Microstructural and spectrophotometric analysis system for metal welding processes

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Abstract. We describe an analysis system for some of the most important methods of metal welding, based on the acquisition, study and comparison of the atomic emission spectra (in the range from 250 nm to 830 nm), hyperspectral imaging between 600 nm and 950 nm wavelengths and microstructural analysis. The radiometric measurement system acquires information while the welding process is in progress and acquired data are then compared with those resulting from the subsequent microstructural analysis. It is known that the process parameters like, for example, the source power or its speed over the parts during welding, significantly affect the mechanical properties and quality of the resulting junction like hardness, porosity, presence of cracks or other damages and so on. On the other hand, these properties and, above all, the changes in the joint features due to unwanted variations in the process parameters or in the materials being welded, can be inferred by studying the microstructure. In this sense, a proper correlation between the in situ spectral analysis and the microstructural properties is of paramount importance for controlling and adjusting the parameters during the process. In line with the requirements of Industry 4.0, the system described is a study of the application of metrology in a production line, designed to increase information about the production parameters of mechanical industry without increasing costs and limiting the complexity of additional installations. In this paper we report a series of experiments performed using LASER and TIG welding systems applied to different metals. The comparison between the welding conditions acquired by the optical systems and the methods of structural analysis are the basis of a project to improve production systems and their automation.

1 Introduction

The integration between metrology and industrial processes, as required by Industry 4.0 directives, has increased significantly over the last few years. The improvement of working conditions, efficiency, product quality, reduction of environmental impact are enabled by better control of the production on processes. Metrology, therefore, assumes a fundamental role in the control of all the operations of production processes.

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One of the most widespread processes in industrial production consists in metal welding. Used in small productions as well as in large-scale productions, the welding process allows objects of considerable complexity to be quickly and cost-effectively produced with great precision. The welding processes, in addition to the consolidated quality control methods of the mechanical products obtained, offer further possibilities. As a matter of fact, a common denominator among all the welding methods used for metals is the emission of a considerable radiation originated by phenomena of excitation and relaxation of the atomic species present in the fusion bath.

In other words, the heating system used for melting and welding the metals constitutes a thermal source that is efficient enough to allow the chemical analysis of the resulting atomic emission spectra of the molten material [1, 2]. The optimal conditions of welding are determined by several factors, many of which are directly or indirectly controllable by the regulation and control equipment. Traditionally, welding stations do not have on-line process analysis capabilities, so the result of the welding process becomes apparent only afterwards.

The following sections describe a complex system for the analysis of the most important methods of metal welding, based on the study and comparison of the atomic emission spectra (in the range between 250 nm and 830 nm), microstructural analysis, and analysis of sequences of images acquired through a hyperspectral camera, operating in 600-950 nm range. The whole optical acquisition system has the possibility to acquire real time information during the welding process and the acquired information are compared with microstructural analyses performed later on.

The process parameters significantly affect the properties of the welded parts, whose features can be inferred by studying the microstructure. Indeed, it is known as the change in power source and process speed determine changes in the microstructural characteristics, which, in turn, influence important mechanical features of the joint. In this sense, a proper correlation between the in situ spectral analysis and the microstructural properties is of paramount importance for controlling and adjusting the parameters during the process.

2 Experiment setup

2.1 Welding system and radiometric acquisition system equipment

The welding test are performed using two different methods, e.g. Tungsten Inert Gas (TIG) and LASER. The laser source is a solid state one, which allows higher efficiencies than the traditional CO_2 systems, and is mounted on a robotic arm that acts automatically. All welding experiments take place in a big closed metal safety box to prevent operators from approaching during robot movements and welding operations.

The radiometric sensors are held in place by a simple mechanical arm near the sample holder. The weld seams that are made have a maximum extension of about 10 cm, so that they are always within the field of view of the optical sensor and the hyperspectral images show the details of interest with proper resolution. Fig. 1 shows the complete welding system with the optical acquisition head and the camera.

Out of the view of Fig. 1, and outside the safety welding box, a NANO-ULT3-KIT01 computer controls the optical systems for acquiring video sequences and UV-VIS spectra.

