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Non-destructive Real Time Monitoring of the Laser Welding Process

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Laser welding is a high power density technology of materials joining that has many advantages in comparison with conventional fusion welding methods, for example, high accuracy, flexibility, repeatability and especially very narrow heat-affected zone which results in minimal workpiece distortions. Since it is still quite expensive technology, minimal spoilage is required. Effective system of quality control and processing parameters optimization must be established to reduce total costs, which is particularly required in industrial production. In this article some results of pulsed Nd:YAG laser welding process monitoring based on the measurement of plasma electron temperature are presented. The ability of designed sensor to detect weld penetration depth has been demonstrated. Plasma spectral lines intensities measurement can discover gap instabilities as well as local sheet thickness reduction.

Keywords defect detection, laser welding, penetration depth, plasma electron temperature

1. Introduction

Real time non-destructive defect detection is a modern approach in weld quality control. Assuming a faultless basic material, the most of welding defects are caused by laser power fluctuations or present misalignment of components to be welded. Weld misalignment monitoring and compensation by means of laser seam tracking systems is quite a common technique (Ref 1, 2). But a non-destructive real time method of inside weld defects detection is still challenging. The biggest snag is usually a lack of penetration which is a result of insufficient beam power application (Ref 3-5). Relatively widely disseminated method of weld fusion zone monitoring is weld pool tracking and its heat radiation signal measurement (Ref 7-10). Another approach is to acquire electromagnetic emission generated during the interaction of laser beam with workpiece material which is usually based on photodiodes. This method was experimentally confirmed for CO_2 laser welding (Ref 6). The disadvantage of this method is the fact that more photodiodes must be used to cover wide spectral emission range. The method presented in this article is based on spectroscopic plasma emission measurement which seems to be a technique that can detect both weld penetration depth with a good accuracy and also very fine initial workpiece defects. Its implementation into new laser welding heads would not be complicated as well as its additional implementation to present working systems is possible. In this way significant improvement of industrial laser welding facilities would be accomplished without the necessity of buying the whole new welding head.

High power density application corresponding to the laser welding leads to the partial vaporization and keyhole formation (Ref 3, 4, 11). During this process, a plasma plume appears inside and above the keyhole. It consists of ionized workpiece metal vapors escaping from the keyhole and can be formed also by ionized protective gas if an unsuitable one is applied. The plasma plume is supported by the partial absorption of incident laser beam through the Inverse Bremsstrahlung mechanism. An excessive plasma plume can attenuate laser beam that leads to the penetration depth reduction (Ref 11). Optical emission spectrum of plasma can be monitored (Ref 12, 13) and its relationship to the penetration depth should be found. Plasma electron temperature measurement based on spectroscopic analysis of generated plasma seems to be a promising technique. The electron temperature of plasma can be used for the penetration depth estimation immediately during the welding process and thus can be applied as the input parameter of the closed loop controller regulating laser power to reach required penetration depth.

2. Plasma Electron Temperature Calculation

The presence of plasma during the Nd:YAG laser welding has been discussed many times (Ref 14) since it was approved that several emission lines of ionized chemical elements can be identified in its spectrum after the background radiation removal (Ref 15, 16).

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To calculate plasma electron temperature, a couple of distinguishable spectral emission lines with high intensity must be identified. Providing that the plasma plume is in local thermo-dynamical equilibrium, its electron temperature T_e can be computed using the ratio of relative intensities $I_{(1)}$ and $I_{(2)}$ of two different spectral emission lines (1) and (2) of the one ion (Ref 17)

$$\frac{I_{(1)}}{I_{(2)}} = \frac{A_{(1)} g_{m(1)} \lambda_{(2)}}{A_{(2)} g_{m(2)} \lambda_{(1)}} \exp\left(\frac{E_{m(2)} - E_{m(1)}}{kT_e}\right)$$

