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GERMAN WELDING SOCIETY

BEST PRACTICE

QUALITY-ASSURING SENSOR EQUIPMENT DURING LASER WELDING

Contents:

Foreword

The technical bulletin gives the user of laser welding technology indications about sensor equipment which can be utilised during laser welding in order to safeguard the processing quality. Consideration is given exclusively to sensor systems which take measurements during or parallel to the welding process, also designated as on-line sensor equipment by the manufacturers. With the sensors presented below, regulation is basically possible or has already been implemented today. However, a single sensor alone is frequently not sufficient in order to safeguard the demanded quality. The structure of the technical bulletin distinguishes between sensors for the:

- detection of the groove geometry (see Section 2)
- process monitoring (see Section 3)
- detection of the weld properties (see Section 4)

Section 1 of the technical bulletin includes a table giving an overview of the sensor principles. The numbering introduced here is taken into account in the subsequent tables. Finally, data sheets with explanations about the measuring principle, the schematic structure and remarks about the application such as the measuring accuracy and speed can be found in Section 5 for each sensor principle.

1 Overview

The sensor systems used at the moment are specified in Table 1. They are arranged in lines according to the functioning method, i.e. the measuring procedure. The columns provide information about the possible positions of the respective measuring procedures relative to the process. In this respect, a distinction is made between procedures which work upstream (detection of the groove geometry), measure near the process (process monitoring) and are downstream (detection of the weld properties).

Table 1. Overview: "Quality-assuring sensor equipment during laser welding".

Position relative to the process
Upstream
Near the process
Downstream
Mechanical procedures
Pneumatic systems
Tactile systems
Electronic procedures
Capacitive systems
Inductive systems
Optical procedures
Measuring methods with auxiliary light sources
Triangulation and point-to-point measurement
Light section
Grey-scale image analysis
Shadow projection
Transmitted light
Measuring methods in the NIR-IR range
Intensity measurement (without location resolution) in the NIR to IR range
Intensity measurement with location resolution in the NIR to IR range

Table 1. Continuation.

Measuring methods in the UV range
Intensity measurement (without location resolution) in the UV range
Intensity measurement with location resolution in the UV range
Measuring methods in the visible range
Intensity measurement (without location resolution) in the VIS range
Measuring methods in the wavelength range of the processing laser
Back-reflection measurement (at the laser wavelength)
Acoustic procedures
Sound emission analysis
Ultrasonic procedure
Laser ultrasonic technology (LUST)

The quality characteristics which can be detected with the individual sensor systems are indicated below for the individual measuring positions relative to the process.

2 Detection of the groove geometry

The groove geometry is detected in the measuring position before the process. The geometrical parameters used in this respect are summarised on Fig. 1 for the relevant joint types. Table 2 lists the sensor types which are, in principle, suitable for detecting the geometry and classifies their applicability to various weld-joint combinations and geometrical variables.

Table 2. Assignment of the detectable, quality-relevant characteristics with various joining geometries to the upstream measuring procedures.

Quality-relevant characteristics
Weld type and joint geometry
Square butt weld in a butt joint
Fillet weld in a lap joint
Fillet weld in a T-joint
Distance
Lateral groove position
Gap size
Can be utilised with restrictions

Square butt weld in a butt joint
Fillet weld in a lap joint
Fillet weld in a T-joint
Distance
Gap size
Lateral groove position

Fig. 1. Definition of the geometrical parameters used.

3 Process monitoring

If the measurement is taken near the process, acoustic or optical signals which the welding process emits are essentially investigated and connected with geometrical or process parameters. In this respect, no unambiguous assignment between the change in the signal and the specific defect is possible in most cases. Instead, a global statement is made about the course of the process.

Table 3. Assignment of the detectable, quality-relevant characteristics with the joining geometries to the procedures measuring near the process.