During the welding operations the spectrophotometer MAS-40 and the hyperspectral camera MQ022HG-IM-SM5X5-NIR acquire images and spectra related to the welding area. The spectra acquired by the spectrophotometer allow the qualitative analysis of the species present in the weld pool.

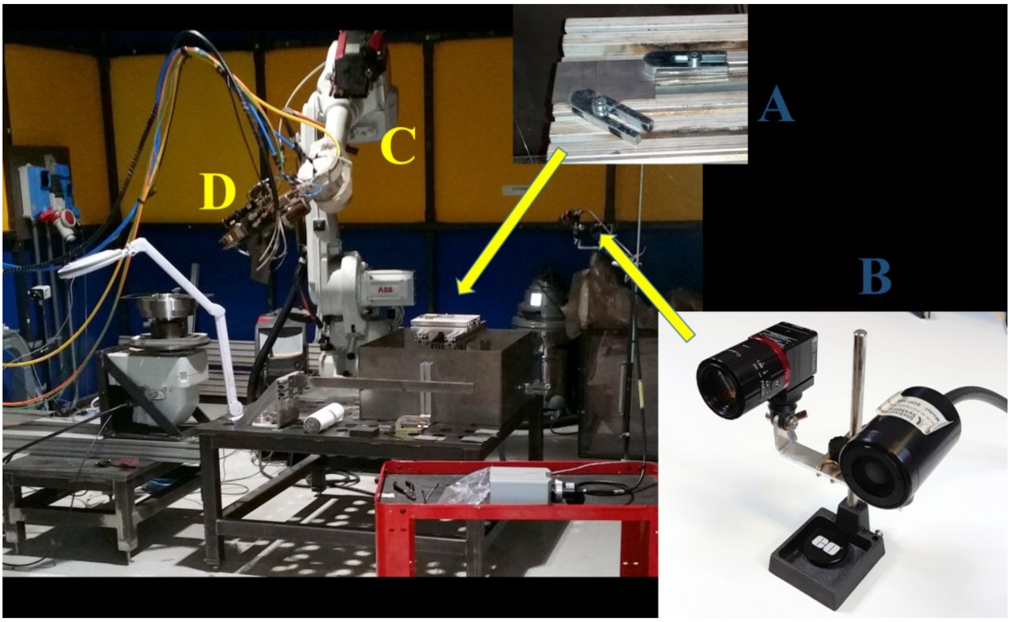

Fig. 1. Welding and radiometric equipment setup: A) sample holder with stainless steel samples; B) hyperspectral camera and spectrophotometer head; C) robotic arm; D) welding LASER head.

An example of a spectrum acquired during the welding of two stainless steel sheets is shown in Fig. 2.

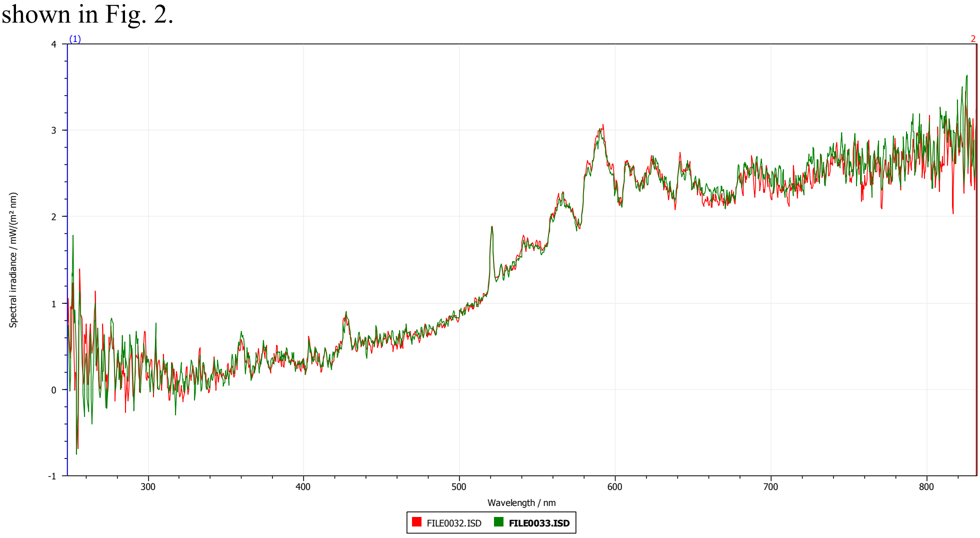

Fig.2. Spectrum acquired during the welding of two AISI 316 steel sheets sample.

