-time accessible data formats for any specific application.

In the following sections the basics of process-surveillance methods are outlined. This includes the discussion of the industrial and scientific user's motivation for establishing process surveillance means, the description of methods for quality indicator detection, signal assessment, and the discussion of the limits for the achievable span of surveillance.

2.8.2.2 Process-surveillance objectives and strategies

Process-surveillance methods are supporting routine industrial laser-treatment applications as well as scientific work aimed to a better theoretical understanding of the laser-treatment processes. The general structure of the different types of process surveillance is sketched in Fig. 2.8.1. The scope of support is briefly addressed below.

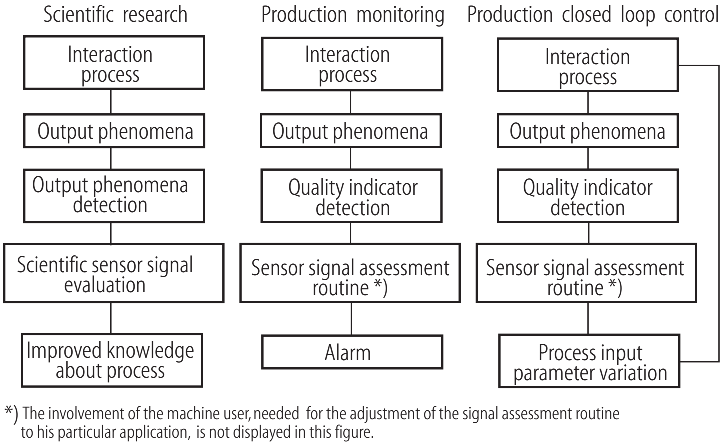

Fig. 2.8.1. General structure of process-surveillance methods.

2.8.2.2.1 Support for scientific research by monitoring of process output parameters

Today's understanding of the interaction between the laser beam and the treated material was gained by thorough research on the influence of the process input parameters on the interaction subprocesses and on the treatment result. The research is still in progress. It is covering an increasing variety of materials which had been regarded to be untreatable or, at least, permitting just poor treatment quality like, e.g., composites, ceramics, Zn coated steel, and materials having extraordinary high reflectivity and thermal diffusivity. The work is being supported by a multitude of scientific process output parameter monitoring and evaluation methods. They are mainly based on optical and acoustic sensing methods which had to be developed for this purpose. As an example, by detecting the optical radiation emission of the plasma/vapor plume created during steel welding and measuring the intensity ratio of two suitable emission lines of Fe atoms the temperature and density of the plume can be calculated and correlated to theoretical models as well as to the treatment results. Occasionally, scientific monitoring schemes have been further adapted for successful industrial use. However, there are also purely scientific designs like, e.g., the X-ray transmission techniques for the on-line monitoring of bubble and pore formation and key hole dynamics, which cannot be transferred to industrial production sites.

2.8.2.2.2 On-line treatment fault probability assessment and documentation during serial production

Most of the relevant machine-related process input parameters are standardly closed-loop controlled in today's laser machines. The numerical parameter levels to be maintained by these control systems are determined by figures to be defined specifically for any treatment application. During the treatment the instantaneous parameter levels are being monitored by machine-integrated detectors like power meters, flow meters, etc. The detectors are not directly linked to the treatment process. Hence this kind of closed-loop control is not further discussed in the following sections.

However, there are several additional input parameters like focal-plane beam features and chemical, dimensional or structural workpiece conditions which are strongly affecting the treatment result but, as a common feature, cannot be closed-loop controlled by the machine-integrated means mentioned above. Depending on the specific situation this may bring up the need for a direct on-line surveillance of one or more treatment quality indicators. If the treatment fault probability calculated on-line exceeds a predetermined level, failure messages may be generated. Retrospective analysis of the recorded process surveillance data may help to trace the origin of the treatment fault. As an example, it can be distinguished quite easily whether a faulty condition occurred suddenly or grew up during several production cycles. At the highest level of current system sophistication, automatic fault class determination may be accomplished to some extend. Even if no faults are detected, the recorded data may be needed to meet the requirements of internationally standardized quality assurance systems.

2.8.2.2.3 Closed-loop control during serial production

By monitoring a few or just one quality indicator(s) and further assessment of the detected signal(s), a controllable process input parameter like beam power, feed speed or focal point position is being automatically adjusted in case the signal assessment is indicating a treatment deterioration. This scheme, however, is still suffering from the fact, that the input parameters which are available for closed-loop control actions as well as the quality indicators are by far outnumbered by the variety of potentially occurring irregularities. Even if there were more suitable input parameters, the system would have to "decide" which of them had to be varied to what extend. Therefore, closed-loop process control systems have to be designed very specifically for the individual treatment application of interest. In particular, they have to be focused just to a few – or even only one – potentially occurring irregularities like, for example, the slightly varying thickness of the sheet during high-speed thin-sheet cutting or the excessive gap width between the sheets during overlap welding.

At a higher level of sophistication, automatic fault tracing and compensating methods are under development for future use. As a prerequisite the cause of any detected relevant treatment irregularity has to be analyzed automatically and traced on-line to its origin. Only then the appropriate process input parameter(s) can be selected by the assessment circuit as control variable(s) for an effective fault-compensating feedback action. However, tracing the origin of faults is complicated by the mutual interdependencies of the numerous intrinsic process parameters. Also, it cannot be foreseen up to now that for any commonly occurring origin of faults future research activities will come up with a suitable process input parameter, which is capable to compensate the treatment irregularities sufficiently and without creating process disturbing side effects. For example, while the axial shift of the laser-beam focus position relative to the workpiece surface created by a slight thermal deformation of the focusing lens or mirror can be monitored and compensated during welding, an increase of the focal beam diameter created simultaneously for the same reason or by, e.g., the plasma plume, cannot be traced unambiguously. Even if it could be traced, it could not be compensated correctly by means of the currently applicable methods.

2.8.2.3 Treatment quality indicators, span of surveillance

Laser-treatment quality is commonly being judged according to some criteria, which are non-exhaustively listed in Table 2.8.1. Concerning the ease of the on-line judgement, the criteria can be classified into two categories: directly and not directly assessable criteria like, e.g., spatter ejection and the degree of weld penetration, respectively.

As already mentioned, the instantaneous condition of the interaction zone is determining the intensity of appearance of the output phenomena. An overview of relevant process output phenomena is given in Table 2.8.2. These phenomena can be characterized quantitatively by numerous process output parameters. For example, the electromagnetic radiation emission of the key hole can be characterized by parameters like, e.g., the spectral frequency pattern, the angular emission

Table 2.8.1. Quality criteria for laser-treatment results.

Laser treatment	Quality criteria
Cutting and drilling	- cut kerf shape (walls flat, parallel and correct angle to surface, shape of edges) - hole shape (walls cylindrical and correct angle to surface) - dross attachment - increased heat-affected zone - surface contamination (spatter, oxidation) - occurrence of cracks (ceramics cutting) - incomplete penetration - burns - surface roughness of cut kerf - accuracy of cut contour
Welding	- occurrence of disturbed seam surface shape (underfill, crater pits, top bead depression, etc.) - spatter occurrence - degree of penetration - occurrence of cracks and porosity - occurrence of incomplete fusion - seam cross section area
Hardening	- depth of hardness - lateral hardness depth profile - occurrence of overheating - degree of hardness - lateral profile of degree of hardness
Alloying and cladding	- constancy of layer thickness and mixing ratio - occurrence of cracks, pores - lateral layer homogeneity - fusion with substrate
Caving	- smoothness of surface - accuracy of depth profile

Table 2.8.2. Process output phenomena.

Process	Phenomenon [a]	Commonly used types of detectors [d]
Cutting and drilling	e.r. emission from interaction zone	photo diode (VIS, IR)
	gaseous workpiece material ejections	photo diode, capacitive
	fluid workpiece particle ejections	photo diode (IR), capacitive
	l.r. scattered back from interaction zone	[b]
	l.r. passing through the kerf	[b]
	acoustic emission	microphone
Welding	e.r. emission from vapor or plasma plume	photo diode (UV, VIS), electronic camera
	e.r. emission from keyhole opening wall [c]	photo diode (VIS, IR), electronic camera
	e.r. emission from keyhole finger part [c]	off-axis photo diode (VIS, IR), on-axis electronic camera
	e.r. emission of melt pool and neighboring area	photo diode (VIS, IR), electronic camera
	acoustic emission through keyhole opening	microphone
	electrical charge of plasma plume	charge-collecting device
	fluid workpiece particle ejections	photo diode (IR)
	l.r. scattered back from interaction zone	[b]
	e.r. emission from the backside of the workpiece	photo diode (IR)
Hardening	e.r. emission of interaction zone	photo diode (VIS, IR)
Alloying and cladding	e.r. emission of interaction zone	photo diode (VIS, IR)
Caving	e.r. emission of interaction zone	photo diode (VIS)
Cleaning	acoustic emission from surface	microphone
	e.r. emission of plume	photo diode (VIS)

[a] e.r.: electromagnetic radiation, l.r.: laser radiation.

[b] Ge- or InGaS-photo diode for Nd:YAG radiation ($\lambda = 1.06$ μm); HgCdTe, pyroelectric detector, bolometer for CO_2 laser radiation ($\lambda = 10.6$ μm).

[c] Keyhole formation occurring during deep penetration only.

[d] Spectral range: IR = infrared, VIS = visible, UV = ultraviolet.

[e] Plasma = ionized vapor containing free electrons.

pattern, mean radiation intensity, variance of radiation intensity time histories, frequency pattern of intensity fluctuations, etc., and combinations and derivatives of these and other parameters.

Basically, the instantaneous condition of the treatment process is determining the treatment quality. Due to this linkage the surveillance of relevant output phenomena is ideally suited to support the on-line assessment of the treatment quality. In fact, it has been shown in numerous applications that several relevant laser-treatment quality degradations can be concluded on-line from monitoring a few, or just one, selected process output parameters. These parameters then may serve as treatment quality indicators for monitoring systems, however not necessarily for closed-loop control systems. In order to be used for reliable process surveillance, quality indicators have to meet some basic requirements. Ideally, they comply with the following requirements:

1. There must be well-known unambiguous functional dependencies of at least one quality indicator on the most relevant treatment-quality criteria for the considered application (limited span of surveillance).
2. Full span of surveillance: There must be well-known unambiguous functional dependencies of a limited number of quality indicators on all relevant treatment-quality criteria for the considered application.

