PROJECT FINAL REPORT

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CLET

Closed Loop Control of the Laser Welding Process through the Measurement of Plasma

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Final publishable summary report

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1. Executive summary

Laser welding process is a technique widely used in industry. The interesting properties of the welded seams obtained and the possibility of automating the welding process has contributed to its diffusion among several kinds of industries. Laser welding has become a common technique in automotive, aeronautical and shipbuilding industries. It can be found both in large and small or medium enterprises (SME).

A problem that can affect laser welding is the presence of defects that can ruin product quality. Typical defects are holes, pores and lack of penetration. Defects have to be avoided not only to guarantee product quality, but also to reduce production costs. In CLET project research efforts to find methods for detecting flaws in laser welding have been made.

Among all the possible defect detection methods suitable for laser welding, CLET project has been focussed on plasma electron temperature. During laser welding plasma is formed and it can be characterised through the electron temperature. This temperature is an energy measure of the free electron that populates the plasma.

In CLET project it has been found out that there is a strong relationship between penetration depth and electron temperature. This relationship exists in CO_2 and continuous and pulsed Nd:YAG laser welding, although it is different for every kind of laser. Based on that relationship it has been possible to design a sensing system capable of measuring penetration depth in real time, in a non-destructive fashion and able to inspect whole production.

The penetration depth sensor is the basis of a closed loop controller able to guarantee penetration depth specifications. This controller adjusts laser power in such a way deviations from desired penetration depth is reduced to almost zero.

The controller has been tested in the SME workshops. It has been proved that it is able to keep penetration depth at desired level. Moreover, the sensing system is able to detect disturbances acting on the system and thus the controller is able to react and change the laser power to compensate the disturbances effects on final welded seam.

2. Project context and objectives

Laser welding is a technique that is getting more common. It is not only used in big factories, like in car manufacturing, but it can also be found in SME workshops. Laser welding have many metallurgical and production related advantages, but it can be also a source of headaches for people on charge of production.

One of the problems associated to laser welding is the presence of flaws in the welded seams. Although those are not at all frequent in fine-tuned facilities, poor material preparation, surfaces contaminants (Figure 1), system degradation and human error can lead to defect occurrence. Moreover, since many laser welding facilities are automated process, a cause of defect can be propagated from a seam to the next for one entire working day.

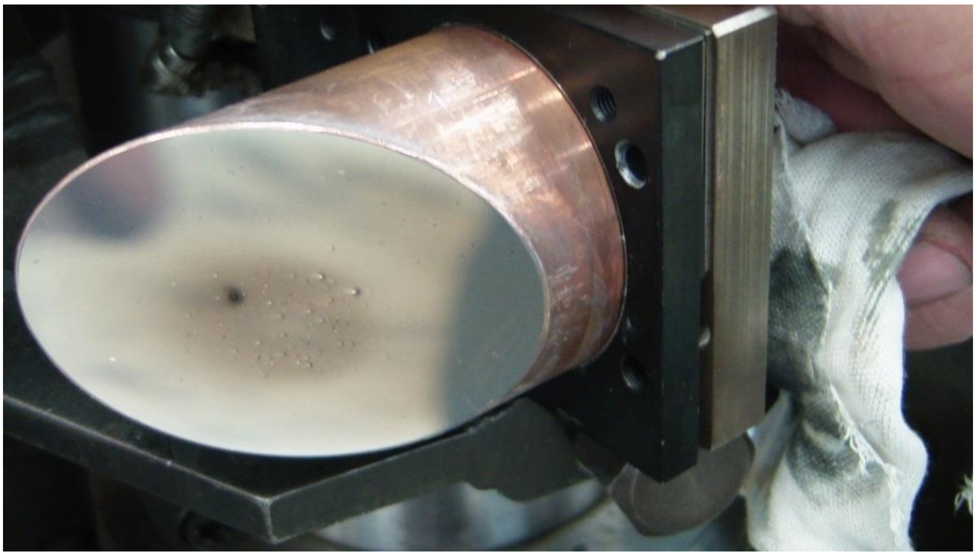


Figure 1: Dirt on mirror, a common flaw cause

For this reason, since laser welding started to be massively used there has been interest on inspection systems. This was not a new problem in industry, where quality control has been a major concern for decades. The first choice is destructive testing. The person on charge of inspection selects some items, break them and according to the quality found and statistical models she or he makes a statement about quality of the whole production.

But the problem with laser welding is that some defects looks like if they have a random behaviour, so on-line inspection systems are more suitable. There are many used in industry, like eddy currents or ultrasonic inspection. The problem with them is that the material to be inspected is very hot and its physical behaviour may be different to the one for which those techniques were designed. So, specific techniques for laser welding are required.

There have been many attempts to design on-line, non-destructive inspection techniques for laser welding. Early efforts focused on the process acoustic emission or electric potential, but they did not success in industrial environments. The best approaches are those based on the electromagnetic radiation emitted by the molten material or by the plasma that appears in laser welding. There are some commercially available products based on those radiations.

In the CLET project, the technique used has been monitoring the plasma electron temperature. The plasma that is formed in the welding process can be characterised by this magnitude, which indicates the energy of the free electrons that populate the plasma. To measure it, the radiation emitted by the plasma is registered by means of a spectrometer and processed by a computer. Changes in the electron temperature indicate changes in welded seam quality. This is an on-line and non-destructive technique. Since it inspects the point in which the laser hits the metal to be welded, it is also a real-time technique.

This technique allows designing a flaw detection system. But, why not to go beyond? Once we have a defect alarm, we want the laser adjust itself in order to avoid the defect. This can be accomplished by means of a closed-loop controller.

Closed-loop controllers are very old. They are used widely in any kind of device and process. Its duty is to maintain one or several system outputs close to the desired values. In our case the system output is its quality, for instance a desired penetration depth. To achieve this, closed-loop controllers manipulates the system inputs. In our case, system inputs are the laser power, the welding speed or any other process parameter. So, for instance, the controller will change in real time the laser power to maintain penetration depth at it desired value in spite of surface contamination, system degradation or human errors. To do this, the controller needs to know the electron temperature.

SME are at the core of the project. They face the same laser welding related problems than big companies but, sometimes, with fewer resources to deal with them. Moreover, in SME is easier to find the problem of short-run manufacturing. This implies constant changes of laser welding parameters to fulfil the new requirements. In this situation flaws can be more frequent than in log-run production.

The general objective of the project is to develop an automatic close loop laser welding control system and to test it at SME workshops. It is based on the measurement of the plasma plume optical emissions coming out from the keyhole area and is able to detect the main flaws that can occur. The controller changes the process parameters in order to avoid flaw propagation.

The specific objectives of the project are:

1. To develop a sensor system: A sensor set able to gather the radiation emitted during laser welding process in the infrared, ultraviolet and visible spectrum ranges and to detect welding defects in real time. The sensors must satisfy some conditions regarding sampling speed in order to be useful for control. The optical system to be designed will be based on a fast spectrometer. Mathematical algorithms for defect detection will be also developed and integrate in the sensor system
2. To develop a feedback controller: Once the sensor and defect detection system is available, the next objective is to develop a closed loop control system for laser welding. The system has to be robust enough for changes in equipment and material and it has to be operated in real industrial conditions as the ones present at the facilities of the SME partners. Moreover, it must be capable of rejecting perturbations. In case of deviations from the desired quality, it has to decide which changes to the process settings must be applied, e.g. by modifying the laser power and/or welding speed.
3. To validate the system: To prove the capability of the system it will be tested and validated in a first stage at a pilot level in laboratories of RTD and at an industrial level in real applications in SMEs in a second stage.

Taking into account that a wide number of applications, configurations, materials, thicknesses and other laser welding configurations are being used in the industry, this project is restricted to some materials and configurations:

- Continuous CO_2 and Nd:YAG laser welding.
- Pulsed Nd:YAG laser welding.
- Stainless steel, thickness ranging from 0.5 mm to 3 mm.

The project has been developed by a consortium of companies and research organizations whose synergic efforts lead to the project results. The consortium is composed by:

Organisation	*Country*
Fundación CARTIF	Spain
CNR-IFN UOS Bari	Italy
University of Twente	The Netherlands
Palacký University in Olomouc	Czech Republic
Josdan Soldadura y Ajuste, S.L.	Spain

Precitec KG	Germany
Vatrans Zlín v.o.s.	Czech Republic
Flexweld b.v.	The Netherlands

3. Main Scientific and Technical results

The main scientific and technical results can be divided into two major parts: the sensing system and the closed-loop controller.

3.1. The sensing system

3.1.1. Electron temperature

The sensing system is based on a miniature spectrometer. One of this and its main characteristics can be found in Table 1.

	
Dimensions	148.6 mm x 104.8 mm x 45.1 mm
Weight	570 grams
Detector range	200-1100 nm
Pixels	2048 (or 3648) pixels
Pixel size	14 (or 8) µm x 200 µm
Entrance aperture	Slits from 5 to 200 µm
Fiber optic connector	SMA
Grating	Several grating options
Wavelength range	Grating dependent
Optical resolution	~0.035-6.8 nm FWHM
Signal to noise ratio	250 : 1
Integration time	1 ms to 65 s
Data transfer speed	Full scans to memory every 1 ms with USB 2.0 port
Computer interfaces	USB 2.0 @ 480 Mbps; RS-232 (2-wire) @ 115.2 K baud

Table 1: Ocean Optics HR2000+ Spectrometer characteristics

Spectrometers allow registering the electromagnetic spectrum in the detection range. The spectrum we are interested in is the one associated to the radiation emitted by the plasma plume. Spectra associated to CO_2 and Nd:YAG laser welding can be seen in Figure 2.

