SILVERWING (UK) LIMITED

MAGNETIC FLUX LEAKAGE TECHNOLOGY

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1. INTRODUCTION

1.1 Magnetic Flux Leakage (MFL) technology has been used in the monitoring of Underfloor or Far Side (FS) corrosion for about 11 years. Silverwing (UK) Limited entered the field ten years ago, in 1991. As with all Non Destructive Testing methods, MFL has both advantages and disadvantages, as well as pitfalls for the unwary. This paper attempts to explain the underlying principles of the method and highlight the advantages, disadvantages and pitfalls.

2. PRINCIPLES OF OPERATION

2.1 GENERAL

MFL technology is similar to Magnetic Particle Inspection (MPI)- without the ink! In both cases the component is magnetised to a level at which the presence of a significant local reduction in material thickness causes sufficient distortion of the internal magnetic field to allow flux lines to break the test surface at the site of the discontinuity. In the case of traditional MPI, a ferromagnetic powder, in wet or dry form, is used to mark the spot so that it is readily visible by the inspector. With MFL, suitable sensors are used to give an electrical signal at the leakage site. This signal may operate an audible or visual alarm to alert the inspector, or may store the event for computer mapping of the area. Thus both techniques require two basic things, a method of magnetisation, and a method of detecting the leakage field.

2.2 In either technique magnetisation can be achieved using Electro-magnets or permanent magnets. Similarly, just as there are several types of ink that can be use in MPI, there are several types of sensor that can be used in MFL. These include Coils, Hall effect sensors, Magnetostrictive and similar devices. Silverwing (UK) Limited use permanent magnets and Hall effect sensors in their MFL technology.

2.3 MAGNETISATION

2.3.1 Because the MFL method responds to both far side (FS) and near side (NS) corrosion it is necessary to introduce a strong magnetic field into the component wall. The closer this field becomes to saturation for the

component, the more sensitive and repeatable the method becomes. For typical steels used in Bulk Liquid Storage Tank construction this value is generally between 1.6 and 2 TESLA. In this range any residual magnetism from previous scans or operations will be eliminated during subsequent scans so that the resulting flux leakage signals remain relatively constant and repeatable. Working below the 1.6 T level will still detect pitting on the first scan, but residual magnetism tends to cause a progressive deterioration of signal amplitude during subsequent re-scanning unless alternate scans are made from opposite directions.

2.3.2 For a given magnet system the flux density achieved in the component will depend on the thickness and permeability of the material. For most storage tanks the steels used are in the mild steel range equivalent to the old EN 2 grade and these steels have similar permeability. So the factor controlling flux density becomes one of plate thickness. There will be an upper thickness limit for each given magnet system above which flux density will be too low to give adequate sensitivity to pitting. One advantage of using an Electro-magnet is that the magnetising current can be increased to cater for a wider range of plate thickness than can be achieved with a given permanent magnet. However, this will be at the expense of size, weight, and the use of an independent (battery) power supply. Silverwing (UK) Limited uses permanent magnets capable of inspecting plates up to 20mm thick as standard. Above 12.5mm wall thickness there is a gradual loss of sensitivity and the residual magnetism effects, discussed in 2.3.1 above, become apparent.

2.3.3 The magnet system used is of the horse shoe type illustrated in Figs 1 & 2. The dimensions of the Magnet Bridge allow scanning widths of 150mm for HANDSCAN and PIPESCAN, and 275mm for MFL 2000 and Floormap 2000 systems. The poles of the magnet are set at about 4mm above the scanning surface.

2.4 SENSORS

2.4.1 Centred between the poles of the Magnet Bridge and stretching the full scanning width of the system is an array of Hall effect sensors. These are spaced at 7.5 mm between centres to give optimum resolution and coverage. The sensing range of each sensor is sufficient to allow overlap with its neighbour. The arrangement is illustrated in Figs 3 & 4.

