tue of a laser cutting system having the features set forth in the enclosed independent claim 4 ~~10~~.

Advantageous modes of implementation of the control method according to the invention and advantageous embodiments of the laser cutting system according to the invention are the subject-matter of the dependent claims, the content of which is to be regarded as being an integral and integrating part of the following description.

In short, the invention is based on the idea of controlling the laser cutting process, including the initial piercing phase, by using as reference signal one or more emission lines specific for the radiation emitted by a gas (be it an assisting gas or a contaminant gas) ~~or, more generally, by any emitting element~~ present in the volume involved by the irradiation of the focussed laser beam and by adjusting, on the base of this reference signal, at least one of the following process control parameters: the power of the laser, the frequency and duty cycle of the laser pulse, the pressure of the assisting gas, the relative speed of the laser with respect to the workpiece, the distance between the laser head and the surface of the workpiece, and the distance between the focal point of the laser beam and the surface of the workpiece.

The control method according to the invention provides therefore for implementing a control loop comprising the following steps:

- the radiation coming from the volume involved by the laser process is detected by sensor means operating in a band centred on a wavelength previously chosen as the most suitable one for controlling the process;
- the signal thus detected is suitably filtered and processed and then sent as input to an electronic control unit; and
- the electronic control unit interprets the signal received as input and, if necessary, changes one of the above-indicated process control parameters.

~~Preferably,~~ The emission lines specific for the radiation which is monitored for the purpose of control of the process (hereinafter referred to as control radiation) ~~are comprised in the range from 180 to 2000 nm and~~ are detected with a bandwidth which is not wider than 100

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nm.

Preferably, oxygen or nitrogen are used as emitting gas. ~~In general terms, it is possible to~~ use as emitting gas a gas which is able to emit in the band comprised ~~between~~ 180 nm and 2000 nm, when it is present inside the volume involved by the laser working process, as a result of the temperature, of the direct interaction with the laser, of transitions to the ionized state ~~or of~~ transitions among roto-vibrational modes of possible compounds produced ~~by the process due to the combination of the gas with the material being processed~~. The gas used as emitting gas may indifferently be an assisting gas or a contaminant gas. In this second case, the gas may indifferently be either a gas normally present in the atmosphere around the workpiece being processed or a gas expressly introduced for this purpose into the volume involved by the laser process.

~~In case a gas is used as the element emitting the radiation to be detected, the control method is based on the following remarks:~~

- If the gas has a mainly reactive function, its emissions can be interpreted as indicative of the level of the intensity with which the reaction process is occurring: a too low level means that the reaction process is not occurring with the rate that would be possible, whereas a too high level means that the reaction process is occurring with an excessive rate, hence with the risk of a situation of uncontrolled or explosive process. In case of a pulsed laser, the derivative of the signal or the minimum level reached by a laser switched-off before the subsequent pulse can give an indication that the process will tend to reduce or increase its intensity, thus becoming on the one hand inefficient and on the other hand uncontrolled or explosive. The same information can be obtained also in case of a continuous laser, by introducing an overmodulation on the laser power and comparing the time derivatives of the signal emitted by the gas during the undermodulation step and during the overmodulation step. Another type of control can be obtained by comparing the levels of emission of radiation at two or more different wavelengths, which indicate the presence or the transformation of at least two specific chemical species or compounds inside the volume involved by the laser working process.

If the gas has the function of contaminant, be it normally present in the atmosphere around the workpiece being processed or expressly introduced in the process for this purpose, its emissions can be interpreted as control signal even in case of a laser cutting process using an inert gas as assisting gas. In case of laser piercing carried out in preparation of cutting, the signal emitted by the contaminant gas gives the information that the piercing cylinder is still closed and that therefore the process is not finished yet. Once the opening in the material has been formed, the control signal decreases significantly and thus shows that the process has come to an end. In case of the laser cutting, an increase in the signal emitted by the contaminant gas gives the information that the leading edge of the cut is tending to become parallel to the surface of the workpiece being processed, thereby expelling less material, less by-products and less contaminant gas, and that therefore the forward speed of the cut is too high, whereas a decrease in the signal emitted by the contaminant gas gives the information that the leading edge of the cut is tending to become perpendicular to the surface of the workpiece being processed, and that therefore the forward speed of the cut is too low.

More specifically

~~Preferably~~, the control method according to the invention provides for monitoring the emission line at 777 nm. This wavelength includes a strong emission from the ionized oxygen, which can be easily detected even when the oxygen is present only as contaminant gas in the process, and more specifically gives the information required for control both of the laser piercing in preparation of cutting and of the laser cutting. In case of a laser piercing process under oxidizing conditions, with the use of oxygen as assisting gas, this wavelength gives a very sensitive anticipation on the rising ramp of the amount of ionized oxygen present in the process volume, which ramp forebodes an explosion. In case of a fusion laser piercing process, with the use of nitrogen as assisting gas, this wavelength gives a very sensitive information about the presence of a still closed volume which is being fused before opening. In case of a laser cutting process, irrespective of whether it is carried out under oxidizing conditions or it is a fusion laser cutting process, this wavelength represents a rich source of information, as it provides both an anticipation of the risk of explosion or lateral diffusion of the oxidizing process, resulting in a reduction in the final quality of the cut, and an anticipation of the phenomenon of the closure of the kerf, and of the associated loss of the cut, independently of the upstream reasons which have led to the closure.

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~~In addition to signals emitted by gases, irrespective of whether they are assisting gases or~~ contaminant gases, it is possible according to the invention to use also signals emitted by the metal elements contained in the material being processed, irrespective of whether they are characterizing elements of the material or elements only present as contaminants. For instance, it is possible to use iron, nickel, chromium, aluminium or copper as emitting elements.

The monitoring of the signal emitted by a gas ~~or by another emitting element~~ present in the volume of material involved by the laser working process allows therefore to obtain information on the state of the process and hence to control the process by adjusting the above-mentioned process control parameters.

With regard to the laser cutting system implementing the control method according to the invention, it basically comprises:

- a laser source, which may indifferently be of the CO2 type or of the solid-state type (Nd:YAG, fiber laser, disc laser, diode laser);
- a laser head comprising a focussing device for focussing the laser beam generated by the laser source and a nozzle for supplying the assisting gas;
- an optical path arranged to transport the laser beam generated by the laser source to the focussing device of the laser head;
- a driving device arranged to move the laser head and the workpiece with respect to each other with an adjustable speed, as well as to control the pressure of the assisting gas, to adjust the distance of the nozzle from the surface of the workpiece and to adjust the position of the focal point of the laser beam relative to the surface of the workpiece; and
- a process control device comprising sensor means for detecting at least one predetermined wavelength band of the radiation emitted by a given gas ~~or a given material~~ present in the volume of material involved by the irradiation of the focussed laser beam, signal processing means for processing the signal detected by the sensor means, and control means for controlling, on the base of the signal received by the signal processing means, the laser source and/or the driving device to adjust at least one of the following process control parameters: the power of the laser, the frequency and the duty cycle of the laser pulse, the pressure of the assisting gas, the relative speed of the laser head with respect to

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- a driving device (not illustrated, but of per-se-known type) arranged to move the laser head 12 and the workpiece with respect to each other with an adjustable relative speed, as well as to control the pressure of the assisting gas, to adjust the distance of the nozzle 16 from the surface of the workpiece and to adjust the position of the focal point F of the laser beam relative to the surface of the workpiece being processed, the driving device being controlled by a numerical control 18; and
- a process control device arranged to control the laser source 10 and/or the driving device (through the numerical control 18) so as to adjust at least one of the following process control parameters: the power of the laser, the frequency and the duty cycle of the laser pulse, the pressure of the assisting gas, the relative speed of the laser head 12 with respect to the workpiece, the distance between the nozzle 16 and the surface of the workpiece, and the distance between the focal point F of the laser beam and the surface of the workpiece being processed.

