US 20130319980A1

(19) **United States**

(12) **Patent Application Publication**

(10) **Pub. No.: US 2013/0319980 A1**

Hesse et al.

(43) **Pub. Date: Dec. 5, 2013**

(54) **DEVICE AND METHOD FOR MONITORING A LASER CUTTING PROCESS**

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(21) Appl. No.: **13/961,596**

(22) Filed: **Aug. 7, 2013**

Related U.S. Application Data

(63) Continuation of application No. PCT/EP2012/051634, filed on Feb. 1, 2012.

(30) **Foreign Application Priority Data**

Feb. 7, 2011 (DE) 102011003717.9

Publication Classification

(51) **Int. Cl.**

B23K 26/38 (2006.01)

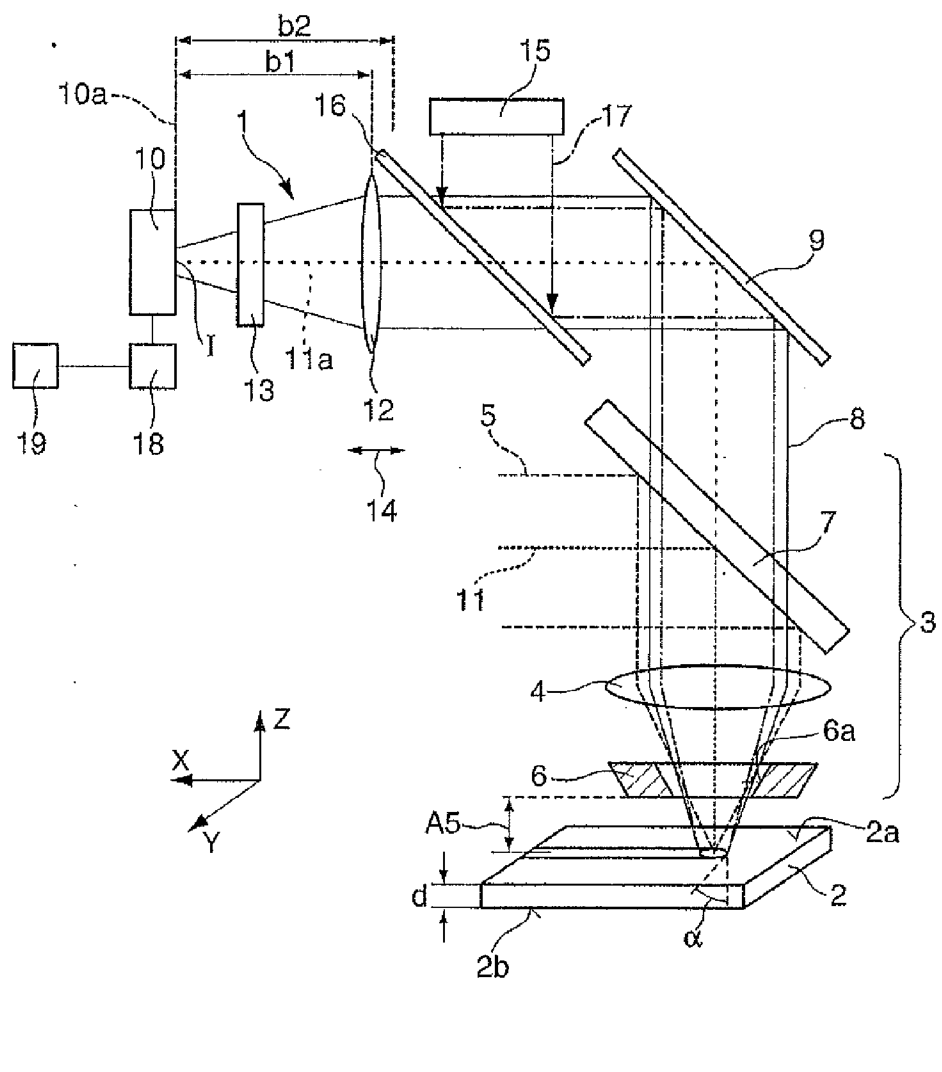
(52) **U.S. Cl.**

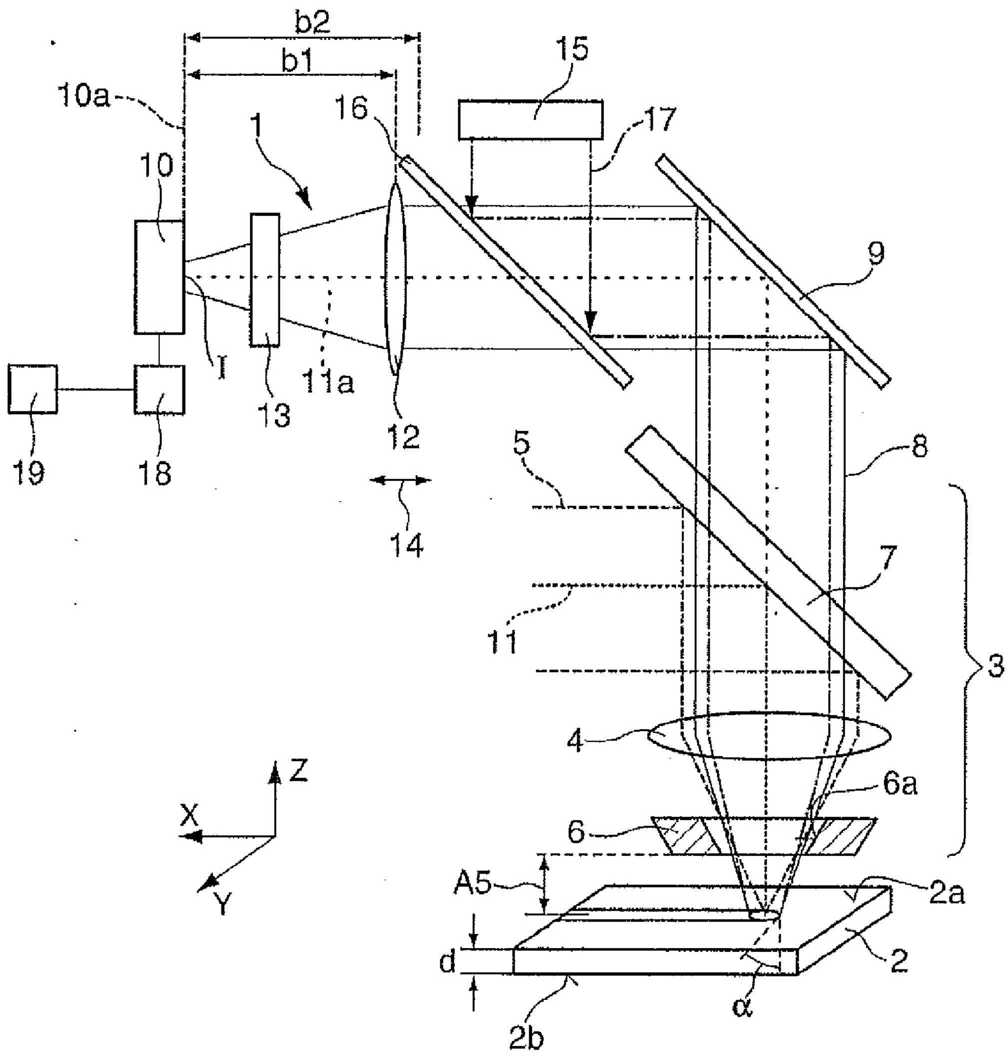
CPC *B23K 26/38* (2013.01)

USPC **219/121.62**

(57) **ABSTRACT**

The present disclosure relates to a device for monitoring and for controlling a laser cutting process on a workpiece, and a method of using the same. The device includes an image capturing apparatus for capturing an image of a region of the workpiece to be monitored, in which the region of the workpiece to be monitored includes a region of interaction of a laser beam with the workpiece, and an evaluation apparatus for detecting material boundaries of the workpiece using the captured image. The evaluation apparatus is configured to determine at least one characteristic value of the laser cutting process based on a geometric relationship between at least two of the detected material boundaries, the region of interaction, or combinations thereof.