Quality-relevant characteristics
Weld type and joint geometry
Square butt weld in a butt joint
Square butt weld in a lap joint
Fillet weld in a lap joint
Fusion seam weld in a T-joint
Focus position
Laser power
Welding-in depth
Weld penetration
Porosity
Spatter
Gap detection
Weld geometry
Weld position
Can be utilised with restrictions

4 Detection of the weld properties

A measurement after the process assesses the produced weld quality.

Table 4. Assignment of the detectable, quality-relevant characteristics with various joining geometries to the downstream measuring procedures.

Quality-relevant characteristics
Weld type and joint geometry
Square butt weld in a butt joint
Square butt weld in a lap joint
Fillet weld in a lap joint
Fusion seam weld in a T-joint
External weld characteristics
Lack of fusion

5 Functional principles of the measuring procedures

5.1 Mechanical procedures

• 1. Pneumatic systems [1]

Detectable characteristic: Distance a.

Compressed air or inert gas in a concentric line flows through an annular nozzle around the laser beam on to the workpiece. The generated dynamic pressure is measured using a pressure transmitter and constitutes a measurement relative to the distance. The systems can also be utilised in the case of non-metallic materials.

Laser beam
Annular nozzle
Annular gas jet
Workpiece

Fig. 2. Schematic representation of a pneumatic system.

• 2. Tactile systems [2 … 5]

Detectable characteristics: Distance a and lateral groove position Δy.

Touching (feeling) sensors are designated as tactile sensors. The measuring principle is based on the mechanical detection of variables and their subsequent conversion, for example, into electrical signals. In the simplest case, these are switches. However, they may also generate proportional measured signals with nearly any dependence on the measured variable. Axial or rotatory movements can be detected with suitable sensors.

A number of procedures are available in order to convert the mechanical variables into electrical signals. Two examples of procedures are: inductive, by inserting an iron core into a coil, or optical, by detecting marks using light barriers. Systems taking absolute and relative measurements are available to the user. The output values are provided in an analog or digital form.

The mostly simple structure of such a tactile sensor makes the system very robust. In many cases, a signal processing device is not necessary. The price is correspondingly lower than that of non-contact sensors.

Because of the simple functioning method, the user can carry out the maintenance and testing of the sensor.

When the sensor is coupled, the effect on the measured object itself must be taken into account since at least the mass and the inertia are changed.

Fig. 3 portrays the structure and functioning method of a tactile sensor for measuring the distance. The tracing pin of the sensor is coupled with a slider on a resistance path (potentiometer). It can be pressed into the housing against the reset force of a spring so that an output voltage U_a which is proportional to the insertion depth or is correspondingly inversely proportional to the distance a can be picked off in this case.

Spring

Fig. 3. Schematic representation of a tactile sensor.

With regard to the application of this sensor, it is important to exclude the tilting of the measuring rod by design means in order to avoid any damage to the measuring surface or the sensor. For this reason, the tip of the rod may be equipped, for example, with rollers or sliding balls.

In the example of an application portrayed on Fig. 4, an upstream, mechanical tracer records the position of the groove in the vertical and horizontal dimensions. The mechanical movement is converted into a voltage signal and is supplied to an evaluating unit. The working range of a typical sensor is ± 5 mm with an accuracy of 0.1 mm.

Laser beam
Tracing needle
Workpiece

Fig. 4. Schematic representation of a tactile system with a tracing needle.

5.2 Electronic procedures

• 3. Capacitive systems [6; 7]

Detectable characteristic: Distance a.

The measuring electrode and the counterelectrode (workpiece) form a capacitor whose capacity depends on the distance between the measuring electrode and the counterelectrode. An imprinted alternating current permits the measurement of a voltage as a function of the distance.

The measuring spot and the required sensor area increase along with the measuring distance. Incorrect measurements may be caused by dust, vapour, spatter and plasma. Adjustments to special geometries are possible. The measuring technique can be utilised at high temperatures.