3. There must be an on-line assessment method available for any treatment-quality indicator signal.
4. The quality indicator must not be susceptible to any intrinsic process parameter without relevance to the treatment quality.
5. The general noise level of the processed sensor signal has to be significantly lower than the sensor signal variations created by relevant process disturbances.

Concerning the span of surveillance it should be considered that in any complex system the probability of the occurrence and the severity and impact of system faults are depending on the type of the particular fault. For laser material treatment there are numerous process-parameter irregularities which potentially may occur in general. Actually, though, occasionally just a few types of relevant irregularities are occurring in practice, if machine, process design, and workpiece preparation meet the state of the art. Consequently, surveillance effort may be focused to a small number of quality indicators, which may be different for different applications. Monitoring more than one quality indicator however usually calls for more sophisticated multiple-sensor arrangements. Depending on the probability ranking of the occurrence of process irregularities in a particular treatment application, it may even be sufficient to concentrate on the monitoring of just one quality indicator. The given laser-treatment situation and the expected results therefore determine the effort devoted to fault-preventing precautions and to the degree of sophistication of monitoring or closed-loop control systems.

2.8.2.4 Process output parameter detection

2.8.2.4.1 Theoretical introduction

As can be seen from Table 2.8.2, electromagnetic radiation emission is the most frequently occurring output phenomenon. Laser radiation is a special case of electromagnetic radiation. The heated ejected materials are emitting electromagnetic radiation, too. Therefore, all phenomena listed in Table 2.8.2 except for the acoustic emissions can be detected with electromagnetic radiation sensors like photo diodes, electronic cameras, pyroelectric detectors, bolometers, etc.

For an ideal black body[1] having the absolute temperature T the electromagnetic radiation energy emitted per second (also called radiation power or intensity) and per surface area unit throughout the entire wavelength spectrum is determined by:

$$\int W_\lambda \, \mathrm{d}\lambda = \sigma T^4 \,, \tag{2.8.1}$$

where $\sigma = 5.669 \times 10^{-8}\ \mathrm{Wm^{-2}\,K^{-4}}$, λ = wavelength and W_λ = energy emitted per second and per surface area unit within the wavelength interval $\mathrm{d}\lambda$.

The temperature of the emitter does not only determine the intensity but also the distribution of W_λ across the electromagnetic wavelength range and, thereby, the position of the radiation maximum $W_{\lambda,\,\max}$. The relation between the temperature and the wavelength $\lambda_{\max}$ of the maximum $W_{\lambda,\,\max}$ of W_λ is given by:

$$\lambda_{\max}\, T = \text{const.} = 2898\ \mu\mathrm{m\,K} \,. \tag{2.8.2}$$

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[1] A radiating "black body" is realized approximately by an isotropically heated cavity, where the dimensions of the radiation-emitting cavity opening are small compared to the cavity's inner dimensions. The opening of an unheated black body therefore appears black to the human eye. The emission of real objects is lower than the emission of a black body of the same temperature. The ratio of the real emission and the emission of a black body is called emissivity.

In general, $\lambda_{\max}$ decreases with increasing temperature. For example, the intensity maximum of materials having room temperature ($T \approx 293$ K) is located in the 10 μm region. The radiation intensity maximum of steel being transformation-hardened ($T \approx 1100$ K) is located just below the 3 μm wavelength region, and there is also a detectable intensity contribution in the visible region.

For gases, the intensity of the emitted radiation is also increasing for rising temperatures. However, the electromagnetic emission spectra of gases are more complex than those of solids or liquids. In general, gaseous spectra exhibit sharp peaks (line emission) located at specific wavelengths which are typical for the emitting chemical element. Commonly occuring line emissions may range from the near ultraviolet to the far infrared spectral region depending on the type and the level of energy excitation of the emitting gas. The spacing between the lines emitted in a particular spectral region may be so small, that individual lines cannot be distinguished unless highly resolving means are used for recording the spectra. Plasma spectra may also show a comparatively weak continuum emission created by electron-ion recombination and electron Bremsstrahlung.

2.8.2.4.2 Radiation emission from the interaction zone

In total, the electromagnetic radiation emitted from the interaction zone contains contributions from heated solid, fluid, and gaseous parts of the workpiece and of the assist material(s). The radiation in its entirety is called process radiation. The detectors respond to all contributing parts of the emission which are covered by their spectral and angular detection characteristics. However, depending on the type of process phenomenon to be detected, just a part of the process radiation carries relevant information. All other parts contribute to the detector signal noise level or even create interferences. Consequently, to enhance surveillance significance and reliability, reducing the broadband detector receiving characteristics frequently is advantageous. This can be done by using spectral-selective means like optical filters or spectrometers.

Normally, the emission of laser-generated vapor and plasma of the workpiece material and assist gas is monitored in the ultraviolet and visible region while the radiation of the heated solid or liquid parts of the interaction zone is observed in the visible and near infrared region. As can be seen from Fig. 2.8.2, CO_2-laser-created weld-process radiation is typically exhibiting a strong UV/blue component which is missing in the Nd:YAG-laser-created process radiation. This component stems from the plasma[2] originated from the steel vapor by strong absorption of the laser radiation. Furthermore, some strong argon assist gas lines are present. Due to its shorter wavelength and for intensities below 10^8 Wcm^{-2}, Nd:YAG-laser radiation is weakly absorbed by the vapor and no plasma formation occurs. Due to spectral clipping of the receiving optical components, the strong short-wavelength plasma components (300…400 nm) of the CO_2-laser weld emissions are not fully developed in Fig. 2.8.2. The intensity emitted by the fluid parts of the interaction zone increases continuously in the near infrared region until reaching the maximum which is located in the 2…3 μm region according to (2.8.2).

2.8.2.4.3 Radiation reflection and transmission at the interaction zone

A fraction of the impinging laser radiation is reflected at the interaction zone. Since the power level and the angular distribution of the reflected radiation is dependent on the shape of that area, these parameters carry some implicit information on the status of the process. Additionally, a small part emerges from the backside of the workpiece in the cases of piercing breakthrough, cutting, and full-penetration welding.

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[2] Plasma = (partly) ionized gas; ionization in that case created due to strong laser radiation absorption.

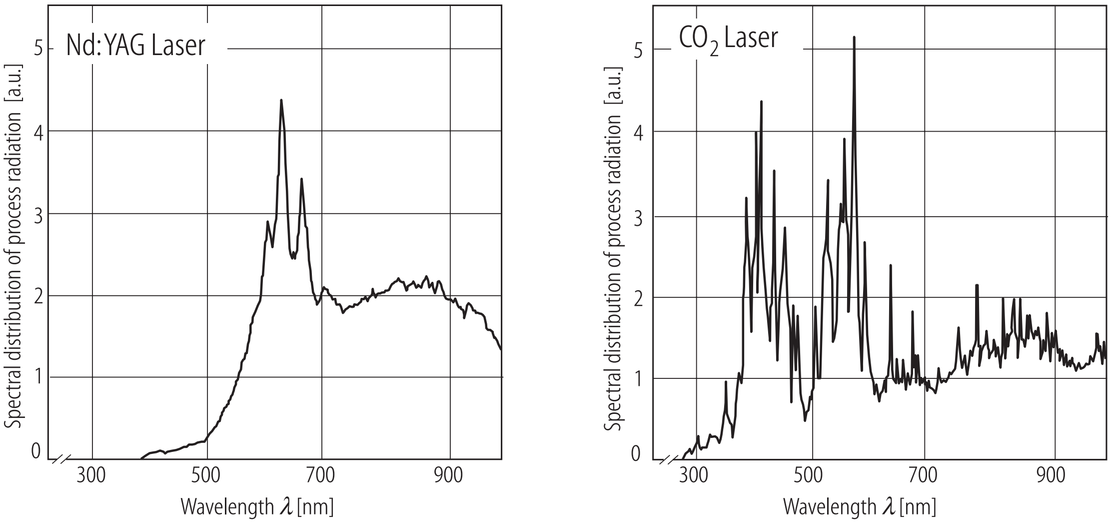

Fig. 2.8.2. Spectral distribution of process radiation created during welding with an Nd:YAG and CO_2 laser. Mild steel, thickness: 5 mm, assist gas: argon [98Tsu]. The curves are modulated by the spectral characteristics of the optical instruments (see text).

2.8.2.4.4 Radiation detection and sensor arrangement

Depending on the process output phenomenon to be observed in a particular application, the sensors and radiation antennas like lenses, mirrors, and front ends of fiber-optical cables may be placed inside or outside the laser-beam delivery systems, above the workpiece or, quite seldom, under the workpiece. Antennas which are placed coaxially with respect to the laser beam axis are providing on-axis insight into the interaction zone. This may be preferable for all three-dimensionally shaped interaction zones occurring during drilling, cutting and key hole welding, where the deeper parts of the interaction zone are blocked against off-axis detection directions. Electromagnetic radiation emitted from the interaction zone of surface treatment applications, from the weld pool, from vapor or plasma plumes, and from spatters can be detected by off-axis antennas as well. On-axis detection needs some beam-separating elements like pinhole mirrors, diffractive bending mirrors, and birefringent mirrors (Fig. 2.8.3).

For cutting and welding there may be a speed-dependent lag of the position of the lower part of the key hole or cut front with respect to the upper part due to the relative movement between laser beam and workpiece. This results in bended key holes or cut fronts. As a consequence, in such cases the upwards guided radiation is maximum in front of the laser beam axis. In any case, all radiation emissions from lower parts of the interaction zone will be superimposed by radiation contributions from upper parts.

Obviously, signals detected at different off-axis angles may contain information from different parts of the interaction zone. Moreover, off-axis signals may be used in multi-sensor schemes to subtract the influence of the upper parts of the interaction zone from the on-axis measured signals to get almost unobstructed information from the deeper interaction zone parts. If the vapor density of the emitted cloud is very low compared to the keyhole vapor density, the vapor/plasma emissions of the deeper interaction zone parts can be estimated with on-axis detector configurations only.

In order to concentrate the signal evaluation on specifically selected relevant parts of interest of the interaction zone and adjacent areas, the angular field of view of the optical detection systems can be limited by optical means like apertures.

