Depth of Penetration Effects in Eddy Current Testing

Shiva Majidnia[1], John Rudlin[2] and Rajogapol Nilavalan[3]
Brunel University
Cambridge CB1 6AL, UK
Telephone 01223 899000
Fax 01223 890689
E-mail shiva.majidnia@twi.co.uk

Abstract

The simple depth of penetration equation used for most eddy current calculations does not take into account the effect of the size of the coil or the effect of flaw morphology. The work described in this paper describes use of the CIVA eddy current model to investigate this effect, and some experimental investigations.
Knowledge of this effect is important in examination of thin sections with eddy currents. Two examples of this are the small sections required to be inspected in laser metal deposition, and welds in thin sections joining dissimilar metals such as copper and aluminium for electrical connections.

1. Introduction

The need to establish the capability of small diameter coils arises because high resolution is sometimes required. Two examples of this additive manufacture and dissimilar metal joints (Figure 1).
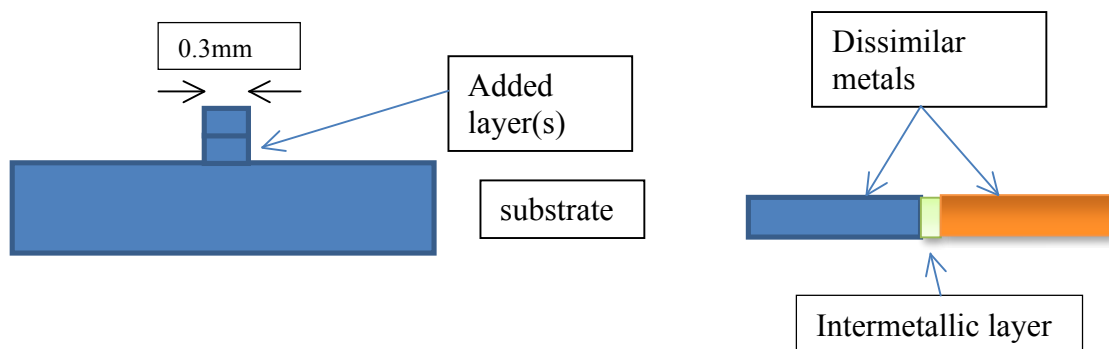

Figure 1. Application examples requiring small diameter coils

In the case of additive manufacture the added layer is required to be examined and this may be less than 1mm in height or thickness. An intermetallic material is sometimes produced when certain dissimilar metals are made and the thickness of this, of the order of microns may be crucial to the performance of the joint. Therefore, eddy current coils with a small diameter are needed to achieve the resolution that is necessary for these inspections.

The depth of penetration for eddy current testing is usually defined by the graph shown in Figure 2, which is derived from the plane wave equation of depth of penetration. However this does not take into account probe design or size or flaw morphology. It is well known that coil size will affect depth of penetration but this has not been quantified in many specific cases. Also it is intuitive that large volumetric flaws will be more easily detected than planar flaws at the same distance below the surface, but again there is no easily available information to help an inspector choose the optimum frequency.

The investigation of these effects has been undertaken both with modelling and experiment. Small probe sizes with air core were used here to make comparison avoiding variety in ferrite properties. It is recognised that the addition of ferrite will give a different performance.
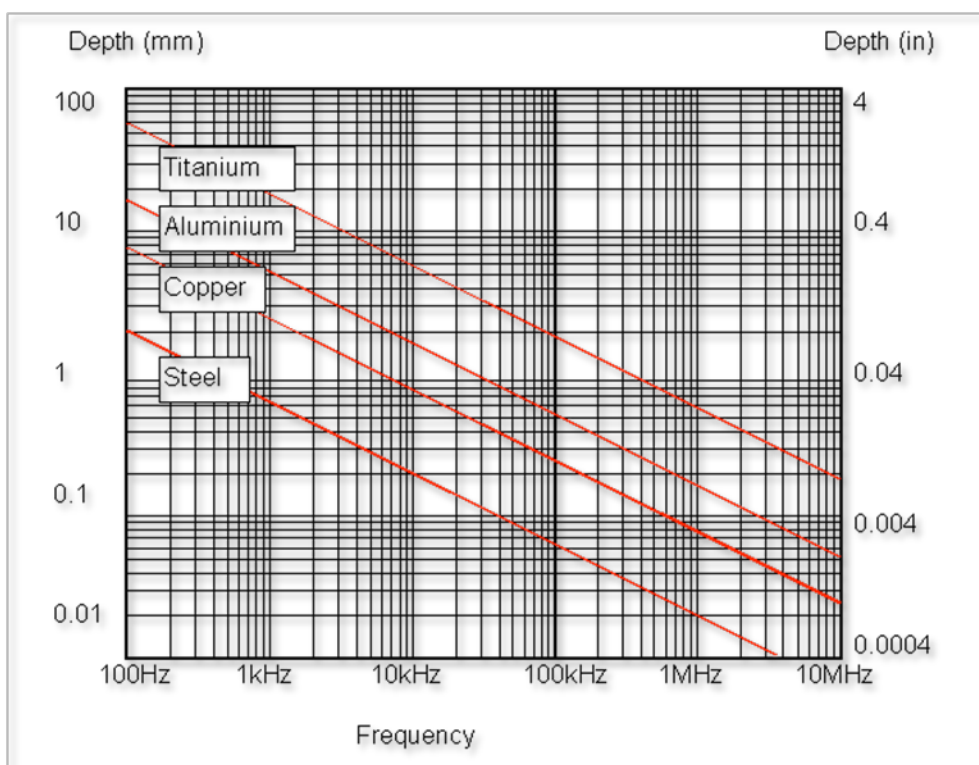

