

# DEFECT CHARACTERIZATION IN TAILOR WELDED BLANKS USING AN EDDY CURRENT AND HARMONIC FLUX LEAKAGE INTEGRATION

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## ABSTRACT

The development of a novel laboratory-based NDT system for the inspection and evaluation of automotive Tailor Welded Blanks (TWB) is presented. This NDT system comprises both Eddy Current and Magnetic Flux Leakage techniques in the same device; therefore, within the framework of the project, it has been necessary to develop and integrate both systems. This new Non-destructive inspection device has been tested to detect and classify artificial imperfections in TWB. It can be shown that different defects lead to different signal pattern acquired from this NDT system; therefore, the potential of the system to the detection of welding defects on a laboratory environment is shown.

**Keywords:** Non Destructive Testing, Magnetic Flux Leakage, Eddy Current, Tailor Welded Blank, inspection, evaluation.

## 1. INTRODUCTION

The EU is the largest automotive production region in the world and the industry comprises 6.5% of the manufacturing sector in the European Union. Direct employment by the automotive industry stands at about 2.2 million employees, while the total employment effect (direct and indirect) is estimated to be about 12 million [1]. Tailor Welded Blanks (TWB) are very popular in car manufacturing [2] because it can enable product and manufacturing engineers to “tailor” the blank so that steel’s best properties are located precisely within the part where they are needed. This process not only reduces the weight of the finished part, but also can be used for part integration, thereby eliminating many reinforcements and stiffeners [3].

The quality of the weld in a TWB is critical due to the posterior forming operations; therefore, the quality requirements for TWB are getting more important. At present, ISO (International Standards Organization) and North American ASP (Auto-Steel Partnership) specify the TWB quality

standards [4]. These requirements demand the development of a reliable quality control to assure the quality of the welded joints. Therefore, different NDT techniques are being developed to assure the quality of TWB joint, mainly electromagnetic techniques, like EMAT (Electromagnetic Acoustic Transducer) [5-6], EC (Eddy Current) [7] and MFL (Magnetic Flux Leakage) [8-9].

However, each one of the feasible non destructive techniques used to inspect the welds have their limitations and the industry do not have a unified criterion about the requirements. The following paper examines the development of a NDT system that comprises Magnetic Flux Leakage (MFL) and Eddy Current (EC) techniques in a novel and economical system to evaluate the quality of the weld. The development of a laboratory set up is described and the ability of the system to detect different defects is demonstrated. In addition, a discussion of signal processing, automatic feature extraction and classification of defects is presented.

## **2. EXPERIMENTAL METHODS**

The proposed system is a low-cost NDT inspection system based on the measurement of Eddy Currents (EC) and Magnetic Flux Leakage (MFL) over TWBs.

### **2.1. MFL TECHNIQUE**

A typical MFL inspection system comprises a magnetic source, a magnetic circuit which couples the magnetic flux in the ferromagnetic sample that it is magnetized to a point closed to saturation in the BH curve. The presence of a defect causes leakage of the magnetic flux due to fact that the reduction of the cross-sectional thickness of the sample cannot accommodate the flux carried by the thicker portion. This leakage flux is measured as a function of spatial position on a sample, with a Hall Effect sensor and a signal acquisition device. The sensitivity of the sensor system depends on the operating point in the BH curves of the sample and Hall sensor position. In case the operating point on the magnetic saturation curves is too low, the part would not be magnetically saturated in the region of defect, so the acquired signals become weak. In case the operating point is too high, the change of the magnetic flux in the defect region would be small, so the change of the sensor signal becomes weak [10]. In this work, the operating point of the magnetic system was selected in order to maximize the change of the magnetic flux in the region of a defect through a magnetic characterization of the sample.

MFL technique is one of the most widely used for inspection in the gas pipeline industry. However, welds in TWBs impose new restrictions and requirements because of the geometrical characteristics of the joint. On one hand, due to the small size of the joint of the laser welding, the inspection

technique should enable to detect a defect with a high spatial resolution. On the other hand, the asymmetric cross-section ensures that the background magnetic flux will be high and uneven across the weld region.

## 2.2. EC TECHNIQUE

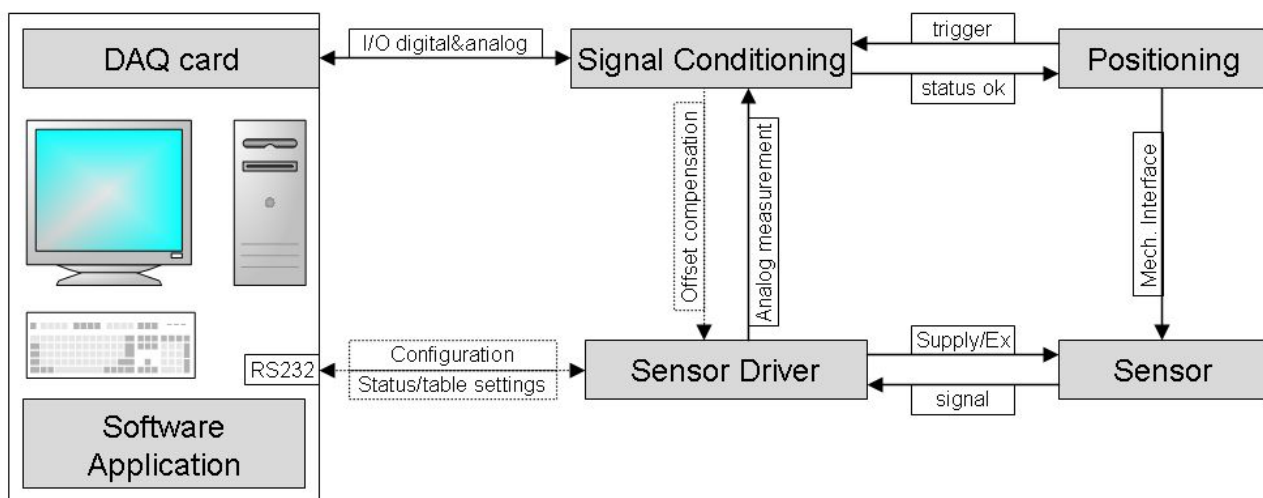
The Eddy Current inspection technique is based on the principle of electromagnetism as the basis for conducting examinations. When alternating current is applied to the conductor, a magnetic field develops in and around the conductor. If another electrical conductor is brought into the close proximity to this changing magnetic field, current will be induced in this second conductor. Eddy currents are induced electrical currents that flow in a circular path [11].