For welding, the observable emission strength of most of the optical output phenomena from the interaction zone is non-isotropic with respect to the observation angle relative to the feed direction. Therefore, for fixed sensors the influence of non-isotropic emissions during varying movement

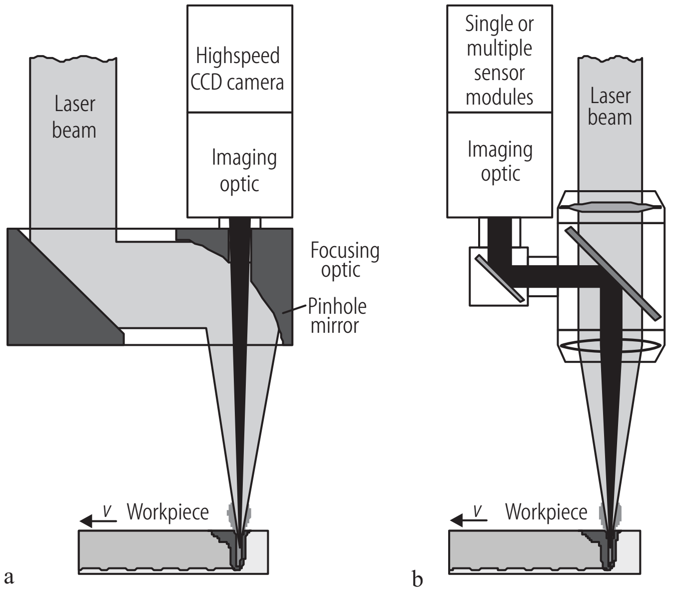

Fig. 2.8.3. Examples for on-axis sensor arrangements. Separation of the imaging beam achieved **(a)** by a scraper mirror for CO_2-laser applications and **(b)** by a birefringent mirror for Nd:YAG-laser applications. By courtesy of Fraunhofer Institut für Lasertechnik, Aachen, Germany.

directions has to be taken into account by, e.g., experimentally taught correction functions. Alternatively, the sensors have to be turned synchronously to any turns of the feed direction.

As already mentioned, optical process radiation can be analyzed with respect to its spectral properties, too. Broadband analysis, as shown in Fig. 2.8.2, is performed by compact spectrographs. Better resolution, up to the discrimination of single emission lines of gases, separated from each other by even less than 0.05 nm, can be achieved by more space-consumptive systems. If a multichannel detection design is used, the speed of the system is determined by the electro-optical components. Narrowband spectral regions of particular interest can also be selected by optical filters, placed in front of photo diodes, having a minimum bandwidth of several nanometers. As mentioned above, the spectral features of the electromagnetic emission carry information on the temperature and on the elemental consistence of the emitting material. Particular emission lines contained in the plasma radiation can be used to calculate temperature and density of the free electrons, which in turn are influenced by the condition of the interaction zone.

Nd:YAG lasers operate in the near infrared region, having an emission wavelength of 1.06 µm. The power level of the laser beam reflections from the interaction zone normally is several orders of magnitude stronger than the process radiation. Therefore, process radiation detectors having a residual sensitivity in the near-infrared region have to be protected against saturating overload by efficient filtering of Nd:YAG-laser stray light, even if the process radiation to be detected stems from the visible spectral region.

2.8.2.4.5 Two-dimensionally resolved radiation emission

Photo diodes integrate the detected radiation laterally across their field of view. Signal processing can therefore only be performed in the domain of time and time derivatives. Electronic camera signals additionally contain valuable information on the radiation distribution in the domain of space yielding two-dimensionally resolved information on the radiative situation of the interaction zone. If arranged in triangulation setups, cameras also may yield 3-dimensional information. Optionally, color cameras give some rough information on the radiation wavelength region. For on-line usage the relevant information content of the camera signals has to be extracted and assessed in time intervals which at least have to be equal to the typical fluctuation time periods of the phenomena to be observed. Some relevant process output parameters may vary significantly within milliseconds. This calls for extremely speedy hard- and software which have to be designed and adapted specifically to any particular application. Up to now, this has been accomplished just in a few cases of production-line applications. However, post-treatment evaluation of high-speed electronic-camera information content is also a valuable tool to support scientific work on the general understanding of laser-treatment processes. Cameras are preferably used in off-axis configurations, but a few on-axis designs have been realized, too.

2.8.2.4.6 Sound detection

Acoustic signals are also created in the interaction zone. Airborne sound is created by the emission of vaporized workpiece material. The vapor is ejected with considerable high flow-speed rates which may range up to several hundred meters per second. Due to beam-workpiece dynamics and resonance effects the ejections are discontinuous. The emerging vapor requires a displacement of the surrounding atmosphere which in turn acts as a source of airborne sound. Sound intensity and frequency spectrum depend on the vapor flow rate fluctuations which of course are influenced significantly by the above mentioned dynamics. Therefore, sound analysis may be considered a tool for monitoring the instantaneous condition of the interaction zone, too. Typical vapor-created sound frequencies are ranging in the audible region. Microphones having a frequency response bandwidth of 20 Hz. . . 20 kHz are convenient for the process-sound pick-up. Workpiece-borne sound may also occur, having frequency bandwidths which range up to 200 kHz. They may also carry information on treatment quality aspects like crack formation, penetration depth, etc., but the sound pick-up has to be accomplished inconveniently by transducers coupled firmly to the workpiece. Airborne acoustic emissions during cleaning treatments are carrying information on the laser flux and the cleanliness of the surface.

2.8.2.4.7 Electrical-charge detection

Due to their high temperature, the gaseous emissions from the interaction zone are electrically charged since they contain free electrons and ions. This can be used for sensing the strength of the emissions by, e.g., charge-collecting devices or by measuring the electrical conductance between the workpiece and an electrode placed near the workpiece, preferably concentrically around the laser beam. For cutting and drilling applications the nozzle of the processing head may serve as an electrode for the detection of charged particles. It should be noted, though, that the particle concentration is subject to rapid variations. Normally, it decreases with increasing distance to the interaction zone due to temperature decrease and recombination, but the particle concentration of gaseous clouds may also increase by the absorption of CO_2-laser radiation.

2.8.2.4.8 Multiple-sensor fusion

It has been demonstrated that combinations of different types of sensors like photo diode and electronic camera, or photo diode and microphone, or combinations of photo diode and filter arrangements being sensitive to either the IR, VIS or UV spectral region, sometimes being aimed at different parts of the interaction zone, give an increased significance for the detection and classification of treatment faults and at the same time reduce the false alarm probability by, e.g., correlation-based signal assessment methods. When correlating acoustic signals to optical signals the time delay due to the comparatively low speed of sound has to be considered.

2.8.2.5 Signal assessment methods

The sensor signals representing the quality indicators selected for a particular surveillance task have to be assessed on-line according to a suitable strategy. The assessment is accomplished in real-time or stepwise in very short time periods, yielding the information needed to create some on-line reactions like setting alarm, stopping the process or perform a closed-loop control action. The user interface, containing means for setting and adjusting the assessment parameters and for the visualization of the assessment results, usually runs under non-real-time conditions. The general structure of such assessment methods is outlined in this section.

While the number of suitable treatment quality indicators is limited by physics, there are less limitations for designing signal assessment strategies. Consequently, a multitude of signal-processing and fault-evaluating methods have been created according to the specific situation of any particular treatment application. Basically, however, all assessment methods created so far for serial production surveillance are structured quite similarly. They are based on the thesis, that constant quality of the treatment results can be accomplished only if there is a good repeatability of the interaction zone condition for any repeated treatment cycle. As a consequence, fairly repeated process output parameters and quality indicator time history patterns for any treatment cycle are created, too. Therefore, as a common element of the assessment methods discussed here, the assessment results are finally achieved by judging the preprocessed sensor signal formats according to some kind of referencing information. This information has to be gained for any individual surveillance system and particular application by the system itself under the condition of accepted treatment quality prior to the start of serial production. The judging is performed according to some general system-inherent criteria which have to be fine tuned by the machine user with respect to the particular treatment situation and quality demands.

In a quite simple design the preprocessed sensor signal is compared with one or more preset upper and/or lower signal level(s), see Fig. 2.8.4. In case of exceeding these thresholds, alarm or control actions may be taken. More sophisticated, prior to any action the instantaneous deviations from the thresholds are being analyzed with respect to the amount and/or the time duration and, sometimes, the frequency of occurrence during predefined time periods. Depending on the application, the preset thresholds are either constant during the entire treatment period or they

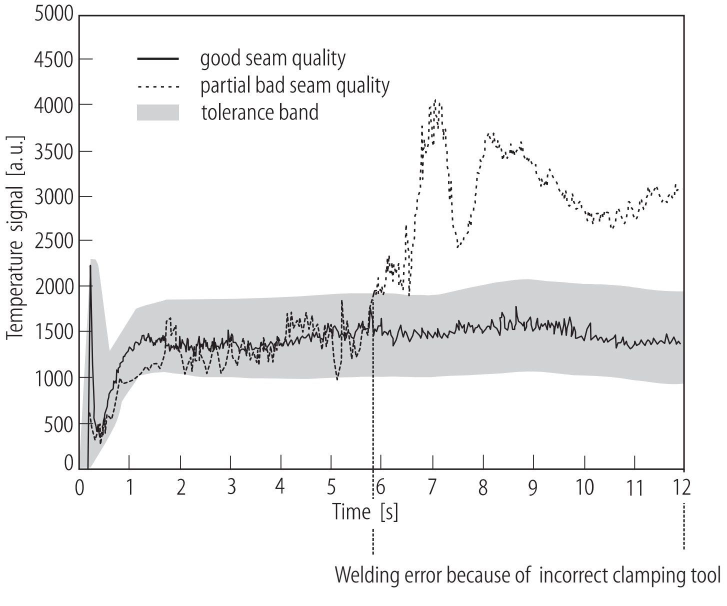

Fig. 2.8.4. Signal assessment by thresholds. By courtesy of Precitec Optronik, Rodgau, Germany.