Figure 2. Depth of penetration graph

2. Modelling Results - CIVA software

The modelling work presented below investigates the current density, depth of penetration and electric field amplitudes at specific locations in the material for a given range of frequencies and coil parameters.

The modelling software used to compute the incident electric field is named CIVA. CIVA is a platform developed by the CEA (Commissariat à l'Energie Atomique, French Research Centre) that gathers in the same environment processing, imaging and simulation tools and therefore allows comparisons between experimented and computed data.

Eddy Current Testing (ECT) modelling is achieved in CIVA using semi-analytical models based on the Volume Integral Method (VIM). Eddy current models in CIVA have no limitations with respect to the thickness of the component, as the methods used for predicting the electromagnetic fields inside the component, or its perturbation by a volumetric flaw, intrinsically take into account the finite thickness of the component. However, the components should be large in order to avoid the "edge" effects.

Other limitations of this simulation tool are:
- Flaws and probe must be located far from the edges of the component.
- Flaws are considered volumetric flaws in the ECT module and the aperture of the flaw is supposed to be large enough. The VIM method is based on a 3D meshing of the flaw and this method imposes a very thin mesh as the aperture of the flaw decreases. In addition to numerical constraints (thin meshing which gives rise to high computation times and memory load), the VIM method will give rise to a quasi null response of the volumetric flaw if its aperture tends to zero which is not realistic. For a classical frequency range from a few kHz to a few hundred kHz, flaws which have an aperture larger than 100 microns are known to be correctly modelled by CIVA. However, extension and depth of the flaw are not limited.

Probe design optimisation and probe parameters were investigated though the modelling experiments. Amongst the most critical probe parameters to take into account are:
- Operating frequency
- Coil parameters (dimension, geometry, number of turns, etc.)

The influence of the materials physical characteristics, (conductivity, permeability) and its dimensions (thin sheets and foils), should be carefully considered as they have significant influence on the electric field distribution in the test piece.

The influence of the shape, location and size of flaws in the sample will be another factor influencing the response of the signal. Note that notches modelled will have a 100 microns aperture (minimum) due to the limitations of the software as explained above. Finite Element Modelling was not carried out at this stage but it could be explored.

For all the experiments described in this section of the report, the samples considered were manufactured from thin sheets of Inconel 50x50x2mm. The number of turns and the height of the probe were kept constant for all the modelling experiments performed using CIVA software. Coil diameter and working probe frequency were the two main variables investigated in the models. Therefore, as shown in Table 1, 3 different coil diameters each operating at 3 different probe frequencies were investigated.

Table 1. Modelling simulations carried out, in red are the variables investigated

Simulations	ECT Coil Parameters	Probe Frequency
Case 1	H=5mm, Nb turns=20, Dint=0.5mm, Dext=1mm	500kHz, 1MHz, 2MHz
Case 2	H=5mm, Nb turns=20, Dint=1mm, Dext=2mm	500kHz, 1MHz, 2MHz
Case 3	H=5mm, Nb turns=20, Dint=2.00mm, Dext=3mm	500kHz, 1MHz, 2MHz

Objectives of the modelling experiments:
- To understand the influence of the probe parameters on both the electric field distribution and depth of penetration in the Inconel sheet
- To predict and evaluate the eddy current system response with regards to flaw detection in the Inconel sheet
- To identify the most suitable probe parameters for flaw detection in a 0.5mm thick Inconel sheet.