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b1
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1
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15
17
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9
I
13
11a
12
19
18
8
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14
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3
4
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Z
X
6
Y
A5
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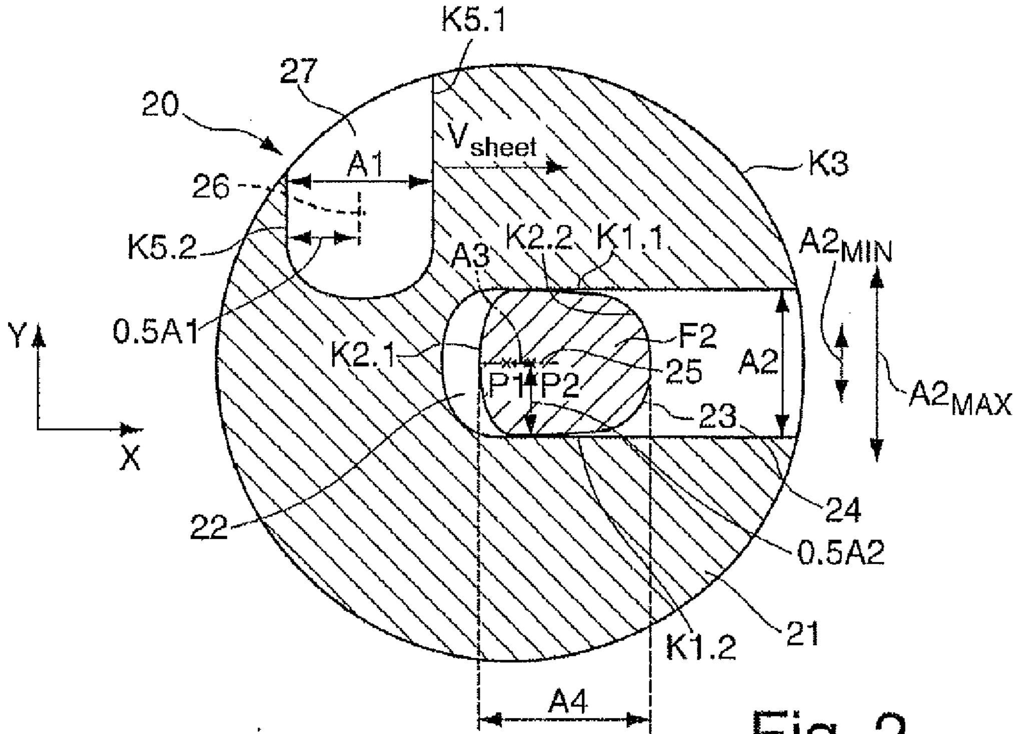
d
2
α
2b

Fig. 1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K3
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K5.2
A3
K2.2
K1.1
A2 MIN
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K2.1
F2
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A2
P1
P2
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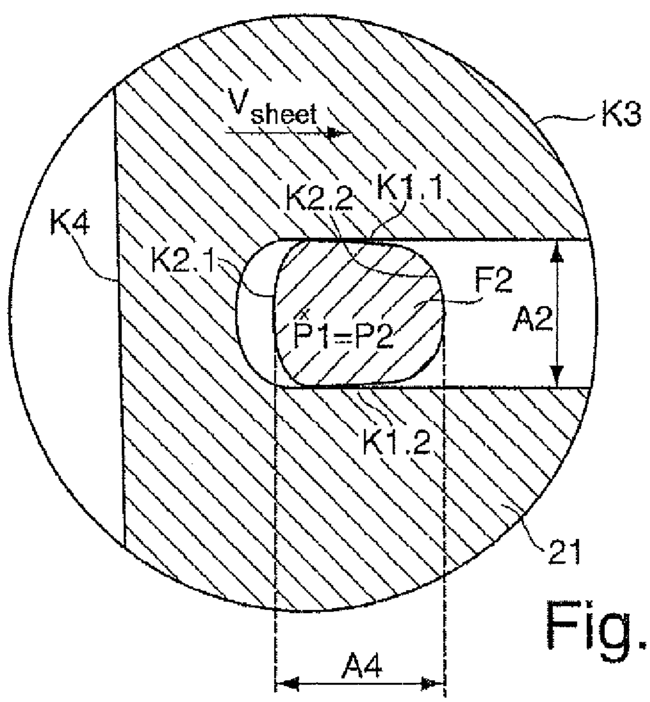
K1.2
A4

Fig. 2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K4
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K1.2
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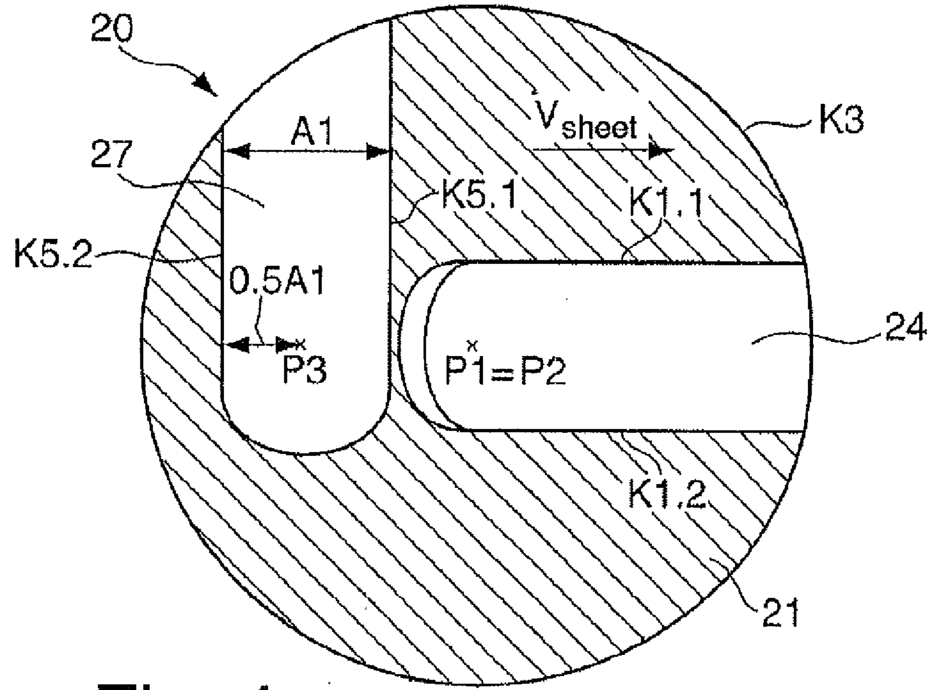
A4

Fig. 3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K5.2
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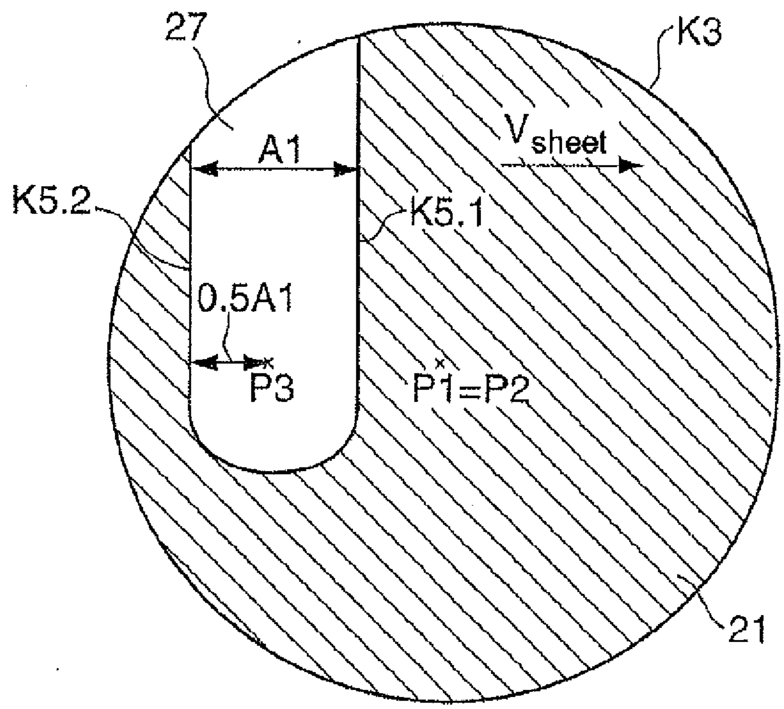
P3
P1=P2
24
K1.2
21