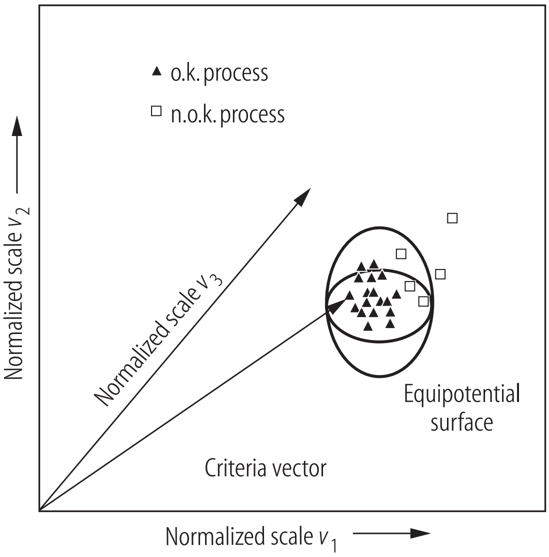

Fig. 2.8.5. Signal assessment by criteria vectors in a 3-dimensional space. By courtesy of LZH, Germany.

can be ramped or taught from recorded data taken under conditions that produced acceptable treatment results. The thresholds may also be allowed for slow floating to some predefined extend during the production shift by using automatically updating refreshing modes. This method allows for the adaptation to some expected, but not avoidable treatment-inherent long-term drift effects of the process, which are not significantly affecting the treatment quality.

Further improvement of the reliability of process surveillance systems can be achieved by multi-sensor fusion systems. In this case the sensor signals are assessed isolated from each other to some extend. The outputs then are linked to each other and assessed as a set in a final stage. This, for example, can be done by creating criteria in a multi-dimensional space, see Fig. 2.8.5.

Obviously, the performance of signal-assessing circuits using predefined referencing information depends on the user's skills about the acquisition of this information, especially setting the thresholds, because there are no general guidelines to be applied for this task. This mainly results from the fact that there are no general rules for theoretically defining the range of the maximum permissible variations of the process parameters, referred to earlier as process window. The widths of the process windows depend on the respective laser-treatment process, the workpiece parameters, and on the particular level of quality required for the particular treatment result. Consequently, they have to be examined experimentally. Therefore, apart from very few exceptions, any current signal-assessing circuit needs the cooperation of a skilled laser machine user for defining the appropriate thresholds or, e.g., the limits of a multi-dimensional decision space which represent the transition from acceptable to non-acceptable treatment quality. By defining these limits the user can emphasize either maximum detection safety or minimum false-alarm probability but reduced fault-detection safety.

Some significant differences between the assessment methods developed so far result from the signal-processing techniques. To give an overview, the numerous techniques are arranged below into the groups of time-domain analysis, frequency-domain analysis, and statistical and neural analysis. The latter methods are also in use for the final assessment stage.

Time-domain analysis: The on-line preprocessing of the instantaneous sensor signal, which has to be sensitive to the relevant quality indicator, may be done by various types of electronic filtering or integrating. Moreover, time derivatives of the signal may be useful for further assessment. Integrating may be applied for time periods ranging from short subsequent or selected processing periods to the entire duration of one treatment cycle. The latter, of course cannot be regarded as a true on-line technique.

Frequency-domain analysis: As mentioned earlier, the time-domain analysis may be sensitive to spurious process-inherent performance changes of the treatment system, the detection system, or the environment, which are not relevant to the treatment quality. Resulting false alarms may be avoided not only by the floating-threshold method mentioned above but also to some extend by analyzing the sensor signal in the frequency domain. In this case the strengths of the signals within selected characteristic frequency bandwidths are compared with each other and/or with preset figures or taught functions as described above. Furthermore, for some applications frequency-domain analysis may yield an increased fault-discrimination performance by, e.g., yielding higher signal-to-noise ratios and at the same time increased inclinations of the quality indicator characteristics. However, frequency-domain analysis by definition needs some time if performed by mathematical means (Fast Fourier Transformation FFT, estimate of signal power spectrum).

Statistical and neural analysis: At a higher level of sophistication and more time consuming, statistical and neural algorithms and correlation computing methods are being used mainly in post-treatment modes in scientific environments. Some of the post-treatment methods developed so far carry the potential of being speeded up to real-time performance which is necessary for on-line usage in industrial production sites. In a few cases experimental real-time neural networks have demonstrated superior reliability in terms of fault-detection probability and defect class separation.

Neural networks are supposed to provide self-adapting capabilities to the machines in the future. However, as a prerequisite, training sets have to be generated for teaching the network to distinguish "ordinary" data events corresponding to acceptable treatment quality from "extraordinary" data events corresponding to unacceptable treatment faults. Presently, it seems to be extremely difficult to create training sets which define one of these events in its entirety. As a consequence, in the near future neural networks most probably will not enable surveillance systems to perform completely self-adapting functions. They will, however, significantly increase the reliability of multiple-sensor fusion-based process-monitoring systems.

A special format of signals to be assessed is produced by electronic cameras. In this case, digital processing techniques generate sets of characteristic numerical figures for every frame according to the application-specific data compressing and extracting algorithms. These figures then may be directly compared against predefined data sets or taught functions. Prior to this last stage of assessment they may be further processed in the frequency domain or by using statistical or neural algorithms. However, due to the high data rate and the speed requirements for the data-processing routines, relatively few camera-based systems were reported so far to be capable of on-line surveillance applications.

The various signal evaluation techniques can be distinguished, among other criteria, by their speed of evaluation. A slow evaluation speed, of course, delays the overall response time of the surveillance system. For closed-loop control systems the response time has to be shorter than the rise time of the irregularity to be compensated. Depending on the kind of irregularity the appropriate rise time may vary by several orders of magnitude. There are stochastic short-term irregularities like keyhole collapsing or spatter ejection affecting the process just for some milliseconds or even shorter, but creating severe treatment defects. On the other hand, there are long-term drifts elongated during hours or days like focal-length variation due to an increasing dust contamination of the lens surface.

2.8.2.6 Control actions

There are several kinds of control actions which may be taken if process surveillance is indicating the beginning of a faulty treatment. The most simple kind of reaction is setting alarm and stopping the process instantaneously. Depending on the kind of treatment application it may be feasible then to restart the process automatically at a workpiece position shortly in front of the fault or at the very beginning. This retry function has up to now been integrated just in some standard software configurations for cutting applications.

Closed-loop control is obviously the most advanced kind of reaction since it keeps the machine producing accepted quality without loss of time. The general structure of closed-loop systems is shown in Sect. 2.8.2.2, Fig. 2.8.1. While there are several process output parameters which are suitable to serve as quality indicators, only a few process input parameters have been used so far as controlling parameters for closed-loop control actions. They are listed in Table 2.8.3. Examples of realized applications are given in Sect. 2.8.3. As mentioned earlier, for a process input parameter to be suitable for closed-loop control, it has to carry the potential to compensate the most probably occurring process disturbances.

Table 2.8.3. Parameters suitable for closed-loop control.

Controlled parameter	Commonly used controlling variable
Total beam power	Average laser material excitation energy
Time of beam-workpiece interaction	Feed speed Beam scanning deflection velocity Excitation energy pulse duration modulation
Axial focus position	Axial lens position Focal length variation by adaptive mirror
Nozzle stand-off distance	Axial position of the focusing head
Lateral beam power distribution	Individually controlled fiber matrix element power delivery Segmented adaptive mirror
Assist material supply	Supply rate (ejection pressure, flow-channel cross section, wire feed speed)

Up to now just a few closed-loop control systems based on quality indicator monitoring have been realized. The process input parameter preferably used for control actions is the laser beam power. This is reflecting the fact that the subprocesses involved in the energy transfer from the beam to the workpiece have a tendency to become unstable, especially during welding and drilling treatments. Moreover, laser power may be reflected back in short bursts from the workpiece into the laser resonator via the beam-guiding system stochastically and at remarkable intensity levels causing strong short-term output-power variations. The need for closed-loop power control also may stem from surface conditions influencing the absorptivity, from the heat sink capacity, which is depending on the mass volume directly surrounding the interaction zone, and on the temperature of this area immediately before the treatment. All these parameters may vary considerably and cannot entirely be predetermined along the processing track.

The energy input into the workpiece can also be varied by controlling the beam-workpiece interaction time. This is accomplished by either changing the workpiece feed speed or the speed of the processing head or the deflection velocity in case a beam scanner is used or by changing the pulse width in case a pulsed laser excitation is used.

By changing the axial position of the focus point, the radius of the impinging beam and consequently the beam power density are varied. The axial position can be changed by simply varying the distance between the focusing head and the workpiece, which however also changes the position of other relevant parts of the head like assist gas nozzles. This can be avoided by movement of the focusing element only or, more speedy, by variations of the focal length performed by beam forming elements (mirror, lens) having controllable radii of curvature.

The stand-off distance of the nozzle of cutting and drilling heads commonly is controlled by axial movements of the entire heads. This, of course, also changes the axial focus position.

The flow rate of gaseous assist materials can be controlled by valves, placed as near as possible to the ejection opening, which determine the internal pressure of the material, or by mass flow meters. The supply rate of filler wire is controlled by motors determining the feed speed.

2.8.3 State of the art of process monitoring and control technology

As discussed in Sect. 2.8.2.2, process-surveillance methods are useful for both scientific and industrial use. The continuous improvement of the mastering of the laser-treatment processes was accompanied from the beginning by process-monitoring means. Pioneering work was done by acoustic and optical monitoring of welding processes and preferably optical monitoring of cutting processes.

The improvement of monitoring methods gained some speed roughly during the late 1980 decade and yielded a variety of new process-surveillance schemes and patent applications, but comparatively few methods were introduced for industrial use during the next ten years [88Bec, 91Jor, 93Miy, 96Kai]. During the last years, however, a growing number of international publications demonstrated the general feasibility and improved reliability of on-line process surveillance techniques. Recent scientific effort is mainly directed to enhance the level of the detection probability of faulty parts and to automatically identify the cause of the faults. There also has been remarkable progress in the theoretical understanding and modeling of laser treatment processes, which was supported by experimental validation based on innovative process-monitoring methods.

Industrial process surveillance proved to be helpful in particular for the laser welding technology to penetrate the markets of large lot-size production. This preferably applies for parts, where structural and/or functional reliability of the final products are key issues. In such cases international production quality assurance standards or at least treatment documentation regulations have to be met. While there are still no standards for the on-line surveillance of the laser treatment quality, there is a growing number of matured methods for industrial on-line process monitoring. For a specific treatment application the most suitable method can be selected and assessed according to its potential of becoming part of the individual production-line quality assurance system that is required by the applying general international standard. Industrial process monitoring also may yield advantages if no standards apply. Depending on the specific circumstances, process monitoring may avoid or reduce the effort and uncertainty of on-line visual inspection or the cost and delay effects of destructive post-process analyses. Skillfully designed signal-processing systems based on taught reference data additionally provide fault class separation capability. This, for the time being, shortens the down-time, and is one of several prerequisites for the design of future highly automated autonomous production cells.