Eddy Current instruments measure the electrical impedance of the coil. If a defect or imperfection is introduced in the tested material, eddy currents are modified and the impedance of the system will change.

Some of the advantages of eddy current inspection include: Sensitive to small cracks and other defects, detects surface and near surface defects, inspection gives immediate results, minimum part preparation is required and test probe does not need to contact the part. Nevertheless, some of the limitations of eddy current inspection include: Only conductive materials can be inspected, surface must be accessible to the probe, surface finish and roughness may interfere, reference standards needed for setup and depth of penetration is limited.

## 2.3 EXPERIMENTAL SETUP

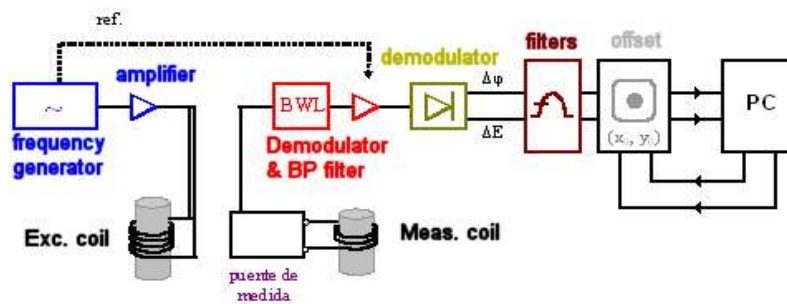
A schematic diagram of the device is shown in Figure 1. The system comprises both an EC device and a MFL device.



**Figure 1. Schematic diagram of the NDT system.**

The EC device (Figure 2) comprises the electronics for adjusting and sending excitation to the sensor probe and collects and processes the sensor response to obtain two main parameters: phase and amplitude. The electronics includes the following elements and features:

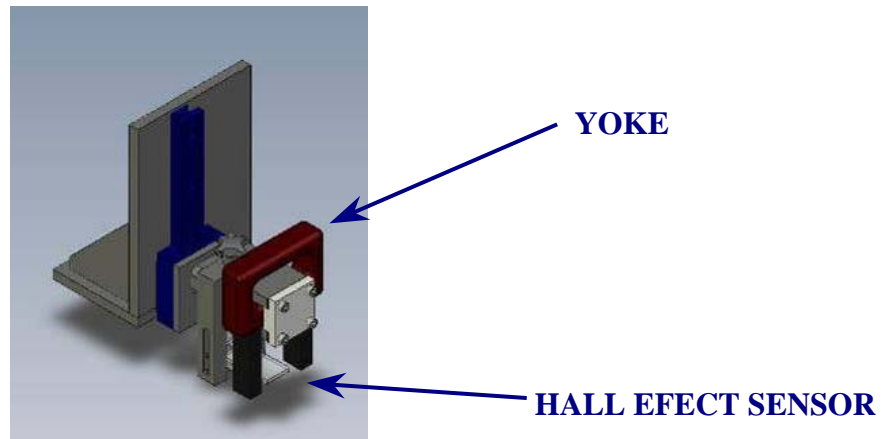
- 16C641 PIC microcontroller.
- AD9835 frequency generator (10Hz-10MHz).
- RS232-C interface.
- Adjustable output attenuation network.
- Adjustable gain output.
- Selectable output impedance, probe select.
- Different digital inputs.
- Signal conditioning of probe secondary signal response.
- Analogue output proportional to amplitude and phase.



**Figure 2. EC device developed.**

The result is a low-cost compact system that could be used for both automated and manual inspection with a working frequency in the range of 100Hz to 1MHz. The commercial probe used in the work was an absolute probe, which can detect both gradual and edge defects, PLA 33-11 from Röhmann GmbH which provide a good response between 3kHz to 500kHz with a sensor area of 10mm of diameter.

The MFL device (Figure 3) consists of a magnetic yoke of two legs with a length of 130mm and a height of 120mm coupled to an NdFeB permanent magnet. The sensor platform was placed in the middle of the yoke.



**Figure 3. Schematic diagram of the NDT system.**

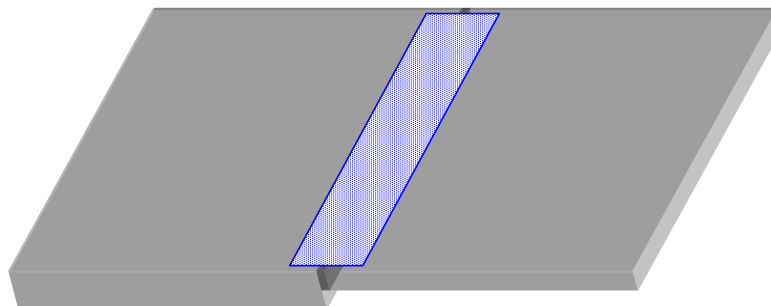
The magnetic sensor used in this work was a Honeywell SS490 series which provide a linear response in the range of -670 to 670 gauss with a sensitivity of 3mV/G.

#### **2.4 ACQUISITION SETUP**

The acquisition setup consists of a computer with an acquisition board (NI-PCI6121), signal conditioning electronics and electronic drivers connected to the sensors for the inspection of TWBs with the aid of a positioning device (2-axis Föhrrenbach positioner system).

Furthermore, it has been necessary to develop a PC software for the analysis of the acquired signals, with a special emphasis to graphical representation, data filtering and data file set managing. This software application runs over a standard PC under Microsoft Windows XP™ and Microsoft Windows Vista™, and has been developed under LabwindowsCVI™, a C-programming language integrated development environment (IDE), from National Instruments.

To inspect the welded joint of the TWB it has been necessary to move the NDT system along the welded joint, in order to cover all the length of the joint. Figure 4 shows the area covered by the inspection device.



