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Illumination for process observation in laser material processing

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Abstract

Process control for laser-material-processing requires access to characteristic features which qualify the operating-point of the process. For laser-based manufacturing-processes, this can either be achieved by detecting the emission of the process or by detecting geometric properties of the process-work piece interaction. Such illumination is usually provided by lasers emitting in the near-infrared. Inherent properties like coherence of these sources and complex optical systems prohibit a wide adoption.
The technological advance in sources such as led's has the potential to deploy small light sources directly to the processing heads but bears new problems in light-ray-delivery, emitter-protection against secondary radiation and cooling. From a scientific point of view, the properties of illumination sources are compared with a special focus on the specific requirements of process observation.

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Keywords: process control; illumination

1. Introduction

Process observation plays a major role in increasing the performance of current manufacturing processes. On the path to self optimizing manufacturing systems, cognition of technical systems plays a vital role(Thombansen et al., 2012). Information about the course of the process can be gained from observing the thermal emission from the laser process and from observing geometrical properties of the material while it is being processed (Kratzsch et al., 2000).

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At the heart of such observation stands the illumination of the area where the interaction takes place in order to subsequently use computer vision algorithms to extract relevant features (Golnabi and Asadpour, 2007).

For manufacturing processes from cutting through welding and brazing, there is a strong requirement for an intense illumination in order to be able to acquire images at short exposure times which are not affected by blur from motion. To achieve such an intense illumination there are currently three technical implementations, LED, Lasers and VCSEL. To identify the areas of application where these solutions fit in best, experiments and criteria are reported.

2. Properties of Illumination for Process Observation

Process observation in general is used to acquire information about the course of the process which is relevant to the processing result. Such information can be contained in radiation which is emitted from the process in the form of thermal radiation, acoustic waves or emission in the visible range (Keuster et al., 2007; Thombansen et al., 2013). Especially in processing of metal surfaces, light which is reflected from the surface of the work piece contains information about geometric properties such as the position of joints, properties of welds or cut kerfs or even in other areas such as milling (Pfeifer and Wiegers, 2000). To detect such properties, proper illumination is required for an imaging system to deliver images which can be processed by computer vision algorithms.

In manufacturing, new laser sources for material processing continuously increase processing speeds while reducing the size of the interaction zone at the same time. This imposes further requirements to the illumination sources as the magnification of optical systems has to increase in order to provide sufficient detail of the work piece. With respect to increased processing speeds, the exposure time of the camera system must be short to limit blurring which results from the displacement of the work piece during exposing the image to the sensor. Blurring reduces the information content of an image by distributing properties of the object to multiple positions in the image. As the electronic imaging sensor has spatially separated pixels, the loss in contrast cannot be undone.

Table 1. Blurring of the image due to exposure time during displacement (unit magnification).

Feed rate	exposure time	motion
0.5 m/min	1 ms	8,3 µm
4.0 m/min	100 µs	6,7 µm
10.0 m/s	1 µs	10,0 µm

Some coaxially acquired images from different applications are shown below. All images are affected at least by the resolution limit due to small numerical aperture.

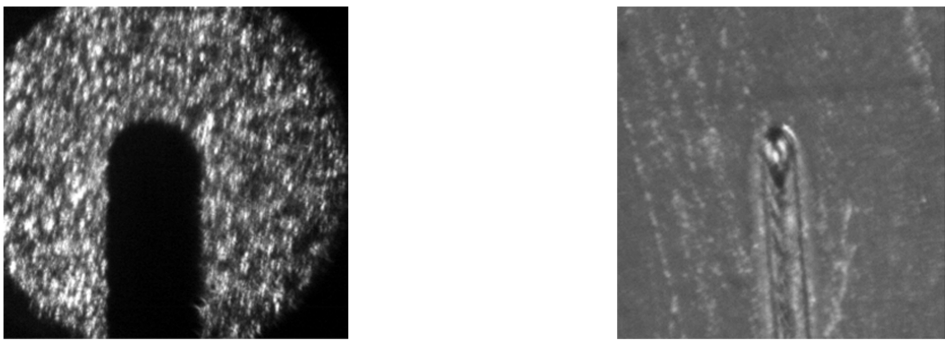


Fig. 1. Images from laser cutting with minimal blur (1) and laser welding with chromatic aberration (2).

