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ADVANCED OPTOELECTRONIC TECHNOLOGIES FOR IN-SITU ANALYSIS OF METALLIC WELD BEADS: COMPARISON WITH CLASSICAL EDS METHODS

BY

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Abstract: This paper presents the results of a study on the development of portable, modular optoelectronic equipment for the in situ qualitative and quantitative analysis of metallic weld beads. Compared to traditional analysis methods, such as EDS spectrometry, the proposed systems offer superior accuracy, real-time analysis capabilities, portability, and energy autonomy. Three patented devices are presented: a portable device without an excitation source, a portable device with a laser excitation source, and a complex modular spectromicroscope. A comparative evaluation was conducted to highlight the advantages of these devices in terms of sensitivity, application flexibility, and integration into production processes.

Keywords: metal welding; light element detection; spectral characterization.

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1. Introduction

The chemical composition of weld beads must be analyzed to ensure the quality of metallic joints. Conventional methods, including EDS, require the extraction of samples, followed by sample preparation and post-process analysis. These methods are inherently limited in their applicability within dynamic industrial environments. In this particular context, the objective of the research was to develop optoelectronic systems with the capacity to perform analysis directly in the field during the welding process.

2. Materials and methods

Three distinct pieces of equipment have been developed and tested:

- The portable equipment without excitation source (Gutt *et al.*, 2015a) using the radiation emitted by the thermal process as the excitation source for atomic emission spectrometry.
- The portable laser excitation source device (Gutt *et al.*, 2015b) using a medium-power laser to excite the sample, allowing precise control of the analysis parameters.
- The complex modular spectromicroscope (Amariei *et al.*, 2015) enabling multiple spectral analysis (emission, absorption, fluorescence, photoacoustic, fluorescence, Raman) combined with microscopic imaging and automation.

2.1. Portable optoelectronic equipment without excitation source

The equipment comprises a miniature spectrometer, a camera for optical centering, a laser rangefinder for focusing, and a USB interface. The analysis is performed using radiation generated by the welding process and Mikropack SpecLine software. This method facilitates the analysis of chromium (Cr), manganese (Mn), iron (Fe), nickel (Ni), and silicon (Si) elements without the necessity of sample processing (Goldstein *et al.*, 2018).

2.2. Portable optoelectronic device with excitation source

The portable optoelectronic equipment with laser excitation source enables qualitative and quantitative in situ chemical analysis by atomic emission spectrometry. The system's efficacy is attributed to the medium-power laser source and integrated telemeter, which ensure precise sample excitation and a constant focus distance, thereby contributing to the accuracy of the results. The equipment is powered by a car battery, is entirely autonomous and portable, and is well-suited for industrial field applications. The compact structure incorporates a miniature spectrometer, a fiber optic system, and a digital interface, thereby enabling rapid, non-destructive, and reproducible analysis of metallic materials.

2.3. Modular complex spectromicroscope

The system incorporates an Nd:YAG source, UV-VIS-NIR spectrometers, a video microscope, and modules for photoacoustic, fluorescent, and Raman analyses (Gutt *et al.,* 2011). This apparatus is capable of performing simultaneous analyses of chemical composition and thermal distribution during the welding process. Its applications include fundamental research and industrial inspection (Bernevig-Sava *et al*., 2019).

3. Experimental methods

The experimental tests were conducted under controlled conditions in the Materials Testing and Characterization Laboratory (Bernevig-Sava *et al*., 2019). The metal samples that were analyzed included carbon steel, stainless steel, copper, and aluminum. For each material, weld beads were fabricated using an electric arc and a Nd:YAG laser welding technique, excluding the use of filler material to avoid introducing additional variables. The equipment was utilized in the following manner:

- The equipment without an excitation source was positioned in the proximity of the electric arc, focused using a laser telemeter on the area of maximum plasma emission, and the spectra were automatically acquired at the points of maximum emission, as identified by the dedicated software.
- The laser source equipment was configured to emit pulses of 8 kW, 60 J, at 1064 nm, focused on the surface of the weld bead. The optimal excitation distance was maintained constant through the use of an optical feedback telemeter.
- The modular spectro-microscope was configured for sequential measurements: UV-VIS for atomic emission, NIR for molecular absorption, and fluorescence for impurity identification. The automatic calibration was executed using the integrated optical software, and the results were then correlated with the microscopic images.