**Figure 4. Area covered by the inspection device.**

According to this inspection strategy, the area of the Unit Under Test (UUT) is calculated and two data-matrixes, which contain average and standard deviation of all measurements, are created. Each cell of the matrixes represents a square portion of the inspected area, and size is calculated according to sensor signal bandwidth. These matrixes are used in feature extraction of the defect.

To analyze the TWB, the software build maps containing the difference between the Unit Under Test and the signal pattern of the good seam (UUT-Control) or the relative distance of the UUT from the pattern of the good seam, using as unit the standard deviation of the good seam.  $((\text{UUT-Control})/(\text{stdControl}))$ . Through a tolerance band, different welded defects can be detected and identified.

## *2.5 TESTED SAMPLES*

In order to test and evaluate the developed NDT system, different laser welded samples with artificial imperfections were produced by a 4,4 kW diode pumped Nd:YAG laser from Rofin. The samples with artificially engineered imperfections were made using different zinc coated sheets steel with a length of 150mm with 1.6 and 0.9mm of thickness, respectively.

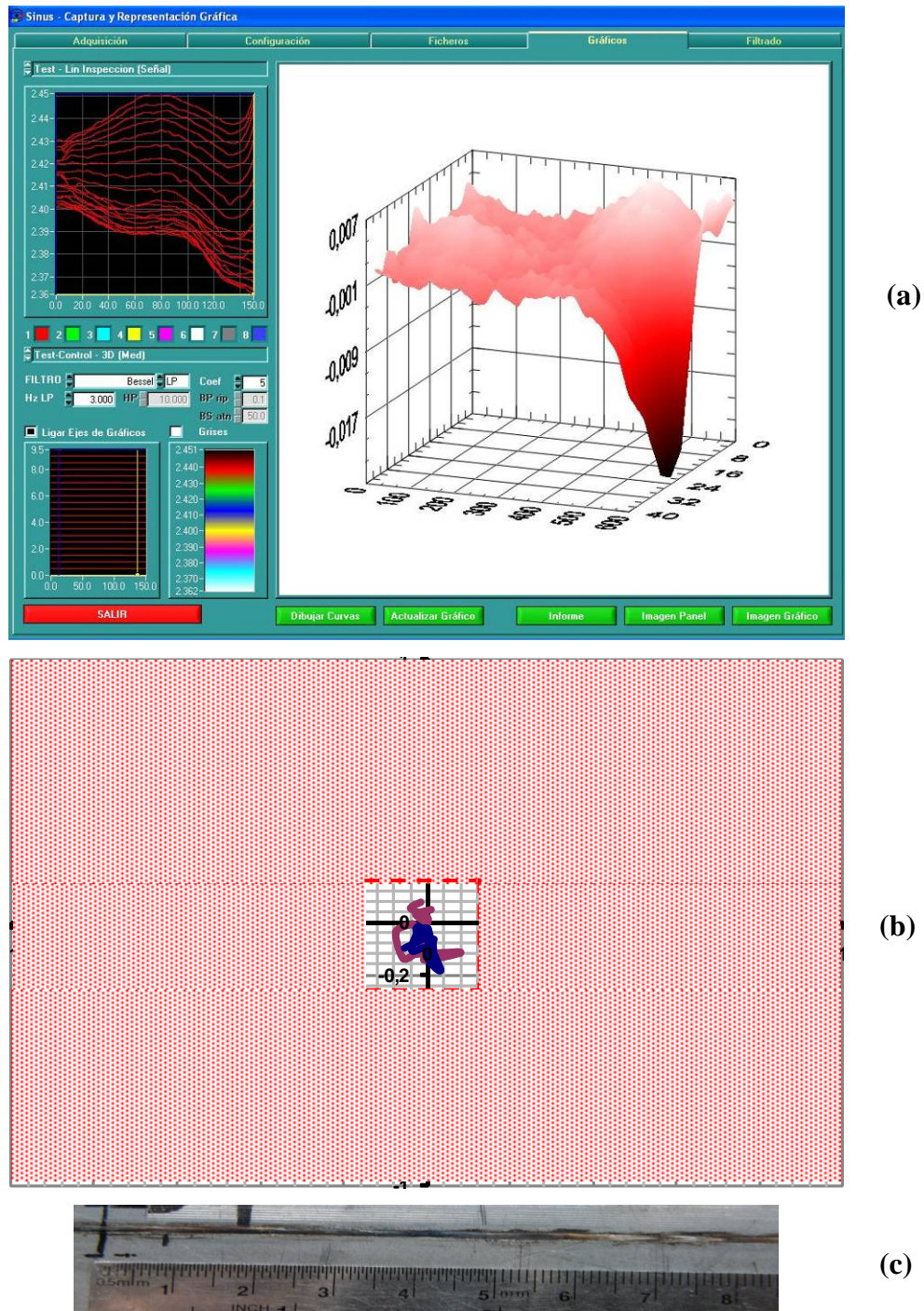
Samples with defects have been manufactured by changing laser welding parameters, such as laser power, focus position, gas shielding conditions, or by deforming the metal sheets in order to test the reliability and sensibility of this NDT system.

## **3. MAIN RESULTS**

### *3.1. GOOD SEAMS*

Initial tests were made to achieve the signal pattern of the good seams, acquired both by the Hall Effect sensor and by the Eddy Current probe. These good samples were manufactured with the following parameters: Laser Power: 2.7 kW, welding speed: 70mm/s, focal point: +4mm, offset: 0.14mm on the thick sheet.

Figure 5 (a) shows both the raw data of a particular good weld, acquired by the MFL system, and the deviation of this measurement compared to the signal pattern of the good seams. Analyzing the figure it is observed that the difference between the measurement and the pattern is not significant, except for the edge effects due to the end of the weld. Figure 5 (b) shows, represented in the impedance plane diagram, the raw data acquired by the EC probe defining, therefore, the area of the good seams. Figure 5 (c) shows the digital photo of good sample.