The spectrum covers the wavelength range 250-830 nm with a resolution of 2.5 nm. Some peculiar spectra lines of the materials contained in the stainless steel samples are evident between 500 nm and 700 nm. The strong intensity of the radiation produced by the molten metal leads the spectrophotometer close to saturation, in particular for the longer wavelength. Moreover, it is not possible to precisely associate the spectrum to a detail of the welding scene, it is rather a sort of average of the whole radiation falling into the field of view of the optical aperture of the instrument sensor head.

Fig. 3A shows a hyperspectral image acquired by the camera in the same moment as the spectrum of Fig. 1 and Fig. 3B shows the spectra extracted from a set of selected pixels at the base of the steel melting bath. These pixels refer to different points of the welding area that are at different temperatures and carry different spectral information.

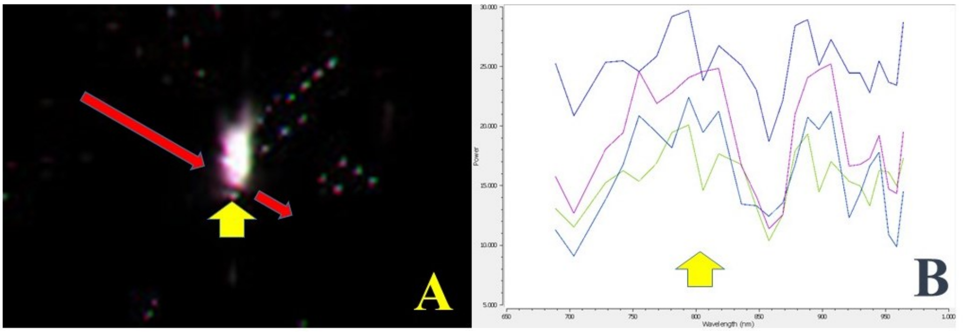

Fig. 3. a) Color reconstruction of the hyperspectral image of the welding plasma and well. The arrow highlights the pixels whose spectra are plotted in b) while the overall spectrum acquired through the spectroradiometer is shown in Fig. 2

However, the spectra extracted from the image are composed by 25 bands having a FWHM of 10 to 20 nm. Nevertheless, the entire welding process can be analysed in detail with hyperspectral technology, evaluating the spectrum of each pixel and comparing it with the micostructural analysis result performed after the completion of the welding phase.

2.2 Material samples

An austenitic stainless steel is selected for the welding test, named AISI 316. The elemental composition is shown in Table 1 (from supplier).

Table 1. Chemical composition of AISI 316 (from supplier)

C %	Si%	Mn%	P%	S%	Cr%	N%	Ni%	Mo%
0.07 ±0.01	1.00 ±0.05	2.00 ±0.04	0.045 ±0.005	0.030 ±0.005	16.5-18.5 ±0.20	0.11 ±0.01	10.0-13.0 ±0.15	2.0-2.5 ±0.10

2.3 SEM analysis

Brinell hardness is measured according to UNI EN ISO 6506-81 standard, applying a load of 187.5 kilograms for 30 seconds and then measuring the diameter of the resulting round impression. A Scanning Electron Microscope (SEM, Zeiss Evo 50 XVP with LaB6 source) is used for studying the samples morphology. The instrument is endowed with detectors for secondary and backscattered electrons collection, and with Energy Dispersion Spectroscopy analyser for the detection of material elements. All the samples were observed in high vacuum mode. SEM analysis is performed both on the welded area and around it.

3 Preliminary measurement results

The AISI sample welded using TIG is shown in Figure 4.