2.1 Influence of the coil diameter and probe frequency on the depth of penetration in the Inconel sheet

As expected, the depth of penetration is affected by the operating frequency and to a greater extent by the coil size. The depth of penetration is calculated here on the same basis as the plane wave formula (ie the depth where the current falls to 37% of its value at the surface)

Figure 3 below shows that case 3 (the biggest diameter coil size) gives a penetration depth less than Standard Depth of Penetration. The coil size could therefore be reduced to achieve the depth coverage required i.e. 0.5mm. Although cases 1 and 2 do not allow this coverage, the modelling experiments demonstrate that there is room for optimisation of the probe design considering coil size, geometry and working frequency. Generally a lower frequency is needed for the same depth of penetration if the coil size decreases.
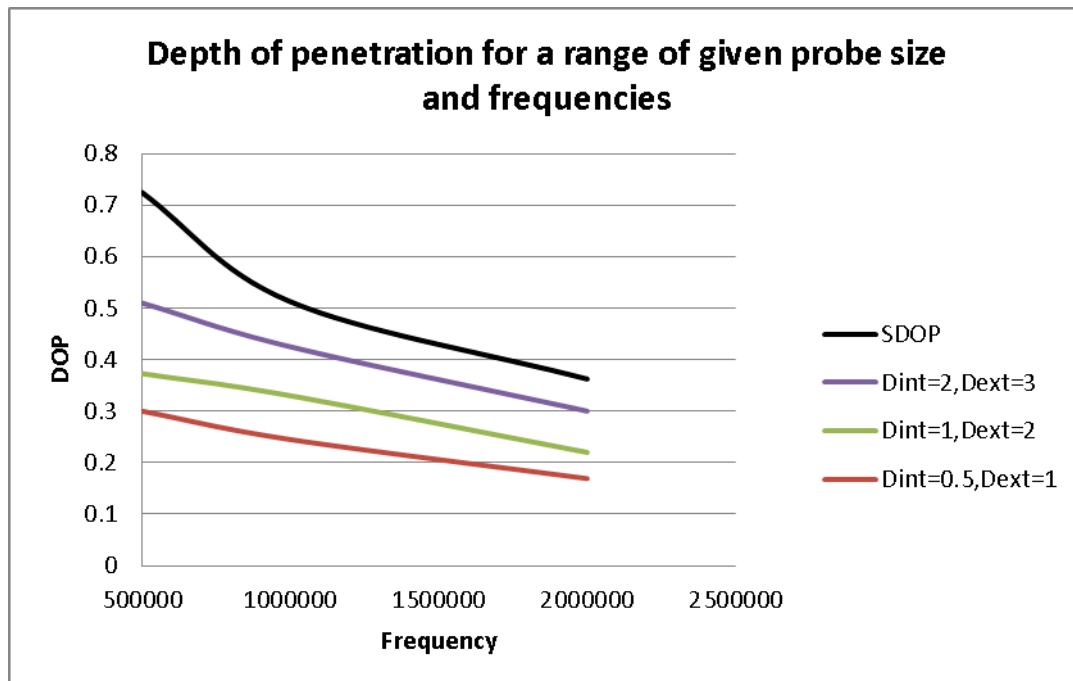

Figure 3. Variation of the depth of penetration for the 3 simulated cases

2.2 Simulation of defect interaction

Simulation of defect interaction was then carried out for each of the three cases described in Table 1 in the section above.

For the purpose of this simulation, four notches of various heights (Table 2) were added at the bottom of the Inconel sheet sample

Table 2. Dimensions of the notches added in the Inconel sheet

Notch	Length (mm)	Width (mm)	Height (mm)
A	10	0.5	0.40 = (20%xt)
B	10	0.5	0.8=(40%xt)
C	10	0.5	1.2=(60%xt)
D	10	0.5	1.6=(80%xt)

A raster scan is performed with the probe located on the top surface of the sheet and then the signal response is simulated. C-scan images of the ECT simulated signal response and impedance plane diagrams can be obtained and analysed. A comparison can be drawn between the responses obtained for three sizes of flaws and for each scenario.

Figure 4 below shows the typical modelling results (C-scans and impedance plane diagrams) for the defect interaction simulation realised at 500 KHz for the coil size of internal diameter of 1 mm and external of 2 mm. The results are available for the other probe sizes.