More specifically, the process control device comprises sensor means for detecting at least one predetermined wavelength band of the radiation emitted by a given gas ~~or by a given material~~ present in the volume of material involved by the irradiation of the focussed laser beam (hereinafter indicated, for the sake of easiness, as process volume), signal processing means for processing the signal detected by the sensor means, and control means for controlling, on the base of the signal received by the signal processing means, the laser source and/or the driving device to adjust at least one of the above-mentioned process control parameters.

The sensor means comprise a photodiode 20 for detecting, preferably with a dynamic range of at least one decade, the predetermined wavelength band(s), a reflector/deflector device 22 arranged to direct onto the photodiode 20 the radiation emitted by the process volume and an optical filter device 24 interposed between the photodiode 20 and the reflector/deflector device 22 to select the predetermined wavelength band(s). The optical filter device 24 may work in transmission or in reflection. In this second case, the optical filter device 24 may coincide with the reflector/deflector device 22. The radiation emitted by the process volume is therefore directed by the reflector/deflector device 22, through the optical filter device 24, onto the photodiode 20, which detects the predetermined wavelength

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band(s). As shown in Figures 5A and 5B, the sensor means may comprise a plurality of photodiodes 20 (in the illustrated example, four photodiodes), as well as a corresponding plurality of reflector/deflector devices 22 and optical filter devices 24, arranged in such a manner that each reflector/deflector device 22 directs onto a respective photodiode 20, through a respective optical filter device 24, the radiation emitted by the process volume in a given angular range. The sensor means may be positioned indifferently above or below the focussing device 14 of the laser head 12.

The signal processing means comprise a signal amplification and filter circuit board 26, which is for instance directly connected to the photodiode 20, and a signal acquisition circuit board 28 connected to the signal amplification and filter circuit board 26 to acquire the signal coming from this latter.

The control means comprise an electronic control unit 30 (for instance an industrial PC) on which a control software is installed which performs a control algorithm described in detail further on. The electronic control unit 30 is connected on the one hand to the signal acquisition circuit board 28 and on the other, through a communication line with input and output interface, both to the laser source 10 and to the numerical control 18, so as to be able to control directly the laser source 10 to adjust the power, the frequency and the duty cycle of the laser, and indirectly, through the numerical control 18, the driving device to adjust the remaining process control parameters mentioned above, namely the relative speed, the pressure of the assisting gas, the distance of the nozzle from the material and the position of the focal point relative to the material.

The aforesaid process control parameters are adjusted on the base of the signal relating to the predetermined wavelength band(s) detected by the sensor means. According to the invention, there is used, as predetermined wavelength band, a wavelength band selected in such a manner as to include at least one emission line of ~~an~~ <-> emitting element ~~(which may be a gas or a metal)~~ present in the process volume. ~~Preferably,~~ The emission lines monitored for the purposes of control of the process ~~are comprised in the range from 180 to 2000 nm and~~ are detected with a bandwidth not wider than 100 nm. Preferably, ~~in case a~~ gas ~~is~~ used as emitting element, ~~this gas~~ is oxygen or nitrogen.

<a pas ou>

The radiation emitted by the oxygen has emission lines at the following wavelengths (in nm): 948, 845, 823, 795 and 777. ~~Preferably~~, the control method according to the invention provides for monitoring of the last emission line mentioned above, and therefore for acquiring the signal at ~~750~~ 777 nm, with a pass-band equal to ±50 nm. As already stated in the introductory part of the description, this wavelength comprises a strong emission by the ionized oxygen, which can be detected easily even when the oxygen is only present as contaminant in the process, and specifically gives the information required to control the laser cutting, as well as to control the piercing operation in preparation of cutting. This wavelength is used according to the invention on the one hand as an information about the tendency of the amount of ionized oxygen in the process volume to increase, which tendency usually anticipates an explosion of the piercing or of the cut, and on the other as an index of the amount of collected contaminant, and therefore as an index of not-yet-completed piercing or of a tendency to the closure of the kerf.

As far as nitrogen is concerned, the emitted radiation by this gas has emission lines at the following wavelengths (in nm): 1358, 1246, 939, 870, 860, 745 and 576. ~~In this case, the following wavelengths (in nm) shall be monitored, with a pass-band equal to ±50 nm: 1350, 1250, 950, 850, 750 and 550.~~

~~In addition to signals emitted by a gas, be it an assisting gas or a contaminant gas, it is pos~~sible to use also signals emitted by metal elements contained in the process volume, independently of whether they are characterizing elements of the material or elements present as contaminants.

In this connection, the control method according to the invention preferably provides for monitoring the radiation emitted by the iron. In case of a workpiece made of carbon steel, the radiation emitted by the iron contained in the material of the workpiece has emission lines in a first band at 517-521 nm and in a second band at 550-600 nm. In this case, it will be sufficient to monitor, with a pass-band equal to ±50 nm, the wavelength at 550 nm. In case of a workpiece made of stainless steel, the radiation emitted by the iron contained in the material of the workpiece has emission lines comprised, in addition to the two bands ~~indicated above, in a third band at 480-500 nm.~~

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The monitoring of the wavelength at 550 nm, with a pass-band equal to ±50 nm, can also be used when the material being processed is aluminium or an aluminium alloy, since the radiation emitted by the aluminium has emission lines comprised in a band at 518-548 nm.

It is also possible to use as emitting element the nickel, whose emitted radiation has emission lines at the following wavelengths (in nm): 361, 352, 349 and 341. In this case, it will be sufficient to monitor, with a pass-band equal to ±50 nm, the wavelengths at 350 nm.

Moreover, it is possible to use as emitting element the chromium, whose emitted radiation has emission lines at the following wavelengths (in nm): 427 and 359. In this case, it will be sufficient to monitor, with a pass-band equal to ±50 nm, the wavelengths at 450 nm and at 350 nm.

In case the copper is chosen as emitting element, whose emitted radiation has an emission line at 325 nm, it will be sufficient to monitor, with a pass-band equal to ±50 nm, the wavelength at 350 nm.