Measuring resolution:	0.1 - 1 % of the measuring range
Measuring accuracy:	0.5 - 2 % of the measuring range
Bandwidth:	10 Hz - 30 kHz
Measuring distance:	0.1 - 20 mm

Fig. 5. Schematic representation of a capacitive sensor system.

• 4. Inductive systems [7]

Detectable characteristic: Distance a.

A coil through which alternating current flows induces eddy currents in a measuring lug (workpiece). For their part, these eddy currents damp the applied alternating current. The distance a at any moment can be established from this physical effect depending on the distance between the coil and the workpiece. A multicoil measuring system permits not only the measurement of the distance between the sensor and the workpiece but also the measurement of the groove position. The measuring principle demands integrating behaviour depending on the coil diameter. The measuring spot and the required sensor area increase along with the measuring distance. The measuring procedure is insensitive to dust, vapour, oil etc.

Measuring resolution:	0.1 - 1 % of the measuring range
Measuring accuracy:	0.5 - 3 % of the measuring range
Bandwidth:	10 Hz - 30 kHz
Measuring distance:	0.1 - 20 mm

Fig. 6. Schematic representation of an inductive measuring system as single-coil (a) and multicoil (b) measuring systems.

5.3 Optical procedures

• 5. Triangulation and point-to-point measurement [8]

Detectable characteristics: Distance a and external weld characteristics.

Detector
Laser beam
Lens
Workpiece
Scattered light

Fig. 7. Schematic representation of the triangulation principle (a) and of a design as an example (b).

Due to the portrayal of the point of incidence of a laser beam with diffuse scattering on the workpiece surface with a non-axial optical system on a position-sensitive detector, a change in the position of the workpiece from P1 to P2 can be detected as a change in the lateral position of the image point from P1' to P2'.

The measuring accuracy is in the range of 1/250 of the measuring range (depending on the surface).

If the downstream triangulation procedure is utilised in order to measure the top side of the weld, conclusions about the porosity and the spatter can be drawn from the established height course.

• 6. Light section [9 … 12]

Detectable characteristics: Distance a, lateral groove position Δy and course, joint characteristics (gap width and height misalignment), external weld characteristics and lack of fusion.

One or several light lines are projected on to the joining contour at a stipulated angle in relation to the surface normal. When this line pattern is viewed vertically, the different heights of the components result in a misalignment in the lines at the joining gap. By means of image processing, the X, Y and Z coordinates of the joining gap are determined from the position of the line misalignment on the camera image and from the known projection angle. Moreover, the formation of the light line misalignment at the joint supplies information about the height tolerance or the gap width between the components. Corrected path data for controlling the movement system is calculated from the joint coordinates. The direct control of additional corrective axes for the welding head is also possible as an alternative. The additional information about the height misalignment and the gap width can be used for quality control and for the dispensing of welding fillers. The downstream light section procedure is utilised in order to measure external weld characteristics not only on the top side of the weld but also (if the component geometry and the weld type permit this) on the bottom side of the weld. It is thus possible to detect the weld penetration and to measure the weld geometry as well as the weld position directly and to detect porosity, spatter and the gap dimension indirectly.

Light line projector
CCD camera
Laser beam
Sensor coordinates
Sensor advance
Feed direction

Fig. 8. Schematic representation of a light section sensor with several projected light lines.

• 6a. Grey-scale image analysis

Detectable characteristics: Local defects (e.g. holes), material ejections, pores, gap width, weld width and texture of the weld.

In the case of the grey-scale image analysis, the weld structure (texture) of the surface of a laser weld is detected by a camera system and is evaluated by means of digital image processing.

In typical designs, megapixel sensors with a resolution of 10 µm per pixel are utilised in the camera systems. During the image recording, the weld surface is floodlit by a light source with a high illumination intensity. In practical application, the grey-scale image analysis and the light section (see No. 6) have been combined until now. Fig. 9 shows the schematic representation of a typical design form of sensor equipment as well as measured results.