Several applications in laser material processing require small processing heads as they have to access complex geometries or as they have to be moved fast. One requirement for illumination systems therefore is to consume minimum space and to be light weighted. Instead of attaching an illumination system aside of a processing head, the request is to integrate illumination it into the head, coaxially if possible (Kaierle, 2005). Such systems rely on dichroic beam splitters which combine the processing laser radiation with the illumination radiation depending on the wavelength. A system which is used in CO_2 laser cutting of stainless steel is shown below.

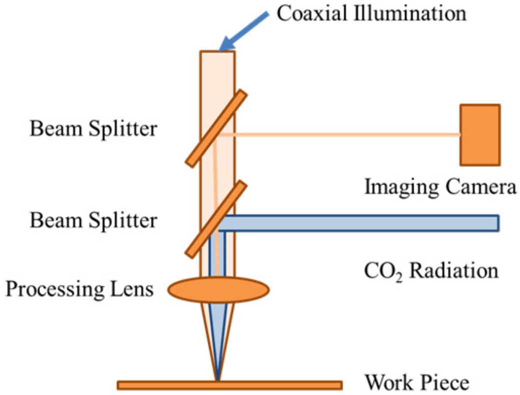


Fig. 2. Coaxial coupling of illumination for process observation in CO_2 laser cutting.

A significant reduction of information with respect to standard image processing can be caused by speckles. Speckles refer to an intensity variation in the image which is distributed all over the image and which is caused by interference of the illuminating light. Such speckling is stronger when the light rays are more coherent as for laser sources with small bandwidths. On the other hand, a small bandwidth is beneficial especially in the case of coaxial coupling as the illumination wavelengths have to be relayed through the processing optics, which typically is designed to have its best performance at the processing wavelength. The wider the bandwidth of the illumination source, the more severe chromatic aberations affect the information content of the image.

Categories of properties which are relevant to process observation in manufacturing can be listed as

- Intensity being delivered per area to allow short exposure times
- Size of the light delivery system at the processing head to ensure applicability in the industrial environment
- Light properties such as wavelength, coherence and bandwidth to conserve information content of the image

3. Properties of laser diodes, light emitting diodes and vertical cavity emitting lasers with respect to illumination for process observation

Illumination sources for process observation are mostly used in the near infrared band at about 800 nm. At this wavelength, the sensitivity of standard CMOS camera systems is still acceptable and the available radiation sources provide considerable optical power. The emission spectra of the three sources in this report are shown in the plot below.