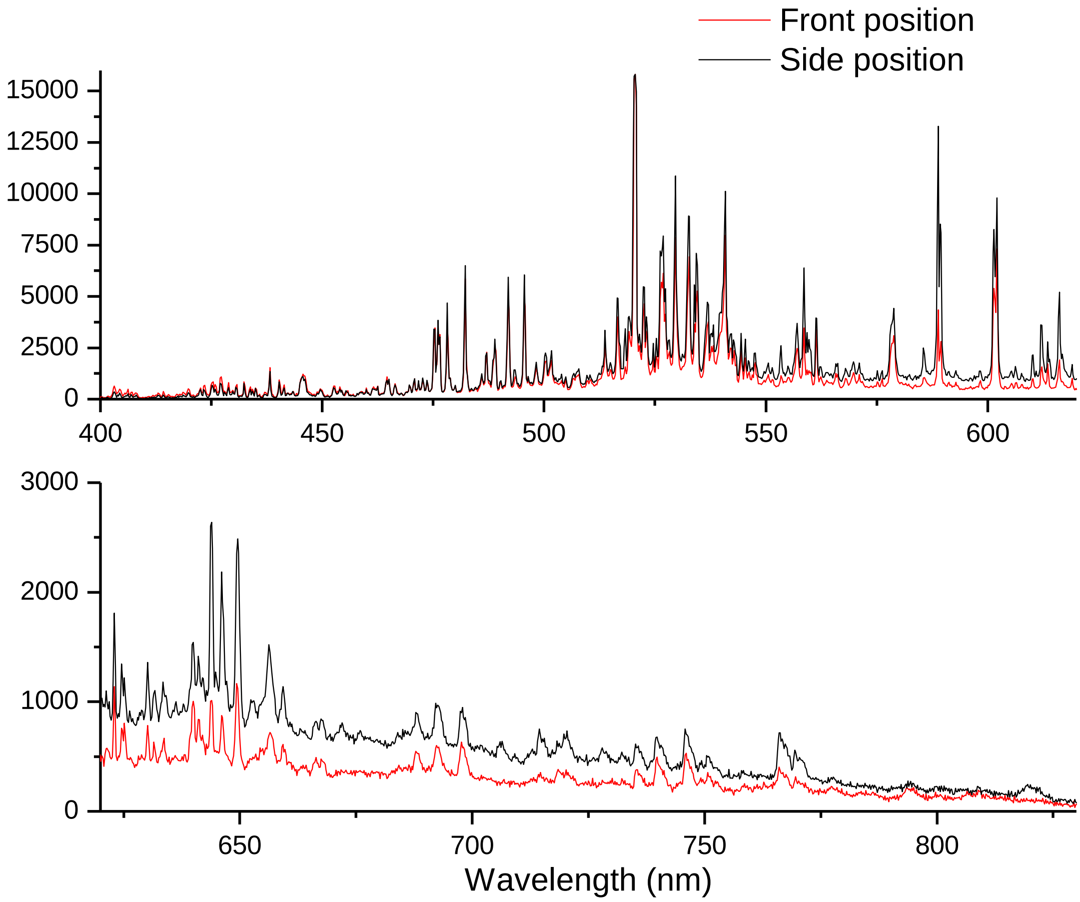


Figure 2: Optical spectra comparison for different optical fiber positions in Helium shielding gas; optical range: [400-835 nm] , integration time = 1ms

It can be seen the major difference among two kinds of spectra is Nd:YAG laser welding spectrum exhibits a bell-shaped background. But the features most important for us are the peaks both spectra have.

When an electron that is in an atom catches energy, it is said it moves to an upper energy level. It remains there until the source of energy that gave it energy is cancelled. Then, the electron moves back to its initial energy level and, in the process, it emits a photon which wavelength is related to the energy the electron losses. The lines observed in the spectrum are these electron transitions between different energy levels. Each line corresponds to one electron and energy level transition.

There is a database where all the lines identified along years of spectroscopical research are stored. It is maintained by the National Institute of Standards and Technology (NIST) of the United States. Thank to this database, it is possible to identify the lines, i.e. to determine which are the chemical species and energy transitions associated to every line in the spectrum. Many lines can be identified in spectra registered during laser welding. Since the material tested is AISI 304, a variety of stainless steel alloy, most lines belongs to Iron, Chromium and Manganese. A selection of them can be seen on Table 2.

Experimental wavelength (nm)	**Ion**	**Observed wavelength (nm)**	**A_{ki} (s^{-1})**	**E_k (cm^{-1})**	**g_k**
457.96	Cr I	458.006	2.40E+06	29420.90	3
459.54	Cr I	459.559	4.70E+07	55516.69	13
478.90	Cr I	478.932	1.14E+07	41393.47	11
495.44	Cr I	495.481	1.20E+07	45354.18	11
513.37	Fe I	513.3690	2.70E+07	53169.170	13
516.67	Fe I	516.7407	2.00E+06	31322.611	7
517.09	Fe I	517.1595	4.46E+05	31307.243	9
523.28	Fe I	523.2339	1.40E+07	42815.858	11
441.96	Mn I	441.978	2.10E+07	60739.42	8
447.27	Mn I	447.279	4.35E+07	46169.93	2
470.98	Mn I	470.972	1.72E+07	44523.45	8

Table 2: Selection of lines identified in spectra registered during laser welding using NIST database

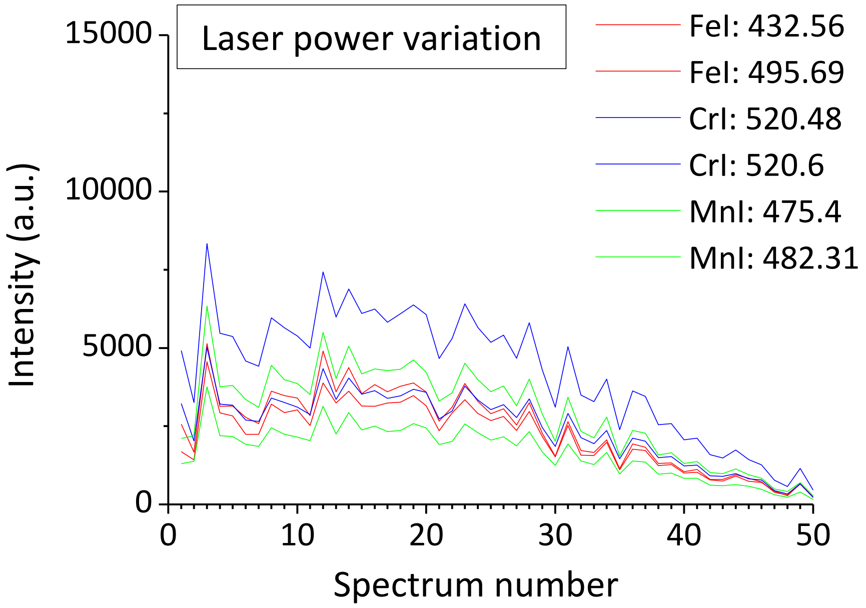


Figure 3: Line intensity signals acquired during a laser welding process performed in Ar atmosphere with increasing laser power (from POPT-10%=1.5 kW to POPT+10%=1,9 kW).

The intensity of the lines, which are related to the peaks height, together with their wavelengths is what we are interested in. Wavelength does not change and is always the same for each line. However, the intensity changes continuously. In Figure 3 the intensity changes along a laser welded seam can be seen.

The intensities, the wavelengths and other associated parameters that area in Table 2 allow us to compute the electron temperature through the so called Boltzmann-plot method. This technique can only be used when some conditions are fulfilled. Those are that the lines used must be free of self-absorption and that the system must in local thermal equilibrium. In Figure 4 the electron temperature for optimal CO_2 laser welding with Helium shielding is show. The same result is obtained in both pulsed and continuous Nd:YAG welding, although the mean value is different.

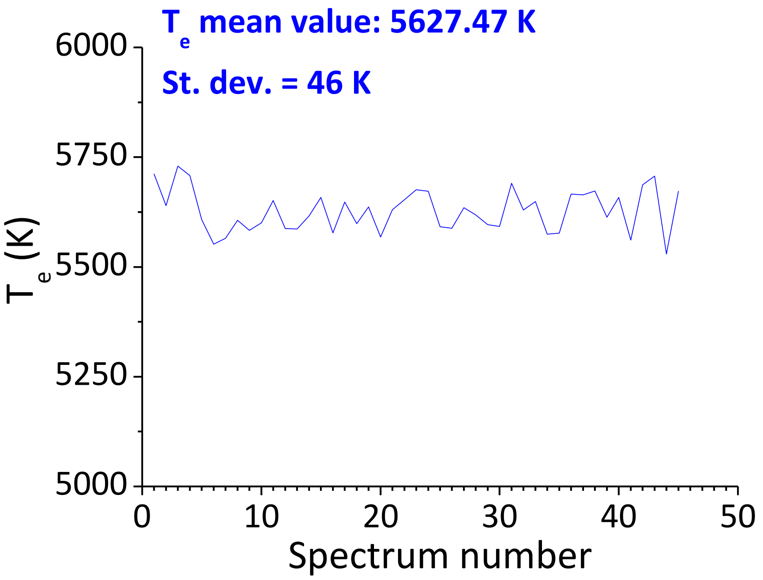


Figure 4: Electron temperature behaviour for optimal welding conditions under He shielding.

3.1.2. Defect detection methodology

The defect detection methodology developed in the CLET project has four steps, which are described in Figure 5 and are summarized below.

Step 1: Data acquisition

There are two data sources: a spectrometer and a photodiode. These two sources are complementary and the defect detection system can be configured with only one of them, although the detection capabilities of the system would be reduced. The data source which can provide more information is the spectrometer and it is considered the basic sensor. Moreover, is the sensor that will be used by the controller.

Step 2: Spectral line selection

The second step in the defect detection methodology is the spectral line selection. This step can only be applied to the data generated by the spectrometer.

During Work Package 2, a set of spectral lines suitable for electronic temperature calculation both in CO_2 and Nd:YAG laser, were identified. This step consists on processing the spectra in order to extract the intensities associated to the wavelengths selected for electronic temperature computation.

Step 3: Signal processing

The processing of the spectral lines intensities and the photodiode signal are the third methodology step.

1. Argon spectral line emission. This method can be used only on CO_2 laser welding processes when the shielding gas is Argon. The data source must be the spectrometer.
2. Electron temperature. Also in this case the data source must be the spectrometer. The method has can be used both in CO_2 and Nd:YAG laser welding processes with any kind of shielding gas.
3. Spectral lines correlation analysis. The data source must be the spectrometer. It can be used in any laser welding process with any shielding gas.
4. Wavelet transform. In this case the data source is the photodiode. This method can be used to any kind of laser welding process.

Step 4: Alarm generation

The alarm generation has two operating modes: a self-learning mode and a real time monitoring one. The self-learning mode aims to calibrate the sensor to the specific welding process that has to be monitored. During the self-learning procedure a reasonable number (set by the operator) of sound-welds are performed and acquired. Based on these preliminary acquisitions a reference temperature signal is computed by the software and saved in a database. If a weld flaw occurred during the sensor calibration it is possible to exclude the related temperature acquisition from the reference signal calculation. The monitoring mode consists on comparing the electron temperature of the welding process under examination to the previously recorded reference baseline and an upper and lower adjustable error thresholds. Those thresholds are defined by the operator, according to the desired sensitivity of the monitoring system, by adding or subtracting an adjustable fraction of the average standard deviation of the calibration signals. If the acquired temperature signal shows and excursion out of the threshold limits an alarm is declared.

One of the main advantages of using this two-step (learning and monitoring) approach derives from the fact that most of the sensors developed by Precitec work in the same way, so that the results of the project could be immediately transferred to the this RTD performer, who is in charge of the dissemination and validation activity.