In the following sections an overview is given on the state of the art of scientific and industrial process surveillance. Due to the large number of publications and patents covering this subject just an exemplary selection can be referenced to. The bigger part of them is dealing with welding applications.

2.8.3.1 Cutting and drilling

2.8.3.1.1 General

Process input parameters influencing the treatment quality of cutting and drilling applications are: lateral laser power density profile, polarization, focus point position relative to the nozzle opening and to the workpiece surface, beam axis inclination relative to the workpiece surface inclination, shape and stand-off distance of the nozzle, cutting speed, workpiece pre-process temperature, pressure and chemical consistence of the assist gas, workpiece consistence and surface cleanliness. The tolerable maximum margins of fluctuations of these parameters determine the process window of a particular treatment. For a wide range of laser-treatment applications the optimum set of parameter figures are filed by the machines' manufacturers. For standard cutting applications the process-window boundaries are comfortably spaced as a result of the continued improvement of the laser-cutting process technology. Also post-process inspection of cutting, drilling and marking results usually can be performed if considered to be necessary. Consequently, the use of process-monitoring means is quite rare but operators still have to be available on site to take appropriate actions in case of obvious process malfunctions.

To ensure constant cutting quality the nozzle stand-off distance is being controlled contactless routinely in many cutting machines [88Top]. A constant stand-off distance between cutting-nozzle front surface and upper workpiece surface ensures a constant lens distance during the treatment as well as unchanged flow characteristics of the assist gas for every repeated production cycle. The permissible stand-off tolerance range is about $\pm 0.05 \ldots \pm 0.25$ mm, depending on the beam characteristic and on the type of application. However, the variations of shape and position of workpieces to be cut in serial production with high-power lasers frequently exceed this tolerance range, which brings up the need for a stand-off distance control. Additionally, due to thermal deformation caused by the heat dissipated from the interaction zone the z-position of the workpiece surface may change during the treatment.

The process windows are getting considerably smaller if the treatments are expected to meet the utmost currently achievable limits of quality or productivity. In such cases the use of process monitoring or closed-loop control systems should be considered.

Comparatively small process windows are also typical for non-standard cutting situations. These include the treatment of highly heat-conducting metals like copper, highly reflecting metals like aluminum, highly reactive materials such as titanium, or metals with increased viscosity of the liquid phase like stainless steel, if the workpiece thickness exceeds certain limits. In the past these limits have been extended continuously towards higher figures.

It should be noted that for running any production-monitoring or closed-loop control system the cooperation of the machine user is needed for adjusting the threshold conditions like, e.g., alarm levels of the signal assessment routines, according to the particular situation of his application.

2.8.3.1.2 Scientific research

2.8.3.1.2.1 Cutting

During the early times of commercial laser cutting considerable research has already been started on the potential of on-line monitoring of the cutting process based on the detection of spatter emerging from the lower side of the workpiece [83Ols], diode detection [84Ish, 86Dec] as well as CCD detection [88Ols] of light emitted from the interaction zone towards the cutting head and laser light passing through the cut front [88Ols]. Later, additional insight into the details of the cutting process was gained [92Miy, 92Ols, 94Hil] resulting in some significant process optimizations. Special emphasis was drawn to the detection of increased roughness, striations and burns of the cut surface of mild steel by photo-diode detection of the light reflected or emitted from the cut front [91Jor, 96Kap, 97Dec] or by air-borne sound detection [92Ols]. It was shown, that the dominating frequency of the diode signal frequency spectrum increases with decreasing roughness and that the diode signal variance increases with increasing roughness and dross attachment while the signal mean value increases significantly in the case of incomplete cuts. CCD-camera analysis of the heat-affected-zone area was reported to correlate to some extend with the cut quality of thin (0.5 mm) stainless steel, too [98Haf]. Camera analysis was also used for the study of the dynamics when cutting transparent material such as soda lime glass [76Ara]. Reflections of the laser radiation were used for the detection of poor cutting quality of aluminum [92Ols]. Minimizing the occurrence and dimensions of cracks during cutting alumina ceramics was accomplished by a closed-loop laser-beam-pulse-frequency control based on the detection of the radiation emission of the plasma plume [98Toe]. Closed-loop process control based on plasma-plume intensity detection was suggested to increase the stability of the cutting process close to the maximum feed speed range for cutting thick (up to 8.5 mm reported) stainless steel [01Toe]. Furthermore, it has been shown that plasma-plume intensity detection can be used for an automatic focal point search and detection routine [02Pre]. By using a CCD camera aligned coaxially to the laser beam axis the mild steel melt dynamics have been monitored [99Abe] in order to support the dross and ripple formation analysis by mathematical modeling [99Sch].

Except for the diode detection of cut-front emissions during high-speed cutting none of these layouts has been further developed and frequently used for routine applications in industrial production sites. This is due to the general high level of reliability of the cutting process mentioned above.

2.8.3.1.2.2 Drilling, piercing

Relatively little research work has been done for monitoring or controlling the drilling and piercing process. In general, the same detection techniques as for cutting are applicable. By measuring the infrared radiation (900 nm) emitted from the interaction zone a laser-pulse-width control system was established which kept the temperature of the interaction zone between an upper and lower limit during oxygen-assisted piercing [89Abe]. Smaller hole diameters for oxygen-assisted piercing of mild steel and shortened piercing times for stainless steel drilling were yielded by this method.

The detection of radiation emitted from the interaction zone also permits the identification of the moment of the breakthrough. Some patents are focused to this subject [91Sch, 96Spo], however, the technique is limited to relatively low aspect ratios (depth-to-diameter-ratio). By measuring the intensity of the reflected laser light or the light of an additional low-power probe laser the time of the breakthrough can be detected, too, up to an aspect ratio of at least 25. The significance of acoustic emissions for breakthrough detection seems to be comparatively limited. They may serve as an additional indicator for future multi-sensor systems, though.

Drilling transparent material has been documented by the use of high-speed photographic images to investigate the instantaneous drilling velocity and melt flow dynamics [00Low].

In case of drilling glass-epoxy-printed wired boards, the end of the process, reaching the bottom copper foil surface, clearly can be recognized by the detection of an increased level of the reflected laser power. Process productivity could be increased by 30 % and the variations of the bottom diameter of the holes could be reduced significantly [98Kar]. By measuring the light emission from the bottom of the hole, layers of residual epoxy resin can be detected if the layer thickness exceeds 2 μm [99Miy2]. Formation of droplets and plasma during CO_2-laser drilling of alumina ceramic has been investigated by high-speed videography (exposure time 10 ns) [02Vil].

The drilling of small hollow workpieces like turbine blades is a non-standard application calling for process control in order to safely achieve the breakthrough and at the same time prevent damages of the inner surface adjacent to the hole. Detection of the radiation emission of the backing material was proposed to solve this problem [00Bec].

2.8.3.1.3 Industrial applications

Apart from standardly used non-contact capacitive nozzle stand-off distance control systems, there are a few industrially used on-line cutting-process control systems aimed at productivity increase:

During piercing, the bottom of the interaction zone produces remarkable light and plasma/vapor emissions. If the aspect ratio does not exceed a certain limit, the emissions can be detected by optical or electronic sensors commonly integrated into the cutting head or placed somewhere along the direction of the laser beam without clipping it. By comparing the instantaneous signal level with a preset minimum value, the end of the piercing process can be detected and cutting can be started immediately without the need for any preprogrammed time-consuming safety margin. Incomplete penetration and even dross formation during the cutting process can be monitored by the same method and a retry function can be started by the machine's CNC.

The emissions are also being used for closed-loop control of the piercing and cutting process. Piercing can be performed in different modes. "Soft" modes avoid material overheating. They take more time but are producing less surface-polluting spatter than "full-power" modes. For minimizing the time duration of soft piercing modes, the temperature of the molten material of the interaction zone has to be controlled within a narrow bandwidth. This again is done by measuring the radiation emission of the interaction zone, comparing the resultant signals with preset upper and lower levels, and accordingly controlling the laser input energy. The same strategy is being applied for piercing stainless steel. This may be accompanied by plasma formation which is retarding the piercing process.

Feed-speed control systems allow the machine to be operated with maximum laser power while the feed speed is kept just below the limit for the occurrence of incomplete cuts. As an indication of an upcoming incomplete cut there is an increased lag of the lower part of the cut front with respect to the upper part. The cut front consists of molten material emitting electromagnetic radiation which is partly directed upwards. Due to the lagging lower part the radiation intensity to be detected above the workpiece is increased. In case the detected signal exceeds a preset level, the feed speed is automatically reduced followed by a stepwise increase as soon as the emissions fall below the preset signal level.

Speed control also is an issue when cutting materials like zinc-plated steel, which are creating strong plasma preferably at high cutting speed. To avoid process disturbances caused by excessive plasma formation the cutting speed has to be reduced temporarily. Closed-loop systems have been commercially realized based on capacitive or optical plasma sensing devices.

2.8.3.2 Welding

2.8.3.2.1 General and historical

Laser welding is performed either by heat-conduction welding or by penetration welding, see also Part 2, Chap. 4. The former is based on a comparatively uncomplex process of surface beam energy absorption and heat conduction. It is restricted to thin-sheet treatment due to the limited energy penetration depth accompanied by a wide Heat-Affected Zone (HAZ), which is characteristic for this technique. However, process irregularities which may call for surveillance actions cannot be excluded totally.

Contrary to this, penetration welding is based on a complex beam-metal vapor/plasma-workpiece interaction. It keeps the HAZ advantageously small while allowing considerable deep penetration depths due to a beam-generated capillary, called key hole. It is pressured and thereby prevented from collapsing by the partly vaporized wall material. As a drawback, the process windows for laser-penetration-welding applications are generally smaller than for conduction welding. This specifically applies for galvanized steel and materials having high reflectivity and heat-conduction coefficients like, e.g., aluminum alloys. Therefore, the quality of penetration-welding treatment results is by far more susceptible to process-input-parameter irregularities. Additionally, keyhole-assisted weld processes are endangered by inherently existing resonances which may be stimulated by minor influences thereby creating severe disturbances of the weld process. This situation causes some considerable and enduring need for quality assuring and documenting measures to be taken. The state of the art of weld process surveillance, based on output phenomena detection, will be addressed in the next sections.

