Defect detection of the weld bead based on electromagnetic sensing

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Abstract. Characterization of flaws of weld bead is imperative for high-quality welding. Methods of weld bead inspection include radiographic, ultrasonic and vision inspection. However, such methods are costly and time consuming. The proposed sensor is light, low-cost and fast. This paper summarizes our work on weld bead monitoring and defect detection using an electromagnetic sensor. Measurements are acquired in the form of S-Parameters, specifically measuring changes in the reflected coefficient $S_{11}$. The weld bead is scanned using the sensor and any form of weld bead defection such as undercutting and excessive penetration is detected and identified.

1. Introduction
The increasing importance of the integrity of structures has led to the development of new and more sensitive non-destructive evaluation methods for welding technology. Non-destructive testing/evaluation (NDT/NDE) techniques have been used for over 30 years. These techniques are analysis techniques used in science and industry to evaluate the properties of a material, component or system without causing damage to the samples.

Currently, weld bead inspection methods that are commonly used include the following: radiography, ultrasonic, vision, magnetic detection, eddy current, and acoustic measurements. However, these methods have limitations, are bulky, costly and time consuming. Many of these defects associated with weld beads are caused by the welder, because of either a lack of care or a lack of skill, and emphasize the need for adequate training. A simple non-destructive examination technique that is sometimes overlooked is that of a thorough visual examination by a suitably trained and experienced welding inspector. Visual inspection is easy to apply, quick, and relatively inexpensive. Visual testing equipment includes rulers, fillet weld gauges, squares, magnifying glasses, and reference weld samples. Such an examination will identify only some defects and will be time consuming and the need for a fast and reliable method is therefore a necessity.

A radiographic test is a non-destructive method that reveals the presence and nature of discontinuities in the interior of welds. This test makes use of the ability of short wavelength radiations, such as X-rays or gamma rays, to penetrate material that is opaque to ordinary light [1-3]. Ultrasonic testing is a non-destructive method of detecting the presence of internal cracks, inclusions, segregations, porosity, lack of fusion, and similar discontinuities in all types of metals. It can be used as the sole type of inspection, or it can be used with other types of testing. It is often used in conjunction with radiographic testing because it determines the depth of the defect from the test...
surface. Ultrasonic inspection is widely used in weld production with flexible operation and low cost [4-6]. Main disadvantages are lack of visual record and requirement for high skilful operators for defect recognition. A number of researchers have used indirect monitoring systems to link elements such as welding pool vibrations, superficial temperature distribution and acoustic emissions to size, geometry or welding pool depth [7]. Other researchers showed that it is possible to detect some interference and to assess the welding quality by measuring the sound and optical emissions as infrared band [8-10].

The advance of high speed computers and cameras has increased the use of vision systems in many applications such as weld bead monitoring. Vision systems are particularly useful in hazardous and hard to reach environments since they can be operated remotely. One of the major advantages of using a visual sensing technology to monitor welding operations is the fact that the visual sensor is not touched or interfered with during the welding process and visual images of the weld pool contain more abundant and accurate information about the welding dynamics. B. M. Abdullah developed a vision system for monitoring of arc welding in real-time. The system uses a camera, an illumination source and a combination of filtering and illumination-camera synchronization techniques. Arc light (noise) is totally eliminated and a substantial amount of information is obtained in real-time, e.g. metal transfer and weld pool geometry [11, 12]. Figure 1 (a) shows the block diagram of the main components of the vision system. Meanwhile, figure 1 (b) shows an image of a TIG welding process obtained by the system in real-time. As can be seen the interference from the arc light is totally eliminated and the image is of very high quality.

![Figure 1. Block diagram of weld monitoring vision system (b) Image of a TIG welding process obtained in real-time.](image)

### 2. Theory

Electromagnetic (EM) waves are waves of energy that travel through a vacuum at the speed of light. They consist of two primary components, an electric (E) field and a magnetic (H) field. The electric field and magnetic field oscillate in phase perpendicular to each other and perpendicular to the direction of energy propagation. Analysis using microwaves is non-ionising with a low power output of 1mW (0dBm). The multi-parameter nature of wide band microwave analysis can provide unique signal spectrum signatures. Typically these would be in the form of a reflected signal (reflection coefficient) $S_{11}$, which are influenced by parameters such as conductivity and permittivity.