Line projectors + grey-scale image illumination

Fig. 9. Left: Schematic representation of sensor equipment with line projection and grey-scale image illumination. Centre: Weld texture of a good weld (top) and of a weld with a pore (bottom). Right: Extraction of the characteristics of the good and poor welds ("herringbone pattern").

In order to describe the texture, the detected data can be reduced by extracting the characteristics. For the assessment of the weld, the characteristics of a good weld without any imperfections are stipulated in order to be able to recognise any deviations in the texture when local disturbances occur.

The grey-scale image illumination with a short exposure time permits the visualisation of the weld texture even at speeds up to 30 m/min.

• 7. Shadow projection [13; 14]

Detectable characteristics: Lateral groove position Δy and course.

This measuring procedure uses that shadow projection of an edge which is caused on the bottom bonding member by lateral illumination in order to detect a joint path. A camera records the shadow geometry of the joint. The edge can be detected by the brightness course on the camera image. If the colour or grey-scale value of the measured object is extremely similar to that of the substrate, the measurement of the shadow of the object leads to better results than the measurement of the edge of the object. Distinct edge jumps in the case of lap welds can be detected with the shadow projection or light section procedure.

Camera
Illumination
Shadow
Workpiece
Shaded area

Fig. 10. Functional principle of the shadow projection (a). Example of an application: Joint detection in the case of a rotationally symmetrical component (b).

• 8. Transmitted light procedure

Detectable characteristics: Lateral groove position Δy and groove course as well as holes.

In the case of the butt joint, the transmitted light procedure is utilised for the detection of the groove position and course as well as for the detection of imperfections in the weld. A camera above the workpiece records the light which is emitted by an illumination device attached below the workpiece and passes through the groove or an imperfection. The position or course of the groove and thoroughgoing weld irregularities (e.g. holes) are determined by evaluating the brightness distribution on the camera image.

Camera
Workpiece
Illumination

Fig. 11. Schematic representation of the transmitted light procedure.

• 9. Intensity measurement1) in the NIR2) to IR range (without local resolution) [15; 16]

1) This is the total intensity which is incident on the detector and not the total intensity which is emitted by the process.

2) NIR - near infrared, wavlength range = 770 - 1,400 nm.

Optical emissions in the NIR-IR range are caused by the temperature radiation of the vapour cavity and of the molten pool. The detectors are often diodes made of germanium or silicon and are utilised at the following positions:

1. Detection of the radiation directly from the interaction zone.
2. Detection of the radiation at the welding bead behind the solidification boundary (solidification front).
3. Detection of the radiation from the bottom side of the workpiece.

Disturbances in the signal course indicate a process irregularity and/or a change in the thermal capacity of the welded component and thus a deviation in the weld geometry.

Molten pool
Vapour cavity opening

Fig. 12. a) Representation of a weld in the top view.
b) Various positions for NIR-IR sensors.

• **10. Intensity measurement with local resolution in the NIR-IR range (temperature field measurement)** [17; 18]

The evolution of the process emissions has already been described in the section on intensity measurement. In contrast with this, geometrical parameters are mostly evaluated in the case of detection with local resolution. The length and width of the downstream molten zone include information about process irregularities and about the altered thermal capacity of the workpiece. This procedure can be utilised predominantly for CO_2 laser welding and, to a limited extent only, for Nd:YAG laser welding since the NIR radiation in the wavelength range of the Nd:YAG laser (= 1,064 nm) is recorded by the camera and this thus acts as a source of disturbances.

Laser beam
CCD camera
Molten pool

Fig. 13. a) Example of the adaptation of the sensor system to a CO_2 laser processing head.
b) Photograph of the interaction zone with the vapour cavity opening and the molten zone [18].