**Figure 5. (a) Raw data obtained by the MFL technique. (b) Impedance plane representation obtained by EC technique. (c) Digital picture of a good seam.**

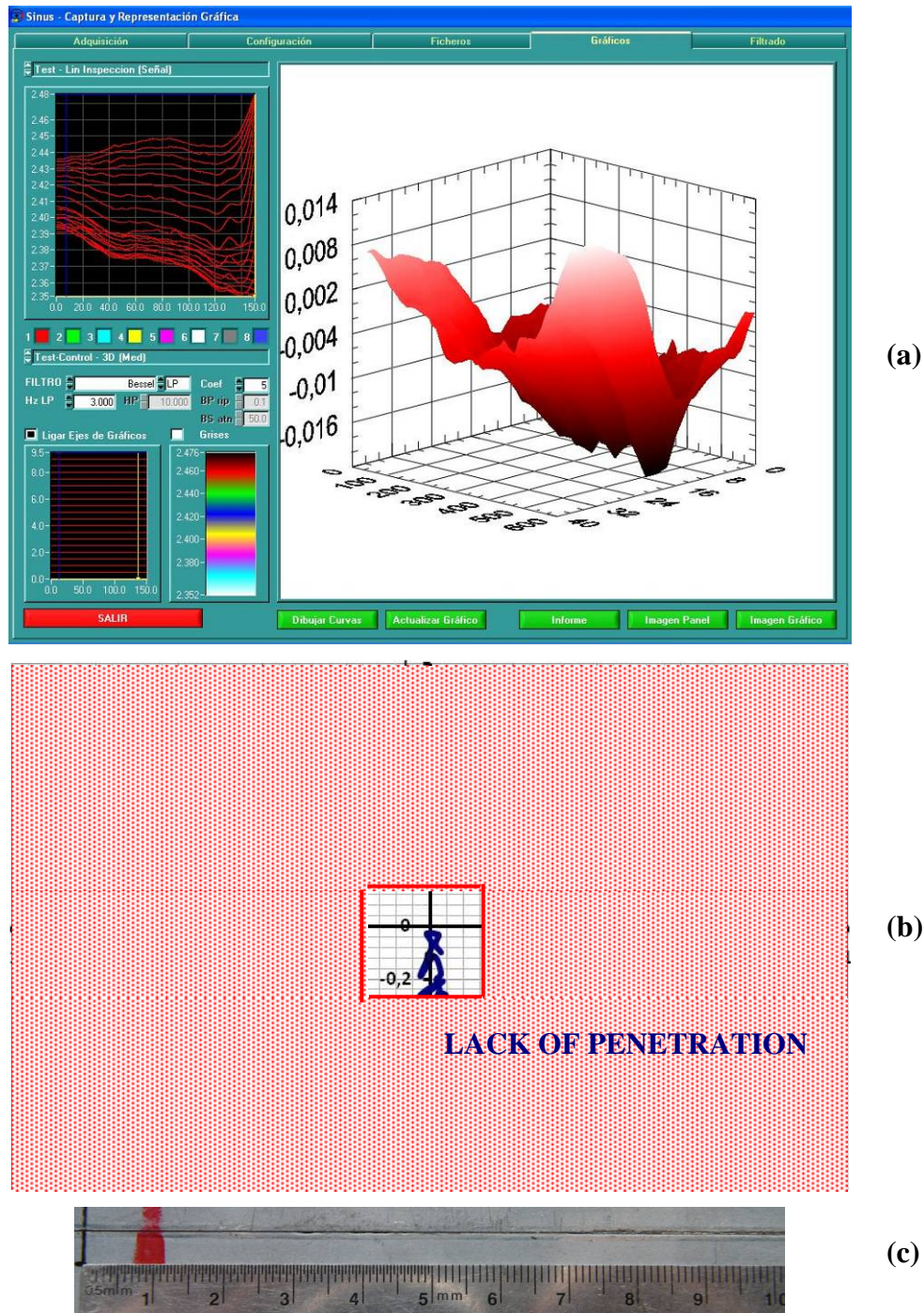
### 3.2. ARTIFICIAL DEFECTS

Only once the signal pattern of good seams is obtained and validated, it is possible to work in the detection and evaluation of the different artificial defects. These different defects have been manufactured by changing laser welding parameters, such as laser power, focus position, gas shielding conditions, or by deforming the metal sheets in order to test the reliability and sensitivity of the developed NDT system. The different signal patterns obtained from both Magnetic Flux Leakage and Eddy Current techniques, for each particular defect, are detailed next.

### 3.2.1 Lack of penetration:

This defect was manufactured by increasing the welding speed in order to obtain a decrease in Heat Input and, therefore, a decrease in the penetration depth capacity. Figure 6 shows the results obtained by the NDT system, for a particular lack of penetration defect when the welding speed was increased from 70 to 150mm/s. Figure 6 (a) shows the raw data and the deviation for this particular defect, compared to the good seams pattern previously obtained by the MFL technique. The results show that this defect causes a slight decrease, only on the joint, of the signal obtained by the Hall Effect sensor. Figure 6 (b) shows the impedance plane representation of this defect obtained by the EC technique. As with MFL technique, this defect causes a slight variation of the signal from the good seams pattern. Figure 6 (c) shows the digital photo of good sample.





**Figure 6. (a) Raw data for a lack of penetration defect obtained by the MFL technique. (b) Impedance plane representation for a lack of penetration defect obtained by EC technique. (c) Digital picture of a lack of penetration defect.**

### 3.2.2 Mismatch:

This defect appears due to a misalignment of the sheets of the TWB. The defect was manufacture by raising the thicker sheet using a gauge of calibrated thickness. Figure 7 shows the results obtained by the NDT system developed in this project, for a particular mismatch defect when the ticker sheet was raised 0.5 mm. Figure 7 (a) shows the raw data and the deviation for this particular defect, compared to the good seams pattern obtained previously by the MFL technique. The results

show that this defect causes a slight decrease, only on the joint, of the signal obtained by the Hall Effect sensor. Figure 7 (b) shows the impedance plane representation of this defect obtained by the EC technique. Contrary to the MFL technique, this defect causes a significant variation of the signal from the good seams pattern. Figure 7 (c) shows the digital photo of good sample.