2.4.2 Hall effect sensors give a voltage signal proportional to the flux density of the field passing through the sensing element. Figs 5 & 6 show the field patterns for sound and pitted material. Because Silverwing (UK) Limited position the sensing elements parallel to the scanning surface, it follows that it is the Normal (Vertical) component of the magnetic flux leakage vector which will be measured. If the sensing elements were to be arranged perpendicular to the surface, then it would be the Tangential (Horizontal) vector that would be measured. There are advantages and disadvantages with both these alternatives and these will be discussed later.

2.4.3 The sensors are arranged to be about 2-3mm above the scanning surface to avoid wear and other mechanical damage during scanning. Since sensitivity is reduced as this distance is increased, lift off is normally only reduced to help compensate for thicker fibreglass coatings.

2.5 SIGNAL PROCESSING

2.5.1 There are two types of noise that will be encountered by the MFL systems described above. The first is the large eddy current signal generated by the movement of the magnet over a conducting surface. The second type of noise is that generated by surface roughness and permeability variations in the plate material.

2.5.2 Eddy current signals are a function of the velocity of the magnet carriage and in a typical scan have three stages- a rising signal during acceleration- a steady state (DC) value at scanning speed- and finally a decreasing value during braking. Eddy current effects tend not to show up when the tangential component of the MFL field is being used and this means that those systems using coils or vertically mounted Hall effect sensors do not need to worry about this noise. However horizontally mounted Hall effect sensors do respond well to the eddy current noise - so it needs to be eliminated. Since the deceleration during braking is sharper than the acceleration during start up, and the signals generated are of opposite polarity, it is convenient to eliminate the stopping signal by rectification of all signals and only measuring positive going components. Passing all signals through a high pass filter with a suitable cut off frequency eliminates the start up and steady state signals.

2.5.3 The remaining noise will be represented by relatively slow changes of permeability and much sharper (higher frequency) signals from vibrations in the system due to surface roughness. Arranging the sensors in differential pairs reduces the first of these, and the second by passing all signals through a low pass filter with a suitable cut off frequency.

2.5.4 On the face of it may seem sensible to choose to measure the tangential component of the field so that eddy current effects are no longer a problem. But it is possible to get the sensor closer to the surface when mounted horizontally and this gives a sensitivity advantage, especially on coated floors. There is also another advantage of the configuration chosen by Silverwing (UK) Limited which incorporates the phenomenon where pits over 40% of plate thickness give larger signals from the FS than those from the NS and this phenomenon is more pronounced in the vertical component of the field. By using this configuration it is possible to adjust alarm thresholds so that 50% NS (Topside) pits are just ignored, but 50% FS (Underfloor) pits are still detected.

3. FACTORS AFFECTING SIGNAL AMPLITUDE

3.1 GENERAL

In general there appears to be a relationship between signal amplitude from a corrosion pit - and pit depth. However, as with many other NDT methods, the relationship is more complex. In particular the similarities with The Ultrasonic method spring to mind. In the case of MFL the factors affecting this amplitude can be listed as follows: -

(i) Flaw depth
(ii) Flaw volume
(iii) Flaw shape or profile
Iv) Flaw aspect ratio (Length to width)
(v) Material permeability
(vi) Material thickness
(vii) Magnet system used (Strength, Lift-off, reluctance, & magnet material)
(viii) Sensor systems used (types, & lift-off)

3.2 It has been argued that, with so many possible variables, it is not possible to make use of the signal information to classify defect severity (penetration) using MFL techniques. But the same argument could be used with ultrasonics when considering signal amplitude versus defect area. The factors affecting this amplitude are: -

(i) Area of the flaw
(ii) Surface roughness of the flaw
(iii) Flaw depth
(iv) Flaw shape and profile
(v) Flaw orientation with respect to the ultrasonic beam
(vi) Material attenuation
(vii) Beam profile at flaw depth
(viii) Beam wavelength in material (Frequency of transducer)

Just as many problems! and an inspector dealing with weldments or castings would rightly say that amplitude information is unreliable. But in the Aerospace and Forging industries flaws in plate and forgings tend to be flat and parallel to the scanning surface, and they <u>do</u> use signal amplitude to accept or reject material. They can do this because they can eliminate some of the variables. By using reference blocks of the same material containing flat-bottomed holes at known depth and diameter scanned with the equipment used in the inspection, they can eliminate variables iii, vi, vii, and viii above. Because of the predictable nature of the flaws, they can also eliminate variables iv, and v. This only leaves flaw area and surface roughness. The reflecting surface will always be rougher than a machined flat-bottomed hole, so a flaw will always be a little bigger than the equivalent flat bottomed hole. But experience has given those industries confidence to base acceptance criteria on amplitude alone.