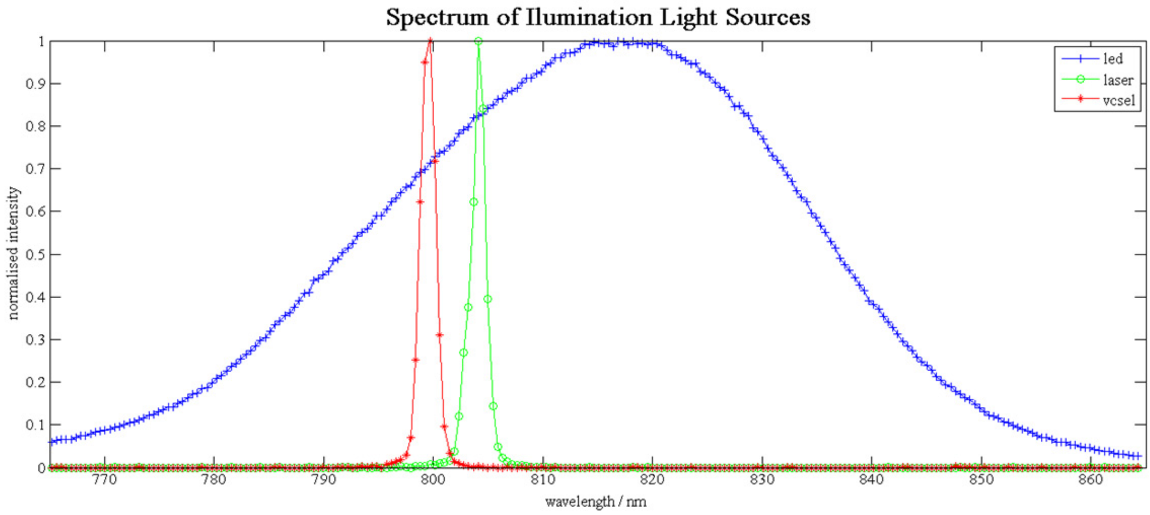


Fig. 3. Emission Spectra of a laser diode, an LED and a VCSEL.

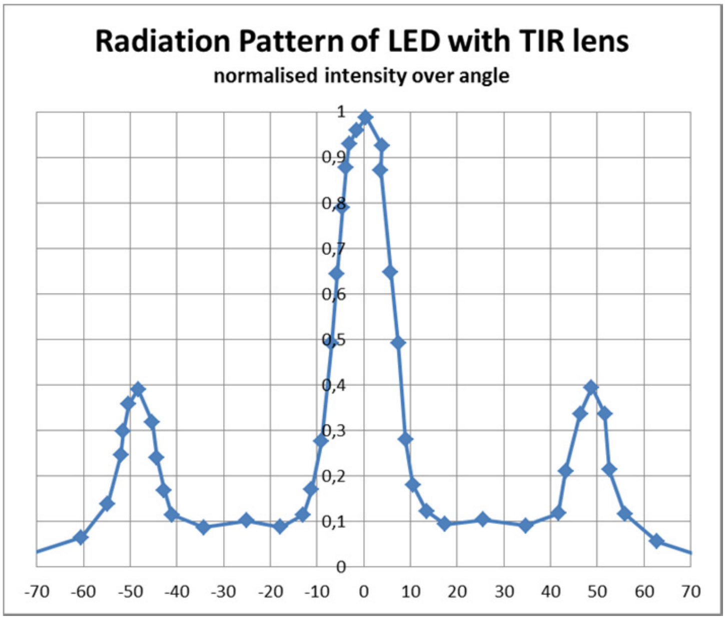
3.1. *LED*

Light emitting diodes have a typical angle of emission of more than 120 degrees for lambertian or 200 degrees for batwing radiation patterns. Both are shown in the plots (b) and (c) respectively. The key measure to focus the radiation is to use epoxy covers on the emitting substrate or lenses with surfaces which form the radiation by total internal reflection (TIR), also attached closely to the emitter. The LED devices employed in the experiments use a full TIR lens which is directly attached to the emitting diode. The resulting radiation pattern is given in subplot (a) which can be evaluated to a FWHM of 7 degrees half angle at an efficiency of 30%. The device converts a power consumption of 1.8 Watts into a total optical power of 200 mW which gives an electric efficiency of 11%. In combination with the optical system, a total conversion efficiency of 3.3 % is reached.

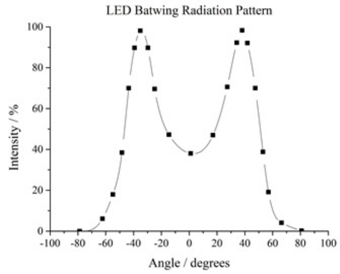
Taking this efficiency, the bandwidth and the radiation pattern into account, LEDs seem to be of limited benefit to process observation in manufacturing. However, it has to be pointed out that the LED does not have any issues with coherence. The emitted power per device makes the LED applicable to ring lights where a multitude of emitters can be combined to deliver an illumination intensity which is sufficient for short exposure times.

Table 2. Properties of the infrared LED used in the experiments.