Fig. 4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A1
V_{sheet}
K5.2
K5.1
0.5A1
P3
P1=P2
21

Fig. 5

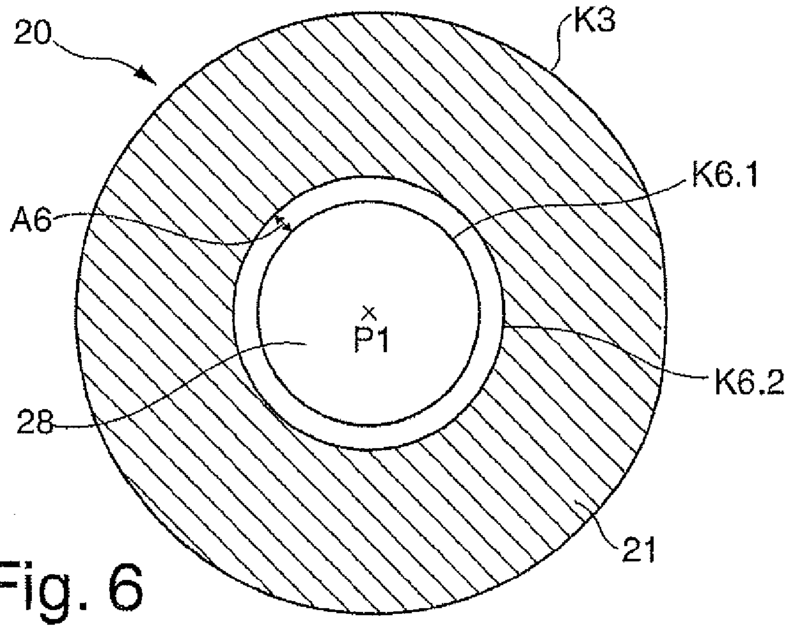

Fig. 6

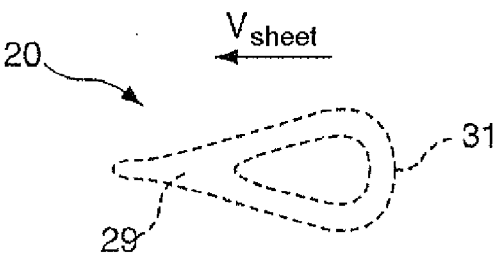

Fig. 7a

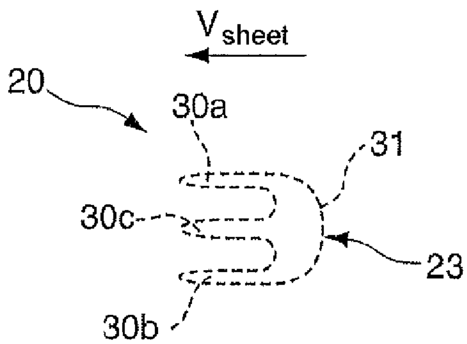

Fig. 7b

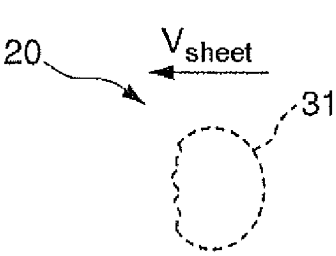

Fig. 7c

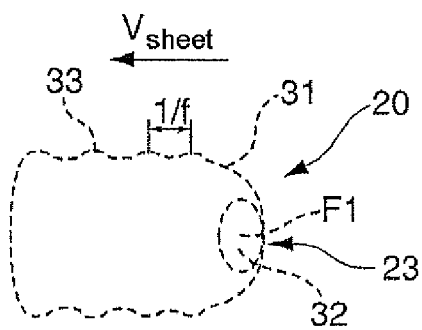

Fig. 8

DEVICE AND METHOD FOR MONITORING A LASER CUTTING PROCESS

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application is a continuation of and claims priority under 35 U.S.C. §120 to PCT Application No. PCT/EP2012/051634 filed on Feb. 1, 2012, which claimed priority to German Application No. 10 2011 003 717.9 filed on Feb. 7, 2011. The contents of both of these priority applications are hereby incorporated by reference in their entirety.

TECHNICAL FIELD

[0002] The present disclosure relates to a device for monitoring a laser cutting process on a workpiece.

BACKGROUND

[0003] An example of a device for monitoring a laser cutting process is disclosed in DE 10 2005 024 085 A1. To monitor a laser machining process, the device described in that reference has, inter alia, a camera and an imaging apparatus, which images the region of interaction between the laser beam and the workpiece on a camera. The output signals from the camera are fed to an evaluation circuit, which processes both the signals from the camera and the signals from a radiation-sensitive receiver, and are used to characterize the course of the laser machining operation. Here, the radiation-sensitive receiver and the camera can cover different spectral ranges. No further information is given about the features used for characterization or the specific evaluation thereof.

[0004] The reference WO 91/04828 likewise discloses a monitoring apparatus, in which a camera arranged on the laser machining head, coaxially with the optical axis of a laser beam guided in the direction of the workpiece, is used for focal position determination during a laser cutting process. Here, the camera detects a zone of interaction between laser beam and workpiece and, by determining the width of the zone of interaction, conclusions are drawn about the focal position or about the distance between the laser machining head and the workpiece.

[0005] The reference DE 10 2008 051 459 A1 discloses a further such monitoring apparatus which, in particular, is used for edge detection during the layer by layer machining of bodies by means of laser radiation. The device comprises an imaging detector for forwarding a digital image, converted into gray stages or true-color/color-coded, to a data processing system.

[0006] The reference DE 43 36 136 C2 describes a method for laser machining in which the laser light reflected at the workpiece, together with secondary light generated in the machining process, passes back to a laser oscillator where, with the aid of a mirror, some of the laser light and of the secondary light is separated off. The secondary light is captured by an optical sensor, separately from the reflected laser light, and a control signal for controlling the laser machining is derived from the secondary light. In one exemplary embodiment, the surface of the workpiece is irradiated and the reflected radiation passing through a nozzle opening is detected in order to determine a cutting path or cutting point during the laser cutting. The position of the cutting point is compared with the center of the nozzle in order to control the laser cutting process such that the position of the cutting point coincides with the center of the nozzle. In addition, by using the observation of the nozzle opening, a deformation or a blockage of the nozzle opening is determined.

[0007] Furthermore, in relation to nozzle eccentricity, the reference EP 1 728 581 A1 discloses a device and a method for aligning a laser beam with the nozzle center, in which an image of an illuminated nozzle and a focused laser beam respectively are captured and related to each other via an image evaluation unit.

[0008] Furthermore, in order to detect material burn-up, an example of monitoring the shaping of the cutting front ("red heat region") is known from the reference JP 07116885. If the latter expands, the system changes over to using an inert gas as cutting gas instead of oxygen. For the same purpose or to distinguish between correct and incorrect machining, the reference JP 11320149 discloses an assessment method of using a comparison between captured optical signals. In the reference DE 101 29 751, in order to detect material burn-up, the temperature of the workpiece in the vicinity of the cut is monitored by using an infrared temperature measuring apparatus and is compared with a temperature limit.

[0009] On the basis of the foregoing references, cited by way of example, it becomes clear that the capturing and evaluation of a multiplicity of characteristics determining the quality of the laser cutting process based on various capturing and evaluation principles is very complex. This relates both to the structure of the capturing and evaluation device itself and to the signal processing.