Fig.4. AISI sample welded by TIG

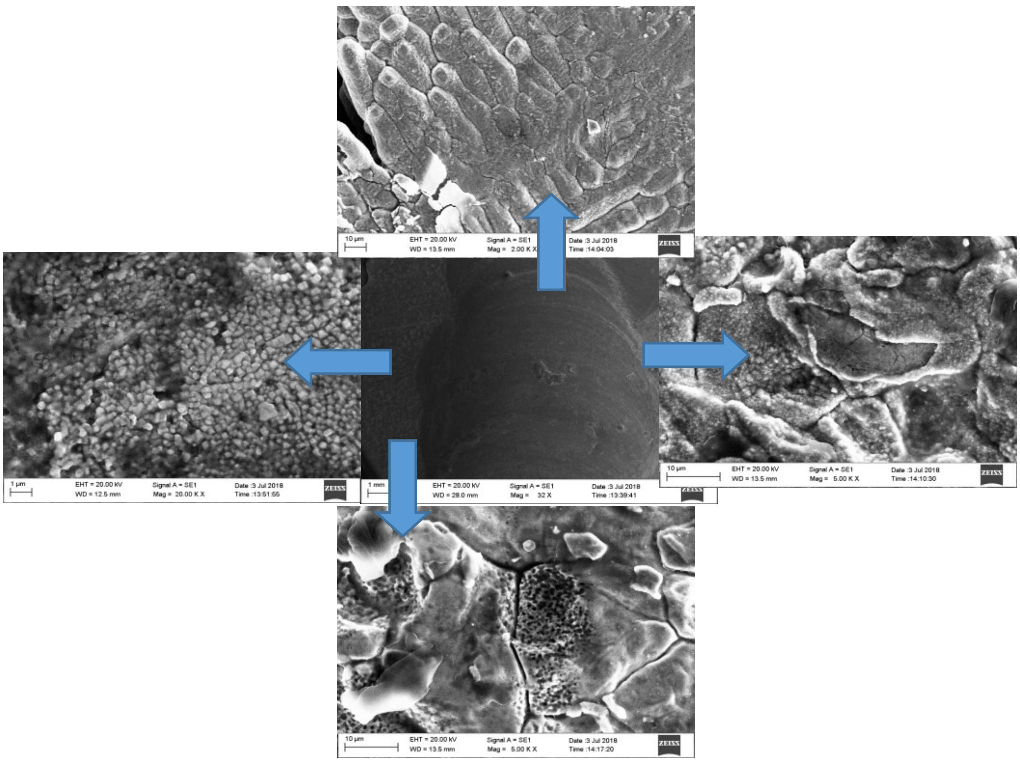

Fig.5. SEM analysis of the welded and external part of AISI 316 sample.

The mean value of the Brinell hardness of the welded area is similar to that of the external part, around 154 HB, lower than the nominal one, that is about 215 HB. As for the morphology, some micrographies are presented in Fig. 5.

The central part of Fig. 5 shows a low magnification micrograph, while the surrounding images are high magnification micrographs collected in the area marked by the corresponding arrows. A high variety of microstructures can be observed, both inside the welded area, that underwent a remelting as a consequence of the TIG process, and in its proximity. Such diversity is probably related to the thermal differences along and around the welded area, causing remelting and quick recrystallisation, together with oxidation phenomena. The observed microstructural variety is interesting for the purpose of the present paper, since it represents an idea of how this features is strictly correlated to the welding process parameters. In the case of the TIG, employed under uncontrolled conditions, the phenomenon is quite evident, then it can be supposed that the possibility to find a strict link between laser parameters and microstructural properties could be concrete.

Conclusions

We have described an experimental setup for evaluating the quality of welds made using TIG or LASER technology. The proposed analysis takes place in two distinct phases, one in line during the welding process, the second after the end of the process. The online analysis consists in the simultaneous acquisition of the emission spectrum by means of a spectrophotometer and a multispectral camera. The second step consists in the microstructural analysis. Cross-analysis of data provided by the systems involved gives important information on the quality of the joints and allows improvement and optimization of the parameters of the welding machines. The future developments of the described technology will consist in the complete automation of the radiometric acquisition systems and in the development of a database of reference spectra correlated to the microstructural analysis of the metals used in the welding field.

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