where $E_{m(1)}$, $E_{m(2)}$ are corresponding energies of upper energy levels; k is a Boltzmann constant; $\lambda_{(1)}$, $\lambda_{(2)}$ corresponding wavelengths; $A_{(1)}$, $A_{(2)}$ transition probabilities; and $g_{m(1)}$, $g_{m(2)}$ degeneracy of upper energy level of studied transition. For this method, it is important to select proper emission lines among the spectrum that must not be affected by self-absorption and must belong to different multiplet states of the same chemical species. Then, the plasma electron temperature can be expressed as follows

$$T_e = \frac{E_{m(2)} - E_{m(1)}}{k \ln \frac{I_{(1)} \lambda_{(1)} A_{(2)} g_{m(2)}}{I_{(2)} \lambda_{(2)} A_{(1)} g_{m(1)}}}.$$

Relevant data can be found in NIST atomic spectra database (Ref 18).

3. Experiment

Pulsed Nd:YAG laser LASAG KLS 246-102 with maximal average power 150 W was used to carry out seam welding experiments to prove the relationship between the laser power, penetration depth, and plasma electron temperature and to show the effect of present initial defects in workpieces to be welded.

Fixed laser processing head with focusing lens with 100 mm focal length was tiled by 8° from the normal to avoid undesirable back reflections. Welding point was 4 mm under the focal plane. Beam diameter on the specimen reached 0.85 mm at this position. Welding speed 4 mm s^{-1}, pulse duration 3.4 ms, and pulse repetition frequency 13 Hz were kept constant during all the experiments. This setup results in 64% pulse overlap leading to the seam weld preparation. Clean degreased AISI 304 stainless steel sheets with thickness 0.6 and 1 mm were processed.

First, preliminary bead-on-plate welding experiment with 0.6 mm thick sheet was accomplished. Pulse energy, sufficient for the full penetration of such metal sheet, was 6.4 J. Dynamic almost 30% energy reduction to the value 4.6 J followed by the comeback to 6.4 J during the welding process was tested. This energy change corresponds to the peak power change from 1.88 to 1.35 kW and back to 1.88 kW.

Second, the effect of laser peak power was investigated in detail during the welding of 0.6 mm onto 1 mm metal sheets in lap joint configuration. Laser peak power was changed from 1.6 to 2.7 kW through the changes of pulse energy controlled by charging flash lamp voltage. This peak power range corresponds to the average power range of almost 50 W and pulse energy range of 3.6 J, respectively.

The last set of experiments focused on the effect of defects present in workpieces before the welding. Intentionally fabricated defects with accurate dimensions were prepared to simulate possible imperfections of workpieces edges or their misalignment. The aim of this experiment was to find out whether the welding monitoring based on plasma electron temperature measurement can detect defects in components to be welded. Two kinds of defects were simulated. The first kind represented an increase of the gap size between the workpieces to be welded. One of two sheets to be butt welded was without any intentional defects while the second one featured 10 mm long, 0.1 and 0.2 mm deep slots distanced by 10 mm (Fig. 1a). Second kind represented workpiece thickness reduction. Original 0.6 mm thick sheet was made locally thinner by surface milling to reach 10 mm long areas along the weldline (Fig. 1b), where the sheet thickness reached 0.5, 0.4, 0.3, and 0.2 mm, respectively.

Welding experiments were monitored by means of plasma spectral emission measurement. The collimator with spatter protecting glass in front position towards the welding point was used to collect the signal coming from the plasma plume and to guide it into the optical fiber connected to the spectrometer. Figure 2 presents experimental setup.