3.3 If we apply the same logic to MFL, the problems may also reduce to a stage

where we can place some confidence in signal amplitude data. Again, if we use the same magnetising and sensing set up on a reference plate of the same material, we can eliminate v, vi, vii, and viii from the MFL list above. This supposes we can define an artificial pit that mimics the typical corrosion pit of equivalent depth in terms of signal amplitude. This aspect of the design of reference (calibration) plates is discussed in sections 4 & 5 below.

4. CHACTERISTICS OF CORROSION PITS

4.1 On first consideration one might assume that the shape, profile, aspect ratio, and hence volume of a corrosion pit might take an infinite number of guises. But it is considered that one can rationalise the general characteristics down to three types illustrated in Figs 7, 8, & 9 below. These characteristics are described as:-

- **(i) Lake or dish-like**
- **(ii) Cone like**
- **(iii) Pipe like**

4.2 These three categories refer to the profile of the pits, a section through the plate thickness. In plan view pits tend to be circular or elliptical in general outline. As corrosion sites grow, these basic shapes tend to merge to give more complex outlines such as shown in the sketches and photographs. At the same time a shallow lake may progress in stages, tending towards cone like and ending up in a pipe like tip such as Fig 10. Although these few sketches represent a simplistic approach, some generalised characteristics emerge. We also know that corrosion pits are unlikely to be slots or flat-bottomed holes, high aspect ratio crack like slits, or pure cones, dishes or pipes. A mathematical model of an 80% deep flat-bottomed hole is shown in Fig 11. It may therefore be possible to incorporate some of the above assumptions to develop artificial pits that bear a close enough relationship to real pits to make some sense of signal amplitude. One such approach is described in section 5 below.

5. CALIBRATION / REFERENCE PLATES

5.1 The earliest performance targets set by the petrochemical industry required the detection of 120° drilled cone 40% of plate thickness in depth. This target was a sensible approach, and more realistic than using flat bottomed holes, an approach taken by some other workers in the field. These artificial pits were introduced into calibration plates of the same nominal thickness and material specification as the floor to be examined. Later a range of conical pits from 20% to 80% material thickness were introduced into the calibration plates so that thresholds could be set to ignore chosen values when inspecting plates with heavy NS corrosion.

5.2 Inspectors in the field soon found, by trial and error, that an MFL system set up to just detect a 40% artificial pit would readily detect real pits of 30%-35% plate thickness. The simple cone, then, tends to over-estimate the depth of real pits, and this error was found to be consistent. The importance of the permeability of the calibration plate compared to the actual floor material also became clear in the few instances where the floor material differed significantly. Permeability changes of this sort can affect depth assessment, whether by thresholding or by mapping techniques, by as much as 25% of the indicated value. The lesson is that material choice is as important in MFL as it is in ultrasonic or eddy current inspection, when producing calibration or reference plates.

5.4 Faced with the experience gained using simple cone shaped artificial pits, Silverwing (UK) Limited carried out experiments and modelling exercises with various designs of artificial pit. The general approach was based on the stepped dish / cone configuration already described in section 4 above. The most successful of these designs was a stepped pit approximately following a 136° cone produced in the plate using a series of end mills.

5.5 Fig 12 and Table 1 give details of typical calibration plates using this design. Using the Floormap 2000 system, real pits have been measured with an accuracy of $^{+}/_{-}$ 10% of the value measured by ultrasonics and pit depth gauging. It should be noted that if the system is calibrated using the type of artificial pit described above, and then used to evaluate pit depth on a plate containing artificial pits of the through drilled hole, drilled cone or flat bottomed hole type - then the error for those artificial pits will be greater than $^{+}/_{-}$ 10%.