In order to carry out the laser piercing in preparation of cutting, an example of control algorithm which can be used by the control means of the laser working system to adjust the process control parameters provides for the steps described here below.

a) First of all, the presence of the material in which to make the hole is checked. For this purpose, a first laser pulse train is sent onto the material by means of the laser head and the signal relating to the predetermined wavelength band(s) is detected by the sensor means. If the detected signal is too low with respect to a predetermined threshold, this information is interpreted by the control means as indicating the absence of the material or as indicating that a hole has already been made before.

b) Once the presence of the material has been confirmed, the laser working process is started with suitable values of the process control parameters indicated above. In particular, the laser source is on for a certain predetermined time interval, at the end of which the laser source is switched off. Specifically, if the process takes place in an environment rich in

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oxygen (used as assisting gas), then the time interval during which the laser source is on varies in the range from 0,5 to 5 msec (preferably 1 msec). If, on the contrary, the oxygen is present only as contaminant gas, then the time interval during which the laser source is on varies in the range from 0,5 to 100 msec (preferably 50 msec).

c) After a certain time (relaxation time) from the switching off of the laser source, the radiation emitted in the predetermined wavelength band(s) is detected by the sensor means and its course is monitored. If the detected signal falls below a given re-ignition threshold, then step b) is repeated, i.e. the laser source is switched on again. During the monitoring of the control signal, the control means can also measure the time derivative of this signal and use this derivative as an indication of the robustness of the adjustment procedure.

The process ends when the detected signal falls below a given end-of-process threshold. Preferably, the end-of-process control is performed in the time interval during which the laser source is on.

The values of the re-ignition and of end-of-process thresholds depend on the material and on the thickness of the workpiece. Preferably, these values are not fixed, but are dynamically changed by the control means in case these latter establish, on the base of the measured time derivative of the control signal, that the process is not very robust.

In order to carry out a laser cutting operation, an example of control algorithm which can be used by the control means of the laser working system to adjust the process control parameters provides for the steps described here below.

a') First of all, the process control parameters are set on those values which are usually chosen depending on the laser source used, as well as on the material and on the thickness of the workpiece.

b') The sensor means detect the signal corresponding to the predetermined wavelength band(s) of the radiation emitted by the process volume. In case at least one of the monitored signals overcomes a given threshold, the control means interpret this excess of emis-

sion either as partial closure of the kerf in case of cutting with an inert gas or as incipient loss of control of the reactive process in case of cutting with a reactive gas, and in either case they suitably vary at least one of the process control parameters indicated above, privileging, if possible, the power of the laser and the relative speed. In case at least one of the monitored signals falls below a given threshold, the control means interpret this reduction of emission as a too slow process and suitably vary at least one of the process control parameters indicated above, privileging, if possible, the power of the laser and the relative speed.

Moreover, if the sensor means of the working system comprise a number of photodiodes arranged so as to keep a space correlation with that portion of the process volume which generates the radiation detected by each of the photodiodes, then preferably the control means correlate the detected signal with the cutting direction, thereby making it possible to obtain an information about the anisotropy of behaviour in all the allowed cutting directions. Such an information gives a measure of the offset of the laser beam with respect to the centre of the nozzle of the laser head, i.e. with respect to the direction of the outflow of the assisting gas, and allows therefore to suitably move the centre of mass of the focussing lens or of the nozzle.

Naturally, control algorithms different from those described above can be implemented within the scope of the present invention, subject to the principle of adjusting at least one of the process control parameters mentioned above on the base of the signal relating to the radiation emitted by the process volume in at least one predetermined wavelength band, such predetermined wavelength band including at least one emission line of a gas or of another emitting element present in the process volume during the laser working.

With reference to Figures 6 to 11, where components identical or corresponding to those of Figures 4 and 5 have been given the same reference numerals, some possible embodiments of the sensor means which can be used in the process control device of a laser cutting system according to the invention will be described now.

In the embodiment of Figure 6, the laser cutting system comprises a laser source (not

shown) of the solid-state type (Nd:YAG, fiber laser, disc laser, diode laser), in which case the optical path comprises a transport fiber 32 and the laser head 12 further comprises a collimation device 34, which is connected to the final end of the transport fiber 32 and comprises one or more collimation lenses. Also in this case, the sensor means (photodiode 20, reflector/deflector device 22 and optical filter device 24) can be placed above or below the focussing device 14. In the first case, the sensor means will be placed between the focussing device 14 and the collimation device 34, as shown in Figure 6.

According to the embodiment of Figure 7, which also refers to the case of a laser cutting system using a laser source of the solid-state type, the reflector/deflector device 22 is formed by a 90-degree deflector, which is placed between the collimation device 34 and the focussing device 14 and is configured so as to reflect at least the 99,9% of the laser radiation and to transmit instead the radiation in the predetermined wavelength band(s). In the proposed example, the sensor means further comprise a focussing lens 36 arranged between the deflector 22 and the photodiode 20 to focus onto this latter the detected signal. Moreover, in the proposed example the optical filter device 24 is arranged between the deflector 22 and the focussing lens 36 and comprises, in the order from the deflector 22 to the focussing lens 36, a first optical filter 38 arranged to cut down the laser radiation and a second optical filter 40 arranged to select the predetermined wavelength band(s). The same configuration of the sensor means can also be obtained with a plurality of photodiodes, of reflector/deflector devices and of optical filter devices, in which case each reflector/deflector device will comprise a respective deflector and a respective focussing lens will be provided between each deflector and the respective photodiode.

According to the embodiments of Figures 8 to 11, which also refer to the case of a laser cutting system using a laser source of the solid-state type, there is provided, instead of a 90-degree deflector, a branching device arranged along the optical path and configured so as to allow the laser beam generated by the laser source to be fully transported to the laser head through the transport fiber and to the radiation which is emitted by the process volume and is transported through the transport fiber to be directed onto the photodiode.

More specifically, according to the embodiment of Figure 8, an optical coupling device 42

is provided along the optical path, by means of which the laser generated by the laser source is launched in the transport fiber 32, the optical coupling device 42 comprising a collimation lens 44 and a focussing and launching lens 46. In this case, the branching device is integrated in the optical coupling device 42 and comprises a beam splitter 48 arranged between the collimation lens 44 and the focussing and launching lens 46 so as to allow the laser beam generated by the laser source to pass completely through the focussing and launching lens 46 and to the radiation which is emitted by the process volume and is transported through the transport fiber 32 to be directed onto the photodiode 20. As in the embodiment of Figure 7, the sensor means further comprise a focussing lens 36 arranged between the beam splitter 48 and the photodiode 20 to focus onto this latter the detected signal. Moreover, also in this case the optical filter device 24 is arranged between the beam splitter 48 and the focussing lens 36 and comprises a first optical filter 38 arranged to cut down the laser radiation and a second optical filter 40 arranged to select the predetermined wavelength band(s).

In the embodiments of Figures 9 to 11, on the contrary, the branching device comprises a secondary fiber 50 welded to the transport fiber 32.