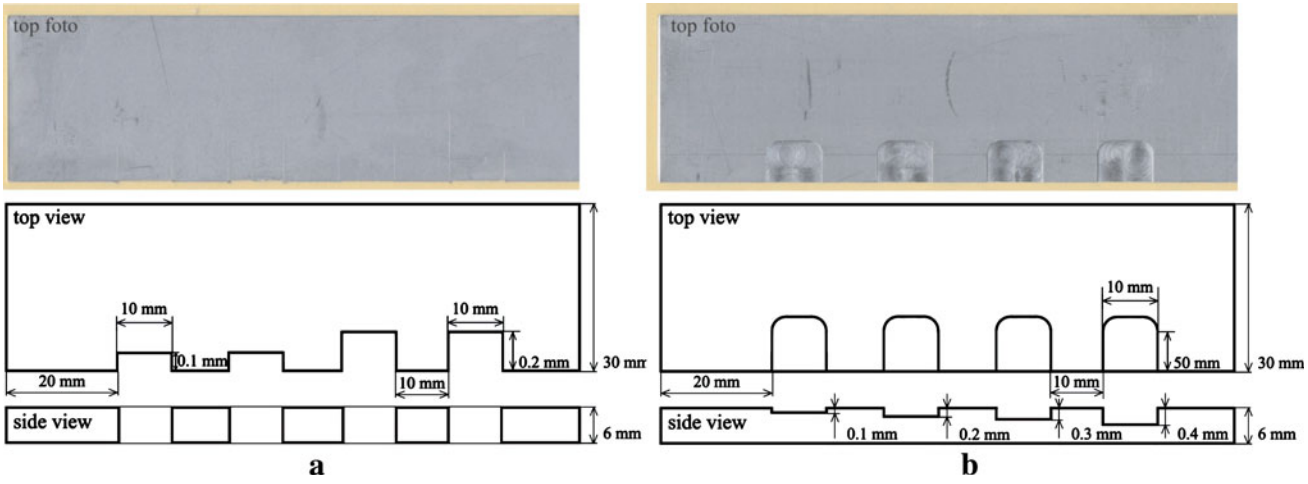

Fig. 1 The first (a) and the second (b) kind of simulated defect

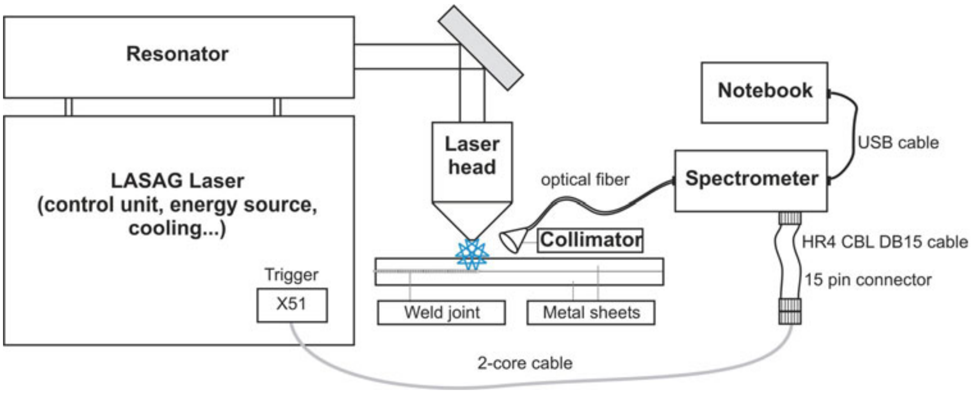

Fig. 2 Experimental setup

Table 1 Ocean Optics spectrometer HR2000+ specifications

Entrance slit	Diffraction grating	Minimal sampling time	Spectral range	Resolution	Detector
10 µm	1800 lines	1 ms	200-525 nm	0.12 nm	2048 CCD array

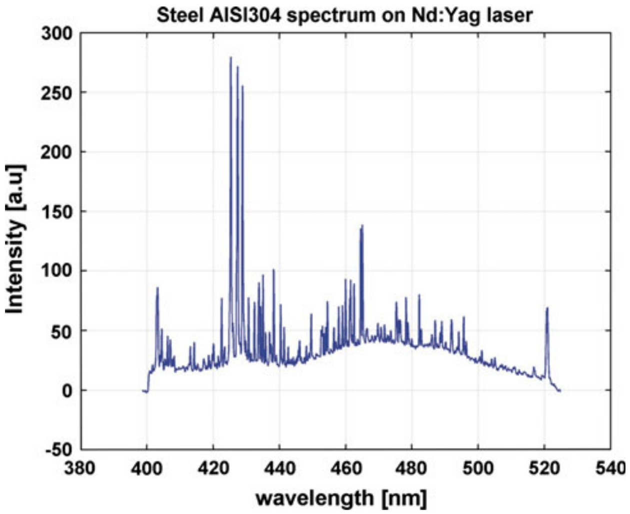

Fig. 3 Mean spectra acquired during Nd:YAG laser welding of AISI 304 stainless steel