Early scientific monitoring work started and partly continued with acoustic monitoring techniques, workpiece-borne [69Jol] or air-borne [78Wes, 82Shi, 83Dix, 85Jon, 86Ste, 89Ham, 92Li, 96Gu], the latter giving information on the dynamics of the plasma/vapor emerging from the key hole, which in turn is related to the shape and temperature of the key hole. Furthermore, combinations with other types of sensors (optical and charge collecting) have been investigated [88Gat, 91Bro, 92Ste]. As it seems now, air-borne sound detection may have the potential to serve as an accompanying method in combination with optical sensing [97Bee, 98Far, 98Kam, 99Far], but not as a stand-alone method.

Pioneering optical-monitoring work showed that the optical emissions of the interaction zone contain the broadest scope of useful information on the instantaneous condition of the process: Infrared and visible emissions carry information on the shape and temperature of the liquid parts of the key hole, weld pool and spatter, while ultra-violet and visible emissions are dependent on the density, temperature and shape of the plasma/vapor inside and outside the key hole. The information can be extracted by spectroscopic analysis [87Roc, 89Sok] or by time history analysis of signals detected by photo diodes [83Dix, 84Ish, 84Miy, 87Bey, 88Bec, 91Che, 91Mai, 92Ste] or CCD cameras [88Ols, 90Voe, 91Hof, 92Bag, 93Miy], the latter being additionally capable of tracing the surface contour and position of the plasma plume, key hole and weld pool. The first proposal to axially resolve the keyhole plasma radiation made use of several diodes arranged at different angles with respect to the beam axis [95Miy].

While the use of single-detector arrangements gained scientific insight into specific aspects of the laser-welding process, sensor-fusion schemes have been primarily developed for industrial process monitoring aimed at false treatment detection. Probably the first experimental sensor fusion made use of the simultaneous recording of air-borne sound and UV plasma plume radiation [83Dix]. The first commercial dual-sensor photo-diode arrangement (UV/IR) aimed at on-line cw CO_2-laser welding monitoring entered the market in the late eighties [90Hat]. About 6 years later pulsed Nd:YAG-laser welding monitoring was successfully demonstrated for industrial production purposes [97Gri]. At the end of the last decade the first camera-based closed-loop control system was introduced into an automotive production site [98Die]. Innovative signal assessment based, e.g., on fuzzy logic algorithms was pioneered since the early nineties [94Gu].

The last 10 years showed the successful diffusion of reliable commercial photo-diode-based process monitors into industrial production lines. Process modeling and monitoring research were considerably intensified, mainly based on camera-type or multiple-sensor systems. Accordingly, new signal assessment algorithms and surveillance schemes have been developed and are still under development. They are aiming at autonomous self-learning production cells. This calls additionally for an advanced understanding especially of the numerous effects forming the fluid flow in the key hole and melt pool. Innovative scientific process-monitoring schemes such as X-ray melt-pool transmission and holographic techniques will support and verify future process-modeling efforts.

2.8.3.2.2 Recent scientific research

The continual momentum driving scientific process-monitoring activities is resulting from the demands for an even better understanding of the conventional welding process fundamentals as well as novel process options and from the increasing need for improved on-line monitoring and control systems. Main targets of recent scientific process-monitoring activities have been: theoretical modeling of the beam-plasma-workpiece interaction; discrimination of partial penetration vs. full penetration; investigation of situations creating treatment quality faults like humping, pores, undercut and burns; giving support to the development of methods for preventing or reducing the occurrence of such faults; developing methods for monitoring the occurrence of unavoidable faults.

The information given in the following sections is arranged according to the type of the detection method.

2.8.3.2.2.1 Optical emissions, photo-diode detection

Currently, the most often investigated optical sensing techniques are based on photo diodes aimed at selected radiation emitting parts of the interaction zone like, e.g. upper parts or full length of the key hole or at the plasma plume above the key hole opening or at parts of the weld pool behind the key hole or at the root side of the weld. The spectral sensitivity of the sensor module has to be optimized by filters according to the spectral properties of the source of emission within the UV, VIS and IR region (see Table 2.8.2).

Since the welding process is highly dynamic, the emissions and thereby the detected signal strength are strongly fluctuating. This, at a first glance, may appear stochastic and consequently of poor value for analytical purposes. However, it has been shown frequently during the last decade that not only useful information can be extracted from optical emission signals in spite of their strong fluctuations, but that also these fluctuations carry valuable information on relevant quality indicators like, e.g., the recognition of full vs. partial penetration [97Sfo, 97Mor, 98San, 99Far, 99Ike], the control of the root-side seam width [03Bag], the recognition of surface defects (holes, burns) [97Sfo], and deep-welding penetration depth [99Miy1]. Analysis of signal fluctuations also created valuable input for scientific process modeling like information on, e.g., laser-beam-plasma interaction [89Sok, 98Far, 98Gei, 99Ino], resonant stimulation frequencies [98Gei] yielding reduced penetration depth variations, keyhole-vapor-emission flow rate, and vapor plume size vs. vapor flow rate [98Far], plasma temperature vs. focus point position. Even the variance of the on-axis measured visible process-radiation fluctuations was shown to be a discriminant between a good weld and non-joining errors, cut and half join and dropping through [98Han]. The time derivative of the plasma-plume emissions turned out to be proportional to the acoustic signal strength [98Far].

Angular and optical broad-band resolution of the visible process radiation confirmed the understanding of the temperature gradients between the plasma temperatures of the plume, in the keyhole opening, and in the keyhole finger part. This in turn experimentally confirmed assumptions on the magnitude of plasma-related laser absorption inside the key hole due to inverse Bremsstrahlung. The same technique confirmed the presence of a wavelength-dependent attenuation of the keyhole plasma radiation due to scattering by particles within or surrounding the surface-borne CO_2 laser plasma plume [02Tu]. A review on investigations of the plume scattering and absorption effects occurring due to clustered particles of the workpiece material in CO_2- and Nd:YAG-laser welding is presented in [02Gre].

Optical narrow-band filters placed in front of the detectors may extract some significant treatment failures such as oxidation of titanium or stainless steel occurring due to insufficient shield-gas supply [98Fox]. Increased process reliability was gained for pulsed Nd:YAG-laser spot welding of titanium by an analysis of the infrared radiation detected on-axis, separately performed for the keyhole-formation phase and the subsequent penetration phase [98Kog]. The occurrence of Laser-Shock-Cleaning-type (LSC-type) plasma shielding during CO_2-laser welding was shown to be correlated with strong radiation emission of nitrogen which was detected on-axis via a scraper mirror in the near IR region [98Sei]. Using a high-speed closed-loop control system (reaction time 50 μs) plasma shielding could be suppressed by switching off the laser power for a short time period (100 μs) [95Abe].

Axial-focus-position closed-loop control based on process-output-phenomena detection has been accomplished by different methods such as intensity and phase detection of plasma-plume intensity oscillations which are intentionally induced by small periodical axial variations of the focal point [97Neg] and by using an off-axis dual-view detection method for monitoring two different parts of the optical plasma-plume emissions [00Gu]. It has been shown, however, that the oscillation method mentioned above may be affected by varying gap widths [00Toe]. Moreover, axial auto-focus control was accomplished by making advantage of the chromatic aberration of the focusing/receiving optics of an Nd:YAG laser system while on-axis detecting the part of the radiation which is emitted by the molten pool [98Kim] or by the plasma [97Har]. Gap detection has been performed by using a twin-spot detection technique. Here one direction views the plasma plume while the other looks through the gap at the front of the radiating liquid wall of the key hole. Based on these signals, an adaptive axial-focus-position control system has been established which is capable of maintaining sufficient welds for varying gap widths [00Gu].

2.8.3.2.2.2 Optical emissions, camera detection

Increasingly frequently, electronic cameras are used for recording two-dimensionally resolved intensity patterns of the plasma plume, the keyhole area, or the whole weld-pool area. The information to be gained from these areas depends on the kind of processing algorithms and on the speed of the camera and the processing means. It has been demonstrated that simultaneous on-line surveillance of a few important parameters such as axial focus position [98Die, 98Koj] and penetration depth [98Die] or shield gas flow rate and absorbed pulsed laser energy [98Koj] can be achieved by the assessment of the camera data with respect to two criteria, like plasma plume intensity and ejection velocity [98Koj] or position of the key hole and size of the weld pool [98Die], respectively. Figure 2.8.6 shows an example of an unprocessed weld pool image of a CO_2-laser butt-welding.

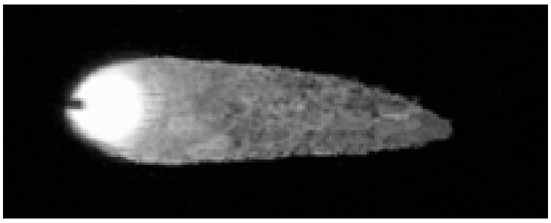

Fig. 2.8.6. Camera-recorded image of the weld-pool area for a non-ideal butt weld configuration: The missing white area in the front part of the keyhole areal is due to a gap between the parts to be welded.

In some cases the extraction of just one criterion turned out to be sufficient for the detection of, e.g., the occurrence of humps [98Bag]. Furthermore, high-resolution on-axis monitoring of the optical emissions of the keyhole area [97Bee, 99Kra] has been demonstrated to yield information on the spatially resolved keyhole shape, penetration depth, seam track deviation, and spatter formation. Weld-pool dynamics and resonant frequencies have been studied for Nd:YAG welding of aluminum alloys by high-speed monitoring of the surface wave movement, illuminated by short (2 ns) periodic Nd:YLF-laser pulses [98Mue]. By using the illumination of an Ar^+-laser during Nd:YAG-laser welding of 10 mm thick stainless steel the optimizing influence of side gas flow on pore reduction and bead narrowing has been investigated [02Kam].

2.8.3.2.2.3 Reflected laser radiation

Up to now this method has been used almost exclusively for Nd:YAG lasers since the near IR wavelength falls within the range of standard photo detectors. As the interaction zone is not capable of totally absorbing the impinging laser radiation, a small part of it is reflected back, even from the lower part of the key hole. Obviously, the level of the reflected radiation is dependent on the shape of the key hole. It gives additional information on the condition of the treatment process, such as the shape of the interaction zone [96Gri, 98Kog, 98Mue, 98Tsu], occurrence of pores and blow holes [98Mue], and gap formation during overlap welds [98Kog]. Deviations of the axial focus point from its optimum position can also be detected [98Mue] since the focus position influences the keyhole shape which in turn determines the level of reflected laser radiation. If the backscattered laser radiation and the emitted near-infrared thermal radiation are analyzed by an electronic camera with respect to the width of the detected lateral intensity distribution, peak amplitude, and peak position on the camera, it should be possible to identify variations of three types of process parameters (axial laser focus position, workpiece temperature, average laser power) [98Pet]. Penetration discrimination (full vs. partial) and hole detection could be achieved with 100 % reliability during laser hybrid butt welding (Nd:YAG laser from top and diode laser from the bottom) of aluminum tailored blanks by photo-diode detection of the backscattered laser radiation from the top and transmitted Nd:YAG-laser radiation from the bottom side [03Ort].