More specifically, according to the embodiment of Figure 9, in which the optical path comprises an optical coupling device (not shown) by means of which the laser generated by the laser source is launched in the transport fiber, the secondary fiber 50 is welded to the transport fiber 32 in a point of this latter positioned downstream of the optical coupling device. Also in this case, the sensor means comprise in order, in addition to the secondary fiber 50, a collimation lens 52, an optical filter device 24, a focussing lens 36 and a photodiode 20, the optical filter device 24 comprising in turn a first optical filter 38 arranged to cut down the laser radiation and a second optical filter 40 arranged to select the predetermined wavelength band(s).

According to the embodiment of Figure 10, the optical coupling device along the optical path is omitted and the secondary fiber 50 is welded to the transport fiber 32 in the same point as the one at which the transport fiber is welded to an output fiber 54 of the laser source. As far as the sensor means are concerned, what has been stated above with refer-

ence to Figure 9 still applies.

Finally, according to the embodiment of Figure 11, the laser source 10 comprises a plurality of laser modules 10.1, 10.2, ..., 10.N able to emit a laser beam independently of each other, and a corresponding plurality of output fibers 54.1, 54.2, ..., 54.N extending each from a respective laser module. The output fibers are connected on the input side to an optical combiner 56, to which the transport fiber 32 is connected on the output side. In this case, the secondary fiber 50 is welded to the optical combiner 56. As far as the sensor means are concerned, what has been stated with reference to Figure 9 still applies.

Naturally, the principle of the invention remaining unchanged, the modes for carrying out the control method and the embodiments of the laser cutting system may vary widely from those described and illustrated purely by way of non-limiting example.

CLAIMS

1. Method for controlling a laser cutting process, the process providing for irradiation of a workpiece (P) by means of a laser beam which is generated by a laser source (10) and focussed by a laser head (12), as well as for supply of a flow of an assistance gas by means of a nozzle (16) of the laser head (12),
the control method comprising the steps of:
a) detecting the wavelength signal of the radiation emitted by an emitting element present in the volume of material irradiated by the focussed laser beam, and
b) adjusting, based on the detected signal, at least one of the following process control parameters: the power of the laser, the frequency and the duty cycle of the laser pulse, the pressure of the assistance gas, the relative speed of the laser head (12) with respect to the workpiece (P), the distance of the nozzle of the laser head (12) from the surface (S) of the workpiece (P), and distance of the focal point (F) of the laser beam from the surface (S) of the workpiece (P),
wherein step a) is performed by detecting the radiation emitted in at least one predetermined wavelength band which includes the wavelength at 777 nm and has a bandwidth not wider than 100 nm, and
wherein the assistance gas or a contaminant gas present in the volume of material irradiated by the focussed laser beam is used as emitting element.

2. Method according to claim 1, wherein in order to perform a piercing operation in preparation of cutting, said step b) comprises the following sub-steps:
b1) switching on the laser source (10) for a first predetermined time interval ranging from 0,5 to 5 msec in case oxygen is used as assistance gas, and ranging from 0,5 to 100 msec in case a gas other than oxygen is used as assistance gas;
b2) switching off the laser source (10) at the end of said first predetermined time interval, and
b3) waiting until the detected wavelength signal has become lower than a given threshold, and only then repeating sub-steps b1) and b2).

3. Method according to claim 1 or claim 2, wherein said step b) is performed in such a

manner that if the wavelength signal detected at step a) exceeds a given threshold, this is interpreted as a partial closure of the kerf in case of cutting with an inert gas or as the beginning of a loss of control of the reactive process in case of cutting with a reactive gas, and at least one of the aforesaid process control parameters is varied accordingly, whereas if the wavelength signal detected at step a) becomes lower than a given threshold, this is interpreted as meaning that the process is too slow, and at least one of the aforesaid process control parameters is varied accordingly.

4. Laser cutting apparatus comprising:

- a laser source (10);
- a laser head (12) comprising a focussing device (14) for focussing the laser beam generated by the laser source (10) onto a workpiece (P) and a nozzle (16) for supplying an assistance gas;
- an optical path for transporting the laser beam generated by the laser source (10) to the focussing device (14) of the laser head (12);
- a driving device for moving the laser head (12) and the workpiece (P) with respect to each other with an adjustable speed, as well as for controlling the pressure of the assistance gas, for adjusting the distance of the nozzle (16) from the surface (S) of the workpiece (P) and for adjusting the position of the focal point (F) of the laser beam with respect to the surface (S) of the workpiece (P); and
- a process control device comprising sensor means adapted to detect at least one predetermined wavelength band of the radiation emitted by the assistance gas or by a contaminant gas present in the volume of material irradiated by the focussed laser beam, signal processing means for processing the signal detected by said sensor means, and control means for controlling, on the base of the signal received by said signal processing means, the laser source (10) and/or the driving device to adjust at least one of the following process control parameters: the power of the laser, the frequency and the duty cycle of the laser pulse, the pressure of the assistance gas, the relative speed of the laser head (12) with respect to the workpiece (P), the distance of the nozzle of the laser head (12) from the surface (S) of the workpiece (P), and distance of the focal point (F) of the laser beam from the surface (S) of the workpiece (P),

wherein said predetermined wavelength band includes the wavelength at 777 nm and has a

bandwidth not wider than 100 nm.

5. Apparatus according to claim 4, wherein said sensor means comprise a photodiode (20) for detecting said at least one predetermined wavelength band, a reflector/deflector device (22) arranged to direct the radiation emitted by the volume of material irradiated by the focussed laser beam on the photodiode (20), and an optical filter device (24) interposed between the photodiode (20) and the reflector/deflector device (22) to select said at least one predetermined wavelength band.

6. Apparatus according to claim 5, wherein the laser source (10) is a solid-state laser source, wherein the optical path comprises a transport fiber (32), wherein the laser head (12) comprises a collimation device (34) connected to the final end of the transport fiber (32), and wherein the reflector/deflector device (22) is a 90-degree deflector arranged to reflect at least the 99,9% of the laser radiation and to transmit the radiation emitted in said at least one predetermined wavelength band.

7. Apparatus according to claim 6, wherein said sensor means further comprise a focussing lens (36) arranged between the reflector/deflector device (22) and the photodiode (20) to focus onto this latter the radiation emitted in said at least one predetermined wavelength band, and wherein the optical filter device (24) is arranged between the reflector/deflector device (22) and the focussing lens (36) and comprises a first optical filter (38) arranged to cut down the laser radiation and a second optical filter (40) arranged to select said at least one predetermined wavelength band.

8. Apparatus according to claim 4, wherein the laser source (10) is a solid-state laser source, wherein the optical path comprises a transport fiber (32) and wherein said sensor means comprise a photodiode (20) for detecting said at least one predetermined wavelength band, a branching device (48, 50) arranged along the optical path (32) and configured to allow the laser beam generated by the laser source (10) to be totally transported to the laser head (12) through the transport fiber (32) and the radiation which is emitted by the laser cutting process and is transported through the transport fiber (32) to be directed onto the photodiode (20), and an optical filter device (24) interposed between the photodi-

ode (20) and the branching device (48, 50) to select said at least one predetermined wavelength band.