The amplitude of the signal and also the phase is different for each flaw; hence the subsurface flaw can also be interpreted with an analysis of phase. Since the amplitude of the signals is our interest here a second graph has been produced based on the amplitude. As expected, in Figure 5 larger probe has a larger response signal to the same flaw. In order to make the comparison more understandable log amplitude was used as in Table 3 to give a better sense of gain needed for an observable signal.
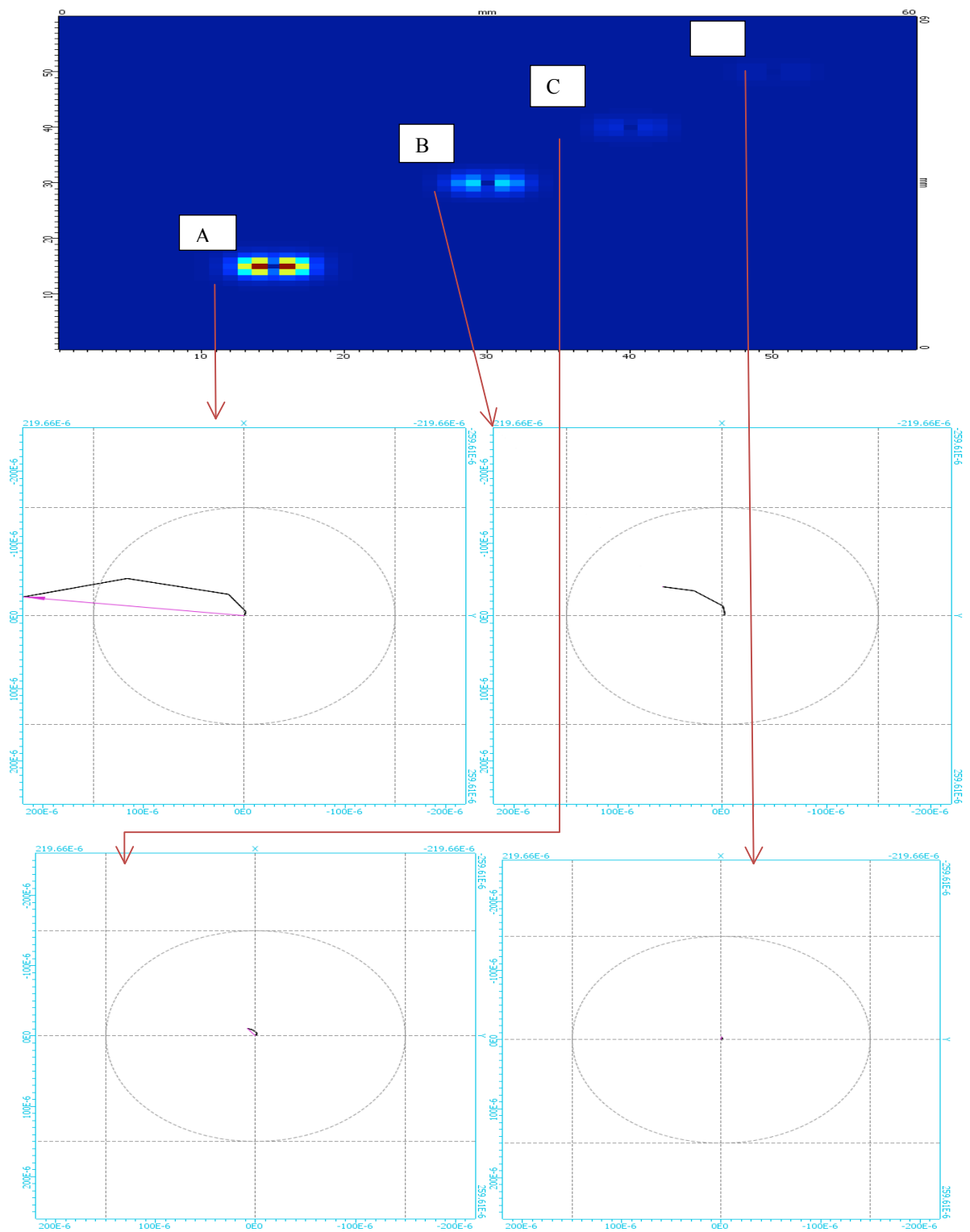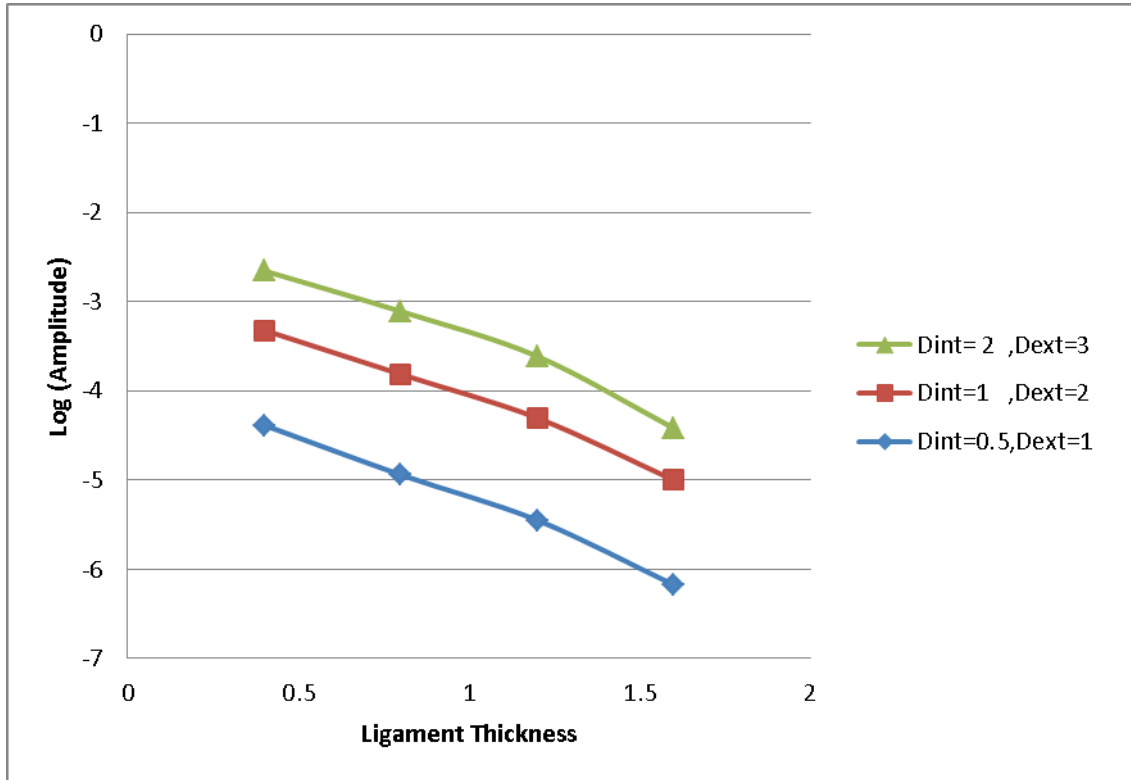
Figure 4. Typical Simulation results obtained from CIVA