[0010] However, via the devices described above and the associated methods for evaluating the process images captured, no complete image which would be suitable for characterizing the entire laser cutting process results. In particular, the cut quality itself is inadequately reproduced and control is not carried out comprehensively over the entire process. In this connection, the entire process is understood not only as the cutting operation as such but it is also possible for the process to comprise both the piercing operation and also a plurality of successive laser cuts within the context of a process sequence.

SUMMARY

[0011] The present disclosure relates to devices for monitoring and for controlling a laser cutting process on a workpiece, in which the devices include: an image capturing apparatus for capturing an image of a region of the workpiece to be monitored, which in particular comprises a region of interaction of a laser beam with the workpiece, and an evaluation apparatus for detecting material boundaries, in particular edges of the workpiece, by using the captured image. The disclosure also relates to methods for monitoring, in particular for controlling, a laser cutting process, comprising the steps of: capturing an image of a region of the workpiece which is to be monitored, which in particular comprises a region of interaction of laser beam with the workpiece, and evaluating the captured image in order to detect material boundaries, in particular edges, of the workpiece

[0012] The devices and methods disclosed herein permit the serial or parallel capturing and evaluation of a large number of features which characterize a laser cutting process.

[0013] According to an aspect of the disclosure, a device includes an evaluation apparatus configured to determine a characteristic value, in particular a cut quality, of the laser cutting process by determining a geometric relationship between at least two of the detected material boundaries and/or by evaluating the region of interaction.

[0014] In order to monitor the laser cutting process, it is proposed to capture an image of a detail (i.e. of a monitored region) of the workpiece, which typically can comprise the zone of interaction between the laser beam and the workpiece during a piercing operation or a cutting operation, i.e. during a relative movement between laser beam and workpiece, and a cut gap (kerf) that is forming or has already been formed. The evaluation unit can detect two or more material boundaries by using the captured image and, by using a geometric relationship between the material boundaries, determine at least one characteristic value of the cutting process. Additionally or alternatively, given a suitable choice of the detected wavelength range, for example in the near infrared (NIR) range, a thermal image of the monitored region, in particular of the zone of interaction, can be captured and the evaluation apparatus can determine at least one characteristic value of the laser cutting process by using the thermal image. Additionally or alternatively, detection of the process luminescence is possible with the aid of UV radiation, in this case the radiation originating from a plasma generally being detected.

[0015] In particular, in the device the characteristic values can be determined with the aid of one and the same capturing and evaluation logic unit, so that the structure of the device and the performance of the method are simplified. Here, the evaluation apparatus is designed or programmed to determine or to calculate the characteristic values by using the data supplied by the capturing apparatus.

[0016] In the device, by using only a few process-induced geometric features that can be captured by the capturing unit, a multiplicity of characteristic values or process features to be used for the process monitoring and/or control can be determined with the aid of the evaluation unit. The characteristic values supplied by the evaluation unit can be used for the control of the laser machining process via an assessment method which can be carried out both in the evaluation unit itself and also in a logic unit (e.g. a control apparatus) connected downstream thereof.

[0017] As characteristic values, it is possible to determine, for example: crater formation during the piercing operation, gap width, cutting failure, and material burn-up (self-burning) during the cutting process, cutting front angle, cut quality (burr formation) during the cutting process, and disruptive influences, for example as a result of inadequate nozzle spacing and non-process-synchronous switching on and/or switching off of the laser beam. The determination of the aforementioned characteristic values will be described in detail below.

[0018] In some embodiments, the evaluation apparatus is designed to detect cut edges of a gap (kerf) formed in the cutting process as material boundaries and to determine a gap width of the gap as characteristic value. The detected cut edges typically run parallel to each other, so that the gap width, i.e. the distance between the cut edges, is substantially constant and can be determined in a straightforward way.

[0019] In further embodiments, the evaluation apparatus is designed to detect material burn-up of the workpiece if a predefined gap width of the cut gap is exceeded and/or in the event of too rapid an increase in the gap width of the cut gap. Material burn-up leads to a widening of the cut edges and of the cutting front which can possibly be so great that, within the monitored part of the workpiece (e.g. when imaging through a cutting gas nozzle), the cut edges can no longer be detected but only the (substantially semicircular) cutting front. If the danger of material burn-up is detected in good time, e.g. by comparing the gap width with a reference value which should not be exceeded, suitable countermeasures can be taken, e.g. the supply of oxygen can be interrupted or reduced in order to counteract the material burning. Further possibilities for the early detection of material burn-up will be presented further below.

[0020] In further embodiments, the evaluation apparatus is designed to detect a cutting failure (penetration failure) if the gap width falls below a predefined gap width. Alternatively or additionally, a cutting failure can be detected by means of a comparison of the area of the observed cutting front with a reference area, which corresponds to the area of the cutting front in a good or quality cut. A cutting failure can also be detected if the radiation intensity emitted by the reference area exceeds a limiting value for a reference brightness in the case of a normal cut. This limiting value has to be previously determined empirically by the brightness of the reference area measured during a laser cutting process in which a good cutting result was achieved.

[0021] In further embodiments, the evaluation apparatus is designed to detect the edges of a cut formed during the laser cutting process as material boundaries and to determine a gap center of the cut gap (kerf) as characteristic value. The gap center can be determined by the determining the distance (perpendicular to the feed direction of the workpiece) between the edges of the gap at several points along the gap. Determining the gap width at several points along the gap is beneficial since, during a laser cutting process, a (possibly not entirely avoidable) change in the gap width can occur, for example when a changeover is made between different cutting conditions (e.g. between large and small contours).

[0022] In some implementations, the evaluation apparatus is designed to determine a gap center in a further gap (kerf) which does not run parallel to the first gap and, by using the two gap centers, to determine a tool center point of the laser cutting process in a plane parallel to the workpiece. The tool center, also called the tool center point (TCP), is used as a reference point, in particular as an origin, for a tool coordinate system. The TCP can be used in particular to define geometric relationships, in particular distances, between the tool (laser machining head) and material boundaries of the workpiece.

[0023] In some implementations, the evaluation apparatus is designed to determine a geometric relationship between the tool center point and at least one detected material boundary, and the device has a control apparatus for switching on or switching off the laser beam as a function of the determined geometric relationship. By using the geometric relationship, in particular the distance between TCP and material boundary, it is possible to define the time at which the laser beam is switched on and off, so that the cut start and the cut end can be made at the desired position on the workpiece.

[0024] In some implementations, the evaluation apparatus is designed to determine a geometric relationship between the tool center point and the edges or the gap center of a gap (kerf) formed during a preceding laser cutting process, the control apparatus preferably being designed to switch on or switch off the laser beam when the gap center is reached by the tool center point. In this way, it is possible to produce a smooth transition or connection between contours which are cut during successive laser cutting processes.

[0025] In some implementations, the evaluation apparatus is designed to determine a geometric relationship between the tool center point and an (outer) edge of the workpiece, and the control apparatus is preferably designed to switch on or switch off the laser beam when the edge is reached by the tool center point. As a result of the timely switching off and switching on of the laser beam when the edge is reached, it is ensured that no cut is made beyond the (outer) edge of the workpiece.

[0026] In further embodiments, the evaluation apparatus is designed to detect a cutting front upper edge on a workpiece surface facing the incident laser beam and a cutting front lower edge on a workpiece surface facing away from the incident laser beam as material boundaries and, from these, by taking into account the thickness of the workpiece, to determine a cutting front angle as a characteristic value of the laser cutting process. The cutting front angle in a laser cutting process depends on several cutting parameters, in particular on the feed or cutting speed. If the cutting front angle deviates from a reference value or a reference range, this can point to a cutting defect, which can be corrected by suitable measures, for example adaptation of the cutting speed.