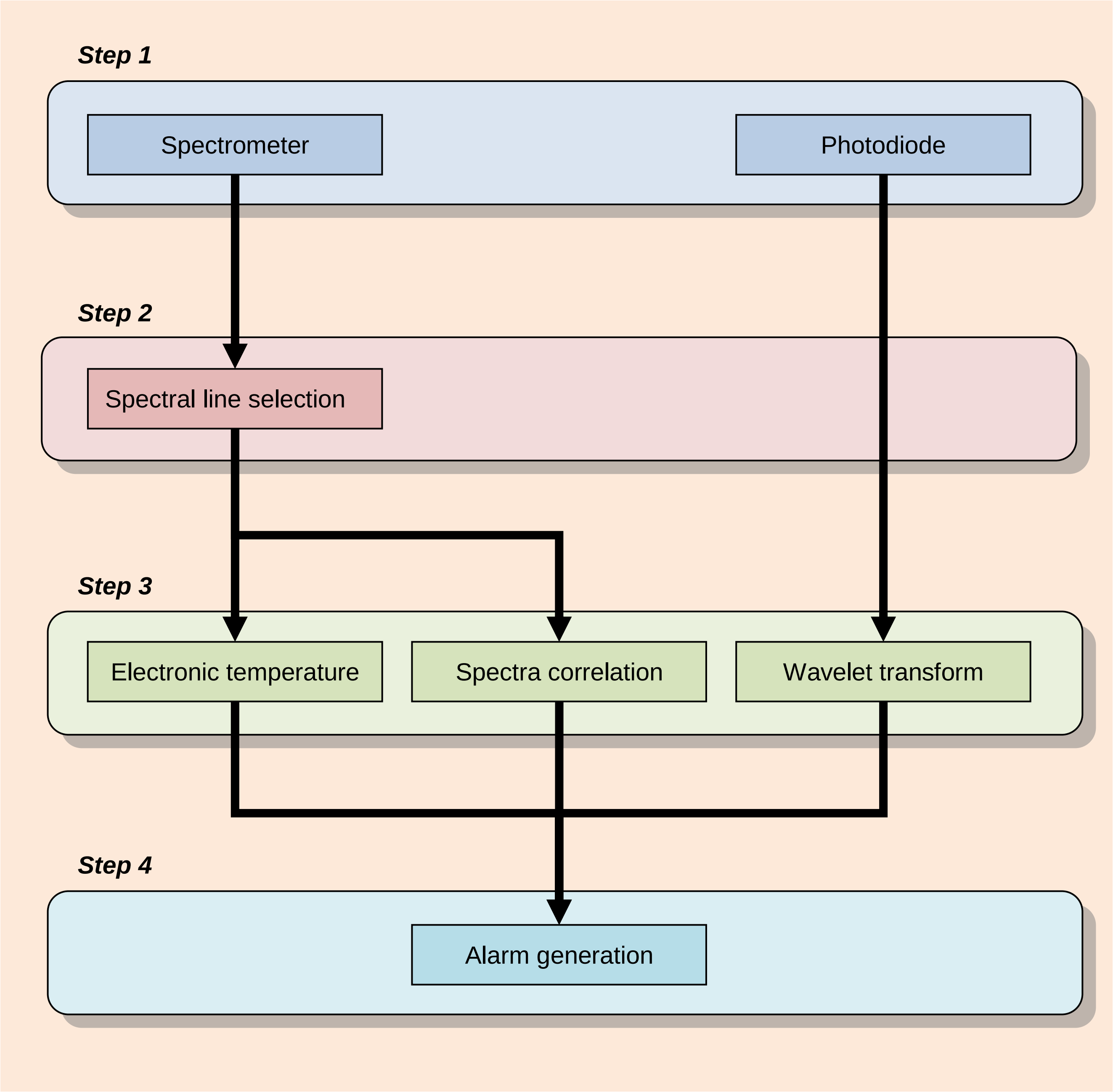


Figure 5: Defect detection methodology

3.1.3. Defect detection system prototype

The objective of this task was to implement all the algorithms developed in the previous activities into software. The software should include an interface able to introduce the parameters and settings specific for each kind of welding process to be monitored and it should also be able to identify the weld flaws.

Figure 6 reports a picture of the light collection system installed on the welding head of the laser facility at the CNR-IFN in Bari. Here, two collimators are fixed on the focusing head looking at the plasma plume by the front and the side with respect to the welding direction. From the experimental results we have seen that the position of the collimator has negligible influence on the morphology of the acquired spectra. Therefore the two collimators can be used indifferently and in case more than one detector (spectrometers or photodiodes) wants to be used, both collimators can be employed at the same time. Fine adjustments screws allow optimizing the collimators alignment in order to improve the light collection. This is a crucial point because as far as the plasma plume light emission is collected more efficiently, the acquisition time of the spectrometer can be reduced without losing too much information from the less intense part of the spectrum. A shorter exposure time enhances the acquisition rate of our devices making the system more reactive to process variations and suitable for an effective closed loop control. Two optic fibers are connected to the collimators, bringing the collected light to the detectors. The choice of these components is subordinated to the size and geometry of the welding installation where the light collecting system has to be embedded. In this case we used fused silica fiber with the highest optical transmittance in the VIS-UV spectral range, core size of 50 μm and a length of 2 m. The distance of the collimators from the working area is sufficient to prevent darkening or damaging of their optics caused by weld spatters or dirt, fume or moisture.

The optic fibers transmit the collected plasma plume optical emission to the entrance slit of one or more detectors. In case of Figure 7 two different spectrometers have been plugged into the optic fibers. The first spectrometer is the core of the sensor system, while the second spectrometer is optional and can be used in specific applications where a wider spectral range of the plasma plume optical emission needs to be investigated. As an alternative configuration, a fast Si PIN photodiode can be connected to the second optic fiber. The second detector is in any case an accessory device which can be added to the system in order to increase its defect sensibility. According to the application and the welding procedure the sensor system can be suitably customized.

In Table 3 the characteristics of the spectrometer that we have used in the sensor prototype are presented. Table 4 summarizes the specifications of the second spectrometer that have been added as an option that might be evaluated according to the process conditions.

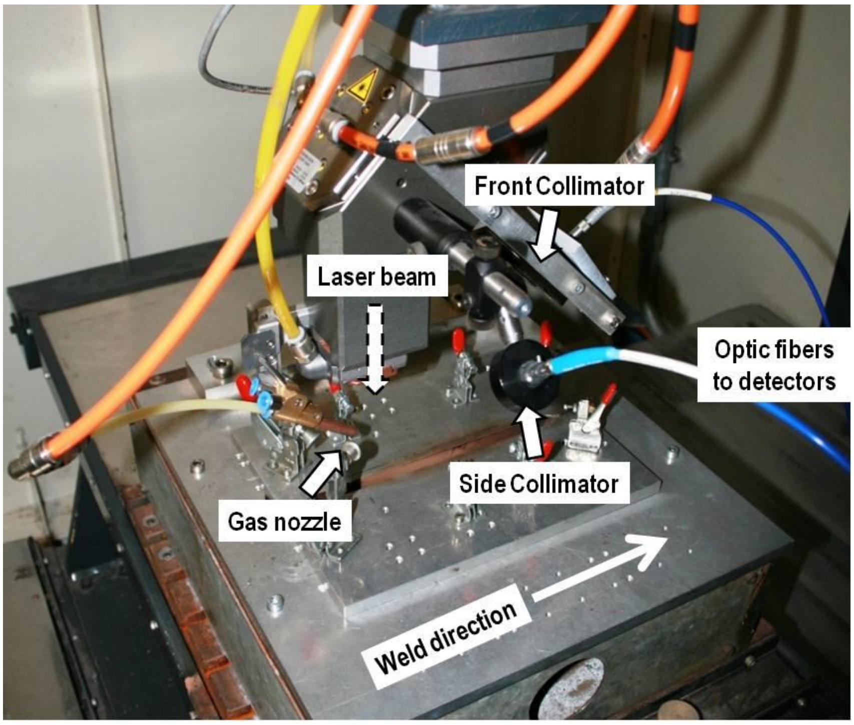


Figure 6: Welding head and light collecting system of the sensor prototype

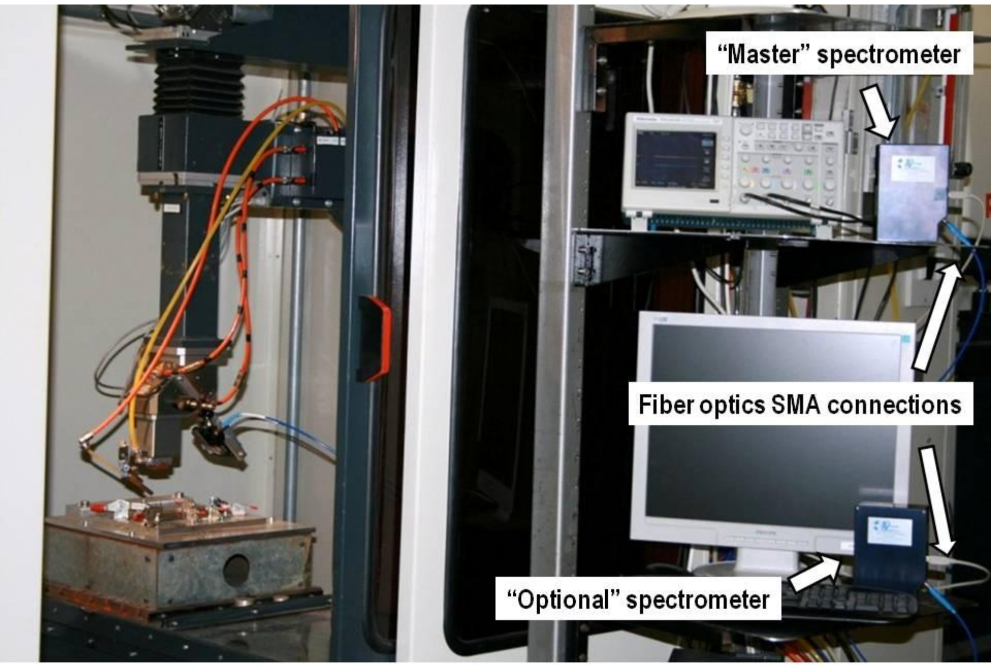


Figure 7: Spectrometers in the sensor prototype

Model	Ocean Optics HR2000+
Diffraction grating	1800 m^{-1} holographic UV
Wavelength range (nm)	400 – 525
Resolution FWHM (nm)	0.12
Detector	CCD array 2048 pixels
Entrance slit	10 μm
Fastest acquisition rate (KHz)	1
Minimum Integration time (ms)	1
Fiber optic connector type	SMA to 0.22 NA fiber
Data transfer protocol	USB 2.0
Options	Longpass order-sorting filter

Table 3: “Master” spectrometer specifications

Model	Ocean Optics HR2000+
Diffraction grating	600 m^{-1} blazed at 500 nm
Wavelength range (nm)	400 – 837
Resolution FWHM (nm)	0.32
Detector	CCD array 2048 pixels
Entrance slit	5 μm
Fastest acquisition rate (KHz)	1
Minimum Integration time (ms)	1
Fiber optic connector type	SMA to 0.22 NA fiber
Data transfer protocol	USB 2.0
Options	Longpass order-sorting filter