First, the Avantes spectrometer AvaSpec 2048-2 disposing of spectral range 200-1100 nm was employed for precise alignment of collimator with respect to the welding point position on the workpiece surface using pilot He-Ne laser (632.8 nm) embedded in our LASAG system. After this procedure, the Avantes spectrometer was replaced by the Ocean Optics spectrometer HR2000+ with narrower spectral range 400-525 nm but with much higher resolution 0.12 nm. Its characteristics are included in Table 1. The spectrometer was triggered with laser pulses to acquire spectra only in the time of flash lamp pulsing. Developed software in C# code was used to control the measurement and subsequent electron temperature calculations.

4. Results

Figure 3 presents the mean spectra after the background removal acquired during the welding. The most intensive peaks can be found in the range 420-470 nm. Two different couples of spectral emission lines of chromium (437.416 nm, 459.139 nm) and iron ions (421.936 nm, 431.508 nm) were identified to calculate plasma electron temperature. These lines were chosen because of their sufficiently high intensity and distinctiveness. Parameters of these lines necessary for plasma electron temperature calculation are summarized in Table 2.

In the first experiment, the pulse energy was decreased during the bead-on-plate welding of 0.6 mm thick metal sheet. The pulse energy decrease led to the decrease of spectral intensities of selected emission lines. Figure 4 presents detected decrease of chromium line intensities. However, the electron temperature of plasma increased in the region of pulse energy decrease (Fig. 5). The difference between the average plasma electron temperatures measured during the welding with energy 6.4 and 4.6 J was about 132.3 K for chromium ion and 115.9 K for iron ion, respectively.

Figure 6 presents the effect of laser peak power on plasma electron temperature investigated in the second set of experiments. Plasma electron temperature had decreasing tendency with increasing laser power both for chromium and iron ions. In the investigated laser peak power range of 1.1 kW electron temperature decreased from 7840 to 7670 K with average standard deviation about 40 K for chromium ion and from 7130 to 7020 K with standard deviation about 45 K for iron ion, respectively, that is about 2.2 and 1.5% change, respectively.

Weld pieces were cut perpendicularly to the welding direction and metallographic specimens of weld cross sections were prepared to identify weld penetration depth. Figure 7 presents some of them. More cross sections of each weld were prepared because of problematic determination of penetration depth in pulsed overlap laser welding, especially when

Table 2 Parameters of selected spectral emission lines for electron temperature calculation (Ref 14)

Ion (line no.)	Wavelength, nm	Upper energy leve, cm^{-1}	Transition probability, s^{-1}	Upper level degeneracy
Cr I (1)	437.416	47,055.31	1.03×10^{7}	11
Cr I (2)	459.139	29,584.62	1.1×10^{6}	5
Fe I (1)	421.936	52,513.349	3.8×10^{7}	13
Fe I (2)	431.508	40,894.986	7.7×10^{6}	5