9. Apparatus according to claim 8, wherein the optical path comprises an optical coupling device (42) comprising a collimation lens (44) and a focussing and launching lens (46), and wherein the branching device (48, 50) comprises a beam splitter (48) arranged between the collimation lens (44) and the focussing and launching lens (46) so as to allow the laser beam generated by the laser source (10) to pass entirely through the focussing and launching lens (46) and the radiation which is emitted by the laser cutting process and is transported by the transport fiber (32) to be directed onto the photodiode (20).

10. Apparatus according to claim 8, wherein the optical path comprises an optical coupling device and wherein the branching device (48, 50) comprises a secondary fiber (50) welded to the transport fiber (32) in a point of this latter which is positioned downstream of the optical coupling device.

11. Apparatus according to claim 8, wherein the transport fiber (32) is welded to an output fiber (54) of the laser source (10) and wherein the branching device (48, 50) comprises a secondary fiber (50) which is welded to the transport fiber (32) in the same point as the one where this latter is welded to the output fiber (54).

12. Apparatus according to claim 8, wherein the laser source (10) comprises a plurality of laser modules (10.1, 10.2, ..., 10.N) able to emit a laser beam independently of each other and a corresponding plurality of output fibers (54.1, 54.2, ..., 54.N) associated each to a respective laser module (10.1, 10.2, ..., 10.N), wherein the optical path comprises an optical combiner (56) to which the output fibers (54.1, 54.2, ..., 54.N) are connected on the input side and to which the transport fiber (32) is connected on the output side, and wherein the branching device (48, 50) comprises a secondary fiber (50) welded to the optical combiner (56).

tue of a laser cutting system having the features set forth in the enclosed independent claim 4.

Advantageous modes of implementation of the control method according to the invention and advantageous embodiments of the laser cutting system according to the invention are the subject-matter of the dependent claims, the content of which is to be regarded as being an integral and integrating part of the following description.

In short, the invention is based on the idea of controlling the laser cutting process, including the initial piercing phase, by using as reference signal one or more emission lines specific for the radiation emitted by a gas (be it an assisting gas or a contaminant gas) present in the volume involved by the irradiation of the focussed laser beam and by adjusting, on the base of this reference signal, at least one of the following process control parameters: the power of the laser, the frequency and duty cycle of the laser pulse, the pressure of the assisting gas, the relative speed of the laser with respect to the workpiece, the distance between the laser head and the surface of the workpiece, and the distance between the focal point of the laser beam and the surface of the workpiece.

The control method according to the invention provides therefore for implementing a control loop comprising the following steps:

- the radiation coming from the volume involved by the laser process is detected by sensor means operating in a band centred on a wavelength previously chosen as the most suitable one for controlling the process;
- the signal thus detected is suitably filtered and processed and then sent as input to an electronic control unit; and
- the electronic control unit interprets the signal received as input and, if necessary, changes one of the above-indicated process control parameters.

The emission lines specific for the radiation which is monitored for the purpose of control of the process (hereinafter referred to as control radiation are detected with a bandwidth which is not wider than 100nm.

Preferably, oxygen or nitrogen are used as emitting gas. The gas used as emitting gas may indifferently be an assisting gas or a contaminant gas. In this second case, the gas may indifferently be either a gas normally present in the atmosphere around the workpiece being processed or a gas expressly introduced for this purpose into the volume involved by the laser process.

If the gas has a mainly reactive function, its emissions can be interpreted as indicative of the level of the intensity with which the reaction process is occurring: a too low level means that the reaction process is not occurring with the rate that would be possible, whereas a too high level means that the reaction process is occurring with an excessive rate, hence with the risk of a situation of uncontrolled or explosive process. In case of a pulsed laser, the derivative of the signal or the minimum level reached by a laser switched-off before the subsequent pulse can give an indication that the process will tend to reduce or increase its intensity, thus becoming on the one hand inefficient and on the other hand uncontrolled or explosive. The same information can be obtained also in case of a continuous laser, by introducing an overmodulation on the laser power and comparing the time derivatives of the signal emitted by the gas during the undermodulation step and during the overmodulation step. Another type of control can be obtained by comparing the levels of emission of radiation at two or more different wavelengths, which indicate the presence or the transformation of at least two specific chemical species or compounds inside the volume involved by the laser working process.

If the gas has the function of contaminant, be it normally present in the atmosphere around the workpiece being processed or expressly introduced in the process for this purpose, its emissions can be interpreted as control signal even in case of a laser cutting process using an inert gas as assisting gas. In case of laser piercing carried out in preparation of cutting, the signal emitted by the contaminant gas gives the information that the piercing cylinder is still closed and that therefore the process is not finished yet. Once the opening in the material has been formed, the control signal decreases significantly and thus shows that the process has come to an end. In case of the laser cutting, an increase in the signal emitted by the contaminant gas gives the information that the leading edge of the cut is tending to become parallel to the surface of the workpiece being processed, thereby expelling less material, less by-products and less contaminant gas, and that therefore the forward speed of the cut is too high, whereas a decrease in the signal emitted by the contaminant gas gives the information that the leading edge of the cut is tending to become perpendicular to the surface of the workpiece being processed, and that therefore the forward speed of the cut is too low.

More specifically the control method according to the invention provides for monitoring the emission line at 777 nm. This wavelength includes a strong emission from the ionized oxygen, which can be easily detected even when the oxygen is present only as contaminant gas in the process, and more specifically gives the information required for control both of the laser piercing in preparation of cutting and of the laser cutting. In case of a laser piercing process under oxidizing conditions, with the use of oxygen as assisting gas, this wavelength gives a very sensitive anticipation on the rising ramp of the amount of ionized oxygen present in the process volume, which ramp forebodes an explosion. In case of a fusion laser piercing process, with the use of nitrogen as assisting gas, this wavelength gives a very sensitive information about the presence of a still closed volume which is being fused before opening. In case of a laser cutting process, irrespective of whether it is carried out under oxidizing conditions or it is a fusion laser cutting process, this wavelength represents a rich source of information, as it provides both an anticipation of the risk of explosion or lateral diffusion of the oxidizing process, resulting in a reduction in the final quality of the cut, and an anticipation of the phenomenon of the closure of the kerf, and of the associated loss of the cut, independently of the upstream reasons which have led to the closure.

The monitoring of the signal emitted by a gas present in the volume of material involved by the laser working process allows therefore to obtain information on the state of the process and hence to control the process by adjusting the above-mentioned process control parameters.