Table 4: “Optional” spectrometer specifications

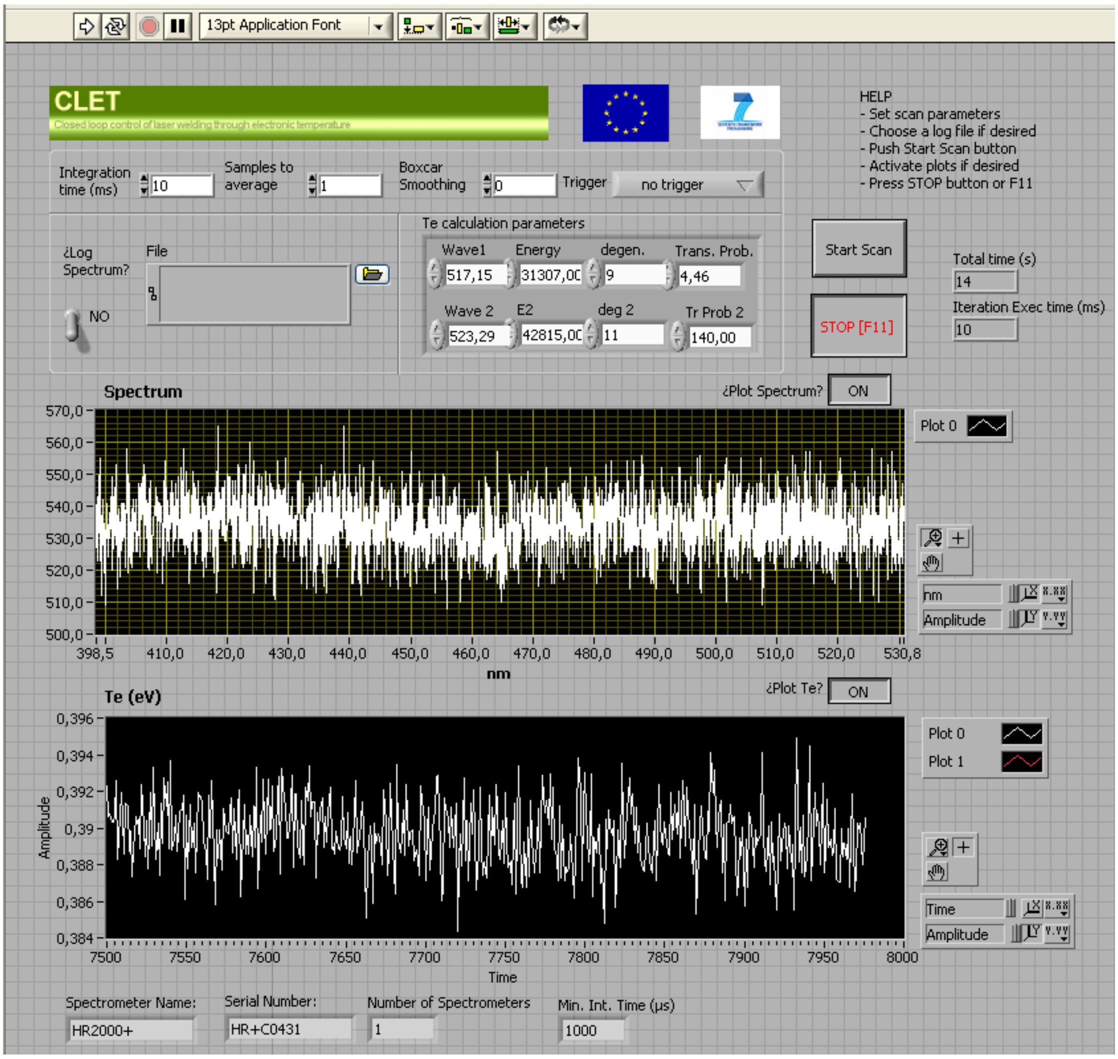
The miniature spectrometers are connected to a computer through a USB 2.0 port, while the signal from the photodiode is firstly amplified and then acquired through a data acquisition board. The sampling rate is of a few tens of microseconds.

The fastest acquisition rate of the spectrometers is 1 kHz. This means that a full plasma spectrum can be acquired and stored into the PC memory every 1 ms. If a proper alignment of the collimators is carried out, such a short integration time is enough to acquire an optical plasma spectrum with a good signal-to-noise ratio. In this way, the fastest acquisition rate of the device is exploited for our application.

The LabView programming environment has been used for the data analysis and visualization. It takes only 1 or 2 ms to transfer the data of each spectrum from the spectrometer to the PC, analyze and store it. For example, considering an integration time of 1 ms we have measured that the LabView code takes 2 or 3 ms to compute and visualize the plasma electron temperature starting from each spectrum. Such a time resolution should be enough to develop the control system.

In the following we describe the LabView program of the sensor. Even if such a program is able to manage at the same time signals coming from more than one device, for the sake of clarity we will show an application with a single spectrometer. Nonetheless it must be taken into account that the data processing rate is slower if more than one signal coming from different devices is desired to be analysed.

The architecture of the software has been designed and developed by the research groups of CARTIF and CNR-IFN. It has been planned to be sufficiently customizable for each welding application and industrial environment. At first only the electron temperature algorithm has been implemented into the LabView code. The layout of the software front panel is shown in Figure 8.



CLET
Closed loop control of laser welding through electronic temperature

HELP
- Set scan parameters
- Choose a log file if desired
- Push Start Scan button
- Activate plots if desired
- Press STOP button or F11

Integration time (ms): 10
Samples to average: 1
Boxcar Smoothing: 0
Trigger: no trigger
¿Log Spectrum? NO
File

Te calculation parameters

Wave1	Energy	degen.	Trans. Prob.
517,15	31307,0	9	4,46
Wave 2	**E2**	**deg 2**	**Tr Prob 2**
523,29	42815,0	11	140,00

Total time (s): 14
Iteration Exec time (ms): 10
¿Plot Spectrum? ON
¿Plot Te? ON
Spectrometer Name: HR2000+
Serial Number: HR+C0431
Number of Spectrometers: 1
Min. Int. Time (µs): 1000

Figure 8: Front panel of the sensor software implementing the electron temperature algorithm

When the spectrometer is plugged in, the software automatically recognizes and visualizes the spectrometer name and serial number. The graphical interface allows the welding operator to introduce the scan parameters (Integration time, samples to average, eventually the external trigger) and all the spectral parameters (wavelength, energy of the transition levels, transition probability, degeneracy of the levels) of the single couple of lines selected for the electron temperature signal calculation. A log file can be defined before the acquisition to save the data in a text format. Now the system is ready to start the acquisition once the “start scan” button is pushed. To visualize the data while the system is running, the “activate plots” button must be selected. Two different spectral data types are acquired, processed and stored: the full sequence of all the plasma optical spectra and the electron temperature signal. Once the “stop” button is pressed the acquisition stops. The total time elapsed from the start can be visualized together with the iteration execution time. The last one is an important information to check if the system is running correctly, without any time jitter if compared to the spectrometer integration time. The system is now ready for a new acquisition.

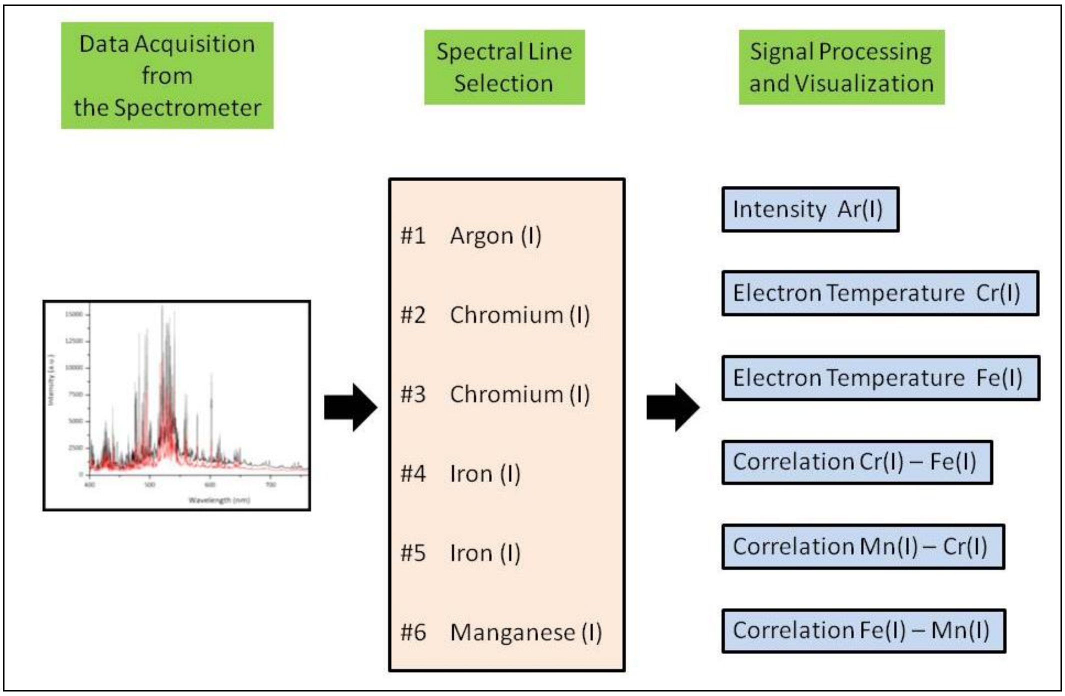
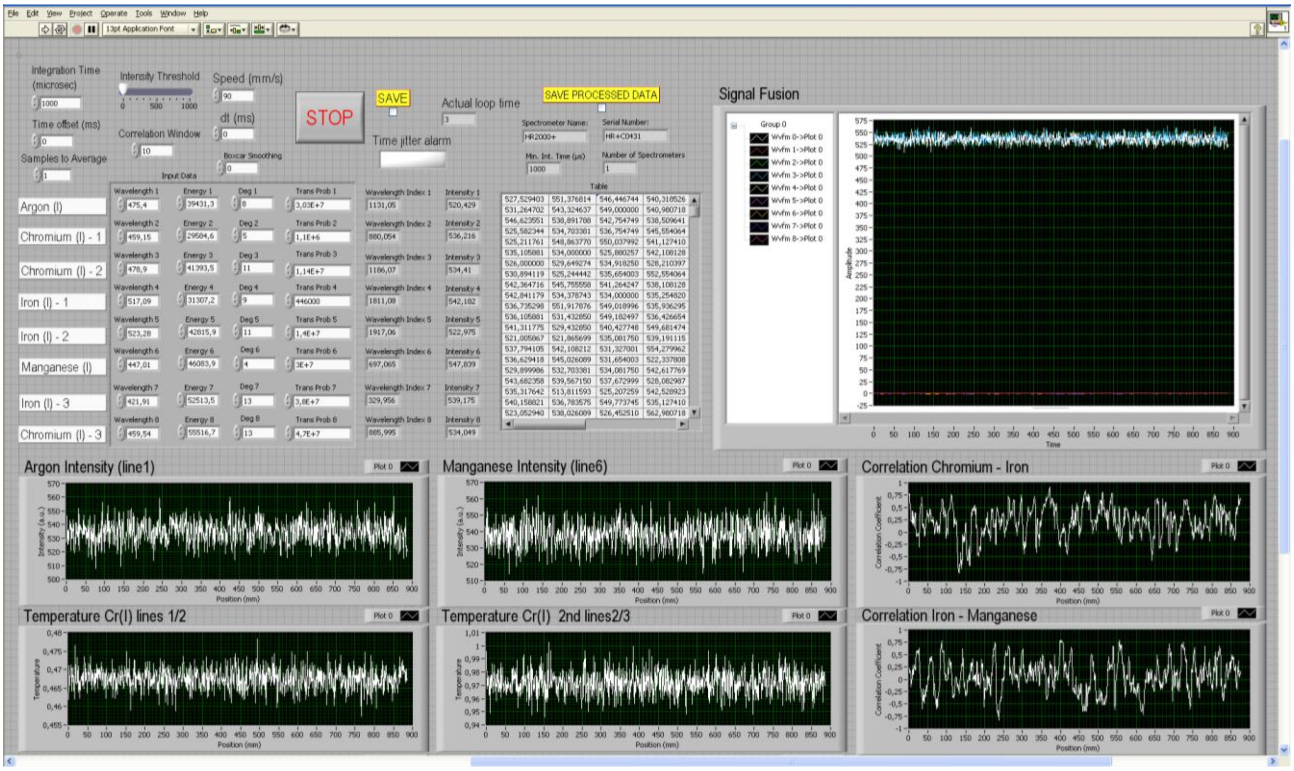


Figure 9: Implementation scheme of the spectral signal fusion

A further more complex version of the software has been also developed along the scheme illustrated in Figure 9. Here, up to eight spectral lines belonging to the chemical species composing the shielding gas or the metal alloy can be selected and their parameters introduced into the interface. Then, during the acquisition mode, the software provides to simply extract and visualize the line intensity evolution or to calculate the electron temperature of each chemical species or even the correlation among different species and lines.