• **11. Intensity measurement without local resolution in the UV range** [19 … 25]
Detectable characteristic:
Intensity of the welding plasma lighting in the UV range

The spectrum of the welding plasma during the processing with the CO_2 laser possesses a high radiation proportion in the short-wave UV range. In order to detect the lighting intensity, preference is given to the utilisation of a photodiode which is sensitive in the UV range. In addition, an optical UV filter arranged in front of the photodiode prevents the detection of daylight and the superimposition of this on the actual measured signal. Four techniques have gained acceptance for the positioning of the detector:

1. Direct observation: The detector is attached in a lateral position observing the process.
2. Direct observation: An optical waveguide guides the optical process emissions to a detector attached far away.
3. Coaxial observation: The process radiation is output coaxially through a borehole in the focusing or first deflection mirror.
4. Observation near the axis: The process radiation is output by a scraper mirror.

The light of the plasma from the CO_2 laser welding process is portrayed on a photodiode with the aid of a lens or mirror system.

There is a close connection between the lighting intensity which is recorded in a computer-assisted method depending on the welding time or the weld length and the weld quality: For example, the plasma becomes darker during the welding of sheets arranged in a butt joint if any damage to the edges leads to holes in the square butt weld or any distortion-induced enlargement of the gap leads to the sinkage of the weld. If the lighting intensity is below a previously stipulated lower threshold value at one position at least, the weld is declared to be defective.

Other weld defects such as inadequate weld penetration as a consequence of welding plasma shielding (non-optimised process gas supply) cause a rise in the lighting intensity. If the lighting intensity now exceeds a previously defined upper threshold value at one position at least here, the weld is also declared to be defective.

For example, holes, external pores, non-welded regions as well as weld sinkage as a consequence of an excessive gap are certain to be recognised with Type 1 sensor equipment for a defect length as from 2 mm at a welding speed of approx. 6 m/min. The system cannot establish the defect type.

- Photodiode
- Imaging lens
- Welding plasma
- Protective glass
- Lighting intensity of the welding plasma
- Threshold value
- Beginning of the welding
- End of the welding
- Welding time

Fig. 14. a) Possibilities of positioning the sensor equipment for measuring the intensity in the UV range.
b) Example of a signal course in the case of a hole in the weld.

• 12. Measurement with local resolution in the UV range [26 … 29]

The optical emissions in the wavelength range of the UV radiation are detected using a sensor system with local resolution (camera) and are evaluated according to geometrical parameters. In this respect, there is a connection between the intensity distribution and the vapour cavity shape in the case of coaxial observation. The system technology structure is similar to that of the Type 3 sensor equipment in No. 11 with the difference that a camera is utilised instead of a detector.

Fig. 15 presents an example of a result with variation of the feed speed from 4 m/min to 8 m/min. The shape of the intensity distribution of the optical emission has changed from a nearly circular appearance to an oblong drop shape.

- Feed
- Width
- Length
- Focus position
- Intensity

Fig. 15. Intensity distribution at various feed speeds

• 13. Intensity measurement without local resolution in the VIS (visible) range [30 … 34]

The optical process emissions in the case of Nd:YAG laser welding do not have any distinct power proportion in the UV range. The process monitoring takes place in the visible to NIR range. Four techniques which are portrayed on the figure have become established as measuring positions:

1. Direct observation: The detector is attached in a lateral position observing the process.
2. Direct observation: An optical waveguide guides the optical process emissions to a detector attached far away.
3. Coaxial observation: The process emissions are output via a dichroic mirror.
4. Coaxial observation: The process emissions are guided via the optical waveguide as far as the laser system where they are output in a decentralised form with a dichroic mirror.

- Photodiode
- Imaging lens
- Nd:YAG laser
- Welding process
- Protective glass

Fig. 16. Possibilities of positioning the sensor equipment for measuring the intensity in the visible range.

• 14. Back-reflection measurement at the laser wavelength [35 … 37]

Detectable characteristics: Welding-in depth and weld imperfections.