2.8.3.2.2.4 Electrical charge collection

The heated gaseous and liquid emissions of the interaction zone carry electrical charge, which can be used for monitoring purposes. It has been shown that a lot of treatment faults and process conditions like, e.g. humping, undercut and varying penetration depth, missing joint of overlap weld, and defocusing, create clearly detectable variations of the signal of the charge-collecting device [90Li, 97Hil, 99Bie]. As for the optical plasma detection, it seems to be impossible to clearly distinguish the treatment faults from the detected signal variations. The significance of statistical signal-assessment methods was shown to be superior to time-history-signal-level analyses or even to Fast-Fourier-Transformation (FFT) analyses [97Hil].

2.8.3.2.2.5 Multiple sensor schemes

Most researchers used more than one sensor in order to document the process condition as completely as possible, which is desirable if an improved understanding of the complex process has to be gained. Multiple sensor arrangements are also increasingly under development to improve the monitoring performance in terms of fault detection probability and false-alarm avoidance. The sensor techniques commonly used for combined analysis are already described in the preceding sections. Additionally, in some cases air-borne noise was recorded. This, however, did not significantly increase the reliability of features extracted from simultaneously recorded plasma-generated UV signals.

Feature extraction from each sensor signal is performed according to the signal pre-assessment methods described in Sect. 2.8.2.5. For final classification or rating of the laser-treatment result various methods like, e.g., Principal Component Analysis (PCA) [02Che], statistical, neural [99Far, 03Gha], or fuzzy networks [98Ogm] have been used, isolated or in combination. As an example, four different methods have been applied in parallel to the signals of three different sensors (UV, IR and microphone) for a binary penetration depth classification during mild steel lap CO_2-laser welding in an automotive production line. PCA accompanied by Class Mean Scatter analysis turned out to be the only method in that case yielding 100 % correct classification for all three types of sensor signals. However, only the UV plasma detection signals yielded 100 % correct classification regardless of the assessment method applied [00Sun].

Applying neural methods to coaxially detected UV, VIS and IR signals in a CO_2-laser automotive transmission weld yielded 93 % porosity detection probability and 0 % false alarm [03Gha], see Sect. 2.8.3.2.3.

Figure 2.8.7 demonstrates the benefits of combined sensor signal assessments in the case of hybrid laser (Nd:YAG, deep penetration-type from top, and diode, heat-conduction-type from bottom) butt welding of aluminum tailored blanks: Since partial penetration and holes as well

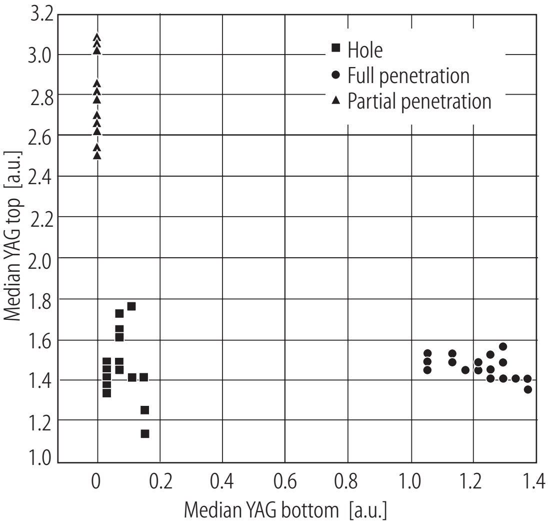

Fig. 2.8.7. Example for the benefits of 2-dimensional feature extraction in combination with statistical methods. Hybrid laser butt welding of aluminum tailored blanks [03Ort]. Sheet thickness: 1.2 mm / 2.5 mm, weld speed: 10 m/min, laser power: 4 kW (top), 2 kW (bottom), shield gas: argon, sampling rate: 50 kHz. Median YAG top and Median YAG bottom: By statistical method pre-assessed amplitude of sensors detecting the backscattered laser radiation of the keyhole area on top and the transmitted laser radiation under the bottom of the workpiece.

as holes and full penetration, respectively, are creating approx. the same signal levels for the discrimination features, plotted in vertical and horizontal direction, respectively, the three situations can only be distinguished by using two quality indicators simultaneously [03Ort]. Alignment errors and supply-gas failures also could be identified by additionally sensing the temperature of the weld bead near the key hole.

2.8.3.2.2.6 X-ray and visible-light shadowgraphy, holography, laser beam probe, ultrasonic inspection

As a quite exotic but informative tool, micro-focused X-ray on-line absorption measurement perpendicular to the key hole and feed direction has been used for the investigation of the sub-surface liquid motion and porosity formation and suppression methods during high-power CO_2 laser welding of specially prepared aluminum alloy specimens [99Mat]. A similar technique was used to observe the key hole and porosity formation during high-power pulsed-Nd:YAG-laser spot welding of stainless steel [98Fuj, 02Kap] and liquid Zn [02Kap]. The results may be used for validation of process-modeling theories [02Dau, 02Fab]. X-ray analysis has already been used for the study of the electron-beam-welding processes though [70Ton]. The smoothing effect of resonant-frequency process stimulation by modulated laser power (400 Hz) on the weld-penetration-depth variations (see also Sect. 2.8.3.2.2.1) and decrease of porosity formation has been demonstrated directly by camera detection perpendicular to the CO_2-laser-induced key hole in frozen glycerin [03Cho].

Examples for further unique arrangements are: the combination of a real-time holographic interferometer and a high-speed digital camera for quantitative visualization of the removal of the laser-induced plume by the shield gas [98Bai], the application of a probe CO_2 laser beam for measuring the lateral plasma plume density variations building up a few milliseconds prior to the occurrence of humping due to resonant process instabilities [98Kla]. Non-contact ultrasonic inspection may have the potential for in-process detection of pinhole defects [00Kle].

In total, numerous sophisticated signal assessment algorithms have been developed during the last decade while there was comparatively slower progress concerning the further improvement of the process-output-phenomena sensing techniques. This is leaving some space for inventions preferably in the latter area, which will be based on innovative commercial sensing hardware like advanced cameras and integrated optical devices.

2.8.3.2.3 Industrial applications

2.8.3.2.3.1 Monitoring systems

A few types of matured commercial photo-diode-based weld-monitoring systems are presently running in several hundred industrial production lines mainly in Europe and North America. Main application areas are the welding of tailored blanks, automotive power train parts, body in white parts, and a variety of small parts for the automotive, medical, and electronic industry such as fuel injection parts and capsules for, e.g., air bags and cardiac pacemakers. The driving forces for in-line installations of process monitoring systems have already been addressed in Sects. 2.8.2.2.2 and 2.8.3. In summary they are: process status documentation, fault detection with or without fault class separation, obeying quality assurance standards while reducing or avoiding effort for conventional quality assurance means like visual inspection and destructive tests.

To obtain maximum surveillance reliability in terms of fault-detection safety, false-alarm prevention, and fault class separation preferably more than one process phenomenon (see Table 2.8.2) have to be monitored by multi-sensor arrangements and assessed simultaneously. The principles of the detection of the process phenomena and the assessment of the sensor signals are described in Sects. 2.8.2.4 and 2.8.2.5, respectively. Commonly used quality indicators are the signal amplitude variations of the optical emission of the key hole or the plasma/vapor plume, in some cases measured simultaneously at different wavelengths, the near infrared radiation of the weld pool or parts of it, and the reflected laser power from the key hole as described in the previous sections.

Several years ago, camera-based systems were also successfully assessed at automotive production sites for the surveillance of the gear-part welding process [98Die, 01Kai]. Yet there is still considerable adaptive work needed for any specific application to gain additional on-line information on the treatment process from a machine vision system compared to the information yield of a matured photo-diode system. However, machine vision systems have already proved to be a valuable tool for post-process inspection of the seam geometry and the detection of seam faults.

A comprehensive review of commercial process-monitoring systems is given in [99Sun].

Commercial on-line weld surveillance systems for industrial applications are usually based on threshold assessing methods. These methods (see Sect. 2.8.2.5) need reference data. They are created by recording and assessing some sensor signal patterns taken for production cycles which yielded proven good treatment quality. Then, by adding tolerance margins, processing thresholds have to be defined. Finally, some parameters have to be entered which influence the analyzing mode of threshold violating data traces. By these measures the surveillance systems are adapted to the individual needs of a specific application. For example, by increasing the tolerance margin and/or increasing the permitted accumulated time of threshold violations, the sensitivity for failure detection is reduced compared to common situations. This may be appropriate, e.g., for welding applications where joints are needed just at a comparatively low percentage of the complete welding track. To make full use of the versatility of commercial surveillance systems, significant skillful work for configurating all assessment parameters and margins has to be performed. If process influencing parts or parameters of the welding equipment are even slightly modified, the configuration of the surveillance system may have to be reworked. Therefore, current weld process surveillance systems are preferably suited for long-lasting single-task applications rather than for frequently changing treatment situations.

Since the invention of the laser continuous effort has been undertaken to increase the span of industrial applications of laser material treatments by using novel approaches like, e.g., the twin-spot technique. During the last years the high power laser welding technology has been further expanded by some new methods like, e.g., remote welding and hybrid (laser/arc) welding. For most applications based on these methods the use of process-surveillance equipment appears to be advantageous, if not mandatory. Both single element detectors and machine vision systems are being used, and in some cases it became obvious that at least a 2-dimensional feature extraction scheme (for example see Fig. 2.8.7) is needed for safe fault detection.

2.8.3.2.3.2 Closed-loop control systems

Closed-loop control systems are supposed to compensate for the unwanted effects of any irregularly changing process parameters on the treatment result. As a prerequisite it is necessary to trace the origin of a detected irregularity of the monitored quality indicators on-line during its occurrence with a reliability close to 100 %. This seems to be a remaining challenge for mid-term future development work.

