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Automatic visual monitoring of welding procedure in stainless steel kegs

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ABSTRACT

In this paper a system for automatic visual monitoring of welding process, in dry stainless steel kegs for food storage, is proposed. In the considered manufacturing process the upper and lower skirts are welded to the vessel by means of Tungsten Inert Gas (TIG) welding. During the process several problems can arise: 1) residuals on the bottom 2) darker weld 3) excessive/poor penetration and 4) outgrowths. The proposed system deals with all the four aforementioned problems and its inspection performances have been evaluated by using a large set of kegs demonstrating both the reliability in terms of defect detection and the suitability to be introduced in the manufacturing system in terms of computational costs.

1. Introduction

Welding processes are used in various industrial applications, like aerospace, automotive and food storage, among others [1–3]; the analysis of steel welded elements is critical because their integrity ensures safety in structures and machine elements. For this reason, quality requirements, in terms of geometry and presence and typology of flaws, have been deeply standardized [4–6]. The continuous improvement of the welding technologies - for example refer to arc and laser welding - has led to well consolidated and reliable results in industry shifting the focus of the research community on quality control and monitoring in welding processes. In modern industrial devices the energy transmission during laser welding is mainly carried out by the laser beam. The continuous interaction between laser beam and welding material is extremely dynamic, and is one of the key factors in the welding quality. Other critical factors are the temperature of the material, that rapidly heats up, and the subsequent effects of vaporization and reflection/absorption of the laser beam; in addition, external factors like vibrations of the materials, and variations in the tension of the laser can produce unreliable welding seams.

Direct visual evaluation by humans is still the most frequent technique in inspection but, this way, the detection of imperfections and flaws is delegated to the skills of human inspectors. Some inaccurate instruments are, sometime, used for this purpose, to measure the width of the weld, its shape and deep. But the inaccuracy of the instruments, and their human skill based usage make this procedure still unsteady. In addition, the above procedures are time consuming and require additional costs not always sustainable.

An automatic inspection of welding quality, most in hardly accessible surfaces, is mandatory to ensure a high level of industrial production, with the goal of minimizing wastes and providing a continuous feedback to the assembly chain. Automatic inspection is a very important field of image processing, and has been largely used in many different contexts [7,8].

Usually, the common approaches to validate welding quality are performed by means of off-line destructive (macrographs) and non-destructive testing (NDT) (e.g., X-ray, ultrasounds, penetrant liquids, magnetic particles). Disadvantages of traditional non-destructive techniques are summarized in Table 1.

The use of an on-line, real-time welding monitoring system able to detect instabilities affecting the welding quality and even to supervise the process by preventing occurrences of defects would be of a great asset [9].

Automatic vision-based systems are quickly growing in this application field; however, they usually have the goal to detect and track the welding seam, instead of detecting defects.

In [10] a seam-tracking system able to track the fillet joint satisfactorily is proposed; it is based on a self-tuning fuzzy controller (SFC), and authors demonstrate that it performs better than that based on regular fuzzy controller (RFC); moreover, they assert it is more robust to disturbances than conventional PID controller. Control strategies for a process of rapid manufacturing of aerospace components is proposed in [11]. This system uses different kinds of sensors, and a software interface has

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Table 1
Main disadvantages of traditional non destructive techniques.

	X-rays	Ultrasounds	Penetrant liquids	Magnetic particles
Expensive	✓			
Safety hazard	✓			
Time consuming			✓	✓
Spurious indications		✓		✓
Require operator Skill and integrity	✓	✓		
Difficult interpretation of results		✓	✓	✓

been developed to study and control the shaped metal deposition (SMD) process. A good overview about laser welding monitoring can be found in [12]. In [13] Gao et al., presented a method to detect the deviations between the laser beam focus and the weld seam position during high-power fiber laser welding. An IR-sensitive high-speed camera is used to catch the molten pool images. IR-technologies are used also in [14–16].

Another commonly used approach for defect detection is based on ultrasonic imaging. An application to aerospace materials was proposed in [17], while an approach for welding inspection has been recently proposed in [18].

Radiometric analysis is the topic of the algorithm proposed in [19]: Boaretto and Centeno introduced a method for automatic detection and classification of defects in radiographic images of welded joints obtained by exposure technique of double wall double image (DWDI).

Thermographic techniques are also exploited for this goal [20] and they are the core of the approaches proposed in [21] as in-situ nondestructive test for welds, and in [22] for the detection and measurement of cracks. Another recent work based on image analysis algorithms, that proposes a novel visual weld recognition method using two directional lights, has been proposed in [23].