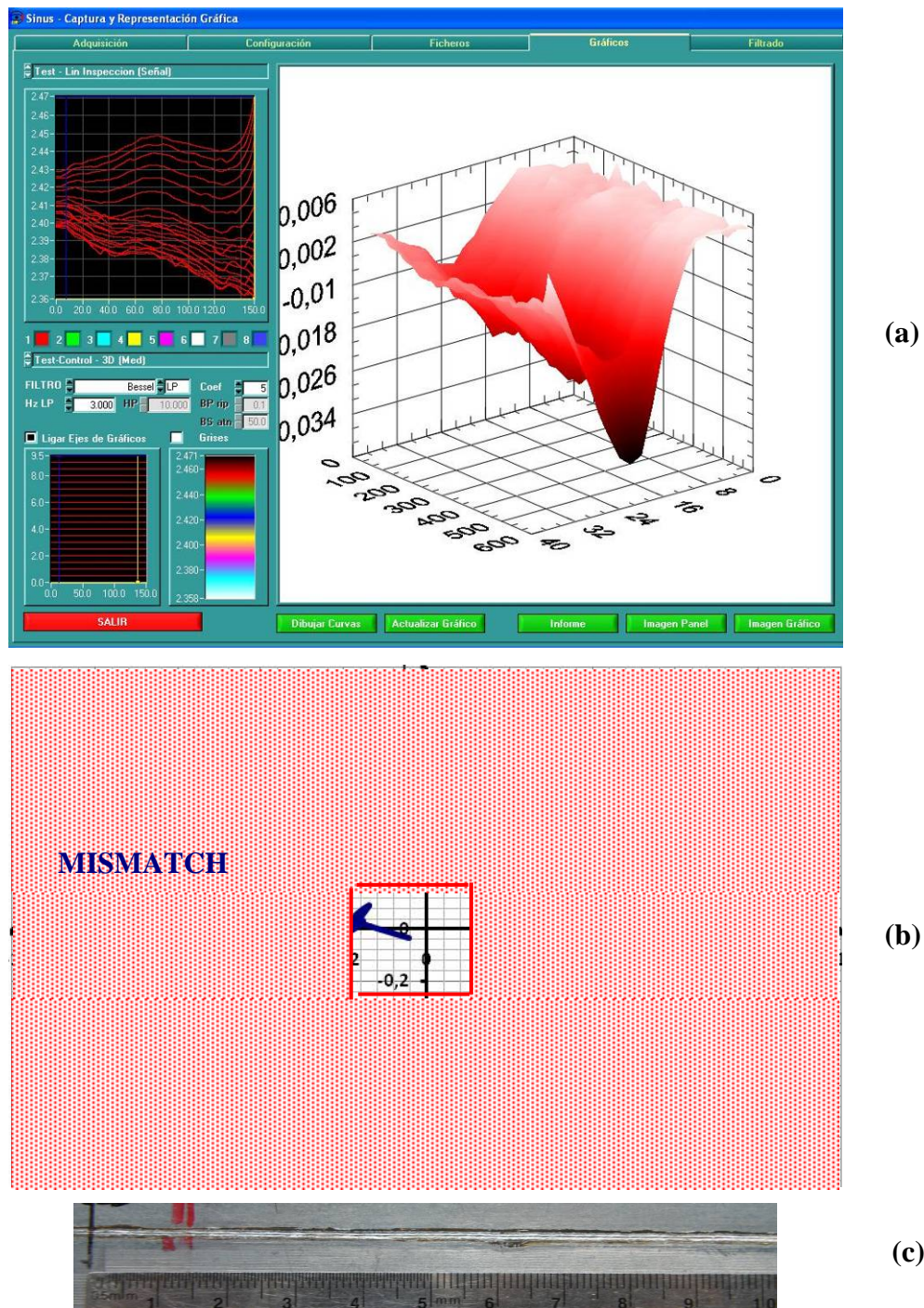
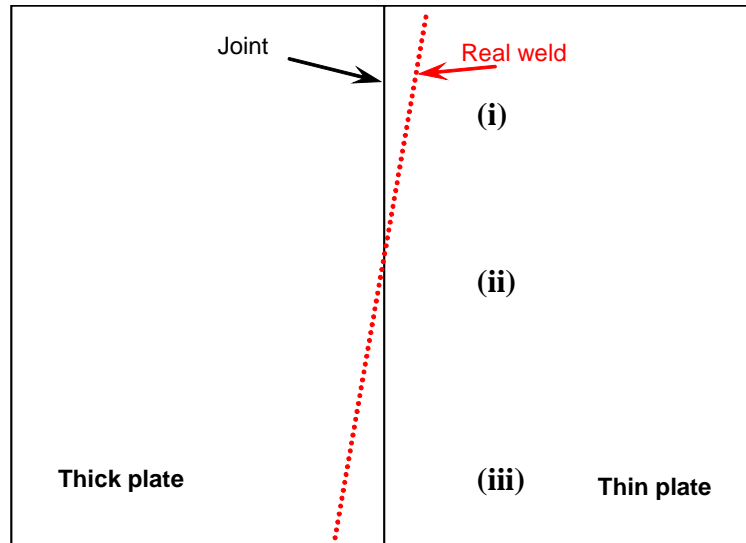


Figure 7. (a) Raw data for a mismatch defect obtained by the MFL technique. (b) Impedance plane representation for a mismatch defect obtained by EC technique. (c) Digital picture of a mismatch defect.