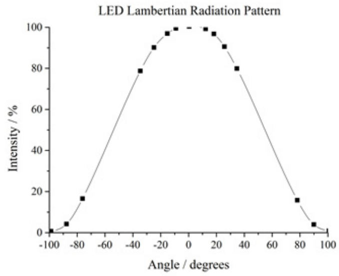
Property (without application specific optics)	Value
FWHM bandwidth	45 nm
Optical power	0.2 Watts
Etendue	3.14 E-6 m²
Conversion efficiency (el.→opt.)	0.11
Coherence	n/a



Radiation pattern of single LED of the LED system in the experiment, data from datasheet (1)



Batwing radiation pattern (2)



Lambertian radiation pattern (3)

Fig. 4. Radiation pattern of LEDs as in the experiment (1); general patterns (2).

3.2. *Laser diode*

Laser diodes in the infrared band can deliver optical power which is tailored to the application. In most cases, the emitting semiconductor is placed in a housing which provides electric current and cooling functions. The radiation is coupled into an optical fiber which delivers the radiation to the optical system. In comparison to the other sources, this system provides the highest amount of radiation per device and the largest etendue making it an ideal solution for small illumination areas and long collimated beam paths. Coherence of the emitted radiation however adds speckles to the images which reduces its information content. The device used in the experiment is coupled into a fiber with a 400 µm core diameter and a NA of 0.22. The properties of the source at the fiber exit are given in the table.

Table 3. Properties of the laser system used in the experiments.

Property (without application specific optics)	Value
FWHM bandwidth	2 nm
Optical power	35 Watts
Etendue	1.95 E-4 m²
Conversion efficiency (el.→opt.)	0.43
Coherence	single laser source

3.3. *VCSEL*

On a surface of two by two millimeters, this illumination source provides more than 2.000 laser sources. Each of these sources emits into a 17 degree cone resulting in an emission with a numerical aperture of 0.15. As can be seen in the spectrogram above, all 2.000 sources emit at bandwidths which result in a total bandwidth comparable to that of a single laser diode. Each of these sources provides an output of 4 Watts of optical power at a conversion efficiency of 30%. This makes it an ideal device for illuminating areas which are larger than the emitter itself, up to applications where the full field of scanning systems is to be observed. As there is only a limited need for beam guidance, VCSELs can be arranged as a set of sources, providing scalable intensities on the work piece illuminating the objects from different angles. The properties of a single device is given in the table below.

Table 4. Properties of the VCSEL used in the experiments.

Property (without application specific optics)	Value
FWHM bandwidth	2 nm
Optical power	4 Watts
Etendue	2.3 E-5 m²
Conversion efficiency (el.→opt.)	0.3
Coherence	sum of 2000 lasers

4. Evaluation of image properties

In manufacturing, surfaces of the work pieces differ by reflectivity and by roughness. While the first can be equalized by adapting illumination intensity, the latter cannot if the roughness lies in the range of the imaging magnification. Algorithms from computer vision must distinguish between work piece features which are relevant to material processing and those which simply result from the properties of the base material. The evaluation focuses on image properties from the perspective of information content due to intensity distributions, general contrast and the searched process relevant features.

4.1. *Stainless steel surface*

The images in the table below show the surface of a stainless steel sample which has been sand blasted with 120 µm glass particles as used for decorative parts. The surface shows a multitude of bright spots which also lead to saturated pixels seen on the right corner of the histogram. Increasing the illumination intensity leads to a brighter image and to a better perception of details as far as human cognition is considered. The histogram shows, that only little information is in the lower range of the intensities. With a limit of 10 counts per intensity level, for the LED illumination, information starts at 91 counts giving 165 different levels. For the laser histogram, the intensities above this limit start at 31 counts providing 225 levels and for the VCSEL at 32 with 226 levels.

Table 5. Properties of the intensity distribution for the stainless steel sample.

