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Innovative distance control for laser cutting based on inline low coherence interferometry

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Abstract

Laser based cutting processes are present today in a large number of industrial applications, processing different materials from micro to macro-ranges with high flexibility and automation levels. Modern systems use different sensor units to monitor and consequently enable a robustness enhancement through a controlled process. In the case of a distance control, e.g. an integrated capacitive sensor monitors the distance between laser cutting head and workpiece, with the aim of maintaining the workpiece within the system's allowed parameter window.
The application of this technique is however just possible on conductive materials, not covering several carbon fiber reinforced plastic (CFRP), plastic or glass workpieces. Additionally the measurement spots of capacitive sensors are very large, in the range of some millimeters, limiting its usage next to workpiece discontinuities.
Within this paper, the integration of a low coherence interferometer in the optical path of a laser cutting head is presented for inline distance measurements. This solution presents a promising alternative to the state of the art, enabling a material and surface independent monitoring / control. Furthermore the dimensions of the measurement spot in the range of micrometers (same range of the laser spot) also enables the monitoring / control next to workpiece discontinuities. The achieved results validate its usage for inline distance measurement in different parameter scenarios.

Keywords: laser cutting; process monitoring; process control; inline metrology; low coherence interferometry;

1. Introduction and motivation

Laser based cutting processes are present today in a large number of industrial applications, in areas as automotive, consumer electronics, aerospace, defense and medical devices. This technology is used for processing different materials in micro to macro-ranges, enabling high adaptability, process flexibility and final quality. Industrial systems are based on fixed or scanning optical set-ups using machines or robots to execute 2D or 3D positioning.

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In laser cutting, the laser beam is focused generating a small local spot. The goal is to reach power densities in very high levels, leading to material processing, i.e. melting or vaporization. As described by Nelson et al., 2012, the achievable spot size at the focus point for an incoming collimated beam is a function of the laser wavelength, the lens focal length, the input beam radius reaching the lens and the laser beam quality. Moving away from the focus point, the spot size increases, decreasing consequently the local power density. Furthermore, the process uses assist gases in order to blow the melted material or support the vaporization process. Inert and active (additional energy through exothermic reaction) gases are used for this assistance depending on the application [Ion, 2005]. Depending on the chosen configuration, the focus point needs to be positioned above, below or on the surface of the workpiece.

In this context, system related fluctuations on the distance between focus and workpiece lead directly to different machining conditions. On the one hand, there is a deviation to the targeted power density. On the other hand, with larger distances to the cutting head, the assist gases are more turbulent, leading to pressure variations. As a consequence, cutting results, such as cutting kerf's width and quality (e.g. kerf roughness), change over the workpiece. This situation can lead, in worse cases, to rejected parts. The involved target / actual positioning fluctuations increase when considering 3D machining of complex shaped parts. For these reasons, one of the major parameters related to stability and final quality in the case of laser cutting processes is the distance between laser cutting head and workpiece [Topkaya, 1989]. This parameter will be further called focus position.

There is consequently a large demand on sensors for the monitoring of the focus positon in laser cutting. Modern systems use mainly integrated precision capacitive sensors for inline monitoring and further automation, as described by Wiesemann, 2003, and Topkaya, 1989. The application of this technique is however just possible on conductive materials, not covering several carbon fiber reinforced plastic (CFRP), plastic or glass workpieces. Moreover the measurement spots of capacitive sensors are very large, in the range of some millimeters, limiting its usage next to workpiece discontinuities (e.g. edges).

Nantel et al., 2003, present a further inline focus position sensor based on laser triangulation. These systems are able to measure independently of the material conductivity and present small measurement spots. However, this technique demands diffuse reflective workpiece surfaces, also presenting a lower precision as well as uncertainty problems due to speckle patterns on the workpiece surface. In addition to these techniques, the process related acoustic or electromagnetic emission can be used for the determination of the focus position, as presented by Bordatchev et al., 2006, and Fox et al., 2002, respectively. These techniques lead however to time and labor-intensive examination of the correlation between the calculated indirect variables, the process parameters and final manufacturing results. Furthermore these systems are sensible to variations on the manufacturing system and overall process (e.g. workpiece material or process parameters).