### 3.2.3 Lack of fusion (LOF):

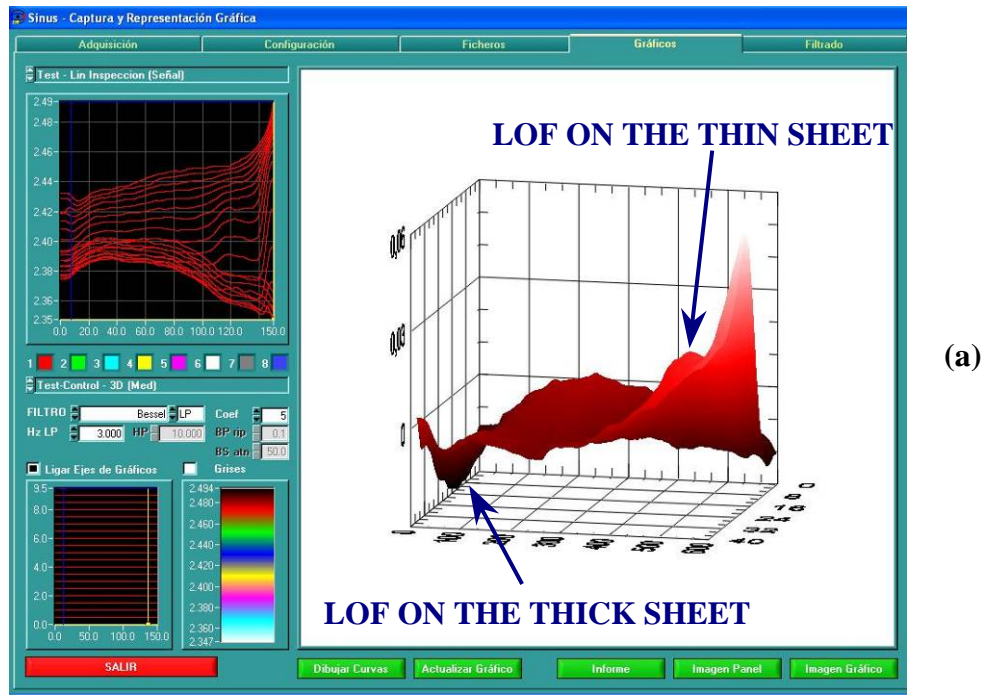
This defect was manufactured by making a misaligned weld from thick sheet to thin sheet (Figure 8). Thus, it is possible to distinguish three zones: (i) lack of fusion over the thick plate, (ii) good weld and (iii) lack of fusion over the thin plate. The main goal to manufacture this misaligned weld is to check the system sensitivity to the detection of this kind of defect.



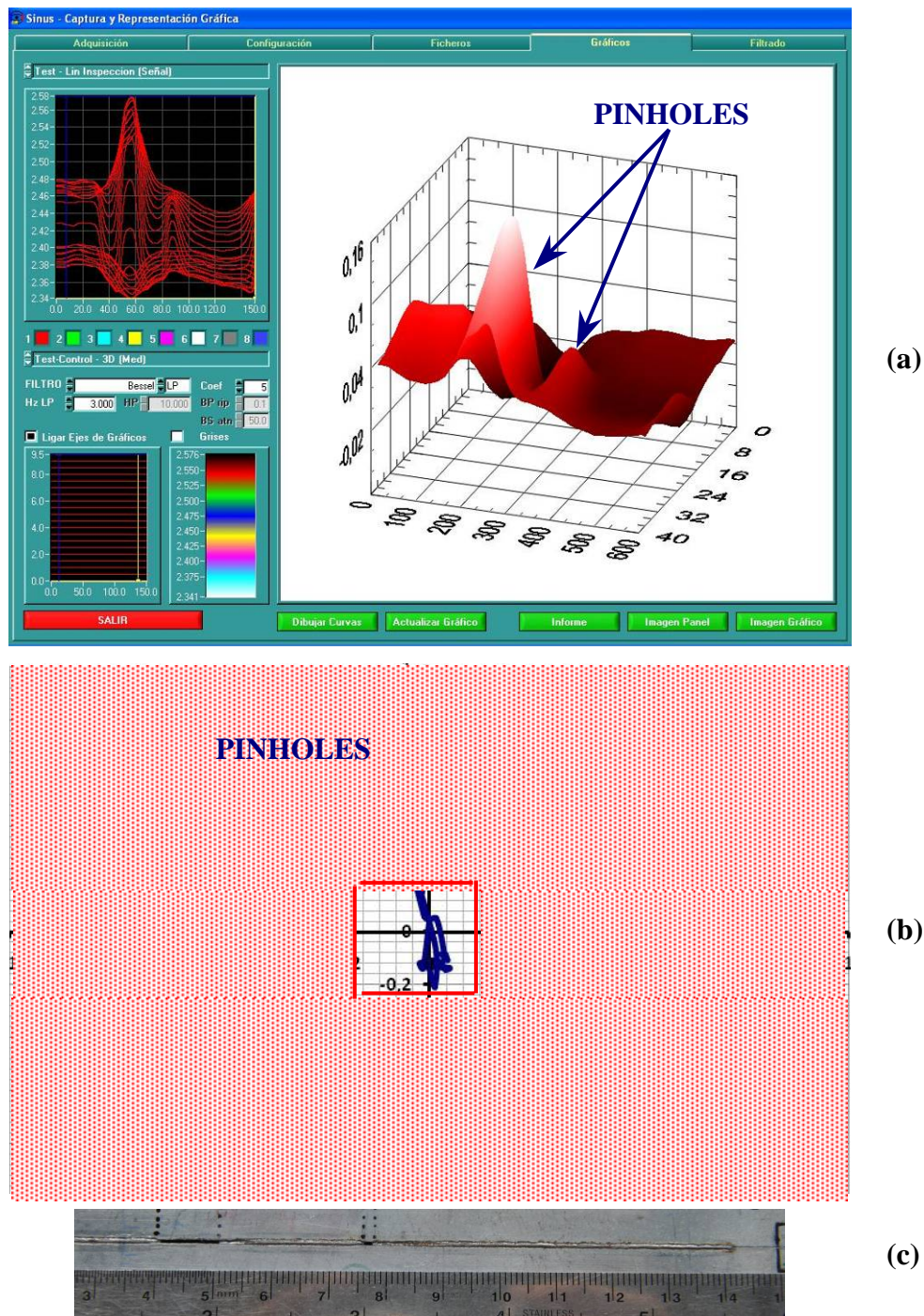
**Figure 8. Misaligned weld produced to simulate a Lack of fusion defect.**