With regard to the laser cutting system implementing the control method according to the invention, it basically comprises:

- a laser source, which may indifferently be of the CO2 type or of the solid-state type (Nd:YAG, fiber laser, disc laser, diode laser);
- a laser head comprising a focussing device for focussing the laser beam generated by the laser source and a nozzle for supplying the assisting gas;
- an optical path arranged to transport the laser beam generated by the laser source to the focussing device of the laser head;
- a driving device arranged to move the laser head and the workpiece with respect to each other with an adjustable speed, as well as to control the pressure of the assisting gas, to adjust the distance of the nozzle from the surface of the workpiece and to adjust the position of the focal point of the laser beam relative to the surface of the workpiece; and
- a process control device comprising sensor means for detecting at least one predetermined wavelength band of the radiation emitted by a given gas present in the volume of material involved by the irradiation of the focussed laser beam, signal processing means for processing the signal detected by the sensor means, and control means for controlling, on the base of the signal received by the signal processing means, the laser source and/or the driving device to adjust at least one of the following process control parameters: the power of the laser, the frequency and the duty cycle of the laser pulse, the pressure of the assisting gas, the relative speed of the laser head with respect to

- a driving device (not illustrated, but of per-se-known type) arranged to move the laser head 12 and the workpiece with respect to each other with an adjustable relative speed, as well as to control the pressure of the assisting gas, to adjust the distance of the nozzle 16 from the surface of the workpiece and to adjust the position of the focal point F of the laser beam relative to the surface of the workpiece being processed, the driving device being controlled by a numerical control 18; and
- a process control device arranged to control the laser source 10 and/or the driving device (through the numerical control 18) so as to adjust at least one of the following process control parameters: the power of the laser, the frequency and the duty cycle of the laser pulse, the pressure of the assisting gas, the relative speed of the laser head 12 with respect to the workpiece, the distance between the nozzle 16 and the surface of the workpiece, and the distance between the focal point F of the laser beam and the surface of the workpiece being processed.

More specifically, the process control device comprises sensor means for detecting at least one predetermined wavelength band of the radiation emitted by a given gas present in the volume of material involved by the irradiation of the focussed laser beam (hereinafter indicated, for the sake of easiness, as process volume), signal processing means for processing the signal detected by the sensor means, and control means for controlling, on the base of the signal received by the signal processing means, the laser source and/or the driving device to adjust at least one of the above-mentioned process control parameters.

The sensor means comprise a photodiode 20 for detecting, preferably with a dynamic range of at least one decade, the predetermined wavelength band(s), a reflector/deflector device 22 arranged to direct onto the photodiode 20 the radiation emitted by the process volume and an optical filter device 24 interposed between the photodiode 20 and the reflector/deflector device 22 to select the predetermined wavelength band(s). The optical filter device 24 may work in transmission or in reflection. In this second case, the optical filter device 24 may coincide with the reflector/deflector device 22. The radiation emitted by the process volume is therefore directed by the reflector/deflector device 22, through the optical filter device 24, onto the photodiode 20, which detects the predetermined wavelength

band(s). As shown in Figures 5A and 5B, the sensor means may comprise a plurality of photodiodes 20 (in the illustrated example, four photodiodes), as well as a corresponding plurality of reflector/deflector devices 22 and optical filter devices 24, arranged in such a manner that each reflector/deflector device 22 directs onto a respective photodiode 20, through a respective optical filter device 24, the radiation emitted by the process volume in a given angular range. The sensor means may be positioned indifferently above or below the focussing device 14 of the laser head 12.

The signal processing means comprise a signal amplification and filter circuit board 26, which is for instance directly connected to the photodiode 20, and a signal acquisition circuit board 28 connected to the signal amplification and filter circuit board 26 to acquire the signal coming from this latter.

The control means comprise an electronic control unit 30 (for instance an industrial PC) on which a control software is installed which performs a control algorithm described in detail further on. The electronic control unit 30 is connected on the one hand to the signal acquisition circuit board 28 and on the other, through a communication line with input and output interface, both to the laser source 10 and to the numerical control 18, so as to be able to control directly the laser source 10 to adjust the power, the frequency and the duty cycle of the laser, and indirectly, through the numerical control 18, the driving device to adjust the remaining process control parameters mentioned above, namely the relative speed, the pressure of the assisting gas, the distance of the nozzle from the material and the position of the focal point relative to the material.

The aforesaid process control parameters are adjusted on the base of the signal relating to the predetermined wavelength band(s) detected by the sensor means. According to the invention, there is used, as predetermined wavelength band, a wavelength band selected in such a manner as to include at least one emission line of a gas as emitting element present in the process volume. The emission lines monitored for the purposes of control of the process are detected with a bandwidth not wider than 100 nm. Preferably, the gas used as emitting element, is oxygen or nitrogen.

The radiation emitted by the oxygen has emission lines at the following wavelengths (in nm): 948, 845, 823, 795 and 777. The control method according to the invention provides for monitoring of the last emission line mentioned above, and therefore for acquiring the signal at 777 nm, with a pass-band equal to ±50 nm. As already stated in the introductory part of the description, this wavelength comprises a strong emission by the ionized oxygen, which can be detected easily even when the oxygen is only present as contaminant in the process, and specifically gives the information required to control the laser cutting, as well as to control the piercing operation in preparation of cutting. This wavelength is used according to the invention on the one hand as an information about the tendency of the amount of ionized oxygen in the process volume to increase, which tendency usually anticipates an explosion of the piercing or of the cut, and on the other as an index of the amount of collected contaminant, and therefore as an index of not-yet-completed piercing or of a tendency to the closure of the kerf.

As far as nitrogen is concerned, the emitted radiation by this gas has emission lines at the following wavelengths (in nm): 1358, 1246, 939, 870, 860, 745 and 576.

In order to carry out the laser piercing in preparation of cutting, an example of control algorithm which can be used by the control means of the laser working system to adjust the process control parameters provides for the steps described here below.

a) First of all, the presence of the material in which to make the hole is checked. For this purpose, a first laser pulse train is sent onto the material by means of the laser head and the signal relating to the predetermined wavelength band(s) is detected by the sensor means. If the detected signal is too low with respect to a predetermined threshold, this information is interpreted by the control means as indicating the absence of the material or as indicating that a hole has already been made before.

b) Once the presence of the material has been confirmed, the laser working process is started with suitable values of the process control parameters indicated above. In particular, the laser source is on for a certain predetermined time interval, at the end of which the laser source is switched off. Specifically, if the process takes place in an environment rich in

oxygen (used as assisting gas), then the time interval during which the laser source is on varies in the range from 0,5 to 5 msec (preferably 1 msec). If, on the contrary, the oxygen is present only as contaminant gas, then the time interval during which the laser source is on varies in the range from 0,5 to 100 msec (preferably 50 msec).

c) After a certain time (relaxation time) from the switching off of the laser source, the radiation emitted in the predetermined wavelength band(s) is detected by the sensor means and its course is monitored. If the detected signal falls below a given re-ignition threshold, then step b) is repeated, i.e. the laser source is switched on again. During the monitoring of the control signal, the control means can also measure the time derivative of this signal and use this derivative as an indication of the robustness of the adjustment procedure.

The process ends when the detected signal falls below a given end-of-process threshold. Preferably, the end-of-process control is performed in the time interval during which the laser source is on.

The values of the re-ignition and of end-of-process thresholds depend on the material and on the thickness of the workpiece. Preferably, these values are not fixed, but are dynamically changed by the control means in case these latter establish, on the base of the measured time derivative of the control signal, that the process is not very robust.