Within this paper, the integration of a low coherence interferometer in the optical path of a laser cutting head for inline distance measurements is presented. This solution presents a promising alternative to the state of the art on the mentioned area, enabling a precise material and surface independent monitoring and control. Furthermore the dimensions of the measurement spot in the range of micrometers (same region of the laser spot) also enable the monitoring and control next to workpiece discontinuities.

2. Concept

2.1. Measurement principle

The measurement system used within this work is based on the spectral domain low coherence interferometry (SD-LCI). Differently from normal low-coherence interferometers, which use a piezo element to find the maximum interference point, in the SD-LCI the depth information is gained by analyzing the spectrum of the acquired interferogram. The calculation of the Fourier transformation of the acquired spectrum provides a back reflection profile as a function of the depth. For the generation of the interference pattern a measurement and a reference path are used, where the optical path difference between these arms is detected. The higher the optical path difference between reference and measuring arm, the higher the resulting interference modulation. A standard SD-LCI setup is presented in Fig. 1.

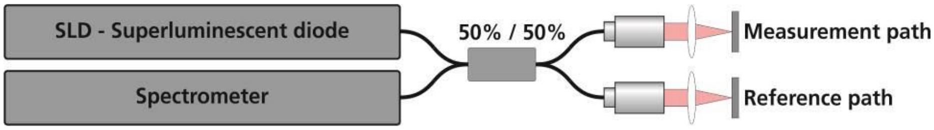

Fig. 1. Spectral domain low coherence interferometry (SD-LCI) Set-up

According to Brezinski, 2006, the total interference signal *I(k)* is given by the spectral intensity distribution of the light source (*G(k)*) times the square of the sum of the two back reflected signals (a_R as the reflection amplitude of the coefficient reference arm and *a(z)* as the backscattering coefficient of the object, with regard to the offset z_0), where *k* is the optical wavenumber (see (1)).

$$I(k) = G(k)\left| a_R \exp(i2kr) + \int_{z_0}^{\infty} a(z) \exp\{i2kn(z)(r+z)dz\} \right| \quad (1)$$

where *n* is the refraction index, *2r* is the path length in the reference arm, *2(r+z)* is the path length in the object arm and *2z* the difference in path length between both arms. By finding the maximum amplitude at the spectrum's Fourier transformation, the absolute optical path difference can be detected.

The measurement range is determined as the region, where the system is capable of detecting a back-reflection from a specimen. Tomlings et al., 2005, describe the maximum measuring depth (Z_{max}) as follows:

$$Z_{\max} = \left(\lambda_0^2 / 4n\Delta\lambda\right)N \quad (2)$$

where λ_0 is the central wavelength, $\Delta\lambda$ is the bandwidth (FWHM - full width at half maximum), *n* is the refraction index and *N* is the number of detector units covered by the light source's spectrum.

The axial resolution (*AR*) is defined by the coherence length of the used light source. Therefore the high axial resolution is implemented independently of the beam-focusing conditions. In other words, this parameter is independent of the used imaging optic. For a light source with a Gaussian spectral intensity distribution, Brezinski, 2006, describes the axial resolution as follows:

$$AR = l_c/2 \approx 0.44\,\lambda_0^2/\Delta\lambda \quad (3)$$

For the measurement of single distance (a single back reflection) the axial resolution can be increased to a sub-micrometric resolution by the usage of signal processing techniques, such as gauss fit.

SD-LCI systems use superluminescent diodes as low coherent light sources. These sources are available in numerous configurations with central wavelengths from 650 until 2,100 nm, with different output power levels and spectral bandwidths. This warrants a large flexibility on the design of SD-LCI systems, enabling an optimization in relation to the final application, as well as processing head's optical system and specimen.