The measuring principle is based on a connection between the reflection factor and the shaft ratio (welding-in depth / focus diameter) of the vapour cavity. The reflection factor indicates what proportion of the laser power was not input into the workpiece. The reflection factor falls as the shaft ratio rises because of increased absorption in the cavity. This connection permits conclusions about the depth of the cavity and about the welding-in depth. Since the cavity serves as a characterising information channel for the reflected power, process instabilities resulting from irregularities in the formation of the cavity geometry are also shown in the measured variable. The wavelength of the CO_2 laser is more suitable for the purpose of the back-reflection measurement. Across wide areas, even small changes in the shaft ratio already lead to larger signal changes than in the case of the Nd:YAG laser. Fig. 17 shows an example of the shaft ratio and the reflection factor in the case of the welding of steel.

- Wavelength
- Reflection factor
- Depth / focus diameter

Fig. 17. Dependence of the reflection factor on the shaft ratio.

- Detectors
- Beam splitter
- Interference filter
- Nd:YAG laser
- Diode array
- Transverse jet
- Focusing lens for CO_2 laser
- CO_2 laser
- Focusing mirror
- Scraper mirror
- Detector

Fig. 18. Examples of the designs of processing heads with integrated sensor equipment for Nd:YAG (a) and CO_2 (b) laser welding [35].

5.4 Acoustic procedures

• 15. Sound emission analysis

The capillary movement during the laser welding process leads to acoustic emissions which permit statements about the course of the process. In the case of the sound emission analysis, a distinction is made between solid-borne sound and airborne sound according to the transmission path.

In order to record the solid-borne sound, it is necessary to couple the sensor element with the solid whose sound is to be measured. Fig. 19 shows the direct coupling of the sensor with the workpiece with Type 1 and the coupling via waveguides with Type 2.

The airborne sound can be measured at various positions, e.g. with microphones either directed or also undirected, e.g. Type 3/4.

- Sound guidance

Fig. 19. Schematic representation of various positions for sensors for measuring the airborne and solid-borne sound.

• 16. Ultrasonic procedure

In the case of this procedure, no acoustic process emission is measured but the echo of an induced ultrasonic wave is analysed instead. Fig. 20 shows the structure and the wave propagation during the measurement of a weld between tailored blanks. If the weld does not exhibit any irregularities, the sound is transmitted into the thicker bonding member without any significant reflection and is reflected by the edge of the workpiece. If there are any irregularities in the weld, it is possible to measure an echo with a considerably shorter travel time. Fig. 20 schematically shows the investigation results on a longitudinal weld with porosities and, in certain sections, an incorrect groove geometry.

- Probe
- Weld
- Sound field of the probe
- Weld imperfections

Fig. 20. Schematic representation of ultrasonic measurement.

• 17. Laser ultrasonic technology (LUST) [38; 39]

Detectable characteristics:
Lack of fusion (e.g. pores and cracks) and wall thicknesses.

In contrast with the measuring method according to No. 16, this procedure is characterised by the fact that the ultrasonic wave is generated and detected without any contact.

An ultrasonic wave is stimulated in the workpiece by a high-energy laser beam pulse with a short duration. Due to the absorbed radiation, the surface of the workpiece expands briefly and, in the case of metals, generates a sound pulse which is predominantly propagated on the surface. This sound pulse is detected by an additional laser beam which scans the material surface displacement arising at the detection location. The phase modulation which this causes in the reflected detection beam is demodulated with the aid of an interferometer and is subsequently converted into electrical signals which are analysed correspondingly.

Scanning rates of 100 Hz are achieved at the moment. The stimulation and the detection can be arranged on the same side or on opposite sides, i.e. they can take place in locations separate from each other.

- Detector
- Shock-wave laser
- Welding laser
- Sound-wave coupling
- Sound-wave propagation
- Feed direction

Fig. 21. Schematic representation of the configuration of a measuring arrangement for the quality control of welds in butt joints.

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