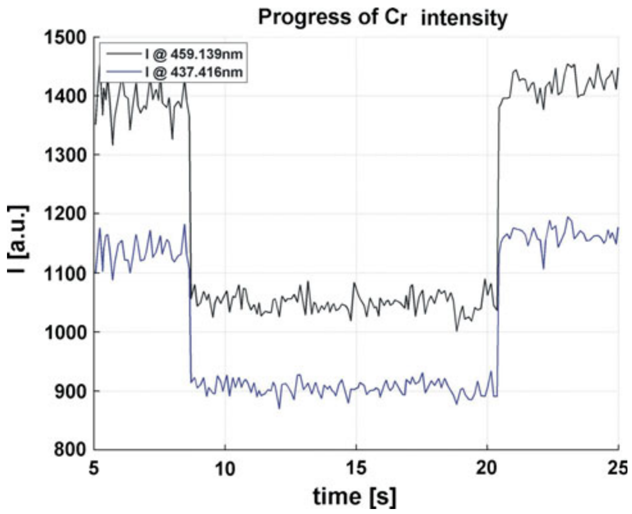

Fig. 4 Progress of chromium line relative intensity during the energy change

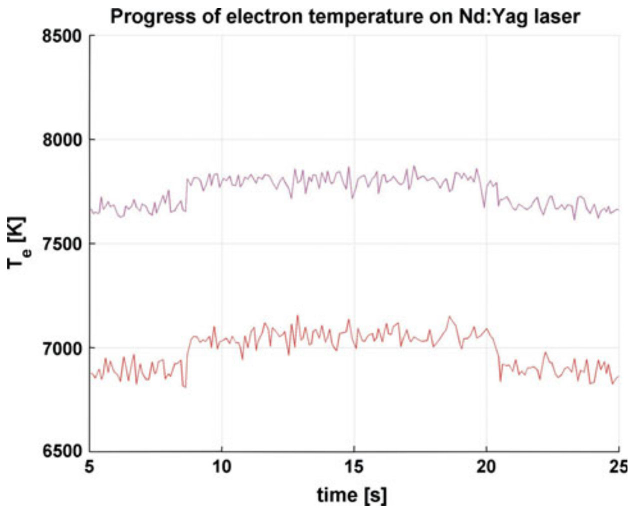

Fig. 5 Plasma electron temperature progress during the energy change

relatively small pulse overlap is applied (Ref 5). The maximal detected depth measured within more cuts of the one weld was considered to be its penetration depth.

Maximal applied laser power was not sufficient for the desired penetration of 1.6 mm thick pieces to be welded (0.6 mm onto 1 mm metal sheet). However, penetration depth—laser power link can be identified. Increasing laser peak power naturally led to the penetration depth increase. Figure 8 presents the relationship between penetration depth and plasma electron temperature. Penetration depth changed from 0.44 to 0.93 mm within the investigated region, which means that 0.5 mm change in penetration depth corresponded to 170 K change of electron temperature computed for chromium ion and 110 K for iron ion, respectively. Electron temperature deviation of about 2% indicates welding defect with dimensions of one half of millimeter. According to the 0.5% standard deviation in electron temperature measurement, even smaller defects caused by laser power fluctuations can be discovered in real time.

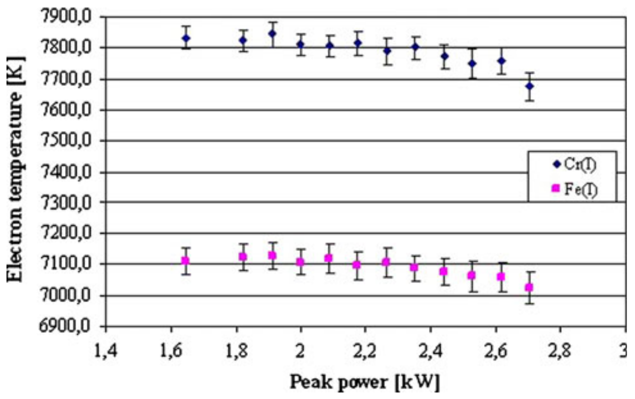

Fig. 6 Plasma electron temperature vs. laser peak power

In the last set of experiments, plasma electron temperature response on fine workpieces surfaces changes was tested. Figure 9 presents the evolution of 425.435 and 458.006 nm chromium lines intensities measured along the weldline. Concerning welding speed 4 mm s^{-1}, 10 mm sections of defect (Fig. 1) correspond to the 2.5 s intervals of intensity decrease in Fig. 9. Chromium intensity decrease can be observed in the defect region of both 0.1 and 0.2 mm deep slots. This decrease is more noticeable in the deeper slot. Competent spectral emission lines must be identified. Here, 425.435 nm seems to be more suitable because of more significant intensity changes. Higher the gap size lower the intensity can be expected because larger part of the beam escapes through the gap and less amount of its power is transferred to the material. Therefore also plasma plume emission is lower. Electron temperature measurements did not prove the presence of initial defects.