The front panel layout of this code is shown in Figure 10. The aim of this software version is to have a more flexible code to study and analyze the spectral signals. Besides the scan and the spectral parameters it is also possible to enter the average welding speed in order to visualize the electron temperature signal directly as a function of the position on the welded joint so that a potential defect and its extension can be immediately located onto the welding sample. Once the acquisition is started, the software automatically begins to store data only when the light coming from the working area exceeds a certain threshold, set by the operator, indicating the ignition of the process. Each spectral signal can be saved after the acquisition. It is possible to visualize all the signals in the same “signal fusion” graph and eventually deselect the less significant ones.

The prototype presented is suitable for any laser type. However, experiments carried out show that a simplified version is also suitable to achieve project objectives. The simplified version has only one spectrometer and no photodiodes. The defect detection algorithm is the same than in the previous case and it is implemented in the same way. As before, radiation is collected by means of the same kind of collimator and lead to the spectrometer by the same type of optic fiber. The differences between both prototypes can be found in Table 5.



Integration Time (microsec) 1000

Time offset (ms) 0

Samples to Average 1

Correlation Window 10

Speed (mm/s) 90

dt (ms) 0

Boxcar Smoothing 0

Actual loop time 3

Spectrometer Name: HR2000+

Serial Number: HR+C0431

Min. Int. Time (µs) 1000

Number of Spectrometers 1

	Wavelength	Energy	Deg	Trans Prob	Wavelength Index	Intensity
Argon (I)	475,4	39431,3	8	3,03E+7	1131,05	520,429
Chromium (I) - 1	459,15	29584,6	5	1,1E+6	880,054	536,216
Chromium (I) - 2	478,9	41393,5	11	1,14E+7	1186,07	534,41
Iron (I) - 1	517,09	31307,2	9	446000	1811,08	542,182
Iron (I) - 2	523,28	42815,9	11	1,4E+7	1917,06	522,975
Manganese (I)	447,01	46083,9	4	3E+7	697,065	547,839
Iron (I) - 3	421,91	52513,5	13	3,8E+7	329,956	539,175
Chromium (I) - 3	459,54	55516,7	13	4,7E+7	885,995	534,049

Table

527,529403	551,376814	546,446744	540,318526
531,264702	543,324637	549,000000	540,980718
546,623551	538,891788	542,754749	538,509641
525,582344	534,703381	536,754749	545,554064
525,211761	548,863770	550,037992	541,127410
535,105881	534,000000	525,880257	542,108128
526,000000	529,649274	534,918250	528,210397
530,894119	525,244442	535,654003	552,554064
542,364716	545,755558	541,264247	538,108128
542,841179	534,378743	534,000000	535,254820
536,735298	551,917876	549,018996	535,936295
536,105881	531,432850	549,182497	536,426654
541,311775	529,432850	540,427748	549,681474
521,005867	521,865699	535,081750	539,191115
537,794105	542,108212	531,327001	554,279962
536,629418	545,026089	531,654003	522,337808
529,899986	532,703381	534,081750	542,617769
543,682358	539,567150	537,672999	528,082987
535,317642	513,811593	525,207259	542,528923
540,158821	536,783575	549,773745	535,127410
523,052940	538,026089	526,452510	562,980718

Figure 10: Software front panel of the implementation scheme

Element	*Prototype*	*Simplified prototype*
Spectrometer “Master”	**X**	**X**
Spectrometer “Optional”	**X**	
Photodiode + amplifier	**X**	
Collimator 1 + optic fiber	**X**	**X**
Collimator 2 + optic fiber	**X**	
Defect detection algorithm	**X**	**X**

Table 5: Prototype and simplified prototype comparison

3.1.4. Defect detection system capabilities

The system is able to detect:

1. Lack of shielding gas.
2. Lack of penetration.

It is capable of detecting these defects on CO_2 laser welding and on continuous and pulsed Nd:YAG laser welding.

Moreover, the system provides a precise estimation of the penetration depth measured in millimetres, so it can be used directly by a human operator. This capability provides the operator with a true penetration depth sensor able to measure in real time and in a non-destructive fashion.

3.2. Closed-loop controller

The objective is to present a controller design. Several approaches can be distinguished. The stationary behaviour of the process can be captured in fuzzy control rules like: “If the sensor responses are like A, then the most appropriate adjustment of process is B”. Knowledge of the dynamic behaviour will be applied to determine optimal settings of dynamic parameters of the feedback controllers like the rate with which process setting have to be modified. Standard controllers like PI or PID controllers can quite often perform this task adequately.

The presented controller design must offer a platform to implement this variety of control actions. Furthermore, the controller must be suited for the lasers used in this project, i.e. both for CO_2 and Nd:YAG laser welding.

For the implementation of the software for the analysis of the spectral data and the real-time control algorithm, a number of platforms are available. The selection is limited by the need to offer the USB interface to the spectrometer. Some platforms for real-time control don’t support USB.

The LabVIEW® environment that has been used so far in the CLET project offers the connectivity to the Ocean Optics spectrometer via the OmniDriver integration pack. Utilizing this connectivity of the Ocean Optics spectrometer to the LabVIEW®, it is possible to have access to an almost limitless world of interfacing possibilities supported by LabVIEW® environment. This includes various solutions to implement the controller e.g. making use of standard modules for standard controller or direct implementation of more dedicated algorithms.

To achieve deterministic, real-time performance for data acquisition and control systems with LabVIEW, the LabVIEW Real-Time Module and RT Series hardware must be used. Making the software developed in this project so far suited for this platform is not straightforward. It uses a “standard” LabVIEW environment, which doesn’t offer hard real-time performance. Running on Microsoft Windows the execution time is not guaranteed and hence may vary. If measures are taken that the operation of the software is not hampered by other tasks, it is expected that the acquisition time remains small for almost all measurement samples. For validation of the controller this performance is acceptable, provided the controller software takes the inherent variations of the acquisition time into account.

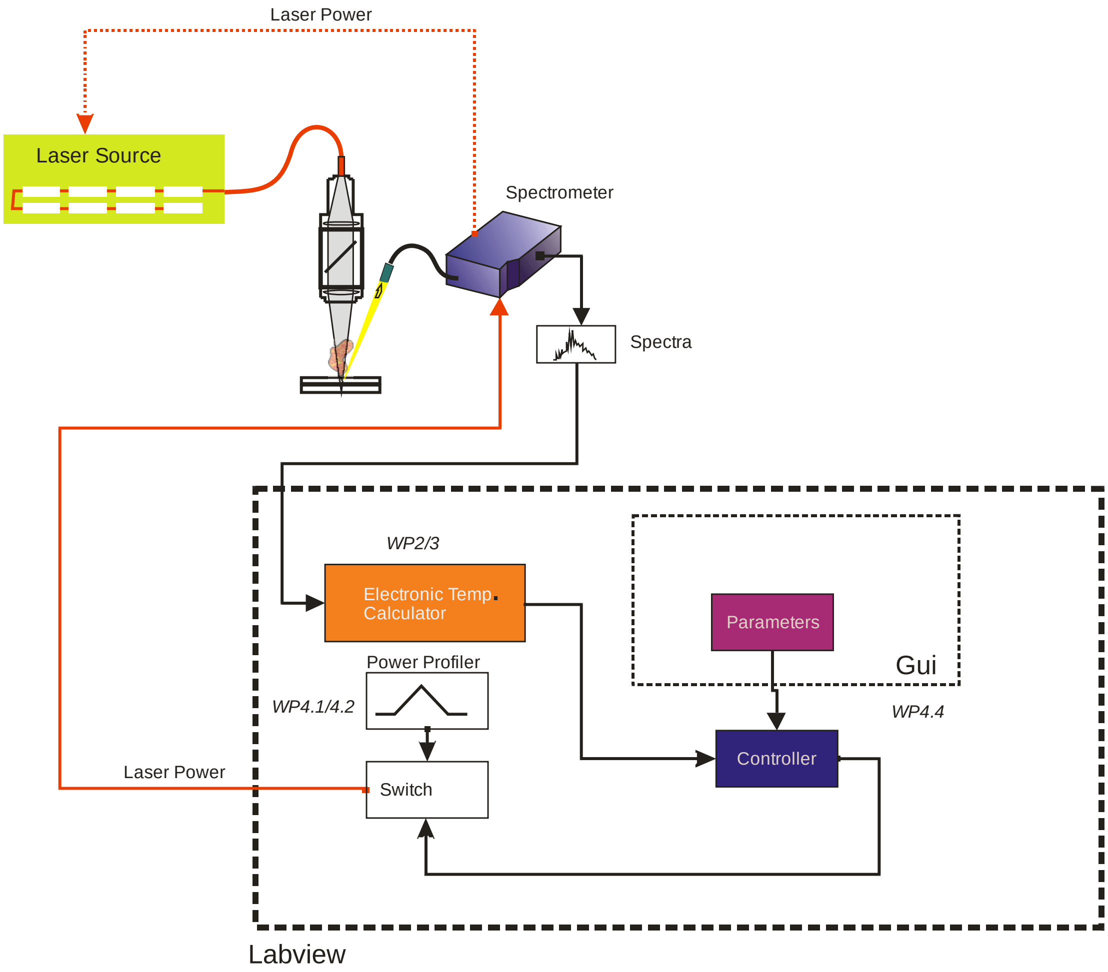


Figure 11: Block diagram of the CLET controller using HR2000+ Spectrometer

Figure 11 gives an overview of the controller and its connections to the equipment. The controller initially acquires the spectra from the spectrometer. The corresponding intensities of selected wavelengths are then used to calculate the electron temperature. The electronic temperature calculator block yields the calculated electron temperature from the acquired intensity values. The temperature signal is used by the controller to stabilize the penetration depth. Changing parameters like shielding gas flow or alignment of the collimator could affect the controller parameters. For that reason a switch makes it possible to input a characterisation profile.