Table 3. Signal amplitude and log signal amplitude for a range of probe sizes

	Dint=0.5,Dext=1	Dint=1 ,Dext=2	Dint= 2 ,Dext=3	Dint=0.5,Dext=1	Dint=1 ,Dext=2	Dint= 2 ,Dext=3
	Ampilitude	Amplitude	Amplitude	log(amplitude)	log(amplitude)	log(amplitude)
A=1.6	6.68E-07	9.94E-06	3.80E-05	-6.175223538	-5.002613616	-4.420559403
B=1.2	3.54E-06	4.96E-05	2.43E-04	-5.450996738	-4.304781081	-3.613572382
C=0.8	1.15E-05	1.53E-04	7.78E-04	-4.940815382	-3.81406141	-3.109271674
D=0.4	4.13E-05	4.78E-04	2.22E-03	-4.384470776	-3.320254222	-2.654626269

Figure 5. Results from the modelling experiments performed at 500 KHz for the three cases investigated. Amplitude of the signal Vs. Slot depth

3. Test Samples

Two test samples were manufactured in Inconel with the same dimensions as used in the simulation.

One plate was made with various thicknesses in the form of a step wedge and the second with a set of EDM slots of different depths. The scan is done from the back wall of the plate so that the effect of ligament thickness can be observed.