Illumination Source	Intensity levels with more than 10cnts / #	Saturated pixels / #	Significant pixels / #
LED	165	1065	64401
Laser	225	1231	64270
VCSEL	226	757	64670

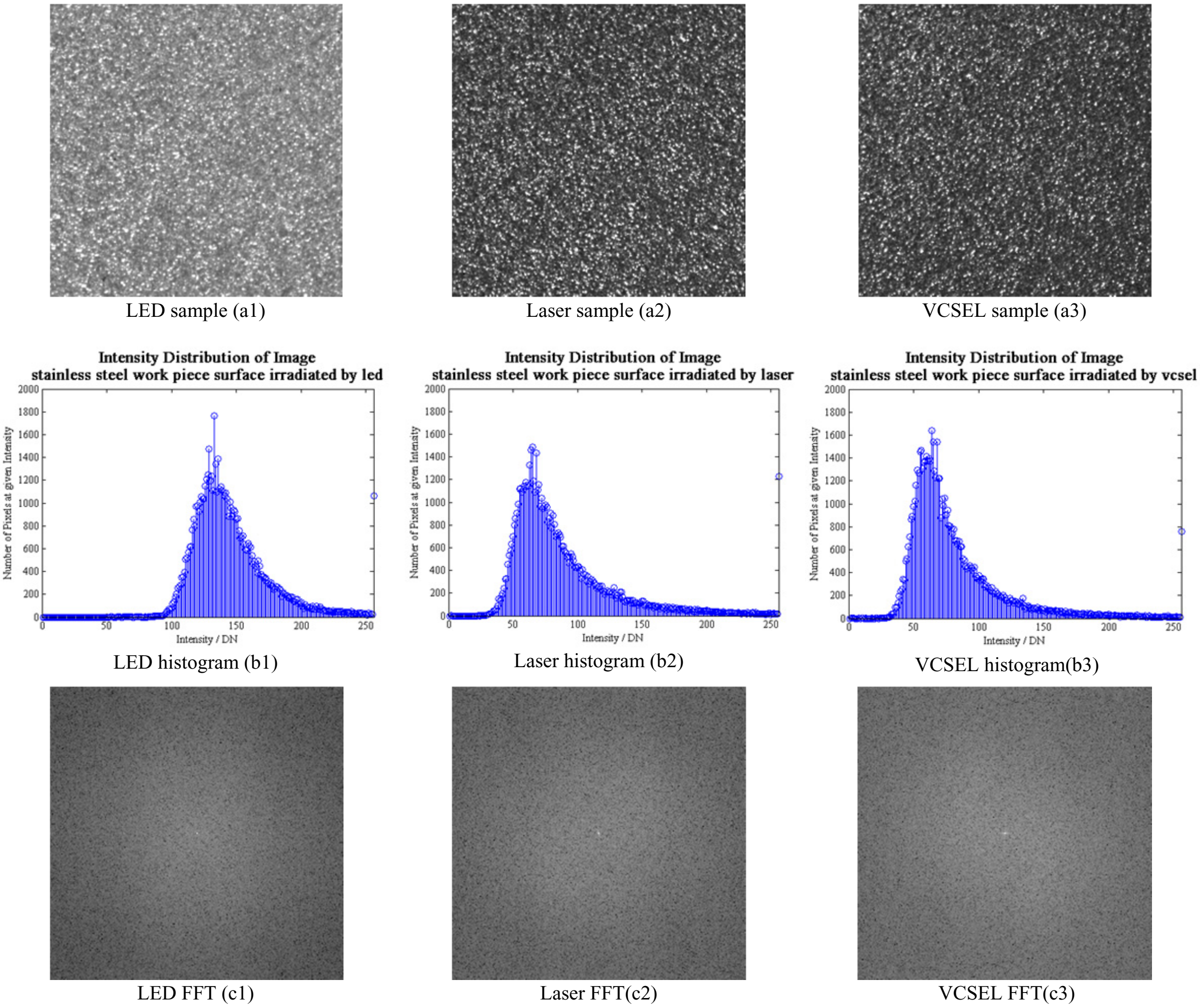


Fig. 5. Images of stainless steel sample, magnification 1:1 on top (a1-a3), corresponding histograms in the middle (b1-b3) and FFT plots at the bottom (c1-c3), Image size 256x256 pixels.