[0027] In some implementations, the evaluation apparatus is designed to capture an outer boundary and an inner boundary of a pierced hole on the workpiece as material boundaries during a piercing operation and to determine the formation of a crater on the workpiece as a characteristic value. Both the chemical material composition and the surface finish of the workpiece, which can vary from manufacturer to manufacturer, have a substantial influence on the piercing operation. In particular, in the case of high metal sheet thicknesses (e.g. more than 15 mm), the piercing operation can be disrupted in the event of an unfavorable material finish, in such a way that the laser beam does not drill a narrow hole. Instead, on account of overheating and an exothermic iron-oxygen reaction that subsequently proceeds, a large conical crater is formed. The material boundaries thereof can be captured and, when a limiting value for the distance between the boundaries is exceeded, countermeasures can be initiated.

[0028] In further embodiments, the image capturing apparatus is designed to capture the region to be monitored coaxially with respect to a laser beam axis. Coaxial capturing of the region to be monitored is possible independent of direction.

[0029] In some embodiments, a distance between an image plane of the image capturing apparatus for capturing the image and an imaging and focusing optics can be varied. The evaluation apparatus is designed to determine a distance between the nozzle for the passage of the laser beam onto the workpiece and the workpiece by detecting at least one material boundary of the workpiece with a first distance between the image plane and the imaging optics, and an inner contour of the nozzle as a material boundary with a second distance between the image plane and the imaging optics. The optics assigned to the image capturing apparatus are used in this case for the sharp imaging of two objects arranged at different distances from the image plane of the image capturing apparatus, specifically by a distance between the optics (e.g., lens) and the image plane being varied. Here, the contours are only detected by the evaluation apparatus if the material boundary to be captured (nozzle or workpiece) is located within the range of the depth of focus of the optics. By determining the displacement distance of the optics which is necessary to image the respective material boundary sharply, the distance between nozzle and workpiece can be determined. If necessary, a respective contour can be detected not only with one distance between the image plane and the optics but within a distance interval. In this case, in order to determine the distance between the nozzle and the workpiece, that distance from the interval is chosen at which the respective contour is sharpest, i.e. can be detected best.

[0030] In further embodiments, the evaluation apparatus is designed to determine the presence or lack of burr formation on the gap (kerf) and, therefore, a cut quality as a characteristic value of the laser cutting process by using the image, in particular by using the thermal image in the NIR/IR range, of the region of interaction. The region of interaction or the geometry thereof can be observed here by means of the image capturing apparatus via a suitable wavelength filter which is transparent to wavelengths for example in the near infrared range or in the UV range (for the detection of the plasma luminescence above the region of interaction). The image capturing apparatus can have different detectors for imaging the material boundaries and the region of interaction. Use of a single detector, e.g. a (CCD) camera, in conjunction with a suitably adjustable wavelength filter for capturing both the material boundaries and the region of interaction is, however, both space-saving and inexpensive.

[0031] In further embodiments, the evaluation apparatus is designed, during a flame cutting process (in particular when cutting mild steel) to conclude that there is a good cut, in particular a lack of burr formation, when a local intensity minimum occurs in the image in the region of the cutting front. In particular, in a laser beam-guided flame process, a local intensity minimum (radiation sink) occurs in the region of the cutting front in the case of a good cut, i.e. with smooth cut edges without any burr formation. This local minimum typically disappears when burr formation occurs at the cut edges.

[0032] In further embodiments, the evaluation apparatus is designed to conclude that burr formation is present during a fusion cutting process (in particular when cutting stainless steel), by detecting the lack of a repeating fluctuation in the radiation intensity of the (thermal) image or the process autoluminescence in the NIR/IR wavelength range in the region of the cut gap and/or upon the occurrence of three luminescent stripes originating from the cutting front. If no sporadically occurring flickering in the kerf is detected, this points to the production of whisker burr. In this case, the entire melt volume feeds the whisker burr, so that no flying sparks are produced which would manifest themselves as flickering in the wake. The presence of burr formation can also be detected by detecting two bright luminescent stripes directed rearward in the region of the two cut edges and a further luminescent stripe which, typically, runs in the center between the two outer luminescent stripes. Here, the luminescent stripes are generally comparatively long, which points to the occurrence of an azimuthal melt flow and therefore to the production of burr in the form of crumb burr, i.e. far back in the wake.

[0033] In some embodiments, the evaluation apparatus is designed to detect striations on at least one cut edge of a gap (kerf) formed during the laser cutting process and, by using a frequency of the striations, to draw conclusions about material burn-up. The striations can be detected well by using the thermal image or the process autoluminescence but can possibly also be detected in the visible range as material boundaries. The frequency of the striations typically decreases in the region of that cut edge at which material burn-up is immediately imminent, so that suitable countermeasures can be initiated even before the occurrence of the material burn-up.

[0034] In further embodiments, the evaluation apparatus is designed to draw conclusions about material burn-up by using a rise in the total intensity and/or by using a fluctuation in the total intensity of the image of the region of interaction. The total intensity (typically detected through the nozzle opening) of the detected radiation (in the near infrared/infrared (NIR/IR range)) rises, since the zone of interaction increases in the event of material burn-up. Additionally or alternatively, material burn-up can also be determined by using an increased fluctuation in the total measured brightness value as compared with a conventional cutting process.

[0035] A further aspect of the disclosure relates to a method which includes: determining at least one characteristic value of the laser cutting process, in particular a cut quality, by evaluating a geometric relationship between at least two of the detected material boundaries and/or by evaluating the region of interaction. In the method for monitoring a laser cutting process, in particular the embodiments described further above in conjunction with the device and with the evaluation apparatus can be implemented as further method steps, which will not be discussed in detail, for the purpose of simplification. In particular, it is also possible for the characteristic values of the laser cutting process cited further above to be determined in the method.

[0036] Further advantages of the disclosure can be gathered from the description and the drawing. Likewise, the features mentioned above and those cited further on can each be used on their own or in a plurality in any desired combination. The embodiments shown and described are not to be understood as a final enumeration but instead have an exemplary character for the description of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0037] FIG. **1** shows a schematic illustration of an embodiment of a device for monitoring and for controlling a laser cutting process, that includes an image capturing unit,

[0038] FIG. **2** shows an illustration of an image of the workpiece, captured by the image capturing unit, by which several characteristic values of the cutting process are determined,

[0039] FIG. **3** shows an illustration of an image of the workpiece, by which a cutting end on a sheet-metal edge of the workpiece is detected,

[0040] FIG. **4** shows an illustration of an image of the workpiece, by which a cutting end on a kerf already cut is detected,

[0041] FIG. **5** shows a further illustration of an image of the workpiece, by which a cutting start is detected,

[0042] FIG. **6** shows an illustration of an image of the workpiece during a piercing operation,

[0043] FIGS. **7***a*, **7***b* and **7***c* show illustrations of a thermal image of the monitored region of the workpiece during fusion cutting and in the presence of a good cut (FIG. **7***a*), a crumb burr (FIG. **7***b*) and a whisker burr (FIG. **7***c*), and

[0044] FIG. **8** shows an illustration of a thermal image during flame cutting in the presence of a good cut.

DETAILED DESCRIPTION

[0045] FIG. **1** shows an exemplary structure of a device **1** for process monitoring and control of a laser cutting process on a workpiece **2** by means of a CO_2 laser machining installation, of which only a machining unit **3** (part of a laser machining head) having a focusing lens **4** made of zinc selenide for focusing a CO_2 laser beam **5**, a cutting gas nozzle **6**, and a deflection mirror **7** is illustrated in FIG. **1**. The deflection mirror **7** is designed to be partly transparent.

[0046] The deflection mirror **7** reflects the incident CO_2 laser beam **5** (having a wavelength of about 10 μm) and transmits the radiation **8** that is relevant to the process monitoring. Radiation **8** is reflected from the workpiece **2** and emitted from the zone of interaction in a wavelength range which, in the present example, lies between about 550 nm and 2000 nm. As an alternative to the partially transparent deflection mirror **7**, a scraper mirror or a perforated mirror can also be used in order to lead the process radiation **8** to the device **1**. However, the use of a scraper mirror typically results in a part of the process radiation being masked out and in the unmodified beam diameter being limited. The use of a perforated mirror generally leads to diffraction effects of the process radiation and to a strong influence on the CO_2 laser radiation.