Analogical results were achieved in case of second kind defect experiment. Chromium line intensity decreases in the regions with defect that were 10 mm long along the weldline (Fig. 10). Intensity decrease corresponds to the change of stand-off distance caused by one sheet thickness reduction, which results in lower laser power density. On the other hand, full penetration was also reached because less material volume must be melted. Plasma plume position towards the collimator could also change and results in intensity changes. Electron temperature measurements were inconclusive similarly like for the first kind of tested defects.

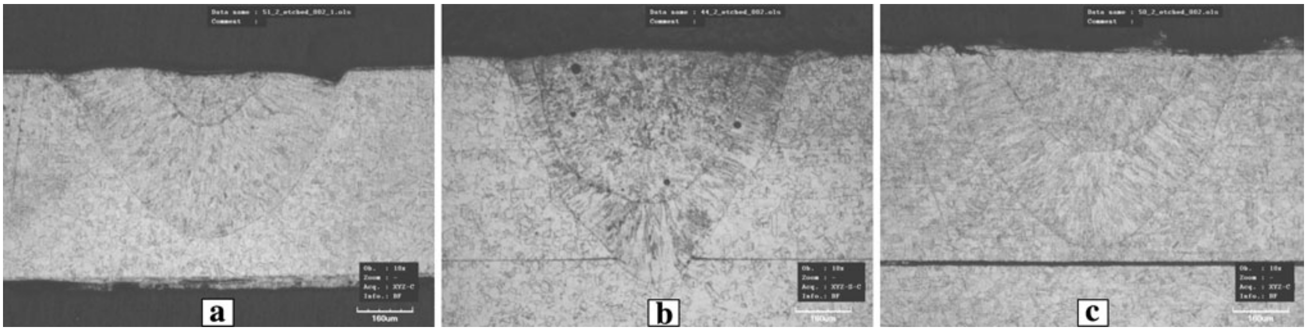

Fig. 7 Weld cross section of sample prepared at 6.5 J (a), 7.1 J (b), and 8 J (c)

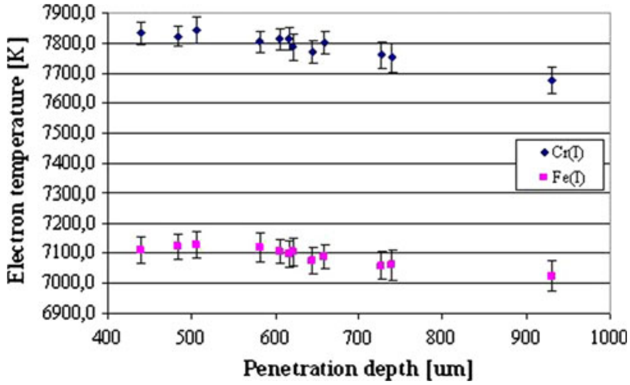

Fig. 8 Plasma electron temperature vs. penetration depth

5. Conclusions

Three series of experiments were carried out to study the effect of processing parameters on plasma plume electron temperature. The correlation between electron temperature and weld penetration depth was found.

Plasma electron temperature measurements did not reveal simulated initial defects. On the other hand, spectral intensity measurement can be useful for initial defects or wrong alignment of workpieces discovery. Timely identification and correction of unsuitable welding conditions or the workpieces with defect edges or faying surfaces detection and replacement can lead to substantial material, energy as well as working time savings required especially in industrial applications.