A different approach is proposed in [24]: it focuses on identification and classification of different kinds of surface defects generally encountered during the friction stir welding (FSW) process using digital image processing techniques.

In [25] Runnemalm and Hyun proposed an approach that evaluates both the thermal and the mechanical error distribution. It is combined with a hierarchic meshing strategy using a so-called graded element. The error indicator together with the known movement of the local heat source is used to predict areas of refinement.

A system for welding quality evaluation of straight seam pipe using image features and Back Propagation Neural Network has recently been proposed in [26].

A detection system (using image analysis techniques) has been proposed in [27] to detect defects in stainless steel material. Three imaging technologies based on UVV visual sensor (wavelength 230 nm–395 nm), auxiliary illumination visual sensor (wavelength 976 nm), and X-ray visual sensor were used to obtain images of welding status. Welding images captured were quantified by way of image processing technology and a prediction model concerning welding status was established by using a Feed-forward Neural Network and a Support Vector Machine classifier. Unfortunately, due to its geometry the above system cannot be exploited for the problem addressed in this paper since, it cannot be inserted inside the kegs for inspection due to the restricted diameter of the annular aperture.

In [28] a study on a structured light system applied to welding inspection is proposed. The authors propose a procedure for the extraction of fundamental quality parameters to assess the quality of welds, which starts from the three-dimensional model remotely obtained with a structured light system. This procedure enables the extraction of metric information about the thickness and the angle deformation of the welds for each point of the weld.

Recently, a vision based system has been used for the detection and tracking of the welding seam [29]. This approach uses Kalman filter to predict the position of the seam, and the final goal is a qualitative description of the welding seam profile, that can be seen as a sequence of segments.

From the literature emerges that systems for inspection of welding process in dry stainless steel kegs are not yet implemented. Stainless steel kegs are often used for food storage, their quality is a priority to preserve also human health and then automatic systems for monitoring their production processes are highly recommended, in order to avoid dependence from personal human skill, experience and fatigue in highly hostile conditions. Unfortunately, monitoring the welding process in stainless steel kegs is more complex than other cases since, the welding has to be monitored from the inner side of keg, where critical conditions arise (among all no natural light, small spaces, reflections when artificial lighting is provided).

This paper proposes a system for automatic visual monitoring of welding process in dry stainless steel kegs for food storage. The proposed visual machine consists of a measuring probe (MP) equipped with two cameras and a mechatronic system for both probe and keg motion. Movements are controlled by a Computer Numerical Control (CNC) and the acquired images through an INTEL i7 based laptop (PC).

The proposed system, in order to monitor the internal weld bead, deals with different problems that can arise during welding process: residuals on the bottom (resulting from welding, pickling, passivation, cleaning or drying processes), darker weld (due to impurities /overheating/porosity/dirty base and/or filler metal), excessive/poor penetration (due to discontinuity of welding parameters) and outgrowths (due to shape irregularities in the metal parts to be welded). Automatic inspection performances have been evaluated by using a large set of kegs, which demonstrates both reliability in terms of defect detection and the suitability to be introduced in a manufacturing system in terms of computational costs.

In the light of the analysis of the state of the art, the main contributions of the paper are:

- it represents the first attempt to monitor welding process in stainless steel kegs for food storage;
- it proposes a system able to work in critical conditions (inside the kegs) since it does not use structured light making exploitable miniaturized hardware for data acquisition;
- it allows the inspection of inner weld bead (whereas existing solutions focus only to the monitoring of external welds);
- it faces both weld following and detection of several types of welding defects;
- it also deals with the detection of possible residuals on the bottom;
- it is made by technological solutions which could be easily adapted to different hardware configurations or operative conditions (i.e. kegs having different size).

The rest of the paper is structured as follows. Section 2 describes the hardware components of the monitoring machine with also a quick report about the technological solutions for movements and synchronisation processes. Section 3 details implemented algorithmic strategies to monitor the welding process. The effectiveness of the solutions is then demonstrated in Section 4 where the properly built datasets are described (Section 4.1) and then quantitative results are reported in Section 4.2 with a set of preliminary tests for detector threshold selection and system assessment. Finally, Section 5 concludes the paper.

2. The monitoring machine

The proposed monitoring machine (schematized in Fig. 1) has been designed to be used in the manufacturing process to build stainless steel kegs for food storage.

In the considered process the upper and lower skirts are welded to the vessel by means of Tungsten Inert Gas (TIG) welding.

The TIG (Tungsten Inert Gas), or GTAW (Gas Tungsten Arc Welding) according to the American Welding Society terminology, is an arc welding process with an infusion electrode (made of tungsten), carried