[0047] In the device **1**, after the partially transparent mirror **7**, there is arranged a further deflection mirror **9**, which deflects the process radiation **8** onto a geometrically highly resolving camera **10** as an image capturing unit. The camera **10** can be a high-speed camera, which is arranged coaxially with respect to the laser beam axis **11**. In principle, there is the possibility of capturing the image by means of the camera **10** in the incident light method as well, i.e. in the visible wavelength range, possibly also in the NIR wavelength range, if an additional illumination source which emits in the NIR range is provided. Alternatively, the capturing of the process autoluminescence in the UV and NIR/IR wavelength ranges is possible.

[0048] For improved imaging, in the present example, between the partially transparent mirror **7** and the camera **10**, there is provided an imaging focusing optical system **12**, depicted as a lens in FIG. **1**, which focuses the radiation **8** that is relevant to the process monitoring on the camera **10**. By means of an aspherical form of the imaging optical system or the focusing lens **12**, aspherical aberrations during the imaging can be prevented or at least reduced.

[0049] In the example shown in FIG. **1**, a filter **13** in front of the camera **10** is advantageous if further radiation or wavelength components are to be excluded from the capturing with the camera **10**. The filter **13** can be formed, for example, as a narrowband bandpass filter with a low full width at half maximum in order to avoid or to reduce chromatic aberrations. The position of the camera **10** and of the imaging optical element **12** and/or the filter **13** along the laser beam axis **11** can be adjusted and varied as required by a positioning system **14** known to those skilled in the art, illustrated by a double arrow for the purpose of simplification.

[0050] In the present example, the camera **10** is operated in the incident light method, i.e. an additional source of illumination **15** is provided above the workpiece **2** and, via a further partially transparent mirror **16**, couples illumination radiation **17** into the beam path, coaxially with respect to the laser beam axis **11**. As an additional source of illumination **15**, laser diodes, for example having a wavelength of 658 nm, or diode lasers, for example having a wavelength of 808 nm, can be provided and can be arranged coaxially, as shown in FIG. **1**, but also off-axis with respect to the laser beam axis **11**. The additional source of illumination **15** can also, for example, be arranged outside (in particular beside) the machining unit **3** and be aimed at the workpiece **2**; alternatively, the source of illumination **15** can be arranged inside the machining unit **3** but not aimed at the workpiece **2** coaxially with respect to the laser beam **5**.

[0051] As shown in FIG. **2**, the camera **10** captures a highly resolved image **20** of a region **21** (detail) to be monitored of the workpiece **2**. The image **20** is delimited by the circular inner contour **6***a* (cf. FIG. **1**) of the nozzle **6**.

[0052] In the example illustrated in FIG. **2**, the image **20** shows the region **21** to be monitored during a laser fusion cutting process, in which the workpiece **2** is moved in a feed direction V_{sheet} relative to the nozzle **6** and to the machining unit **3** (laser machining head). Alternatively or additionally, the relative movement between the workpiece **2** and the nozzle **6** or the machining unit **3** (laser machining head) can be executed by the movement of the nozzle **6** or the machining unit **3**. During the fusion cutting process, a region of interaction **22**, **23** is formed between the laser beam **5** and the workpiece **2**, which region comprises a preceding heat zone **22** and a cutting front **23**, which are adjoined in the feed direction V_{sheet} by a cut gap **24** (also designated kerf below).

[0053] An evaluation apparatus **18** shown in FIG. **1** is used to evaluate the image **20** and in particular to detect material boundaries within the monitored region **21** on the upper side **2***a* and the underside **2***b* of the workpiece **2**. The evaluation apparatus **18** has a signal connection to a control apparatus **19**, likewise shown in FIG. **1**, which controls and regulates the laser cutting process, specifically as a function of characteristic values of the laser cutting process determined by the evaluation apparatus **18**.

[0054] Amongst other things, by using the camera image **20**, the following features of a laser cutting process can be determined by the evaluation unit **18** in order to determine characteristic values: material boundaries on the workpiece upper side **2***a* and underside **2***b*, in particular edges of the workpiece, a nozzle edge and a nozzle center of the laser machining nozzle, geometric dimensions of the kerf (not only opposite edges but also the region of the zone of interaction, e.g. of the cutting front), position of the kerf relative to the nozzle edge/center, or position of already cut regions relative to the current cutting position, among other features. The detection of these and further features for determining characteristic values of the laser machining process will be described in more detail below.

[0055] In the example shown in FIG. **2**, as a characteristic value, the gap width A**2** of the kerf **24** is determined on the basis of the high resolution camera image **20**, by the evaluation unit **18** detecting the cut edges K**1**.**1** and K**1**.**2** of the kerf **24** and the spacing thereof, which coincides with the cut gap width A**2**. In the case of a laser cutting process, the cut edges K**1**.**1**, K**1**.**2** generally run (virtually) parallel, so that the cut gap width A**2** is (virtually) constant, in particular in a good cut.

[0056] The evaluation unit **18** itself or logic unit connected downstream thereof, e.g. the control apparatus **19**, is able to determine, via the comparison with a reference cut width that is defined previously and stored for comparison, whether for example when the cut gap width falls below a minimum $A2_{min}$, a cutting failure (penetration failure) has occurred, i.e. a complete lack of a kerf, or when the cut gap width exceeds a maximum $A2_{max}$, material burn-up (self-burning) is present or, in the case of an oxygen flame cutting of mild steel, washouts (pits) are present.

[0057] Alternatively or additionally, material burn-up can also be determined via the change in the cut gap width A**2** with time—both with regard to an absolute change and via the rate of change. A number of evaluation methods relating to the gap width can also be used in parallel. Material burn-up leads to a widening of the cut edges K**1**.**1**, K**1**.**2** and the cutting front **23**, which can possibly become so large that the cut gap **24** becomes wider than the nozzle opening **6***a* or the nozzle contour K**3**, so that the cut edges K**1**.**1**, K**1**.**2** are no longer detectable in the monitored region **21**. In this case, the image **20** shown in FIG. **2** of the cut gap **24** changes to a quasi-semicircular cutting front, and the detail **21** of the workpiece **2** exhibits only a radius corresponding to the cutting front. In the event of material burn-up, the cutting front does not end directly with the laser beam **5** but is displaced in front of the latter since, in this case, the cutting gas dominates the burning process.

[0058] Alternatively or additionally to the gap width falling below the minimum spacing $A2_{min}$, a cutting failure (penetration failure) can be detected by using an area F**2** which is formed between a front edge K**2**.**1** and a rear edge K**2**.**2** of the detected cutting front **23**. For this purpose, the area F**2**, which corresponds to the projection of the cutting front **23** in the XY plane, is related to a reference area. A cutting failure is detected if the area F**2** reaches the size of the reference area, the ratio reference area/F**2** is therefore equal to one. The reference area in this case corresponds to the area of the projected cutting front in the case of a good cut, i.e. in the case of a cut with good cutting quality. A cutting failure can additionally be detected, if the brightness of the cutting front **23** is greater than in the case of a reference good cut, it being possible for the luminescence to occur continuously and/or sporadically and the luminescent area being approximately equal to or greater than the kerf width A**2**.

[0059] By using an image **20**, as illustrated in FIG. **2**, pits during the oxygen flame cutting of mild steel can also be detected if these begin from above (i.e. from the workpiece upper side **2***a*), specifically by detecting a non-periodic increase in the cut gap width A**2** or by detecting the (at least temporary) loss of parallelism between the cut gap edges K**1**.**1**, K**1**.**2**. When observing process luminescence, as will be described below in conjunction with FIGS. **7***a-c* and FIG. **8**, pits can also be detected via a drop in brightness and via the occurrence of flashes, i.e. short and intensive increases in the brightness in the region of the cutting front **23**, to be specific typically in a punctual manner on the outside of the cutting front, in the region of the transition to the parallel cut edges K**1**.**1**, K**1**.**2**.