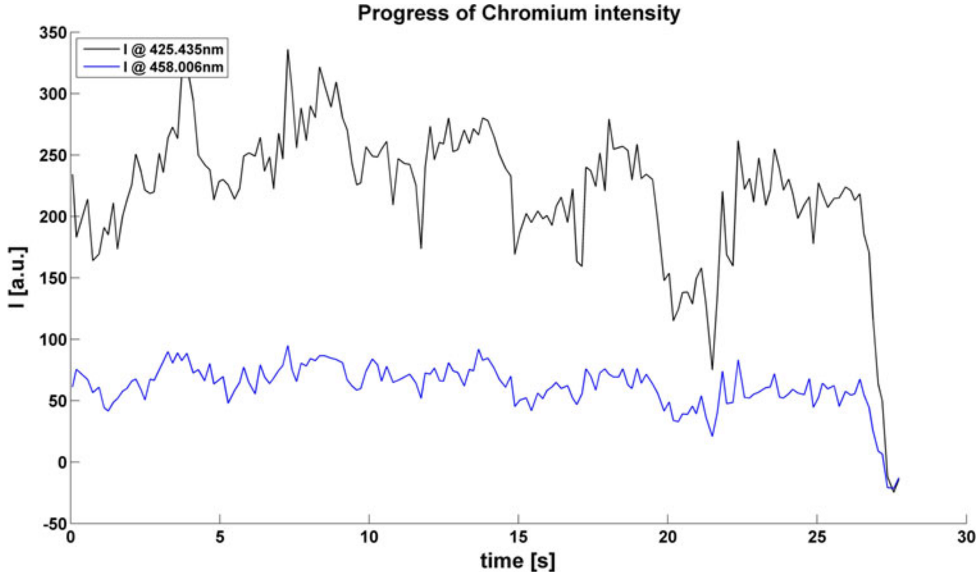

Fig. 9 Plasma plume intensity (Cr I) evolution along the weldline measured for the workpiece with the first kind of intentionally fabricated defects

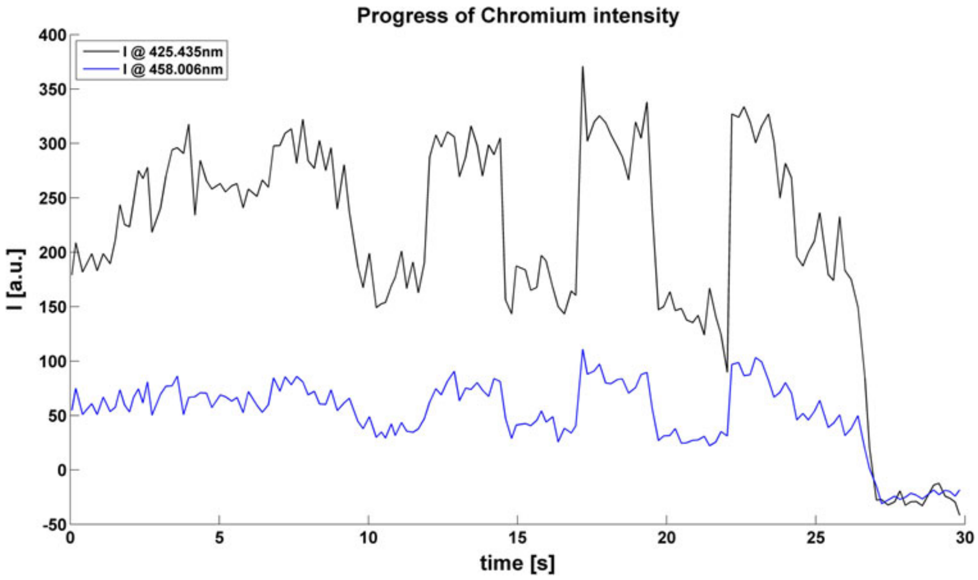

Fig. 10 Plasma plume intensity (Cr I) evolution along the weldline measured for the workpiece with the second kind of intentionally fabricated defects

The most important result of this research is that the electron temperature monitoring can provide us with information about weld penetration depth. Reference plasma electron temperature corresponding to the optimal welding conditions in each welding situation can be found. In this way the feedback welding controller can be designed to control the laser power to prevent possible defects occurrence.