For comparative purposes, the same samples were also analysed using EDS (Energy Dispersive X-ray Spectroscopy) on a Hitachi SU-70 SEM microscope equipped with an Oxford Instruments EDS energy dispersive spectrometer (Goldstein *et al*., 2018).

4. Results and discussions

The utilization of portable devices in the acquisition of spectra has been demonstrated to yield more intense and stable signals, a consequence of the employment of multiple spectral averages and the automatic signal averaging system.

The laser systems employed in actively excited equipment facilitate precise detection, even of elements with low atomic mass, thus surpassing the well-known limitations of EDS in this field.

Table 1 provides a clear overview of the key differences between the classic EDS system and the patented equipment. The patented equipment has multiple advantages: firstly, it does not require sample extraction, secondly, it allows real-time analysis, thirdly, it has excellent portability and high sensitivity to light elements (through spectral averaging). Furthermore, the device can be integrated with the welding process through temperature control. Conversely, the conventional EDS system necessitates sample extraction, restricts real-time analysis, and exhibits limitations in detecting elements with $Z < 11$. It has been demonstrated that the patented equipment necessitates lower operating and maintenance costs.

Table 1

Comparative features of classic EDS technologies and the patented equipment

Comparative feature	EDS Clasic	Patented equipment
Need for sample extraction	Yes	No
Real-time analysis	No	Yes
Portability	Reduced	Very good
Type of analysis	Qualitative + quantitative	Qualitative + quantitative
Light elements sensitivity	Limited ($Z < 11$)	High - through spectral mediation
Integration with the welding process	No	Yes (through temperature control)
Cost of operation and maintenance	High	Low

The following table provides a comparison (Table 2) between the proposed methods and the classical EDS method:

Table 2
Comparative results of classic EDS technologies and the patented equipment

Parameter	Portable optoelectronic equipment	Modular Complex Spectromicroscope	EDS Oxford Instruments	Comments
Detected elements	Fe, Cr, Mn, Ni, Si	Fe, Cr, Mn, Ni, Al, Cu	Fe, Cr, Mn, Ni, Si	Comparable detected elements
Accuracy (%)	±2%	±1%	±1%	Accuracy comparable to EDS
Analysis time	4 s	3-5 s	60-90 s	Much shorter time to developed methods
Portability	Very high	Medium	Low	EDS requires laboratory
Need for sample processing	No	Minimum	Yes	EDS requires sampling and polishing

Figure 1 illustrates the disparities between the examined methodologies. The following analysis provides an average time for each method.

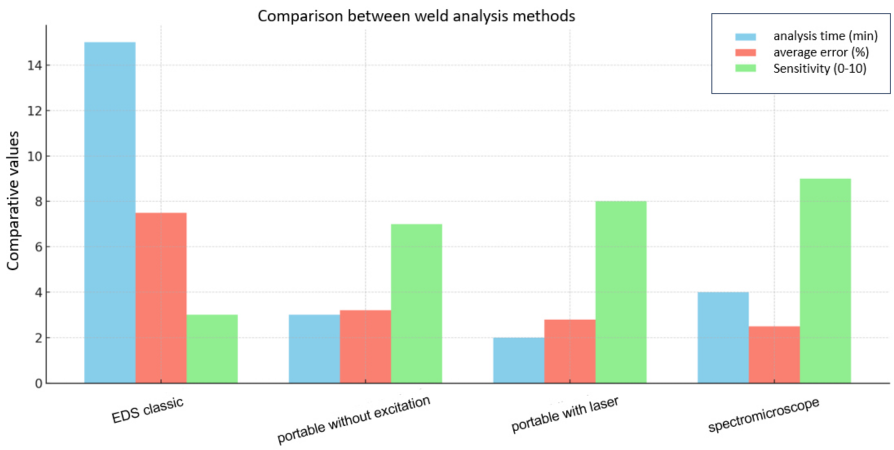

Fig. 1 – Graphical representation of the differences between the analyzed methods.