2.2. Inline distance measurement

Based on the description presented on the previous section, it can be stated, that the SD-LCI technique presents a series of positive characteristics regarding an integration and application in laser based cutting units, which are listed below:

- High axial resolution independent of the imaging optics;
- High axial measurement range independent of the imaging optics;
- High lateral resolution and depth of focus possible (dependent of the imaging optics);
- High measurement frequencies possible;
- Exclusively the portion of the acquired light coherent to the reference beam generates an interference pattern, leading to an enhanced robustness against external sources of radiations, e.g. process emission;
- Furthermore the fiber core acts as a pinhole, coupling optimally the measurement beam when within the focus point.

In order to enable an inline measurement and evaluate the usage of this measurement technique in laser cutting applications, 2 different integration concepts were designed (Fig. 2):

- Integration concept for a single point distance measurement;
- Integration concept using a 1D / 2D scanning unit for a direct section / topography measurement.

The first concept focuses on a single point focal position monitoring. This approach works similarly to the previously presented inline sensing tools, allowing a direct adjustment of the laser cutting head's position in relation to workpiece shape variations. The distance between processing head and workpiece is constantly measured and feedback to the machine control for a consequent process adaptation.

The second concept extends the options of the first solution with the possibility of a fast beam positioning over the workpiece surface. By scanning a previously defined line, circle or area, a unidirectional focal position monitoring can be executed. Furthermore, a scanning concept also enables a quasi-simultaneous inline inspection of focal position as well as the cutting kerf width and its edge quality or even shape deviations within the heat affected zone. Based on this set-up a post process assessment can be achieved, which can be used for a process adaptation.

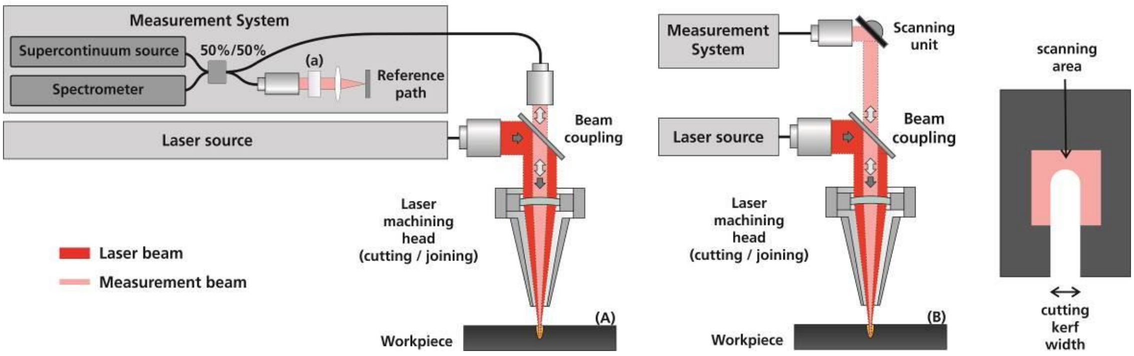

Fig. 2. (a) Integration concept for a single point distance measurement; (b) Integration concept using a 2D scanning unit for a direct topography measurement (on the side is a schematic view of a possible scanning area).

The achievable lateral accuracy of the solution is dependent on different measurement system and processing head parameters. As described by Nelson et al., 2012, the spot size on a defined axial position is a function of the beam wavelength, the defined axial position, the lens focal length, the input beam radius reaching the lens and the beam quality. The measurement spot of the low coherent measurement beam turns to be bigger on the surface, due to achromatic aberrations on the applied focusing lens. These aberrations lead to a minimal axial focus position shifting within different wavelengths, which increases the final measurement spot diameter. In the case of a scanning unit integration, the measurement beam spot also varies its diameter in dependency of the scan angle. In this case the beam reaches the lens with an angle, which leads to a lateral shifting of the focus position associated to the axial focus position shifting. However, the final reachable lateral accuracy stays close to the laser spot diameter. This feature presents a direct improvement to the standard of the art.