The slots are 0.4, 0.8, 1.2 and 1.6 mm deep giving ligaments of 1.6, 1.2, 0.8, 0.4 mm respectively. The thickness measurement is done on a step wedge of 0.4, 0.8, 1.2 and 1.8 mm. A schematic of the test pieces are shown in Figure 6 and 7.
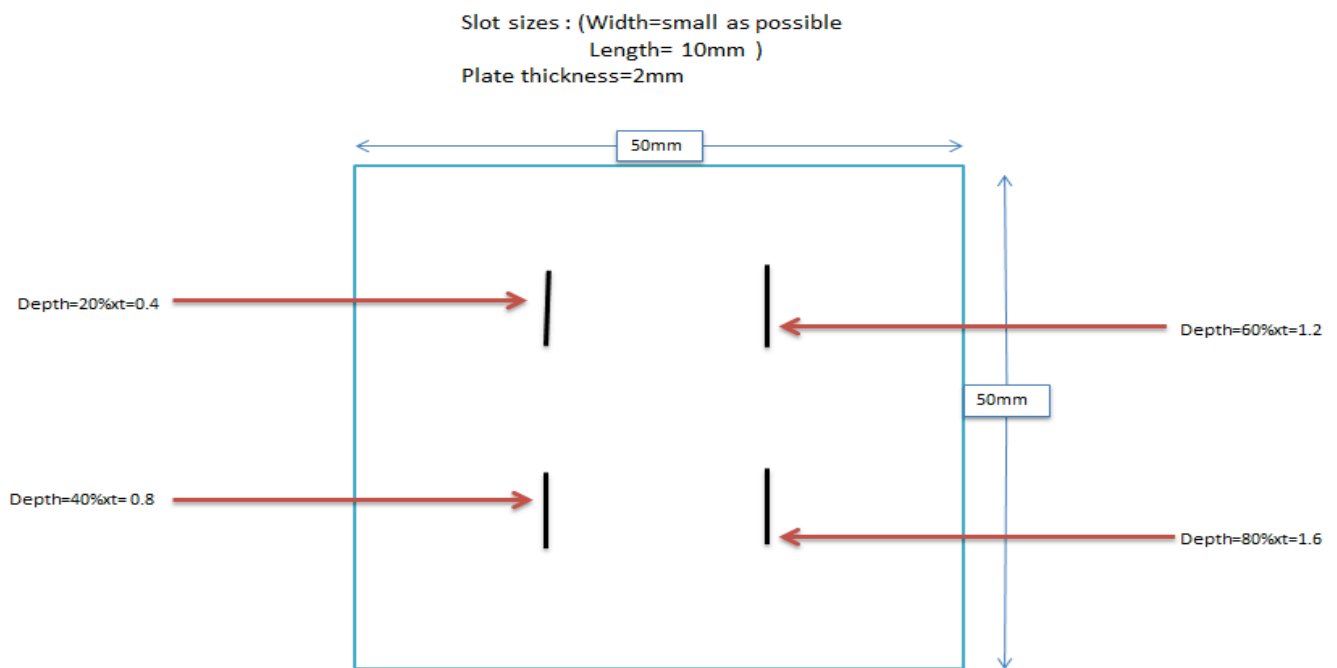
Slot sizes : (Width=small as possible
Length= 10mm)
Plate thickness=2mm

50mm

50mm

Depth=20%xt=0.4

Depth=40%xt= 0.8

Depth=60%xt=1.2

Depth=80%xt=1.6

Figure 6. EDM notches on the surface
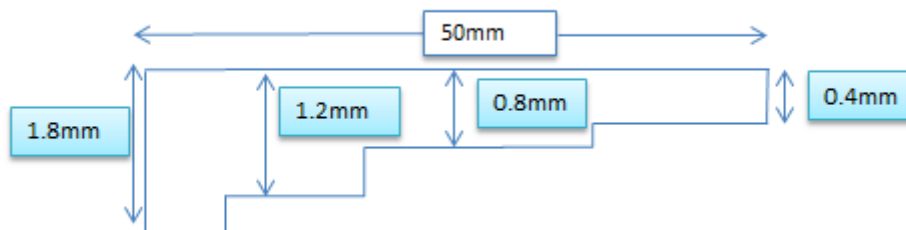
50mm

1.8mm

1.2mm

0.8mm

0.4mm

Figure 7. Thickness plate

The probe is a 20 turn air cored of dimensions of external diameter 4 mm, internal diameter 2 mm and height of 1 mm.

Figure 8. Air-cored probe a) top view b) side view

4. Experimental work

4.1 Results

The experimental work has been done with a 20 turn air cored coil shown above in Figure 8.

The results show that the type of flaw has an impact on the effective depth of penetration. For a given frequency, 300 KHz for instance, shown in Figure 9, the thickness was detectable with a gain of 50 dB whereas in Figure 10 and 11 the slot of the same depth could only be detected with a higher gain of 65 dB. Having done the experiment for a range of frequencies, it is observable that the type of defect has a significant impact on the effective depth of penetration. It has been noted that the probe is more sensitive to changes of plate thickness at the same depth as ligament when using the same gain.