In order to carry out a laser cutting operation, an example of control algorithm which can be used by the control means of the laser working system to adjust the process control parameters provides for the steps described here below.

a') First of all, the process control parameters are set on those values which are usually chosen depending on the laser source used, as well as on the material and on the thickness of the workpiece.

b') The sensor means detect the signal corresponding to the predetermined wavelength band(s) of the radiation emitted by the process volume. In case at least one of the monitored signals overcomes a given threshold, the control means interpret this excess of emis-

sion either as partial closure of the kerf in case of cutting with an inert gas or as incipient loss of control of the reactive process in case of cutting with a reactive gas, and in either case they suitably vary at least one of the process control parameters indicated above, privileging, if possible, the power of the laser and the relative speed. In case at least one of the monitored signals falls below a given threshold, the control means interpret this reduction of emission as a too slow process and suitably vary at least one of the process control parameters indicated above, privileging, if possible, the power of the laser and the relative speed.

Moreover, if the sensor means of the working system comprise a number of photodiodes arranged so as to keep a space correlation with that portion of the process volume which generates the radiation detected by each of the photodiodes, then preferably the control means correlate the detected signal with the cutting direction, thereby making it possible to obtain an information about the anisotropy of behaviour in all the allowed cutting directions. Such an information gives a measure of the offset of the laser beam with respect to the centre of the nozzle of the laser head, i.e. with respect to the direction of the outflow of the assisting gas, and allows therefore to suitably move the centre of mass of the focussing lens or of the nozzle.

Naturally, control algorithms different from those described above can be implemented within the scope of the present invention, subject to the principle of adjusting at least one of the process control parameters mentioned above on the base of the signal relating to the radiation emitted by the process volume in at least one predetermined wavelength band, such predetermined wavelength band including at least one emission line of a gas or of another emitting element present in the process volume during the laser working.

With reference to Figures 6 to 11, where components identical or corresponding to those of Figures 4 and 5 have been given the same reference numerals, some possible embodiments of the sensor means which can be used in the process control device of a laser cutting system according to the invention will be described now.

In the embodiment of Figure 6, the laser cutting system comprises a laser source (not

shown) of the solid-state type (Nd:YAG, fiber laser, disc laser, diode laser), in which case the optical path comprises a transport fiber 32 and the laser head 12 further comprises a collimation device 34, which is connected to the final end of the transport fiber 32 and comprises one or more collimation lenses. Also in this case, the sensor means (photodiode 20, reflector/deflector device 22 and optical filter device 24) can be placed above or below the focussing device 14. In the first case, the sensor means will be placed between the focussing device 14 and the collimation device 34, as shown in Figure 6.

According to the embodiment of Figure 7, which also refers to the case of a laser cutting system using a laser source of the solid-state type, the reflector/deflector device 22 is formed by a 90-degree deflector, which is placed between the collimation device 34 and the focussing device 14 and is configured so as to reflect at least the 99,9% of the laser radiation and to transmit instead the radiation in the predetermined wavelength band(s). In the proposed example, the sensor means further comprise a focussing lens 36 arranged between the deflector 22 and the photodiode 20 to focus onto this latter the detected signal. Moreover, in the proposed example the optical filter device 24 is arranged between the deflector 22 and the focussing lens 36 and comprises, in the order from the deflector 22 to the focussing lens 36, a first optical filter 38 arranged to cut down the laser radiation and a second optical filter 40 arranged to select the predetermined wavelength band(s). The same configuration of the sensor means can also be obtained with a plurality of photodiodes, of reflector/deflector devices and of optical filter devices, in which case each reflector/deflector device will comprise a respective deflector and a respective focussing lens will be provided between each deflector and the respective photodiode.

According to the embodiments of Figures 8 to 11, which also refer to the case of a laser cutting system using a laser source of the solid-state type, there is provided, instead of a 90-degree deflector, a branching device arranged along the optical path and configured so as to allow the laser beam generated by the laser source to be fully transported to the laser head through the transport fiber and to the radiation which is emitted by the process volume and is transported through the transport fiber to be directed onto the photodiode.

More specifically, according to the embodiment of Figure 8, an optical coupling device 42

is provided along the optical path, by means of which the laser generated by the laser source is launched in the transport fiber 32, the optical coupling device 42 comprising a collimation lens 44 and a focussing and launching lens 46. In this case, the branching device is integrated in the optical coupling device 42 and comprises a beam splitter 48 arranged between the collimation lens 44 and the focussing and launching lens 46 so as to allow the laser beam generated by the laser source to pass completely through the focussing and launching lens 46 and to the radiation which is emitted by the process volume and is transported through the transport fiber 32 to be directed onto the photodiode 20. As in the embodiment of Figure 7, the sensor means further comprise a focussing lens 36 arranged between the beam splitter 48 and the photodiode 20 to focus onto this latter the detected signal. Moreover, also in this case the optical filter device 24 is arranged between the beam splitter 48 and the focussing lens 36 and comprises a first optical filter 38 arranged to cut down the laser radiation and a second optical filter 40 arranged to select the predetermined wavelength band(s).

In the embodiments of Figures 9 to 11, on the contrary, the branching device comprises a secondary fiber 50 welded to the transport fiber 32.

More specifically, according to the embodiment of Figure 9, in which the optical path comprises an optical coupling device (not shown) by means of which the laser generated by the laser source is launched in the transport fiber, the secondary fiber 50 is welded to the transport fiber 32 in a point of this latter positioned downstream of the optical coupling device. Also in this case, the sensor means comprise in order, in addition to the secondary fiber 50, a collimation lens 52, an optical filter device 24, a focussing lens 36 and a photodiode 20, the optical filter device 24 comprising in turn a first optical filter 38 arranged to cut down the laser radiation and a second optical filter 40 arranged to select the predetermined wavelength band(s).

According to the embodiment of Figure 10, the optical coupling device along the optical path is omitted and the secondary fiber 50 is welded to the transport fiber 32 in the same point as the one at which the transport fiber is welded to an output fiber 54 of the laser source. As far as the sensor means are concerned, what has been stated above with refer-

ence to Figure 9 still applies.

Finally, according to the embodiment of Figure 11, the laser source 10 comprises a plurality of laser modules 10.1, 10.2, ..., 10.N able to emit a laser beam independently of each other, and a corresponding plurality of output fibers 54.1, 54.2, ..., 54.N extending each from a respective laser module. The output fibers are connected on the input side to an optical combiner 56, to which the transport fiber 32 is connected on the output side. In this case, the secondary fiber 50 is welded to the optical combiner 56. As far as the sensor means are concerned, what has been stated with reference to Figure 9 still applies.

Naturally, the principle of the invention remaining unchanged, the modes for carrying out the control method and the embodiments of the laser cutting system may vary widely from those described and illustrated purely by way of non-limiting example.