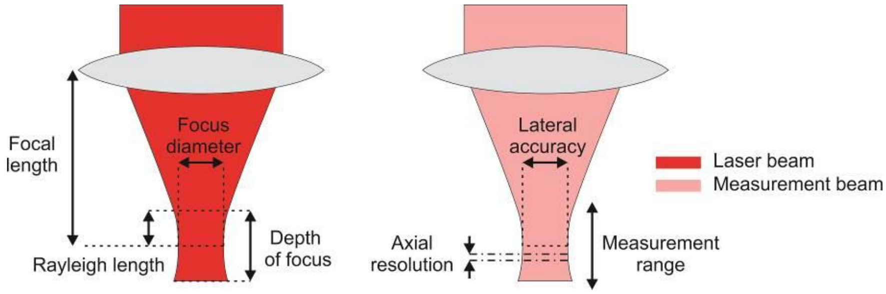

Fig. 3. (a) Laser beam focusing parameters; (b) related measurement system parameters

3. Experimental

3.1. Measurement system prototype

The measurement system set-up was designed with the aim to optimize the laser and measurement beam coupling and minimize optical aberration caused by the focusing lens. Therefore the defined wavelength range for the measurement beam was defined to be 781 ±50 nm, close to the machining laser wavelength (1070 nm). The light source used in the system is a superluminescent diode covering the defined wavelength range with a max. optical power of 18 mW. The spectrometer for the interference signal acquisition was developed with a wavelength measuring range of 101 nm. As a detector a silicon based line camera was used. The theoretical measuring range (maximum depth scan) of the developed SD-LCI using the presented SLD light source was calculated to be of 2.281 mm. The available measurement range was evaluated using a precision linear translation table. The results showed a maximum distance measurement of 2.210 mm using a specimen of aluminum with a technical surface, which simulates the workpieces used for the laser structuring. The calculated theoretical axial resolution of the system is 2.676 µm. The usage of a gauss fitting algorithm to find the modulation frequency after the Fourier transformation of the acquired light spectrum, increases the axial resolution by calculating a sub-pixel accurate curve maximum. Based on this technique an increased axial resolution could be achieved. The standard deviation of the distance measurement values acquired was characterized to be of less than 250 nm (without specimen movement).

3.2. Laser cutting system with integrated inline distance measurement system

The laser cutting experiments with integrated inline distance were carried out in a 3 axis CNC machine using a IPG ytterbium fiber laser, model ylr-6000-s2, with a central wavelength of 1070 nm and a cutting head from Precitec, laser cutting head YR30. The used laser source works in the continuous wave regime with a maximum optical output power of 6 kW. The fiber used for the guidance of the laser radiation to the processing head has a core diameter of 200 µm. The complete system also provides a connection to process gases and a cooling system.

The integration of the measurement system was implemented with an adjustment unit for the measurement beam alignment (Fig. 4). The 2 optical mounts used on the adjustment device enable a 2 angle tilt and x-y position adjustment, leading to a direct measurement spot positioning to the laser spot.