6. SURFACE CONDITIONS & SPURIOUS INDICATIONS

6.1 CLEANLINESS

As with other NDT methods, the effectiveness of an inspection using MFL is influenced by cleanliness and surface preparation. MFL is more tolerant of general dust and debris than ultrasonics, and it is not essential for grit blasting of floor surfaces in all cases. Nor does the method rely on either wet or dry surfaces although clearly any water on the surface should not be deep enough to submerge the sensor head that is only water resistant. Ferro magnetic debris is a little more important because under certain circumstances it may lead to spurious signals. Light corrosion products, often from the roof of the tank, tend to be swept up and cling to the magnet poles during scanning. From time to time clods of this debris detach themselves, pass under the sensor head, and give a spurious signal. However, the operator can see this happen and rescan this area after cleaning the magnet poles.

6.2 OTHER SOURCES OF SPURIOUS INDICATIONS

Compacted corrosion products on the NS, heavily ribbed scale, weld spatter and welded repairs to NS pits can all give large spurious indications.

If these surface imperfections are extensive, the inspection may be severely restricted. The first two can be seen during initial visual inspection, and those areas grit blasted as necessary. The operator can see Weld spatter and then spot check by ultrasonics if doubt remains. Weld repairs, especially those which have been ground flush with the surface, are the most difficult to confirm so that after ultrasonic back up they are often considered to be failures of the MFL system.

6.3 NS PITTING

MFL users are often asked to scan floors with extensive top surface pitting. In the early days this was considered to be impracticable. Nevertheless there are two ways of tackling the problem, one using the MFL 2000 and one using Floormap 2000.

6.3.1 When using the MFL2000, the inspector needs to carry out a visual inspection of the pitted area and assess the average pit depth and the deepest pits. If the deepest pitting is within the corrosion allowance, then he should calibrate the MFL 2000 with the artificial pits on the NS, adjusting the threshold to just fail to detect the 40% pit. He should then turn the calibration plate over and scan the artificial pits on the FS, noting the smallest pit detected. He can then scan the plate concerned knowing that only FS pits above the noted limit will give indications. If there are some pits that exceed the corrosion allowance, he should mark these for repair and use the average value for the remaining pits as a NS threshold as before.

6.3.2 Floormap 2000 will store and report all indications above a predetermined threshold. This threshold can be varied during the reporting stages so that the most severe indications are chosen for visual or ultrasonic confirmation first and the shallower indications gradually brought into the report and confirmed subsequently.

7. CONCLUSIONS

MFL is a useful tool that allows the rapid monitoring of large surface areas for both NS and FS corrosion. It is capable of giving information of both the location and relative severity of pitting so that the amount of ultrasonic prove up is minimised and directed to very specific locations. Although an apparently simple method, it does require careful setting up and use, and is prone to some errors, omissions and spurious results just as are other NDT methods.