Figure 2 shows a block diagram of a typical microwave system. Reflected signal is of paramount importance in this study. A microwave sensing system is constructed of a microwave sensor, an oscillator and a detector. The purpose of the oscillator is to provide a microwave signal to the sensor, while the detector measures the response of the sensor. This functionality is embodied in a typical vector network analyser (VNA) such as the Rohde and Schwarz ZVL 6 which is used throughout this study.
The characteristic impedance of a typical transmission line is highly dependent on key parameters of the transmission line such as, resistance, conductance, capacitance and inductance. From the perspective of a microwave device (i.e. a sensor or antenna) which is exposed to a real world environment, changes which occur in this environment can be measured as they influence the device’s characteristic impedance, and therefore its response at varying frequencies.

![Diagram of a typical microwave system](image)

**Figure 2.** Bock diagram of a typical microwave system

### 3. Experimental Methodology

For this work a large rectangular steel plate with dimensions of 100cm by 50cm and a thickness of 2.0mm is cut into two pairs of rectangles each 25cm wide and 50cm long. Each pair is welded together as seen in figure 3. Each plate is welded with the intention of producing a weld bead with a variety of defects. Plate A contains less defects than plate B. The welding bead in plate B has more craters as can be visually seen due to improper weld termination. Both plates suffer from spatter due to metal drops expelled from the weld and sticks near the weld bead.
Figure 3. Two identical steel plates are cut then welded together (a) Plate A, minimum defects (b) Plate B, maximum defects.

A patch antenna operating at microwave frequencies (2.0GHz) is chosen as such devices are flat with a reasonably large contact area. They can be pressed uniformly against the welded piece of metal. A software model is constructed using the Ansys High Frequency Structure Simulator (HFSS) package to ascertain appropriate dimensions for the patch sensor, and this model is shown in figure 4. Once appropriate dimensions are attained, the software model is then constructed on double sided FR4 substrate. Only the top layer is routed, the under layer is left untouched and acts as a ground plane. The patch has a single SMA connector to allow measurements to be taken using a Vector Network Analyzer (VNA) via a coaxial connection. All measurements are acquired in the form of S-Parameters, specifically measuring changes in reflected signature (electromagnetic wave spectrum) back from the antenna when interacting when different media (this is commonly denoted $S_{11}$).

Figure 4. (a) Ansys HFSS model showing electric field and (b) Constructed patch sensor.

4. Results and Analysis
Figure 5 shows the reflection coefficient measurements for both plates. Each plate is divided into sections and each section is scanned with the sensor. Figure 5 (a) shows the spectrum response when the sensor is used to scan a weld bead on plate A. The different peaks correspond to different defects
present in each section of the plate. Meanwhile, figure 5 (b) shows the spectral response when the sensor is used to scan the weld bead on plate B.

As we can see from the results shown, defects elicit a change to the frequency response and each section of the plate where there is a defect produces its own unique signature. Each defective section has a distinctive frequency shift as can be seen. This is a significant result as prediction of the presence and type of defects can be easily determined.

Figure 5. Spectral response of the constructed patch sensor highlighting the principle of weld bead defect detection. Peak shifts corresponding to different defects.
5. Conclusion
There are a number of NDT methods available for inspection of weld bead. However, many of these are expensive and time consuming. The results obtained so far using the patch sensor show that weld bead defects can be detected and identified using an electromagnetic sensor. The sensor scans the surface of the weld bead for defects. Defects in the weld bead elicit a change in the sensor spectral response. The results show that the size and type of defects give rise to a unique sensor signature. Each defect has its own signature and hence an appropriate action can be taken to rectify the defective section. Thus the challenge for the subsequent phases of this work is to develop a system which can be applied and be robust enough to operate in the toughest of environments without an operator.

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