For quality assurance like penetration depth control the controller can adjust the power level to attain the desired level of penetration. As an example the required penetration depth d is controlled for which several kinds of controllers can be used like PID or fuzzy logic control. The electron temperature T_e is a measure of the penetration depth. The actual electron temperature is compared to a reference value $T_{e,ref}$ that is set in agreement with the process settings and desired penetration depth d. This difference is the input for the controller that outputs the laser power P to the plant. The required parameters are summarized in the parameters main block. The complete controller software is designed and tested in the Labview® environment.

A PI (Proportional-Integral) controller is employed to control the penetration depth for different weld conditions for Nd:YAG and CO_2 laser welding.

Based on the characteristics of electron temperature vs. penetration depth relation the control operation is best handled by a PI type controller. The process does not require the derivative action to be in control as the high noise would make the control difficult. The noise in the process needed to be suppressed by the controller. The PI controller is also chosen to filter the signal and on the other hand to control welding process.

Like the P-only controller, the Proportional-Integral (PI) algorithm computes and transmits a controller output (CO) signal every sample time, T, to the final control element (e.g., laser power, welding speed). The computed CO from the PI algorithm is influenced by the controller tuning parameters and the controller error, $\Delta T_e(t)$.

PI controllers have two tuning parameters to adjust which makes them more challenging to tune than a P-Only controller.

Integral action enables PI controllers to eliminate offset, a major weakness of a P-only controller. Thus, PI controllers provide a balance of complexity and capability that makes them a widely used algorithm in process control applications.

The task objective is to test the controller capacities under laboratory conditions. Experiments in both continuous Nd:YAG and CO_2 laser have been carried out.

An experiment performed with a CO_2 laser can be seen in Figure 12. The objective of this experiment is to achieve and maintain full penetration. In the picture at the top it can be seen that the power is out of control up to position 47 mm. It has a constant value and full penetration is not reached, as can be seen in the picture at the bottom, where the side opposite to the one the laser hits is shown. At position 47 the CLET controller starts to command the power and as a result of this the laser power is increased around 500 W. This can be seen in the second picture from the top, where the blue line is the effective power reaching the sheet. As a consequence of this, full penetration is achieved.

In the case of continuous Nd:YAG laser welding the experiment consists of keeping a constant penetration depth equal to the top metal sheet thickness. It is show as a dashed pink line. It can be seen how after a short stabilisation time (500 ms), the penetration depth is around the desired value.

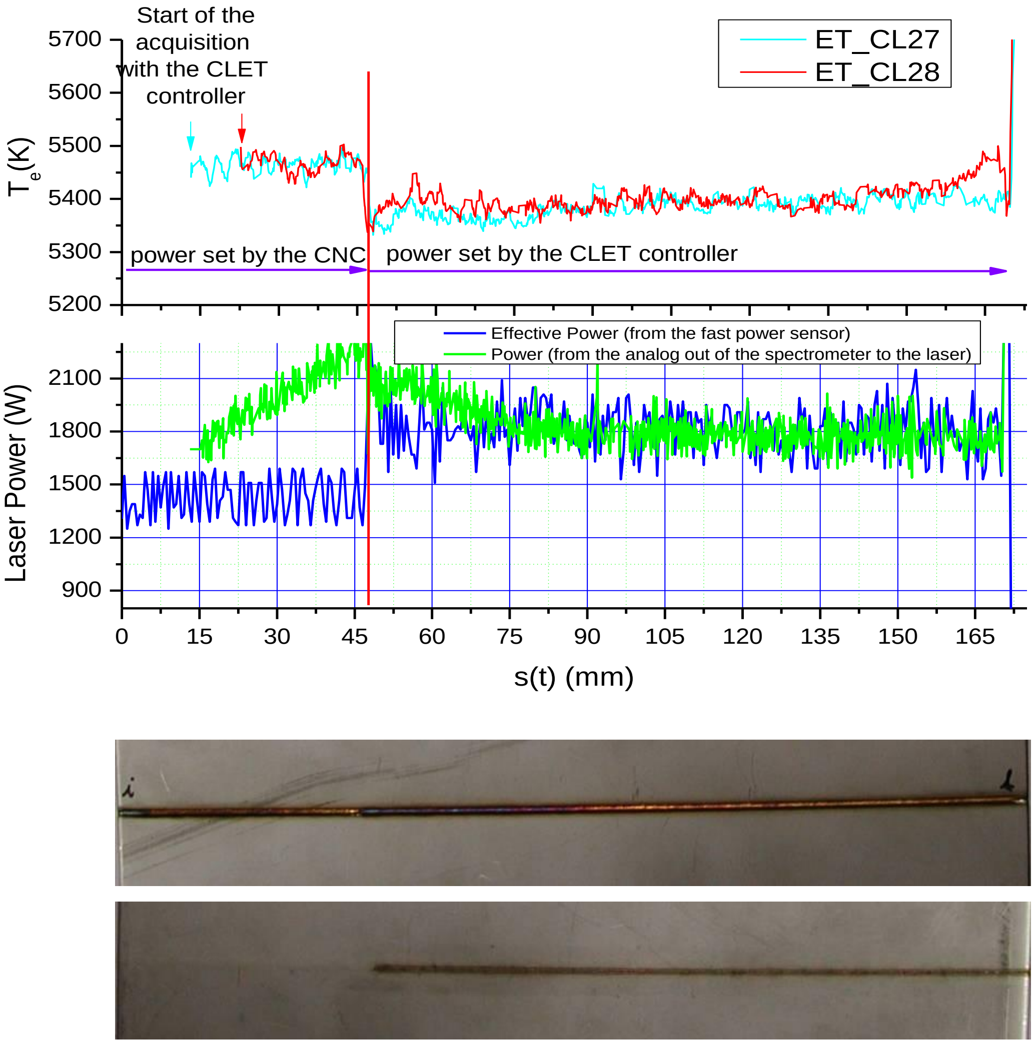


Figure 12: Fe(I) electron temperature signal behaviour calculated by using the closed loop control algorithm with 421.91-517.09 couple of emission lines, in Ar atmosphere. Controller parameters: Te_set_point = 5400K corresponding to a Pset_point = 1700W; kp = -2; Ti = 150. Initial power = 1360W (Pset_point -20%)

3.3. System testing at SME workshops

The objective is to install system in SMEs workshops both for CO_2 and Nd:YAG laser system.

Josdan S.L. operates two Alpha Laser ALM 200 pulsed Nd:YAG laser. These devices are portable and manually operated and are not intended to be integrated in an automated manufacturing process. For this reason, the machines are not equipped with external ports able to receive power commands from an external device.

Josdan S.L. personnel have been in contact with Alpha Laser Spanish brand and also with the German headquarters in order to check the possibility of externally commanding the laser power. They have found out that it is not possible to operate their laser machines in this way. For this reason it is not possible to implement the CLET controller in the Josdan laser machines.

The Flexweld BV robotic welding installation can be seen in Figure 13 and Figure 14. It consists of a laser source TRUMPF HL 2206D (flash lamp pumped continual Nd:YAG laser), with optical fibre output to guide laser beam to the laser processing head Trumpf BEO 7000210p with CCD camera for weld line tracking and cross hair generator. Relative motion of laser head and work piece is realized by 6 axis robotic system Motoman Hp 20 and 3 axis manipulator RWV2-250. The manipulator has two rotating tables for manipulating the work pieces during the welding process and the 3rd axis for loading and unloading work pieces outside the production cell. Argon N46 is used as shielding gas

Figure 13: Laser welding installation in Flexweld b.v.

The laser beam is focused on the stainless steel work-piece by 200 mm focal length. The focal position is aligned to the keyhole and on the top of the material surface. The fibre had a core diameter of 600 µm. The process light is collected with the quartz collimator which has a 200 mm focal length too and it is coupled to an Ocean Optics spectrometer. Nd:YAG filter with a cut-off frequency of 900 nm is used to filter the 1064 nm wavelength laser radiation. The collected light was transmitted by a 400 μm core-diameter optical fibre. The signals were analysed with the spectrometer. The welding trials were performed on 1+2 mm thick plates of AISI304 stainless steel on overlapped configuration.

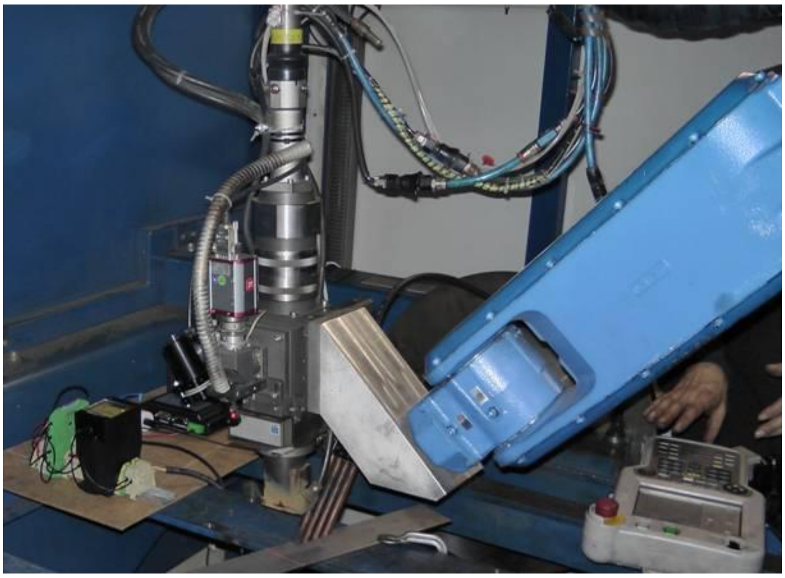


Figure 14: Experimental setup in Flexweld

Continual CO_2 laser is used in SME Vatrans v.o.s, Czech Republic as a tool for longitudinal pipe welding. Laser processing head is fixed in optimal position against moving semi product – collecting metal strip, configured for butt joint in deep penetration – keyhole welding. Laser power is set up manually by adjusting knob, independent on transport line velocity. Mixture of helium and nitrogen is used as a shielding gas.