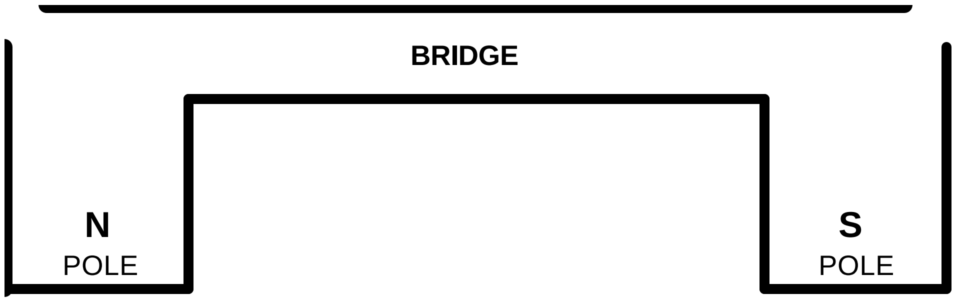


Fig. 1

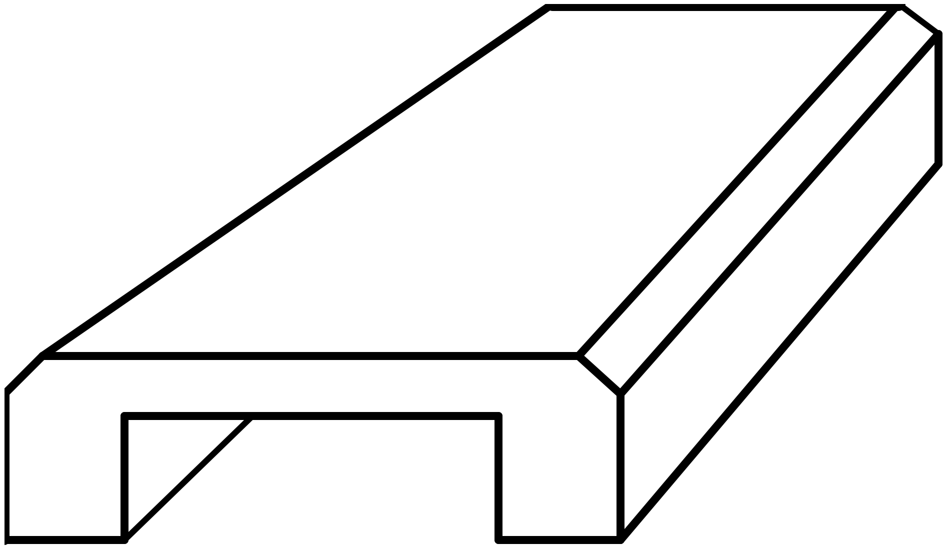


Fig. 2

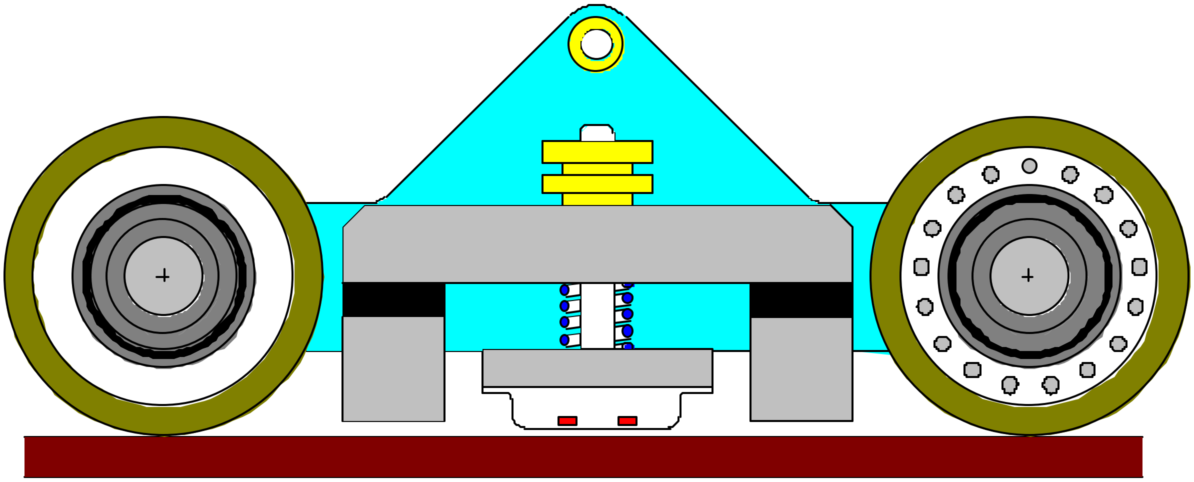