The results shown below are gathered from the Veritor eddy current instrument which can capture the screen and the setting. In Figure 9, the coil is balanced on a 2mm thick plate and the indication from thinner plates can be observed at different frequencies. In order to achieve the same indicated amplitude from the plate thickness and ligament thickness measurement, the gain needs to be increased. At this stage only the nearest subsurface flaws of 0.8 and 0.4 mm could be detected. The probe could detect the same defects at 100 to 500 KHz. At higher frequencies of 1 MHz only the 0.4 mm thick plate could be distinguished as shown in Figure 12. At 2MHz the ligament thickness cannot be measured using this probe, Figure 13.
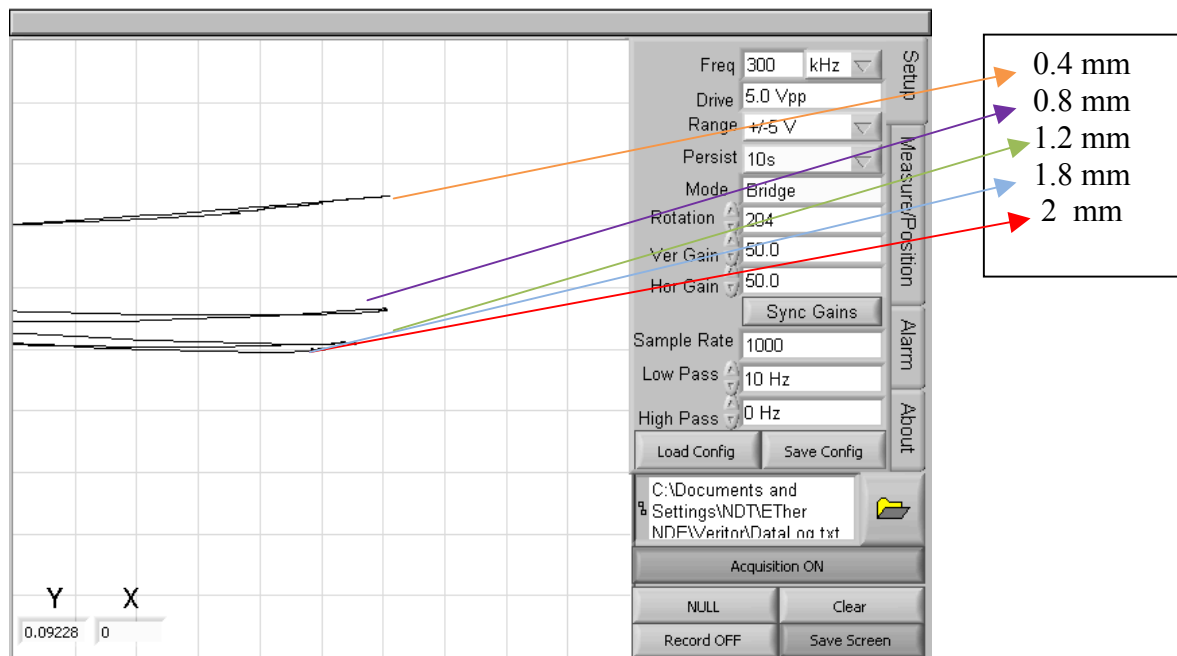

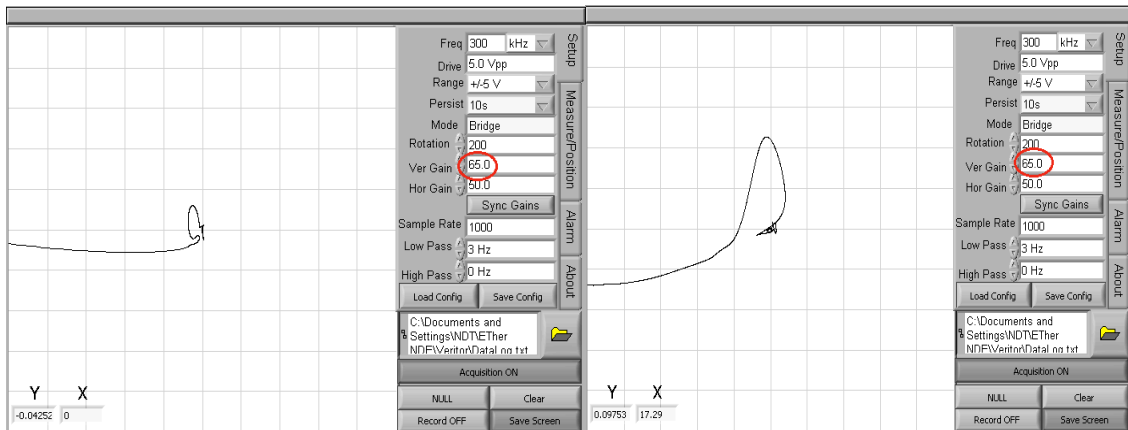**Figure 9. signals attained from the thickness plate**