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References

1. Ch. Anderson, R. Mandel, Improve Welding Quality with 3D Laser Seam-Tracking, Welding—Design and Fabrication, Penton Media, 2006, Available online from http://weldingdesign.com/processes/news/wdf_38778/
2. P. Bergvist, *Seam Tracking in a Complex Aerospace Component for Laser Welding*, University of Trollhattan/Uddevalla, Department of Technology, Mathematics and Computer Technology, Sweden, 2004
3. W.M. Steen, *Laser Material Processing*, Springer, London, 2003
4. J.F. Ready, *LIA Handbook of Laser Materials Processing*, Laser Institute of America, Orlando, 2001
5. H. Lapšanská, H. Chmelíčková, and M. Hrabovský, Effect of Beam Energy on Weld Geometric Characteristics in Nd:YAG Laser Overlapping Spot Welding of Thin AISI, 304 Stainless Steel Sheets, *Metall. Mater. Trans. B*, 2010, **41**(5), p 1108–1115
6. T. Sibillano, A. Ancona, V. Berardi, and P.M. Lugarà, A Real-Time Spectroscopic Sensor for Monitoring Laser Welding Processes, *Sensors*, 2009, **9**(5), p 3376–3385
7. Y. Kawahito, M. Kawasaki, and S. Katayama, In-process Monitoring and Adaptive Control During Micro Welding with CW Fiber Laser, *J. Laser Micro/Nanoeng.*, 2008, **3**(1), p 46–51
8. Y. Kawahito, M. Kito, and S. Katayama, In-process Monitoring and Adaptive Control for Laser Spot and Seam Welding of Pure Titanium, *J. Laser Micro/Nanoeng.*, 2006, **1**(3), p 269–274
9. Y. Kawahito and S. Katayama, In-process Monitoring and Feedback Control During Laser Microspot Lap Welding of Copper Sheets, *J. Laser Appl.*, 2004, **16**(2), p 121–127
10. Y. Kawahito, M. Kito, and S. Katayama, In-process Monitoring and Adaptive Control for Gap in Micro Butt Welding with Pulsed YAG Laser, *J. Phys. D: Appl. Phys.*, 2007, **40**, p 2972–2978
11. W.W. Duley, *Laser Welding*, Wiley, New York, 2009
12. T. Sibillano, A. Ancona, V. Berardi, E. Schingaro, P. Parente, and P.M. Lugarà, Correlation Spectroscopy as a Tool for Detecting Losses of Ligand Elements in Laser Welding of Aluminium Alloys, *Opt. Laser Eng.*, 2006, **44**, p 1324–1335
13. T. Sibillano, A. Ancona, D. Rizzi, V. Lupo, L. Tricarico, and P.M. Lugarà, Plasma Plume Oscillations Monitoring During Laser Welding of Stainless Steel by Discrete Wavelet Transform Application, *Sensors*, 2010, **10**, p 3549–3561
14. J. Sabbaghzadeh, S. Dadras, and M.J. Torkamany, Comparison of Pulsed Nd:YAG Laser Welding Qualitative Features with Plasma Plume Thermal Characteristics, *J. Phys. D: Appl. Phys.*, 2007, **40**, p 1047–1051
15. S. Dadras, M.J. Torkamany, and J. Sabbaghzadeh, Spectroscopic Characterization of Low-Nickel Copper Welding with Pulsed Nd:YAG Laser, *Opt. Laser Eng.*, 2008, **46**, p 769–776
16. D. Lacroix, G. Jeandel, and C. Boudot, Spectroscopic Characterization of Laser-Induced Plasma Created During Welding with a Pulsed Nd:YAG Laser, *Appl. Phys.*, 1997, **81**, p 6599–6606
17. V.K. Unnikrishnan, K. Alti, V.B. Kartha, C. Santhosh, G.P. Gupta, and B.M. Suri, Measurements of Plasma Temperature and Electron Density in Laser-Induced Copper Plasma by Time-Resolved Spectroscopy of Neutral Atom and Ion Emissions, *Pramana*, 2010, **72**, p 983–993
18. NIST Atomic Spectra Database, Available online from http://www.nist.gov/pml/data/asd.cfm