To compare the contrast of the images, a two dimensional Fourier transform is executed on the images. The result is plotted in the table above showing different intensity distributions in the plane. Numerical evaluation of the values reveals, that the amount of high frequencies in the image of the sample is higher if illuminated with the VCSEL source. This can be quantified as in the table below. The sum of the intensities in a sub window of 50 by 50 pixels in the upper left corner of the plane results in what is called focus factor.

Table 6. Amount of high frequencies of stainless steel sample (sum of 50x50 pixel hf window from 2d-fft).

Illumination	Focus factor
LED	834
Laser	943
VCSEL	1035

4.2. *LMD Track sample*

In process observation, work pieces provide surfaces with contours like the LMD track in the sample below. This track is generated with laser metal deposition where powder fed through a process nozzle coaxially to the laser beam. The molten powder comes together with the molten base material resulting in a track which lies on top of the work piece. The images below show a strong reflection parallel to the track which originates as a direct reflection from the illumination source. Correspondingly, the histogram shows a significant amount of saturated pixels.

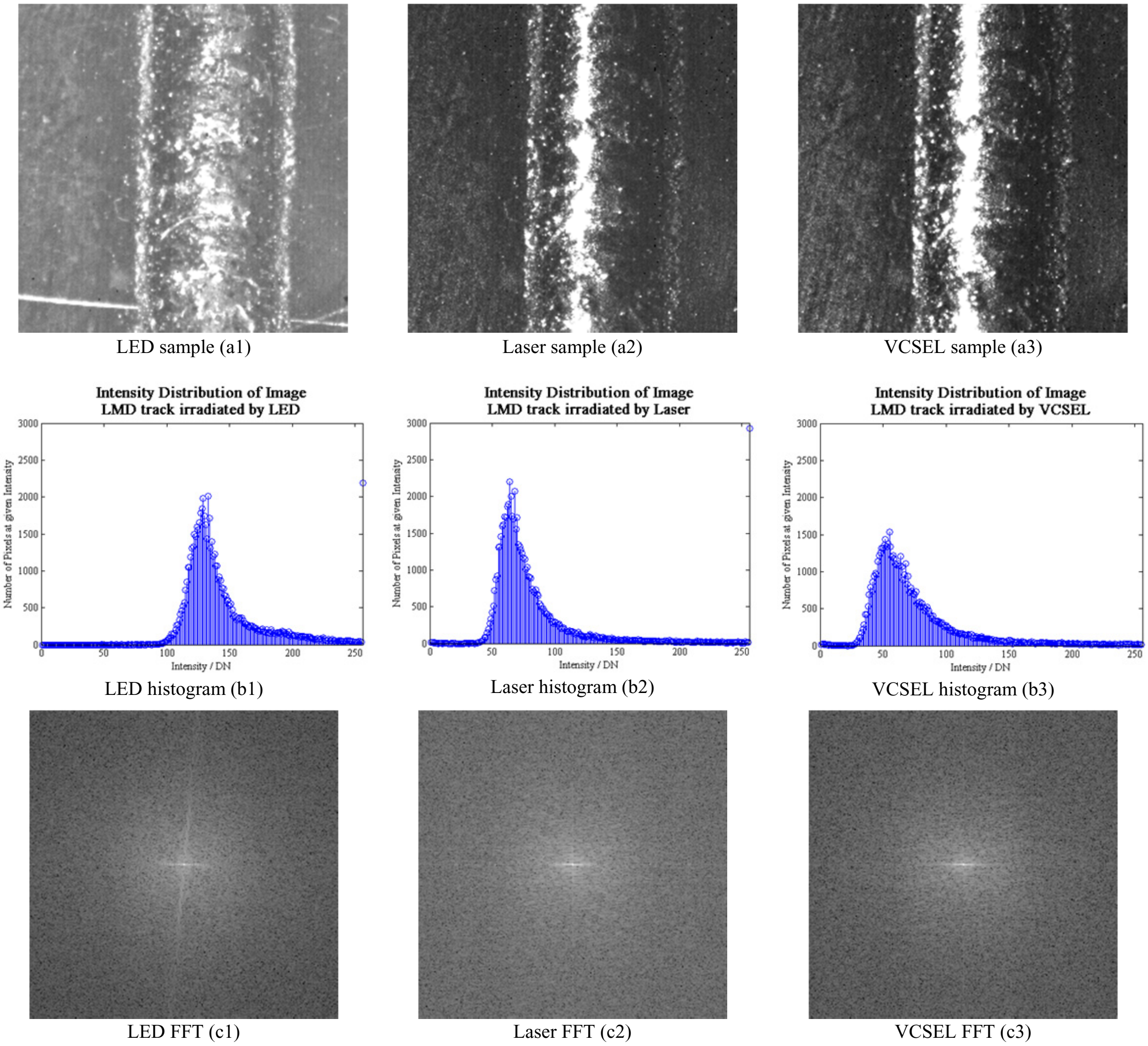


Fig. 6. Images of LMD track sample, magnification 1:1 on top (a1-a3), corresponding histograms in the middle (b1-b3) and FFT plots at the bottom (c1-c3), Image size 256x256 pixels.

Table 7. Properties of the intensity distribution for the LMD track sample.

Illumination Source	Intensity levels with more than 10cnts / #	Saturated pixels / #	Significant pixels / #
LED	158	2189	63235
Laser	214	2922	61174
VCSEL	227	4102	59911

Table 8. Amount of high frequencies of LMD track sample (sum of 50x50 pixel hf window from 2d-fft).

Illumination	Focus factor
LED	814
Laser	1038
VCSEL	871

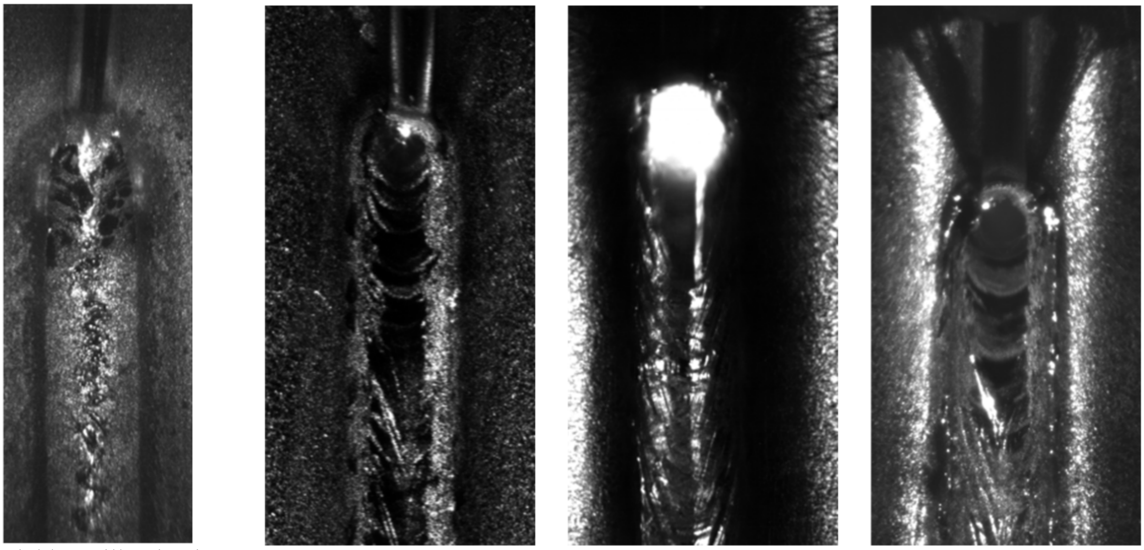
The result of the FFT shows a lower amount of high frequency components in the image for VCSEL illumination. This correlates with the higher number of saturated pixels although the maximum of the intensity distribution is lower than that of the laser illuminated image.