[0060] In addition to the determination of a cutting failure or material burn-up or pits, via the kerf width A**2** it is also possible to determine the position of the tool center P**2**, which will also be designated TCP (Tool Center Point) below. The position of the TCP P**2** in the Y direction is defined by a center line **25**, which extends in parallel to and centrally between the opposite cut edges K**1**.**1**, K**1**.**2** of the kerf **24**. The position of the TCP P**2** can additionally also be determined in the X direction as a center line between the edges K**5**.**1**, K**5**.**2** of a further kerf **27** which, in the example shown in FIG. **2**, has been produced in a preceding laser cutting process (with workpiece feed direction in the Y direction). By using the two kerfs **24**, **27**, the tool center point P**2** can be defined unambiguously in the XY plane (parallel to the workpiece surface). In principle, instead of the kerf **27** shown extending at right angles to the kerf **24**, any other kerf not extending parallel to the kerf **24** can be used to determine the tool center point P**2** in the XY plane.

[0061] The tool center point P**2** determined in this way can be used for adjusting and monitoring the nozzle position of the cutting nozzle **6** through which the laser beam **5** passes, specifically by means of reference to the nozzle center **P1**. The nozzle center **P1** is determined from the circular nozzle (internal) contour **K3** captured via the image capturing unit **10**, the nozzle center **P1** being determined as the center of the circle of the latter. In this way, a distance **A3** between the nozzle center **P1** and the tool center point **P2** can be determined. In particular, in the event of a deviation between nozzle center **P1** and tool center point **P2** being detected, action can be taken in the laser cutting process with the aid of the control apparatus **19** in order to correct the position of the laser beam **5** relative to the nozzle **6**, so that the tool center point **P2** coincides with the nozzle center **P1**.

[0062] During the detection of the internal contour **K3** of the nozzle **6**, in particular by detecting the geometric shape of the cutting nozzle, information can also be obtained about mechanical damage to the latter, specifically by detecting deviations from the (typically circular) reference contour of the nozzle **6**. The damage can be caused, amongst other things, by a collision of the nozzle **6** with the workpiece **2**, with the workpiece supporting grid (not shown), or with other interfering contours, or by a high level of laser beam eccentricity (in relation to the nozzle center **P1**), in which the laser beam **5** touches the nozzle inner edge **6*a*** and as a result melts the latter locally. As a result of such damage, which can generally not be detected by the machine operator, the cutting gas dynamics and thus the cut quality can be changed detrimentally.

[0063] By using the illustrations of FIG. **2** and FIG. **1**, the determination of the cutting front angle during a laser cutting process will be explained below. In order to determine the cutting front angle, first a distance **A4** between the cutting front upper edge **K2.1** and the cutting front lower edge **K2.2** is determined which, as described above, are detected as material boundaries with the aid of the evaluation apparatus **18**. The cutting front angle α shown in FIG. **1** is given by the trigonometric function $\alpha=\arctan(A4/d)$ from the distance **A4** between cutting front upper edge **K2.1** and lower edge **K2.2**, measured along the gap center **25**, and from the thickness d of the workpiece **2**.

[0064] With the aid of the device **1** from FIG. **1**, it is also possible to determine a distance **A5** between the cutting gas nozzle **6** and the workpiece **2**, more precisely the workpiece upper side **2*a***. For this purpose, the lens **12** installed upstream of the image capturing unit **10** is displaced along the optical axis **11** with the aid of the positioning system **14**, so that a distance between an image plane **10*a*** of the image capturing apparatus **10** for capturing the image **20** and the lens **12** changes. At a first distance **b1** between the image plane **10*a*** and the lens **12**, the upper side **2*a*** of the workpiece **2** lies within the range of the depth of focus of the image capturing apparatus **10**, so that at least one material boundary of the workpiece **2**, e.g. the cut edges **K1.1**, **K1.2**, can be detected. At a second distance **b2**, the nozzle **6** lies in the range of the depth of focus of the image capturing apparatus **10**, so that the evaluation apparatus **18** detects an internal contour **K3** of the nozzle **6** as a material boundary. By using the difference **b1**−**b2** between the two distances **b1**, **b2** at which the nozzle internal contour **K3** and the cut edges **K1.1**, **K1.2** are detected by the evaluation apparatus **18**, the distance AS between the nozzle **6** and the workpiece **2** can be calculated.

[0065] FIG. **3** shows cutting end detection when reaching or traveling over a metal sheet edge **K4** at the outer edge of the workpiece **2**. The position of the detected metal sheet edge **K4** in this case is compared to the tool center point **P2**, in order to determine a distance (not shown in FIG. **3**) between the tool center point **P2** and the metal sheet edge **K4**. By knowing this distance, the control device **19** can switch off the laser beam **5** as soon as the latter reaches the metal sheet edge **K4**, so that damage to the separated workpiece **2** falling down by the laser beam **5** is avoided. Depending on the application, such a switch-off can also be performed before the metal sheet edge is reached by the tool center point **P2**, specifically as soon as the distance of the TCP **P2** to the metal sheet edge **K4** is sufficiently small in order still to be able to implement complete separation of the workpiece **2** despite switching off.

[0066] In a way analogous to FIG. **3**, FIG. **4** shows cutting end detection when reaching an already cut contour, i.e. an already existing kerf **27**. The laser beam **5** can be switched off in a way analogous to reaching or traveling over the metal sheet edge **K4** in FIG. **3**, replacing the edge **K4** in the image **20** shown in FIG. **3** by the first edge **K5.1** of the kerf **27** in the image **20** shown in FIG. **4**.

[0067] Alternatively, via the detection of the two already present cut edges **K5.1**, **K5.2** of the gap **27**, the gap width **A1** and, from this in turn, the end point **P3** of a further gap **24** running into the kerf **27** can be defined. This end point **P3** is typically arranged centrally, that is to say at the same distance (0.5*A1) from the opposite edges **K5.1**, **K5.2**. Depending on the application, this end point **P3** can, however, also be displaced in the direction of the edge **K5.1** reached first by the further cut, for example when the incoming kerf **24** is larger than the kerf **27** running transversely thereto and already present. In the opposite case, i.e. when the incoming kerf **24** is smaller than the kerf **27** running transversely thereto, a reverse displacement of the end point **P3** can likewise be beneficial, as long as the laser beam **5** is at least switched off in such a timely manner that damage to the rear edge **5.2** of the kerf **27** is avoided.

[0068] In general, by means of the detection of the relative position of a kerf **27** already cut in relation to a tool center point (TCP) **P2** determined in the actual process, a path deviation can also be detected and, if a tolerance range is exceeded, can be corrected with the aid of the control device **19**.

[0069] The case illustrated in FIG. **5** of the detection of the cutting start is carried out in a way comparable to the detection of the cutting end described in FIG. **3** and FIG. **4**. As opposed to the cutting end detection, however, the laser beam **5** is not switched off but switched on as a function of the (positional) relationship of the tool center point **P2** to the kerf **27** running transversely (or else at another angle). The detection of a cutting starting point on a metal sheet edge **K4** is carried out in a way analogous to the procedure described in conjunction with FIG. **3**. Cutting start detection is particularly suitable when resuming a cutting process following a cutting failure or else when resuming a cutting process after a relative movement between machining unit **3** and workpiece **2**, for example when due to clock cycles the laser cutting process is interrupted and has to be started/resumed at exactly the same point again at a subsequent time.