Figure10. 0.8 mm Ligament
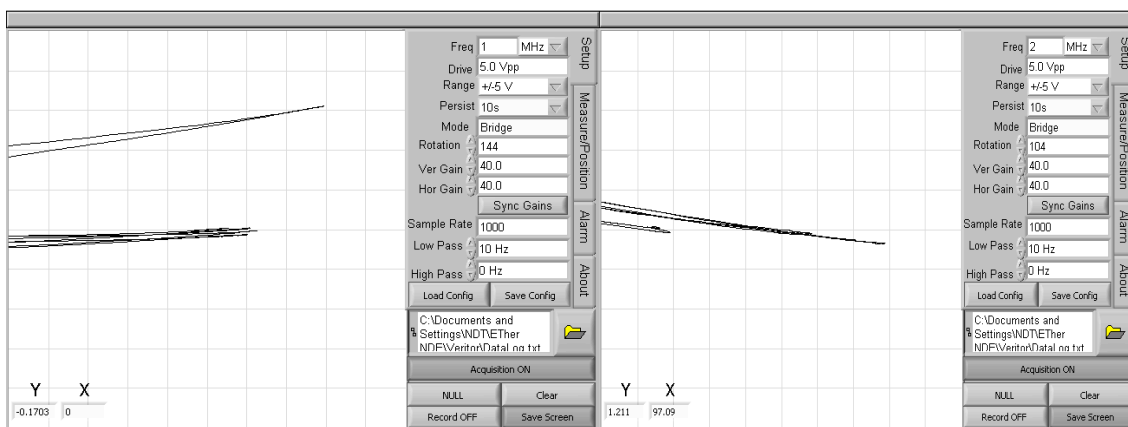

Figure 11. 0.4 mm Ligament

Figure12. 1 MHz plate thickness

Figure13. 2MHz plate thickness

The graph below in Figure 14 is an example for signal amplitude difference between plate thickness and ligament at 200KHz It shows the difference of gains in dB that needs to be added when scanning the flaw in order to achieve the same amplitude for the signal. Differences between the two are 15dB and 9.5 dB as shown.
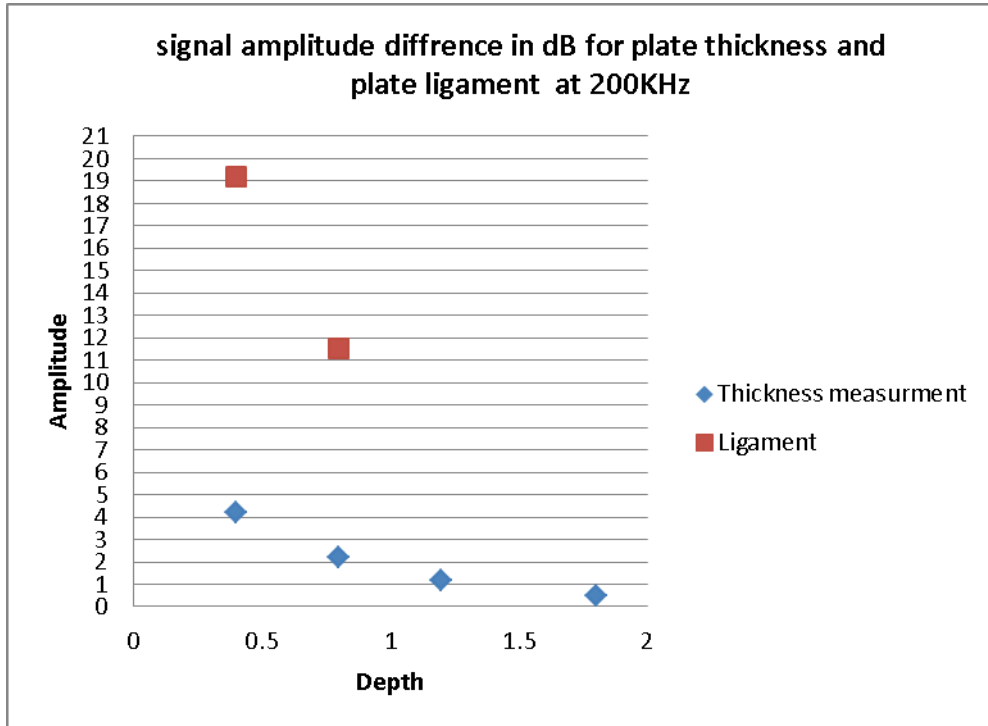
Figure14. Signal amplitude difference in dB for plate thickness and plate ligament at 200 KHz

In simulation the software will automatically increase the gain until an indication is visible. When using an eddy current instrument, there are limitations in the useable maximum gain because of electronic noise.

For the Veritor instrument which was used for this investigation, the gain can be increased to 75 dB due to noise, while the lowest low pass filter 3 Hz is used. Note that the probe design also affects the noise.

5. Conclusion
- Comparison of depth of penetration results shows that the effective depth of penetration depends on the probe size and operation frequency.
- The depth of penetration is not affected by flaw type, but the gain required to display different flaw types, it can be 14 dB.

6. Future work
The work described in this paper will be extended to cover a larger range of test samples, probes and instruments.
A COMSOL model will also be developed to extend the range of scenarios that can be modelled.