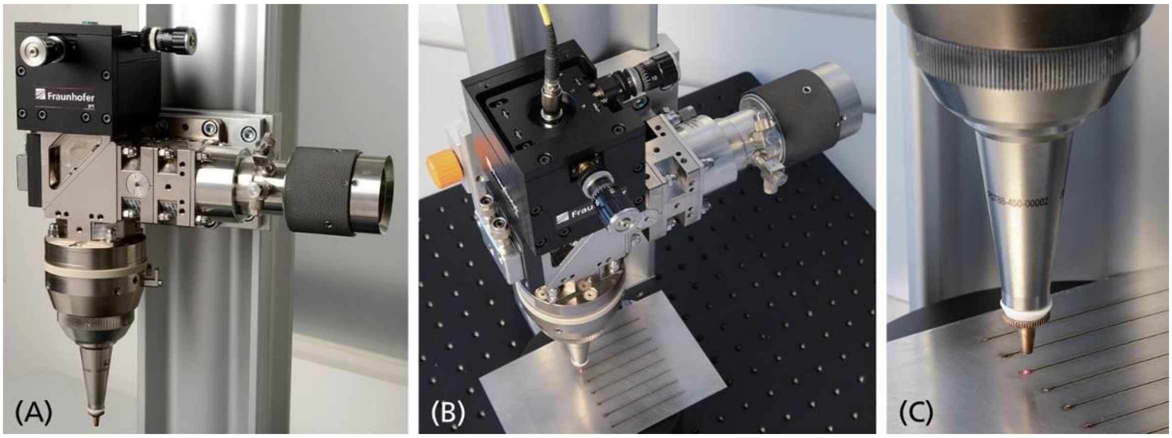

Fig. 4. (A) (B) (C) Laser cutting head with a coupling unit for the integration of the inline distance measurement system

3.3. Experiment definitions

The experiment scope was set-up to be executed for stainless steel sheets with 2 mm thickness. The defined cutting area was of 60 mm with a feed rate of 300 mm/min. For the cutting experiments, a series of different optical output power levels was used covering a range between 200 W and 1000 W with steps of 100 W. Argon (Ar) was applied as processing gas with a final pressure of 7 bar.

A SD-LCI system measures optical path lengths, which are directly dependent on the physical length traveled and the refraction index values over the entire path. Therefore variations on the physical length as well as on the refraction index influence the measured results. For this reason the effects of process temperature, gas and pressure need to be taken into account and evaluated.

On the one hand, based on values presented by Börzsönyi et al., 2008, the refraction index of Air and Argon are almost identical with values very close to 1, for a wavelength at 780 nm and for 1 bar and 0°C. For the small distances measured here, this small difference can be neglected.

On the other hand, the effects of temperature and pressure play an important role on the variation of the refraction index values. As described by Ciddor, 1996, on the consideration of ideal gases, the refraction index of gases is proportional to the involved pressure and inversely proportional to the involved temperature.

In order to characterize the mentioned influences in the praxis, each experiment was carried out in 3 configurations: without processing gas and without laser radiation, with processing gas and without laser radiation, and finally with processing gas and with laser radiation. In total 27 cutting experiments were conducted.

For the focal position monitoring, the measurement beam spot was shifted in several micrometers from the laser spot. Due to this positioning, the measurement spot do not stay within the processing zone, which could lead to a bad measurement beam coupling. The adjusted displacement enables the system to measure the focal position just before the laser material interaction starts.

4. Results

Figure 5 presents an example of the inline measurement values within a series of experiments. As expected there is a distance variation between a measurement with and without processing gas. This results due to the increase of the pressure around the processing area from ~1 bar to 7 bar (refraction index of gases is proportional to the involved pressure). Once the laser radiation and the laser-material interaction are started and the temperature around the processing zone increases, another variation on the measured distance occurs. As expected the difference to a measurement without processing gas and without laser radiation decreases in relation to the previous results. This occurs as the refraction index of gases is inversely proportional to the involved temperature levels. The same behavior and value distributions were also experienced for the other experiment series using different power levels.