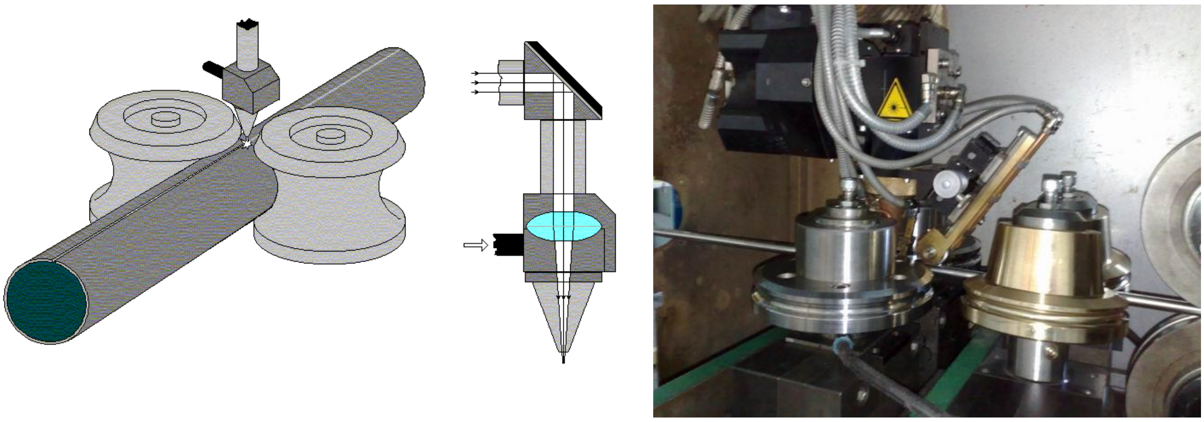


Figure 15: Welding configuration in Vatrans

Commercial manufactured Profile Welding System (PWS) offered by ROFIN consist of high power continual CO_2 laser DC 050 and a complete beam guiding system with an integrated process sensor system (Figure 15). The system detects and tracks seam gaps for safe and reliable laser welding of tubes and profiles. Precision linear actuator positions the laser beam within a few μm of the seam gap while achieving welding speeds of up to 6 m/min.

Because of different voltage scaling on spectrometer output and laser source input, opto-coupler was constructed to change voltage 0 – 5 V from spectrometer to 0 – 10 V range.

Several experiments were carried out at Vatrans facilities in order to test the controller capabilities. Due to the fact that penetration depth is constant in pipe manufacturing, the main challenge the controller faced was disturbance rejection.

Two kinds of disturbances can affect the process at Vatrans facilities: Mirror reflectivity degradation due to contamination on its surface and pressure changes in the disk that assures correct alignment.

Surface degradation is a common problem in CO_2 lasers and preventive maintenance actions are carried out to ensure correct operation. These actions usually consist on cleaning the surface every time certain amount of operation hours is exceeded. The effect of this disturbance is that less power than expected hits the specimen. If preventive maintenance is not carried out or its period is too long, it could be possible that lack of penetration appears due to a lack of effective power.

Although the CLET controller is not able to identify the mirror degradation, it is able to detect changes in electron temperature. Since every penetration depth has a corresponding electron temperature value and the mirror degradation originates changes in electron temperature, the controller reacts changing laser power in order to keep the adequate electron temperature and thus the desired penetration depth. During the experiment, that lasted for one entire day, the controller was able compensate the power losses caused by mirror degradation. At the start of the experiment, with mirrors in perfect condition, the controller set power at 3200 W. At the end of the day mirrors were degraded and laser power was 3400 W. The difference in power is the effect of the controller reacting after changes in the mirrors. In this way, product quality was satisfactory in despite of mirror degradation.

The second disturbance is related to variations in the pressure the disks. Variations in the pressure exerted by the disks can affect product quality. These variations are reflected in electron temperature oscillations (Figure 16). The controller was set to compensate these changes and to obtain optimal seams.

In Figure 17 a control experiment in continuous Nd:YAG laser welding is shown. The power value is generated by the controller and the resulting penetration depth is shown. The controller is activated at time 200 ms and it can be seen how the power is changed in order to achieve the desired penetration depth (1.1 mm).

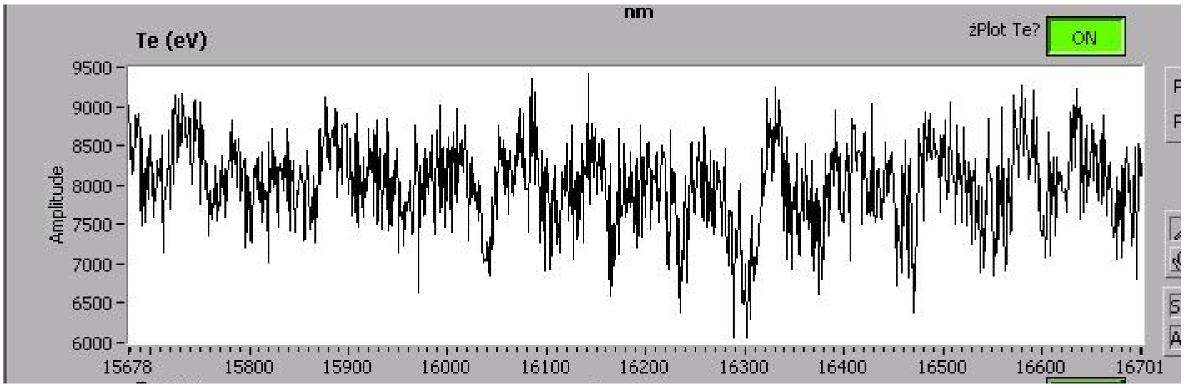


Figure 16: Chromium electron temperature amplitude oscillations related to changes in pressure exerted by pressure disks

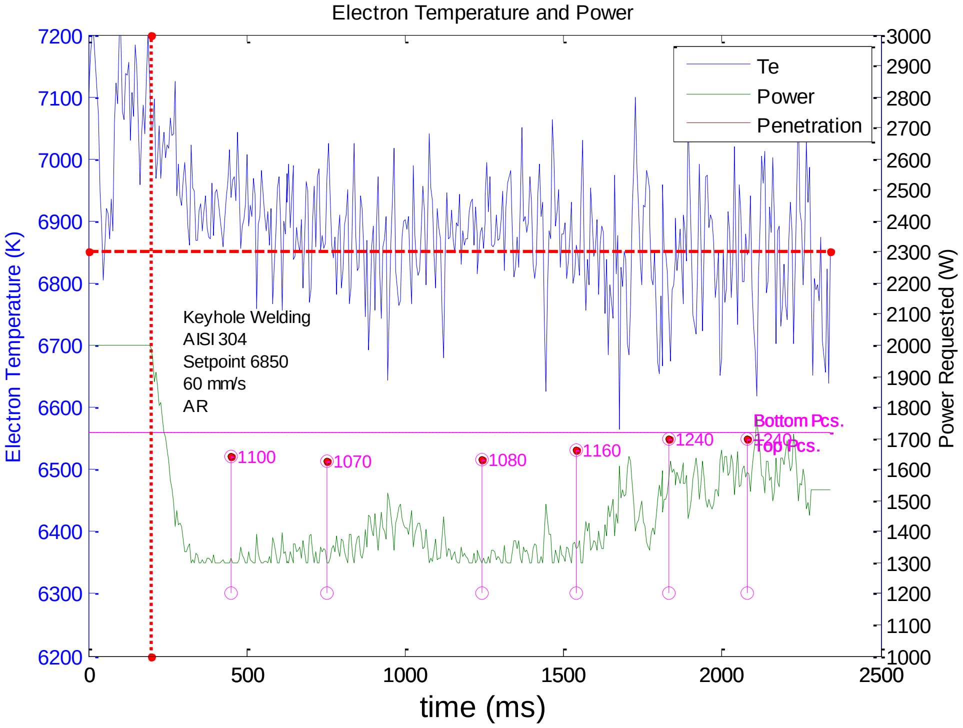


Figure 17: Control experiment in Nd:YAG laser welding

4. Potential impact

In the twenty-first century, photonics is a driver for technological innovation as well as one of the most important key technologies for markets and products such as photonic systems, components and optical consumer goods. Yet the economic impact of photonics extends well beyond these products.

Since 2005, the dynamic photonics industry and market have grown considerably. The world market for photonics grew from €226 billion in 2005 to €70 billion in 2008, representing an increase of about 20%. The European photonics industry benefited disproportionally from this positive trend, increasing production volume by 30% from € 43.6 billion in 2005 to € 55 billion in 2008. Moreover, more than 5 000 European companies created over 40 000 additional jobs in Europe in the same period. Europe accounts for more than 20% of the worldwide production volume in the photonics industry. In its core sectors such as lighting, production technology, medical technology, defence photonics and optical components and systems, market shares around the globe range from 25% to 45%. Photonics products also provide decisive competitive advantages for other vital European industries which still have production sites in Europe.

The technological leadership of photonics is evident in the application of laser systems for material processing in the automotive, aeronautics and microelectronics industries.

Europe leads the international market for industrial laser technologies. Many of the world's largest laser companies have their headquarters in Europe. In order to stay competitive with Asian companies, we have to further invest in innovative laser technology and to guarantee the high quality of European laser systems and components.

Laser-based production processes offer an enormous potential for highly flexible production on demand.

Photonics has a large impact on employment in Europe in three ways:

1. The photonics industry is mainly based on SMEs. Growth in demand will create proportionally more jobs in SMEs than it will in any sector made up of big companies.
2. New photonic technologies will secure the competitiveness of existing industries and so maintain jobs in manufacturing which are threatened by companies moving production to low-wage countries outside the EU.
3. Gaining the technological lead in photonics will enable us to create new manufacturing jobs for novel consumer.

Today, the photonics industry employs about 290 000 people all over Europe, not including employment with subcontractors. In comparison to 246 000 employees in 2005, this enormous increase shows that photonics is a significant creator of jobs throughout Europe. As a cross-sectorial technology, photonics has a strong impact on numerous other industries. It triggers important innovations in areas such as mechanical, automobile and aircraft engineering, microelectronics and the medical devices industry, where Europe holds particular expertise. This clearly illustrates the enormous importance of photonic solutions and technologies within Europe.

If we promote and support the manufacturing of high quality products in Europe, we will guarantee the further creation of employment in photonics throughout Europe.

Potential impact of CLET project addresses three main topics:

A. SME innovation process

There are two kind of SME in the CLET consortium. Three of them are laser welding performers and they can be CLET controller end-users. The fourth company manufactures laser welding related equipment and sensing systems form quality control in laser welding.

The main impact for Precitec is they can introduce in their portfolio a new product, i.e. a controller able to guarantee penetration depth in despite the disturbances that affect the system.

This is an important point because Precitec has a wide commercial net across Europe; so many companies will be noticed about the new product and will be able to update their laser welding facilities. This shall lead to a cost reduction with increased final product quality.

Moreover, Precitec is a company with RTD capacity. They can transform the CLET controller in such a way it operates with the sensors they already manufacture. In this way, the CLET controller may be available for more process and also could be able to reject wide bandwidth disturbances that can affect the final quality.

The other three SME in the CLET consortium are good representatives of European companies that operated laser welding facilities. The main innovations these companies can introduce by adopting the CLET controller are:

1. The possibility of welding demanding parts in which several penetration depths are required in an automatic fashion. This can reduce tuning times and improve the product final cost.
2. A flaw detection system able to inspect the whole production with no delays and in a non-destructive fashion.
3. The controller can compensate the degradation of some welding facility components, like those exposed to dust and dirt. In this way, maintenance operations can be spaced on time, which leads to production rate improvement and, so competiveness enhancement.

B. New skills and competence

The adoption of the CLET project can affect the employee’s competence. This came from the fact that the latest CLET controller needs to be parameterised properly in order to obtain a good performance.

The laser welding operators will have to learn the basics and tuning procedures for PID controllers. Since this kind of controller is widely used in industry this can improve their professional competence.

They will be also introduced in laser welding specific non-destructive inspection techniques.