4.3. *Application to laser brazing*

In laser brazing, the space occupied by illumination devices is of major interest. During processing of work pieces, the brazing head has to be guided orthogonal to the joint which leads to limitations in the case of complex parts and complex joint geometries. Control of the process can only be executed in the case the process observation system is robust against different roughness of the surface (Ungers et al., 2010). As seen above, this requires sufficient amount of radiation and an equal distribution of the illumination. The area of interest for laser brazing amounts to 50 by 20 millimeters making LEDs and VCSELs an ideal choice for illumination. However, as processing speeds of 6 m/min lead to the requirement of short exposure times for limited motion blur, LEDs in combination with the space restrictions have their limits.

The implementation of the illumination systems involves specially coated lenses and beam splitters in the case of the coaxially coupled version. It preserves the size of the processing head and the light source can be placed externally, saving weight for robotic applications. For image processing algorithms, the reduced contrast of the image shown in subplot 1, which is caused by scattered light inside the optical system, provides difficulties in robustness. In the case of the laterally applied laser, a diffusor plate had to be used to reduce speckles which reduces optical efficiency and adds to the optical system in the vicinity of the processing head.

The LED system with six sources demonstrates the limitation of the radiated power and light ray delivery. From a practical point of view, the epoxy of the LED lenses cannot be brought close enough to the processing zone as the laser radiation and the process emit to much heat. The image on the right shows the result of using four VCSELs at an exposure time of 30 µs.



coaxial laser illumination 100 µs at 15 Watts (1)

lateral laser 100µs at 20 Watts (2)

lateral LED illumination six sources 250 µs at 0.2 Watts (3)

lateral VCSEL illumination four sources 30 µs at 4 Watts (4)

Fig. 7. Illumination systems for laser brazing.

5. Discussion

The comparison of the selected LEDs, fiber guided Lasers and VCSELs shows advantages and limitations for using these sources for process observation in laser material processing. Where LED's with a low unit price allow the implementation of illumination systems with multiple sources which provide light from several directions images can be acquired with minimal number of saturated pixels. For laser material processing, the bandwidth of 30 to 50 nm is a problem in the design of the optical system as it leads to abberations caused by the monochromatic processing optics. In addition to this, maximum available intensity and poor beam delivery are a major drawback if short exposure times and small equipment sizes are required.

Systems based on laser sources have the advantage of providing scalable intensities of light through a light fiber delivering the best beam quality of all three solutions. Where the latter is beneficial to coaxial coupling which requires beam collimation, this concept also has the restriction of providing light from only one position. In industrial applications, this requires individual adaptation to the specific requirements of an application in order to be robust against disturbances from changes in material or changes in geometry of the work piece. Such systems also imply the necessity for rack space with the diode case, the optics and external cooling by air or even water.

Using VCSELs for illumination opens the possibility to provide several distributed sources with high intensity and limited space requirements. The divergence angle of 17 degrees allows illumination of operating fields of scanners even without the need to apply additional optics. Still, from the basic data, the illumination source can be collimated to relay the radiation through the optical system of a laser processing unit. Depending on the practical application, cooling can be provided at the processing head as a drop off from the cooling which is available per se.

The LEDs used in this experiment proves to create a limited amount of information which can be seen in the width of the histogram representing the distribution of the intensities. Looking at the results from the experiments, VCSELs are very much comparable to the imaging properties achieved with fiber guided lasers. The advantage of having several sources from different positions to illuminate the area surrounding the interaction zone has been shown with the brazing sample where all process relevant details could be detected.

As a resume, it can be concluded that lasers and VCSELs can deliver the intensity per area which is required allow short exposure times for micro and macro processes, that the size of the light delivery system can be kept small with VCSELs and with laser sources and that light properties for both concepts are suitable.

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