[0070] FIG. **6** shows the image **20** of a region **21** of the workpiece **2** to be monitored during a piercing operation, in which a circular hole **28** is introduced into the workpiece **2**. The two main influencing factors on the piercing process, namely the chemical material composition and the surface finish of the workpiece **2**, can vary from manufacturer to manufacturer and from batch to batch. During the piercing operation, in particular in mild steel, e.g. with material thicknesses starting at 15 mm, problems may occur during the piercing operation on account of these differences in the material properties. The piercing operation in thick mild steel is disrupted in such a way that the laser beam does not drill a narrow hole but that, on account of the overheating and the exothermic iron-oxygen reaction that subsequently proceeds, a conical crater is formed, the contour of which is shown in FIG. **6**. Here, the evaluation apparatus **18** can detect the internal contour K**6.1** of the hole **28** and the outer crater edge K**6.2**, so that looming crater production can be detected and the control apparatus **19** can initiate suitable countermeasures, e.g. a cooling pause. The countermeasures can be initiated, for example, when a limiting value for the distance A**6** between the inner boundary K**6.1** and outer boundary K**6.2** (crater edge) of the pierced hole **28** is exceeded. It is also possible to conclude that there is crater formation when the outer contour K**6.2** of the pierced hole **28** becomes so large that said contour disappears from the region **21** captured by the camera **10** through the nozzle **6**.

[0071] FIGS. **7***a-c* each show an image **20** of the process autoluminescence in the NIR/IR range of a region of interaction **31** in a fusion cutting process, which image has been captured with the camera **10** by using a filter **13** which was transparent only to process radiation **8** in the (near) infrared range. The contours shown represent the boundaries between regions of different intensity of the process radiation **8**; and the contours of the workpiece **2** cannot be seen. The process radiation **8** registered by the image **20** is autoluminescence of the laser cutting process, which typically comprises (at least to some extent) the melt bath. The image **20** of the process autoluminescence cannot be equated directly with a temperature distribution, since the measured intensity I (cf. FIG. **1**) depends on the temperature T substantially in accordance with the following formula: $I=\epsilon^*T^4$, where ϵ denotes the emissivity (between 0 and 1). Since the emissivity ϵ in the present case can be close to zero, it is difficult to derive information about the temperature from the intensity distribution. Nevertheless, for the purpose of simplification, the measured intensity distribution will occasionally also be designated a thermal image below.

[0072] By using the (thermal) images **20**, the formation of burrs or their absence during laser cutting, and thus the cut quality, can be determined. Here, FIG. **7***a* shows the image **20** of the region of interaction **31** in which a quality cut is being produced (with smooth cut edges). The region of interaction **31** exhibits a single central tail or a single luminous track **29** along the feed direction V_{sheet}. In addition, when observing the wake of the region of interaction **31** over a relatively long time period (several seconds), sporadic flickering additionally occurs. The shape of the region of interaction **31** shown in FIG. **7***a* and the sporadic flickering (i.e. the repeating increase and decrease in the brightness) can be traced back to homogenous melt expulsion which, in a quality cut, oscillates rearward and forward in the feed direction. If no flickering can be detected, this is an indication of the formation of burrs during the cutting process (and specifically of the presence of whisker burrs).

[0073] FIG. **7***b* shows an image **20** of the region of interaction **31** in the presence of burr formation, specifically during the formation of what is known as crumb burr. In this case, two bright luminescent stripes **30***a*, **30***b* directed rearward from the cutting front **23** can be seen at the two cut edges (not shown), as well as a further luminescent stripe **30***c* which runs in the middle between the two outer luminescent stripes **30***a*, **30***b*. The luminescent stripes **30***a-c* are comparatively long, which points to the occurrence of an azimuthal melt flow with production of crumb burr far behind in the wake.

[0074] The image **20** of the region of interaction **31** shown in FIG. **7***c* likewise points to the formation of burr, specifically what is known as whisker burr. In this case, no tail or luminescent stripe can be seen, since the complete melt volume feeds the whisker burr. In addition, no flying sparks occur directly underneath the cutting gas nozzle **6**, so that in this case no flickering occurs; instead, the laser cutting process proceeds without noticeable fluctuations in the detected intensity of the process radiation **8**.

[0075] FIG. **8** shows a thermal image **20** or an image of the process autoluminescence in the NIR/IR range, such as occurs in a mild steel flame cutting process (using oxygen as cutting gas). In such a process, the upper parts of the cut edges have periodically repeating grooves, which can be seen in the thermal image **20** as striations **33**. In the region of the cutting front **23**, a local minimum **32** with a radiation intensity that is reduced as compared with the intensity in the surroundings occurs in the image **20** of the region of interaction **31** when a good cut is present, i.e. without burr formation. The size of the area F**1** of the intensity minimum **32** (radiation sink) can be monitored. When the size of the area F**1** decreases too sharply, burr formation can be counteracted by the process parameters being changed suitably.

[0076] By using the thermal image from FIG. **8**, imminent material burn-up can also be detected. Here, use can be made of the fact that the frequency f of the striations **33** in the thermal image **20** of the region of interaction **31** decreases in the region of that cut edge at which material burn-up is imminent, so that suitable countermeasures can be taken in order to suppress the occurrence of the material burn-up. The striations **33** or a decrease in the frequency f of the striations can alternatively also be detected in the visible range.

[0077] In addition, material burn-up that has already arisen and/or is just imminent can be detected by detecting a rise in the brightness of the overall intensity of the thermal image **20**, since the luminescent area observed through the nozzle **6** increases in the event of material burn-up. Additionally or alternatively, material burn-up can also be detected by an increased fluctuation in the overall brightness value as compared with a conventional cutting process.

[0078] The thermal images **20** can be compared with the material boundaries (contours of the workpiece **2**) detected (at wavelengths in the visible range), in order to improve the determination of values characteristic of the laser cutting process. Here, in particular in the case of workpieces made of stainless steel, a cutting failure can be detected when the width of the luminous area registered in the thermal image, which corresponds substantially to the width of the cutting front, is greater than the width A**2** of the gap at right angles to the feed direction V_{sheet} (cf. FIG. **2**).

[0079] Both the capturing of the material boundaries and the capturing of the thermal image of the region of interaction in the apparatus shown in FIG. **1** are carried out with the aid of a single camera as image capturing apparatus. For this purpose, the wavelength filter **13** is suitably tuned or suitably moved into the beam path of the process light **8** and out again. For the purpose of parallel detection of material boundaries and thermal image, the image capturing apparatus **10** can also have further cameras and/or detectors.

[0080] A number of embodiments have been described. Nevertheless, it will be understood that various modifications may be made without departing from the spirit and scope of the invention. Accordingly, other embodiments are within the scope of the following claims.

What is claimed is:

1.-**19**. (canceled)

20. A device for monitoring and for controlling a laser cutting process on a workpiece, the device comprising:

an image capturing apparatus for capturing an image of a region of the workpiece to be monitored, and

an evaluation apparatus for detecting material boundaries of the workpiece using the captured image, the material boundaries including edges of a first gap formed during the laser cutting process,

wherein the evaluation apparatus is configured to determine at least one characteristic value of the laser cutting process based on a geometric relationship between at least two detected material boundaries, the characteristic value including a first gap center of the first gap cut in the workpiece.

21. The device according to claim **20**, wherein the characteristic value includes a second gap center in a second gap cut in the workpiece, wherein the second gap center does not run parallel to the first cut gap, and wherein the evaluation apparatus is configured to determine a tool center point of the laser cutting process in a plane parallel to the workpiece based on the first and second gap centers.

22. The device according to claim **21**, wherein the evaluation apparatus is configured to determine a geometric relationship between the tool center point and at least one detected material boundary, the device further comprising a control apparatus configured to switch a laser beam on or off as a function of the determined geometric relationship.

23. The device according to claim **21**, wherein the evaluation apparatus is configured to determine a geometric relationship between the tool center point and a gap center of a further gap cut in the workpiece in a previous laser cutting process, and wherein the control apparatus is configured to switch the laser beam on or off when the gap center of the further gap cut is reached by the tool center point.

24. The device according to claim **22**, wherein the evaluation apparatus is configured to determine a geometric relationship between the tool center point and at least one detected edge of the workpiece, and wherein the control apparatus is configured to switch the laser beam on or off when the at least one detected edge is reached by the tool center point.

25. The device according to claim **20**, wherein the region of the workpiece to be monitored comprises a region of interaction of a laser beam with the workpiece.

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