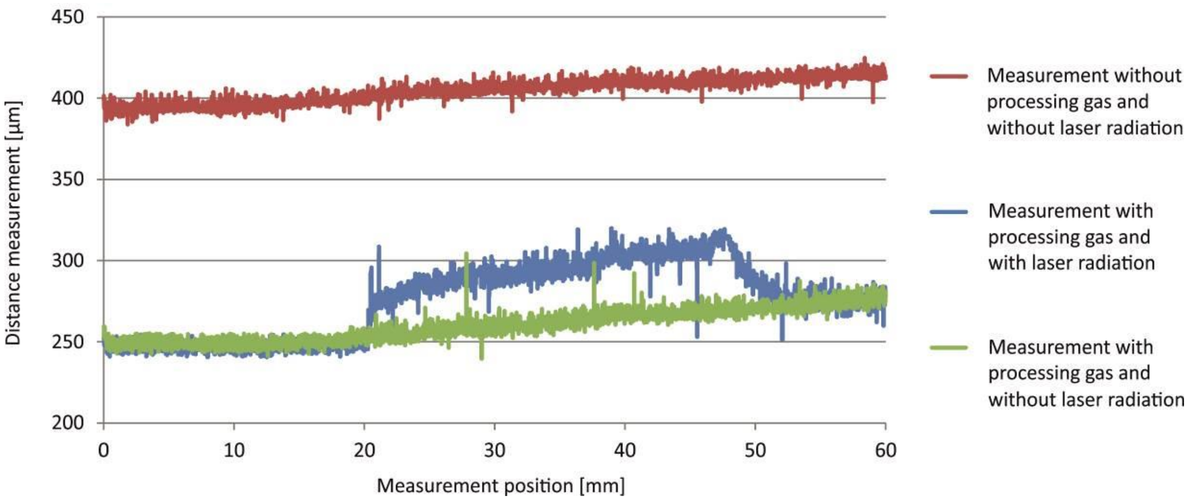

Fig. 5. Experiment results for an laser output power level of 400W. [Red] Measurement without processing gas (Ar) and without laser radiation; [Blue] Measurement with processing gas (Ar) and with laser radiation; [Green] Measurement with processing gas (Ar) and without laser radiation.

The measurement system is by default calibrated for standard conditions (22°C and 1 bar). The refraction index changes related to the cutting process demand therefore a compensation on the system signal processing and its results. The involved changes on the measurement values need to be analyzed for every process configuration in dependency of the needed process precision levels and compensated on the measurement system software. This can be executed in a calibration step, previous to the process start, which should be repeated depending on process variations.

The measurement values (without compensation) presented at Figure 5 were also analyzed regarding its variation and stability by means of the standard deviation. In the presented results (Fig. 5), the measurement without processing gas and without laser radiation present a standard deviation of 2.516 µm.

These initial values are more related to the surface roughness of the used workpiece. The measurement with processing gas and without laser radiation present a standard deviation of 3.250 µm. The measurement with processing gas and with laser radiation present a standard deviation of 4.769 µm. Based on these values, it can be also shown that the instability of the measurement values and consequently its uncertainty increases with the addition of the process related components, i.e. processing gas and laser radiation. Another effect leading to the increase over the standard deviation of the measurement values can be associated to the missing compensation of the refraction index changes.

However the achieved values show a robust and stable long term behavior. Considering a further process control based on the focal position, the values can be further averaged to reduce the variation levels.

5. Conclusion and outlook

Within this paper, the integration of a spectral domain low coherence interferometer in the optical system of a laser cutting head for direct process monitoring was presented. This solution presents a promising alternative to the state of the art, enabling a material and surface independent monitoring and control.

The achieved results on this work qualify the SD-LCI technique for a usage as a tool for the process monitoring of the focal position in laser cutting applications. Furthermore it also presents the extra ability to visualize the process results as the cutting kerf width and its edge quality or even form deviations within the heat affected zone. Process related effects on the measurement results were analyzed and their behavior enables it to be compensated for an inline application of the system.

Due to its flexibility regarding the applied measurement wavelength and the definition of the measurement range, this solution can be adapted and optimized to be applied in different machine configurations, process parameters and materials (metals, glass, fiber reinforced polymers, ceramics, etc.).

There is however still a large room for improvement specially regarding the effects of processing related temperature gradients and pressure, which influence the measurement results and uncertainty. Especially in the case of cutting 3D shaped parts, the temperature and pressure levels can fluctuate within the procedure, which can affect the measurement results and the process control. This application would demand further investigations. Nonetheless, a calibration step to compensate the refraction index should be implemented and used.

Another important aspect for further evaluation is related to the influence of the thermal effects on the cutting head's lens properties, which could influence the measurement beam (e.g. focal position shifting). Moreover additional experiments for the laser cutting of other materials as carbon reinforced polymers, plastics, glasses and ceramics are planned, which will provide a further insight into this technique and its advantages and limitations. Finally the usage of the measurement values for a direct focal position control and its relation to the final cutting parameters is planned also to be researched.

Acknowledgements

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