C. Employee’s trust

As a result of CLET controller and sensing system adoption, the employees trust in operating properly the laser welding facility will be increased. This is due to:

1. Many flaws in laser welding are originated by the operator. In many cases the cause is mistaken parameters choose. The CLET system will be able to detect the defects and also to change the parameters in order to avoid the defect.
2. Operators will have guidance in their work. When no penetration depth is demanded and the CLET controller changes the laser power it is because something is going wrong and the controller is compensating it. In this way, operators will have a clue about abnormal system behavior and can supervise the process. Without the CLET system the malfunction could go unnoticed until total failure.

4.1. Dissemination activities

The project web page has been developed with three objectives:

1. Dissemination of project results

   The dissemination of the results intents to attract SMEs that could be interested in the controller to be developed. The web site will be the show room of the project.

   Dissemination will be based on the publication of those project results that project partners can disclose without threatening the knowledge protection. For this reason some results will not be published in the web page before all protective measures have been taken.

   Besides project results, including meeting presentations, specific ad hoc material will be developed in order to clarify the project objectives and achievements to non-specialised public. This will be of particular importance because the system to be developed is not based on techniques commonly used in industry.

2. Getting feedback

   Project partners are interested in possible customers' opinions. For this reason a 'Contact us' section has been enabled in the web site. Currently any interested user has the chance to send a message through the form that can be found in that section. In the future this will be enhanced by means of a questionnaire in which interested people will introduce specific data describing their laser welding process and the kind of defects they want to avoid.

This will allow the consortium to discover laser-welding applications that maybe are not represented by the activities of the SMEs partners or new SME necessities.

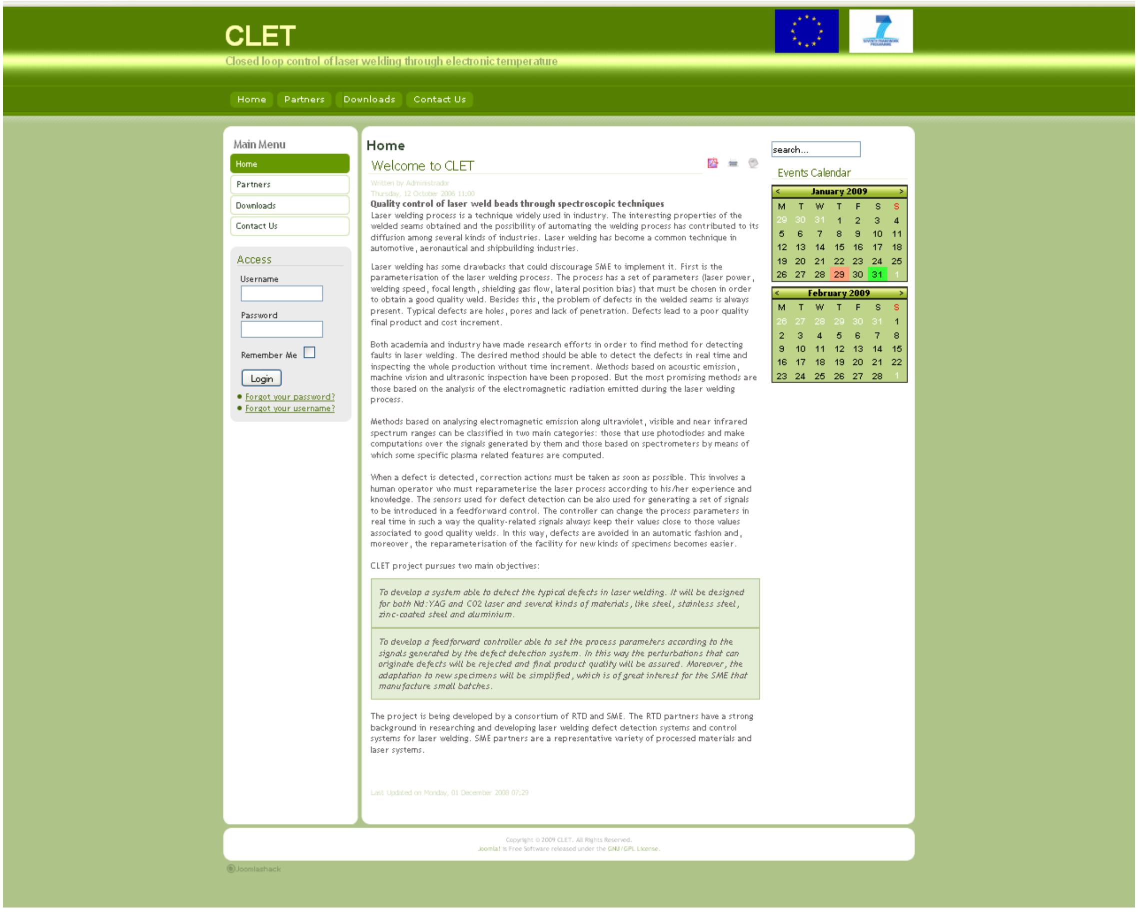
Moreover, it will be a tool for attracting attention from possible customers interested in the controller pursued in this project.

3. Consortium information interchange

   The web site features a calendar in which the main project events will be introduced. This will allow partners to be aware of major events in an easy way.

   Besides this, the web site has restricted areas to which only partners have access. Those areas will be used for document and file interchange.

The web page is hosted in one of the Cartif's web servers and its address is www.cartif.com.es. The front page can be seen in Figure 18.



Home

Welcome to CLET

Written by Administrador

Thursday, 12 October 2006 11:00

Quality control of laser weld beads through spectroscopic techniques

Laser welding process is a technique widely used in industry. The interesting properties of the welded seams obtained and the possibility of automating the welding process has contributed to its diffusion among several kinds of industries. Laser welding has become a common technique in automotive, aeronautical and shipbuilding industries.

Laser welding has some drawbacks that could discourage SME to implement it. First is the parameterisation of the laser welding process. The process has a set of parameters (laser power, welding speed, focal length, shielding gas flow, lateral position bias) that must be chosen in order to obtain a good quality weld. Besides this, the problem of defects in the welded seams is always present. Typical defects are holes, pores and lack of penetration. Defects lead to a poor quality final product and cost increment.

Both academia and industry have made research efforts in order to find method for detecting faults in laser welding. The desired method should be able to detect the defects in real time and inspecting the whole production without time increment. Methods based on acoustic emission, machine vision and ultrasonic inspection have been proposed. But the most promising methods are those based on the analysis of the electromagnetic radiation emitted during the laser welding process.

Methods based on analysing electromagnetic emission along ultraviolet, visible and near infrared spectrum ranges can be classified in two main categories: those that use photodiodes and make computations over the signals generated by them and those based on spectrometers by means of which some specific plasma related features are computed.

When a defect is detected, correction actions must be taken as soon as possible. This involves a human operator who must reparameterise the laser process according to his/her experience and knowledge. The sensors used for defect detection can be also used for generating a set of signals to be introduced in a feedforward control. The controller can change the process parameters in real time in such a way the quality-related signals always keep their values close to those values associated to good quality welds. In this way, defects are avoided in an automatic fashion and, moreover, the reparameterisation of the facility for new kinds of specimens becomes easier.

CLET project pursues two main objectives:

To develop a system able to detect the typical defects in laser welding. It will be designed for both Nd:YAG and C02 laser and several kinds of materials, like steel, stainless steel, zinc-coated steel and aluminium.

To develop a feedforward controller able to set the process parameters according to the signals generated by the defect detection system. In this way the perturbations that can originate defects will be rejected and final product quality will be assured. Moreover, the adaptation to new specimens will be simplified, which is of great interest for the SME that manufacture small batches.

The project is being developed by a consortium of RTD and SME. The RTD partners have a strong background in researching and developing laser welding defect detection systems and control systems for laser welding. SME partners are a representative variety of processed materials and laser systems.

Last Updated on Monday, 01 December 2008 07:29

< January 2009 >

M	T	W	T	F	S	S
29	30	31	1	2	3	4
5	6	7	8	9	10	11
12	13	14	15	16	17	18
19	20	21	22	23	24	25
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< February 2009 >

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9	10	11	12	13	14	15
16	17	18	19	20	21	22
23	24	25	26	27	28	1

Figure 18: Web site main page

Title	*Author*	*Type*	*Media*	*Place and date*
Spectroscopic analysis of plasma optical emission from laser welding process control	CNR-INFM	Conference paper	LIM (Lasers in Manufacturing) 2009	Munich (Germany) June 2009
Spectral analysis of the process of emission during laser welding of AISI 304 stainless steel with disk and Nd:YAG lasers	Twente University	Conference paper	ICALEO (International Congress on Applications of Lasers and Electro-Optics) 2009	Orlando (USA) November 2009
Flexweld doet mee in Europees onderzoeksproject naar laserlasoptiek	Flexweld	Promotional paper	Vraag en Aanbod	The Netherlands
Plasma Plume Oscillations Monitoring during Laser Welding of Stainless Steel by Discrete Wavelet Transform Application	CNR-IFN	Peer to peer reviewed paper	Sensors, Vol.10, issue 4	April 2010
Spectroscopic, energetic and metallographic investigation of the laser lap welding of AISI 304 using the Response Surface Methodology	CNR-IFN	Peer to peer reviewed paper	Optics and Lasers in Engineering. Vol. 49, issue 7	July 2011
A real-time spectroscopic sensor for monitoring laser welding processes	CNR-IFN	Peer to peer reviewed paper	Sensors. Vol. 9, issue5	May 2009
Spectroscopic monitoring of penetration depth in CO2 and Nd:YAG laser welding processes	CNR-IFN	Peer to peer reviewed paper	Journal of Materials Processing Technology	Under review
Study of the correlation between plasma electron temperature and penetration depth in laser welding processes	CNR-IFN	Conference paper	Physics Procedia	2010
Process Control of Stainless Steel Laser Welding using an Optical Spectroscopic Sensor	UT	Conference paper	Physics Procedia	2011
Discrete wavelet analysis of the optical emission during CO2 laser welding of stainless steel	CNR-IFN	Conference paper	LIM 2009 – Lasers in Manufacturing	Munich. June 2009
Study on the correlation between plasma electron temperature and penetration depth in laser welding	CNR-IFN	Conference paper	LANE 2010	Erlangen. October 2010

High power laser process sensing and applications	CNR-IFN	Conference poster	National Conference of the Institute for Photonics and Nanotechnologies	Milan. July 2010
High power laser process sensing and applications	CNR-IFN	Conference poster	Festival dell' Innovazione Puglia	Bari. December 2010
Process Control of stainless steel laser welding using an optical spectroscopic sensor	UT	Conference paper	LIM 2011 – Lasers in Manufacturing	Munich. May 2011
Spectroscopic control of penetration depth in CO_2 and Nd:YAG laser welding proces	UT	Conference paper	LIM 2011 – Lasers in Manufacturing	May 2011
Sensore spectroscopico per il monitoraggio in tempo reale del processo di soldadura laser	CNR-IFN	Conference paper	Fotonica 2011	Genova. May 2011

5. Project web address and contact information

Project web address:

http://clet.cartif.com.es/

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