Additionally, there is the issue of *focus-point positioning.* Especially for butt joints a very precise lateral positioning of the focus point is mandatory so that the beam hits the center of the gap between the parts to be joined. Deviations of ±0.05 mm from the optimum position may already be crucial. The positioning is achieved by commercially available non-contact optical or inductive gap-following systems. The optical systems are based on high-resolution pattern-recognition methods while the inductive systems detect the strength of magnetic fields created by electrical eddy currents induced by the sensor itself within the surface layer of the two parts to be joined. The accuracy of the inductive systems is limited to about ±0.05 mm. High-end optical systems are more accurate and they are capable of calculating the gap volume of butt joints, thereby creating input data for adaptive filler-wire feed-control systems. Since the field of view of the sensors is adjusted in front of the interaction zone, some feed-speed-dependent coordinate-transformation effort is needed for the control actions. Mechanical contacting sensor modules can also be used for lateral focus-point positioning if the topography of the joint area is suitable for steering the contact pin which, e.g., is the case for overlap joints. The lateral position of the focus point is considered as a machine parameter, like the position of the workpiece. Moreover, none of the mentioned gap-tracking methods is based on any process output phenomenon. Therefore, the state of the art of lateral focus-point monitoring systems is not further discussed in this section. Both inductive and optical systems are also measuring the stand-off distance.

Less critical than the lateral focus-point misalignment are axial misalignment and defocusing effects, if these are small compared to the Rayleigh length of the focused beam. They may result from thermal drift effects of the beam-guiding optics, from workpiece shape and position tolerances, incorrectly taught robot motions, and from plasma lensing effects. Monitoring the axial position may be accomplished by detection of process radiation, charge-collecting devices or backreflected laser power, however, these methods yet have to mature for industrial applications. Matured capacitive and optical triangulation technologies using pilot beams have the disadvantages of measuring the distance to the surface rather than the axial focal position while the measured area is not exactly coincident with the interaction zone either. Some capacitive systems tend to be sensitive to plasma occurrence. This may restrict their application to pulsed systems (measurement during the off-periods) and to Nd:YAG systems.

2.8.3.3 Transformation hardening

Laser transformation hardening of ferrous material is performed by shortly rising the temperature of the material above the austenitizing temperature but well below the melting condition, maintaining the temperature for a short time, and by a subsequent rapid temperature drop (10^4 K/s) occurring while the laser beam passes by, due to the heat dissipation into the bulk material. The austenitizing temperature for common materials is ranging about 1100 ± 100 K depending on the material. The achieved degree of hardening mainly depends on the content of carbon atoms being reoriented during the short high-temperature maintaining period. The resulting hardness depth mainly is a function of the peak temperature which depends on a variety of parameters like laser power density, feed speed, temperature level immediately prior to the beam exposure, workpiece shape, and surface conditions influencing the absorptivity. Therefore, by monitoring the surface temperature at the location of the impinging laser radiation the achieved depth of hardening can be indirectly surveyed or even controlled.

Increased accuracy for reaching and maintaining the correct temperature is needed for materials having a comparatively small difference between austenitizing and melting temperature. Temperature control is also of increased importance if preheating effects occur like during large-area hardening by repeated treatments with adjacent and partly overlapping treatment tracks.

The surface temperature determines the intensity and the spectrum of the electromagnetic radiation emitted from the surface according to (2.8.1). Thereby, the temperature can in principle be calculated from the measurement of the radiation level. The calculation, however, is quite complex because (2.8.1) has to be adapted to the specific conditions of the measuring device and the material's properties. Fortunately, sticking to the basic formula is not necessary. Even for adaptive control it is sufficient to compare the on-line measured intensity levels with a preset level generated from proven good treatments and to control the laser power accordingly. Temperature fluctuations can be limited to ±5 K by that method.

Up to now no commercial systems for laser-hardening process monitoring or control systems have entered the market. However, a few successful pioneering industrial applications have been reported covering the high-volume treatment of torsion springs for car doors [00Dre] and the treatment of coated crankshafts including laterally resolved control of the power distribution profile [99Dre]. The latter application has been realized by a matrix of 20 fiber cables which transmitted the power emissions of 20 independently controlled diode lasers.

2.8.3.4 Cladding, alloying

Like hardening, cladding and alloying are surface treatment processes. The processing patterns mostly consist of repeated partly overlapping treatment tracks. This, like during hardening, may cause preheating situations, which cause the instantaneous temperature of the interaction zone to leave the boundaries of the process window. Poor treatment quality is the result. Also, variations of the powder flow rate and geometrical variations of the workpiece influence the temperature of the interaction zone. To achieve acceptable treatment quality, the interaction-zone temperature has to remain constant. Regularly occurring preheating can be accounted for and the effects of intentionally varied powder flow rates on the temperature may be compensated by ramping the feed speed or laser beam power according to pretested and optimized functions. However, this preparative procedure may turn out to become uncomfortably time-consumptive. Furthermore, this scheme provides no adaptation to stochastically occurring disturbances.

As for hardening applications, temperature closed-loop control systems provide more safety and flexibility. Mainly depending on the materials and masses involved, the melt pool surface temperatures may range from 930 K to 2330 K. According to (2.8.2), this calls for radiation sensors having their maximum sensitivity in the near-infrared region. Therefore, thermographic CCD cameras or IR diodes are used for measuring the melt-pool dimensions and temperature distribution, and the average surface temperature, respectively. After some pioneering feasibility demonstrations [98Bac] a closed-loop control system having a set of sensors integrated into a commercial cladding head entered the market recently [03Pre].

2.8.3.5 Cleaning, caving

During laser-surface-cleaning applications every pulse creates a rapidly expanding plasma which in turn emits a shock wave. By detecting these waves via microphones placed near the interaction zone [95Lu] and analyzing the data according to their frequency spectrum, amplitude distribution or chromatic properties (dominant frequency, energy level, excitation purity), for example the laser flux [98Lee1] and the surface cleanliness [98Lee2] can be monitored by using neural networks for signal assessment. Potential for serving as quality indicators has been predicted also for reflection measurements and the determination of plume radiation intensity and plume radiation dominant wavelength vs. number of laser pulses [00Lee].

Scientific research of pulsed-laser ablation has been performed for about 15 years [88Chr]. The photoacoustic sensing method has been used to determine the damage threshold and energy coupling efficiency vs. several variables such as: number of pulses, kind of material, and surface cleanliness [00Ito]. Spectroscopic methods (e.g. Laser-Induced Breakdown Spectroscopy, LIBS) proved to be a valuable tool for determining the elemental composition [03Rod] and to investigate micro machining processes [03Rus]. Process monitoring for industrial caving treatments is aimed at depth control and on-line surface roughness measurement. Conventional on-line non-contact depth monitoring systems are not applicable because of the required high resolution (< 10 μm) and the need for measuring exactly at the position of the interaction zone. Consequently, the process radiation is used directly for triangulation. As a main feature, the sensor must not be sensitive to variations of the lateral shape of the interaction zone and to variations of the angular emission characteristics [95Hae].

2.8.4 Outlook

The advantages gained so far by today's commercially available surveillance systems for laser material-treatment applications are already indicating the huge potential of future improved and integrated process-surveillance strategies. Triggered by the customers needs, there will be an increasing impetus driving the further refinement of the mastery of laser material-treatment processes.

The production industry has to cope with a permanently growing demand concerning cost, quality, functionality, environmental and resource saving aspects, etc. which applies to production methods and product features as well. This situation calls for an increased and skillful future usage of innovative production methods like laser treatment even in areas where these methods are uncommon at present or are regarded as risky like, e.g., treatment of components being part of safety devices, low personnel or fully automated large-volume production of costly parts, laser treatment with hand-held processing heads, large volume laser micro-material treatment, and laser treatment of materials, combinations of materials and shapes, which presently are regarded as unreliably treatable. This development will be supported by a further increasing knowledge of the laser-treatment fundamentals, new designs of compact laser sources allowing for increased production-cell-design flexibility, and still decreasing cost per kW of laser power.

The areas of innovative laser-treatment applications mentioned above represent a considerably growing production volume for which for economical reasons and such of safety there is a need to avoid as completely as possible the production of faulty devices. Therefore, process surveillance presently can be regarded to be just in an intermediate stage of need and acceptance. There will be a growing need for standardly accepted treatment surveillance and documentation methods, the latter requested by international-certification and quality-assurance standards. To keep up with the increasing need for standardization the relevant committees are – even though a little bit slowly – evaluating, which of the currently accepted surveillance principles are suitable for being part of an upcoming system of laser-treatment quality-assuring standards.

To keep pace with the demands of the production industry, future systems of laser process monitoring and control have to provide a further increasing level of reliability and flexibility. This will be accomplished by innovative and highly sophisticated real-time signal assessment systems, which are fed by extended reference and calibration data files, which are a-priori defined and/or self-generated for specific treatment situations, and by the on-line acquired signals of integrated multi-sensor fusion setups. In spite of increased internal sophistication and complexity, standard future systems need to be more user friendly than current products. This includes features like standardized interfaces and increased autonomous functionality. Presently, the latter appears to be partly visionary for industrial applications. It includes features like, e.g., automated start-up monitoring and assessment-parameter acquisition and setting, automated functional self-test routines, automated fault class identification and fault probability calculation, and suggestion of correctional measures.

Spin-offs of further developments may also result in low-cost systems of reduced functionality. They may be used for monitoring situations which tolerate an increased false-alarm rate like mass production of relatively simple devices of lower value or for parts which can be easily refed into the production process for a repeated treatment cycle.

But also the highest level of the technological high end of process monitoring and signal assessment, being too sophisticated for industrial use, is under need of further innovative progress to continuously support the ongoing research of the complex nonlinear laser-workpiece-interaction processes.

The scientific and technological potential for the improvement of already existing monitoring and control techniques and for the creation of innovative new features and methods is demonstrated, e.g., by the continuously increasing number of so far several hundred patents covering the area of process surveillance.

Peculiarly, just a very small percentage of the patent claims which focuse on closed-loop control have been realized so far for industrial use. This reflects the difficulty of identifying automatically the origin of any commonly occurring treatment fault and of addressing the correct process input parameter which is capable of compensating the fault origin without any unwanted side effect. Evidently, for these reasons closed-loop control is also an issue carrying remarkable potential for future innovative development activities which then will overcome these obstacles.

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