The estimated relative error percentage is contingent upon the analysis method employed. The relative sensitivity of the methods is demonstrated by the arbitrary score.

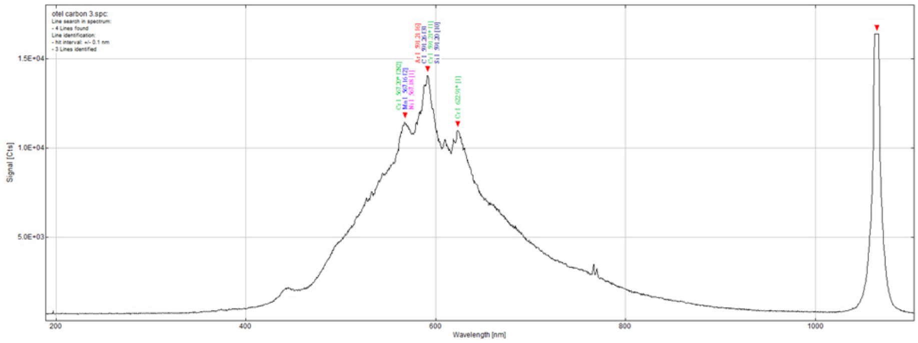

Fig. 2 – Spectrum emitted by thermal plasma in laser welding of carbon steel.

As illustrated in Fig. 2, the process of identifying spectral lines and elements in thermal plasma during laser welding of a carbon steel sample utilises a complex modular spectroscope and Mikropack SpecLine software.

Comparative tests were performed between the complex modular spectromicroscope and the Shimadzu EDX-900HS X-ray dispersive spectrometer, using welded samples of carbon steel and stainless steel (Woldman, 2020). The evaluations were performed on the same weld beads, analyzing the elements Cr, Ni, Mn, and Si. The observations that were made were as follows:

- The accuracy of Cr and Ni determination was higher for the modular spectromicroscope (error <2%) compared to the Shimadzu EDX-900HS. (4–5%).
- The detection limit for light elements (Si, Mn) was lower in the case of the modular system.
- The flexibility of the analysis included combined spectroscopy (UV-VIS, Raman, fluorescence) and topographic visualization.
- Total analysis time: ~4 min (spectromicroscope) vs. >15 min (EDX-900HS).

These results support the superiority of the modularity and analysis speed of the developed system, especially in in situ applications.

5. Conclusions and perspectives

The developed systems represent a viable and technologically superior alternative to classical EDS methods, especially in applications where fast, accurate, and non-destructive analysis is essential. The integration of real-time analysis with welding parameter control offers opportunities for the development of automated and intelligent industrial processes.

Further research is recommended on the applicability of these technologies in areas such as aerospace, energy, and additive manufacturing (metal 3D printing), where real-time composition control is critical.

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TEHNOLOGII OPTOELECTRONICE AVANSATE PENTRU ANALIZA IN SITU A CORDOANELOR DE SUDURĂ METALICE: COMPARAȚIE CU METODELE CLASICE DE TIP EDS

(Rezumat)

Acest articol prezintă rezultatele cercetărilor privind dezvoltarea unor echipamente optoelectronice portabile și modulare, destinate analizei calitative și cantitative in situ a cordoanelor de sudură metalice. Comparativ cu metodele clasice de analiză, cum ar fi spectrometria EDS, sistemele propuse oferă o precizie superioară, capacitate de analiză în timp real, portabilitate și autonomie energetică. Sunt prezentate trei echipamente brevetate: dispozitivul portabil fără sursă de excitație, echipamentul portabil cu sursă de excitație laser și spectromicroscopul modular complex. Evaluarea comparativă evidențiază avantajele acestora în ceea ce privește sensibilitatea, flexibilitatea aplicativă și capacitatea de integrare în procesele de producție.