CLAIMS

1. Method for controlling a laser cutting process, the process providing for irradiation of a workpiece (P) by means of a laser beam which is generated by a laser source (10) and focussed by a laser head (12), as well as for supply of a flow of an assistance gas by means of a nozzle (16) of the laser head (12),
the control method comprising the steps of:

a) detecting the wavelength signal of the radiation emitted by an emitting element present in the volume of material irradiated by the focussed laser beam, and

b) adjusting, based on the detected signal, at least one of the following process control parameters: the power of the laser, the frequency and the duty cycle of the laser pulse, the pressure of the assistance gas, the relative speed of the laser head (12) with respect to the workpiece (P), the distance of the nozzle of the laser head (12) from the surface (S) of the workpiece (P), and distance of the focal point (F) of the laser beam from the surface (S) of the workpiece (P),

wherein step a) is performed by detecting the radiation emitted in at least one predetermined wavelength band which includes the wavelength at 777 nm and has a bandwidth not wider than 100 nm, and

wherein the assistance gas or a contaminant gas present in the volume of material irradiated by the focussed laser beam is used as emitting element.

2. Method according to claim 1, wherein in order to perform a piercing operation in preparation of cutting, said step b) comprises the following sub-steps:

b1) switching on the laser source (10) for a first predetermined time interval ranging from 0,5 to 5 msec in case oxygen is used as assistance gas, and ranging from 0,5 to 100 msec in case a gas other than oxygen is used as assistance gas;

b2) switching off the laser source (10) at the end of said first predetermined time interval; and

b3) waiting until the detected wavelength signal has become lower than a given threshold, and only then repeating sub-steps b1) and b2).

3. Method according to claim 1 or claim 2, wherein said step b) is performed in such a

manner that if the wavelength signal detected at step a) exceeds a given threshold, this is interpreted as a partial closure of the kerf in case of cutting with an inert gas or as the beginning of a loss of control of the reactive process in case of cutting with a reactive gas, and at least one of the aforesaid process control parameters is varied accordingly, whereas if the wavelength signal detected at step a) becomes lower than a given threshold, this is interpreted as meaning that the process is too slow, and at least one of the aforesaid process control parameters is varied accordingly.

4. Laser cutting apparatus comprising:

- a laser source (10);
- a laser head (12) comprising a focussing device (14) for focussing the laser beam generated by the laser source (10) onto a workpiece (P) and a nozzle (16) for supplying an assistance gas;
- an optical path for transporting the laser beam generated by the laser source (10) to the focussing device (14) of the laser head (12);
- a driving device for moving the laser head (12) and the workpiece (P) with respect to each other with an adjustable speed, as well as for controlling the pressure of the assistance gas, for adjusting the distance of the nozzle (16) from the surface (S) of the workpiece (P) and for adjusting the position of the focal point (F) of the laser beam with respect to the surface (S) of the workpiece (P); and
- a process control device comprising sensor means adapted to detect at least one predetermined wavelength band of the radiation emitted by the assistance gas or by a contaminant gas present in the volume of material irradiated by the focussed laser beam, signal processing means for processing the signal detected by said sensor means, and control means for controlling, on the base of the signal received by said signal processing means, the laser source (10) and/or the driving device to adjust at least one of the following process control parameters: the power of the laser, the frequency and the duty cycle of the laser pulse, the pressure of the assistance gas, the relative speed of the laser head (12) with respect to the workpiece (P), the distance of the nozzle of the laser head (12) from the surface (S) of the workpiece (P), and distance of the focal point (F) of the laser beam from the surface (S) of the workpiece (P),

wherein said predetermined wavelength band includes the wavelength at 777 nm and has a

bandwidth not wider than 100 nm.

5. Apparatus according to claim 4, wherein said sensor means comprise a photodiode (20) for detecting said at least one predetermined wavelength band, a reflector/deflector device (22) arranged to direct the radiation emitted by the volume of material irradiated by the focussed laser beam on the photodiode (20), and an optical filter device (24) interposed between the photodiode (20) and the reflector/deflector device (22) to select said at least one predetermined wavelength band.

6. Apparatus according to claim 5, wherein the laser source (10) is a solid-state laser source, wherein the optical path comprises a transport fiber (32), wherein the laser head (12) comprises a collimation device (34) connected to the final end of the transport fiber (32), and wherein the reflector/deflector device (22) is a 90-degree deflector arranged to reflect at least the 99,9% of the laser radiation and to transmit the radiation emitted in said at least one predetermined wavelength band.

7. Apparatus according to claim 6, wherein said sensor means further comprise a focussing lens (36) arranged between the reflector/deflector device (22) and the photodiode (20) to focus onto this latter the radiation emitted in said at least one predetermined wavelength band, and wherein the optical filter device (24) is arranged between the reflector/deflector device (22) and the focussing lens (36) and comprises a first optical filter (38) arranged to cut down the laser radiation and a second optical filter (40) arranged to select said at least one predetermined wavelength band.

8. Apparatus according to claim 4, wherein the laser source (10) is a solid-state laser source, wherein the optical path comprises a transport fiber (32) and wherein said sensor means comprise a photodiode (20) for detecting said at least one predetermined wavelength band, a branching device (48, 50) arranged along the optical path (32) and configured to allow the laser beam generated by the laser source (10) to be totally transported to the laser head (12) through the transport fiber (32) and the radiation which is emitted by the laser cutting process and is transported through the transport fiber (32) to be directed onto the photodiode (20), and an optical filter device (24) interposed between the photodi-

ode (20) and the branching device (48, 50) to select said at least one predetermined wavelength band.

9. Apparatus according to claim 8, wherein the optical path comprises an optical coupling device (42) comprising a collimation lens (44) and a focussing and launching lens (46), and wherein the branching device (48, 50) comprises a beam splitter (48) arranged between the collimation lens (44) and the focussing and launching lens (46) so as to allow the laser beam generated by the laser source (10) to pass entirely through the focussing and launching lens (46) and the radiation which is emitted by the laser cutting process and is transported by the transport fiber (32) to be directed onto the photodiode (20).

10. Apparatus according to claim 8, wherein the optical path comprises an optical coupling device and wherein the branching device (48, 50) comprises a secondary fiber (50) welded to the transport fiber (32) in a point of this latter which is positioned downstream of the optical coupling device.

11. Apparatus according to claim 8, wherein the transport fiber (32) is welded to an output fiber (54) of the laser source (10) and wherein the branching device (48, 50) comprises a secondary fiber (50) which is welded to the transport fiber (32) in the same point as the one where this latter is welded to the output fiber (54).

12. Apparatus according to claim 8, wherein the laser source (10) comprises a plurality of laser modules (10.1, 10.2, ..., 10.N) able to emit a laser beam independently of each other and a corresponding plurality of output fibers (54.1, 54.2, ..., 54.N) associated each to a respective laser module (10.1, 10.2, ..., 10.N), wherein the optical path comprises an optical combiner (56) to which the output fibers (54.1, 54.2, ..., 54.N) are connected on the input side and to which the transport fiber (32) is connected on the output side, and wherein the branching device (48, 50) comprises a secondary fiber (50) welded to the optical combiner (56).