Fig. 3

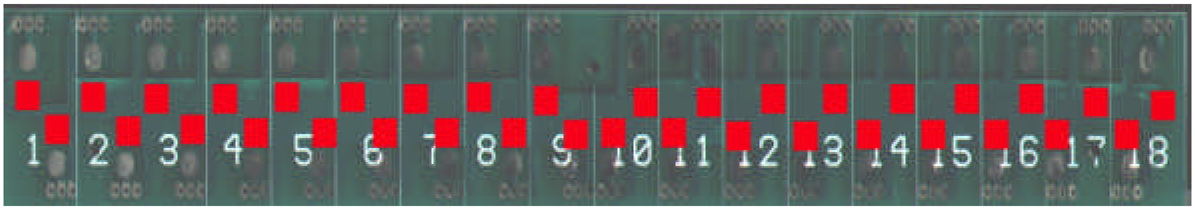


Fig. 4

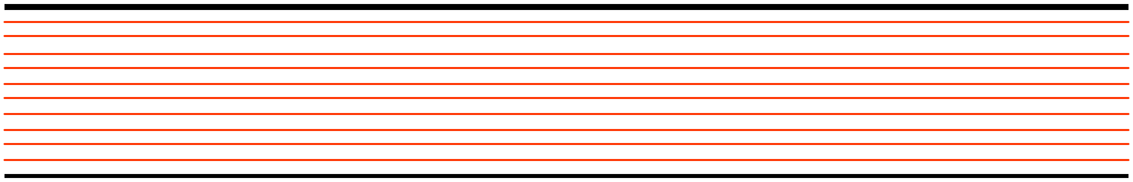


Fig. 5

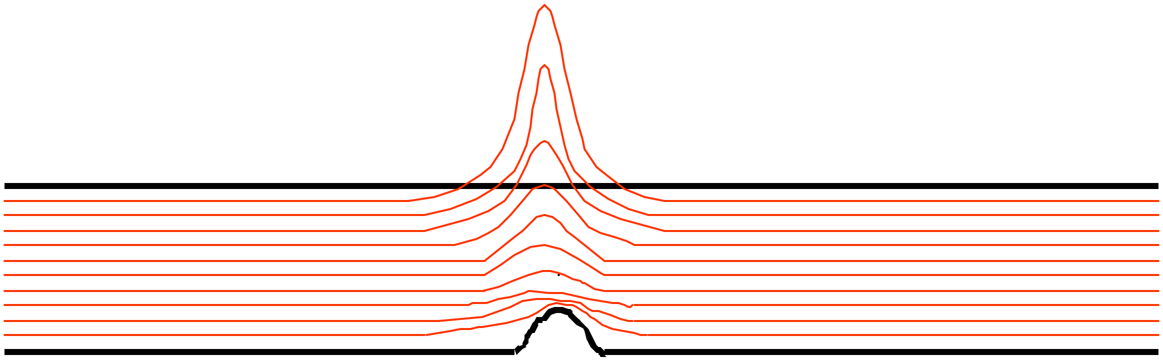