Figure 9 shows the results obtained by the NDT system developed in this project, for a misaligned weld of 0,6mm from thick sheet toward 0,6mm of thin sheet. Figure 9 (a) shows the raw data and the deviation for this kind of defect, compared to the good seams pattern obtained previously by the MFL technique. The results show that it is possible to detect this defect, both in the thick and thin sheet, although sensitivity for the detection of the lack of fusion is higher in the thin sheet. Particularly, with the NDT system developed in this project. Analyzing the results obtained by the Hall Effect sensor, it is possible to conclude that this technique can detect misaligned welds from 0,4mm on the thick sheet and misaligned welds from 0,2mm on the thin sheet. Figure 9 (b) shows the impedance plane representation of this defect obtained by the EC technique. This defect does not have significant variation on the signal acquired by the EC technique. Figure 9 (c) shows the digital picture of lack of fusion sample.





by a local increase in the Magnetic Flux Leakage. Figure 10 (b) shows the impedance plane representation of this defect obtained by the EC technique. As with MFL technique this defect causes a strong variation of the signal from the good seams pattern, nevertheless, due to the size of the probe used (PLA 31-11 from Rohmann GmbH probe with 10mm of sensor area), it has not been possible to detect pinhole defects less than 1mm in diameter. The sensitivity could be improved by using probes with smaller sensor areas. Figure 10 (c) shows the digital picture of lack of fusion sample.



**Figure 10. (a) Raw data for a pinhole defect obtained by the MFL technique. (b) Impedance plane representation for a pinhole defect obtained by EC technique. (c) Digital picture of a pinhole defect.**



### 3.2.5 No-weld:

This defect was manufacture by introducing a pulse signal in the laser control to drop the laser power to 0W during a fixed period of time. Figure 11 (a) shows the raw data and the deviation for different no-weld defects, compared to the good seams pattern obtained previously by the MFL technique. As pinhole defects, this kind of defect is detected by a local increase in the Magnetic Flux Leakage. Figure 11 (b) shows the impedance plane representation of this defect obtained by the EC technique. As with MFL technique, this defect also causes a strong variation of the signal from the good seams pattern. Figure 11 (c) shows the digital photo of good sample.

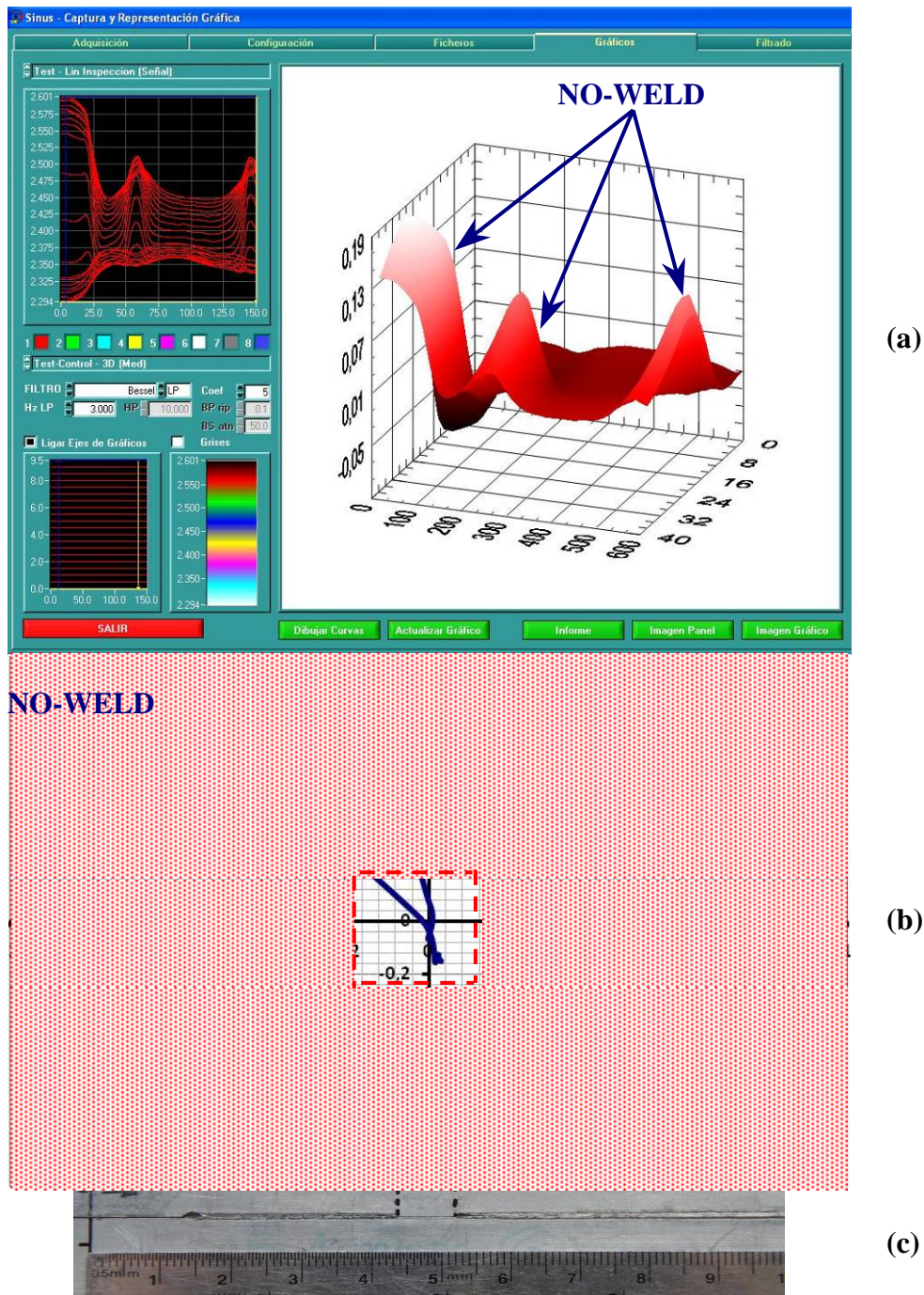
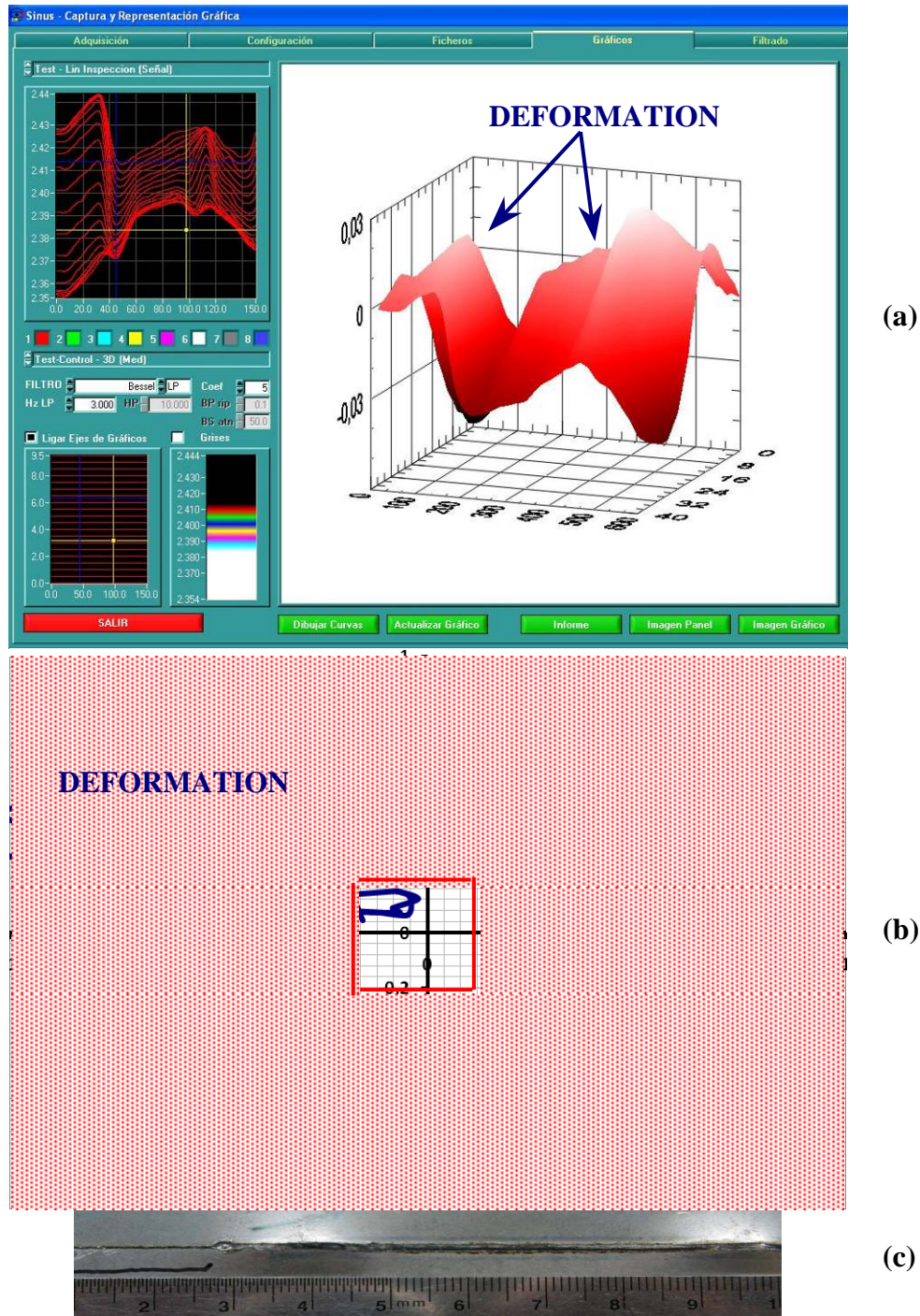


Figure 11. (a) Raw data, for a no-weld defect, obtained by the MFL technique. (b) Impedance plane representation for a no-weld defect obtained by EC technique. (c) Digital picture of a no-weld defect.

### 3.2.6 Sheet deformations:

This defect was manufactured by pre-deforming the metal sheets before the TWB welding. Figure 12 (a) shows the raw data and the deviation, for different deformation defects of the metal sheets, compared to the good seams pattern obtained previously by the MFL technique. Figure 12 (b) shows the impedance plane representation of this defect obtained by the EC technique. This defect causes a strong variation of the signal from the good seams pattern. Figure 12 (c) shows the digital photo of good sample.



**Figure 12. (a) Raw data for a deformation defect obtained by the MFL technique. (b) Impedance plane representation for a deformation defect obtained by EC technique. (c) Digital picture of a deformation defect.**

#### **4. DISCUSSION OF RESULTS**

Eddy Current and Magnetic Flux Leakage techniques have been tested and integrated for the detection and classification of different defects on TWB; thus, the results obtained from both techniques are complemented for a better detection and classification. For example, lack of fusion defects are quite difficult to detect by Eddy Current technique, although Magnetic Flux Leakage technique is quite sensitive to these defects. On the other hand, mismatch defects are more detectable by Eddy Current technique than Magnetic Flux Leakage. Furthermore, the integration of these electromagnetic two techniques (EC and MFL) will not only allow for the detection, but also for the classification (due to the different signal pattern obtained by the EC technique) of the different artificial defects tested in this project.

Therefore, the integration of both electromagnetic techniques will increase the capability of the NDT system to detect and characterize the signals associated to the common defects in TWB (mismatch, lack of fusion, lack of penetration, pinholes, deformation, etc.).

It can be concluded that the main results obtained from the inspection of welding defects indicate that the integration, in the same device, of Magnetic Flux Leakage and Eddy Current techniques is a potential and viable technology for Non-destructive evaluation and classification of defects in TWBs. Thus, the development of this NDT system allows the detection of different defects such as lack of fusion, lack of penetration, mismatch, no-weld, deformation and pinholes. It is also shown that there is a influence between the size of the defects and the magnitude of the acquired signals. Nevertheless, the inspection depth reached with this system is limited to surface and sub-surface defects and, therefore, defects such as pores, concavity on top of the joint, etc. are difficult to detect.

Based on these results, development of the NDT system for inspection of TWBs is continuing with especial emphasis on the development of a robust classification algorithm that will be able to subtract the differences due to the thickness sheets variations.

#### **ACKNOWLEDGMENTS**

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