Fig. 6

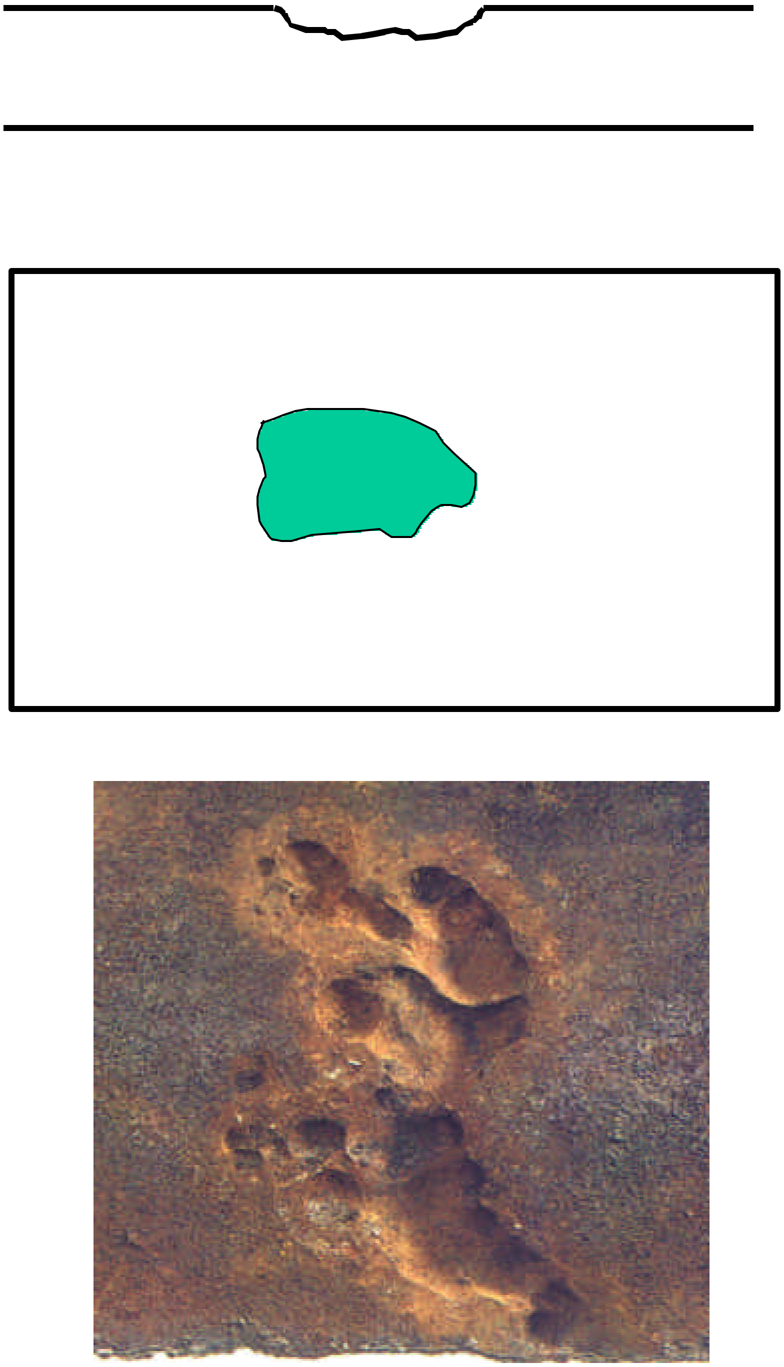


Fig. 7

Fig. 8

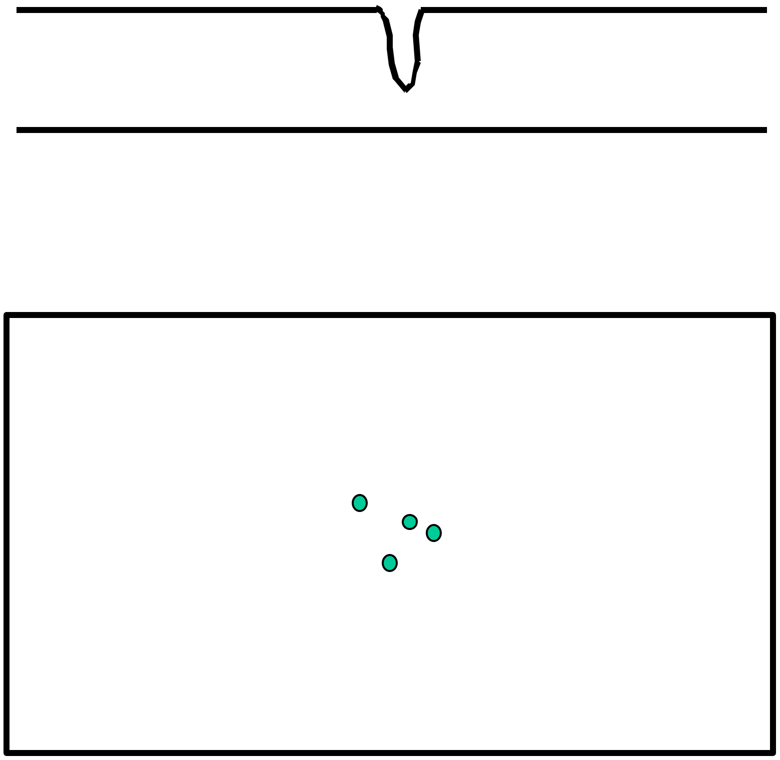


Fig. 9

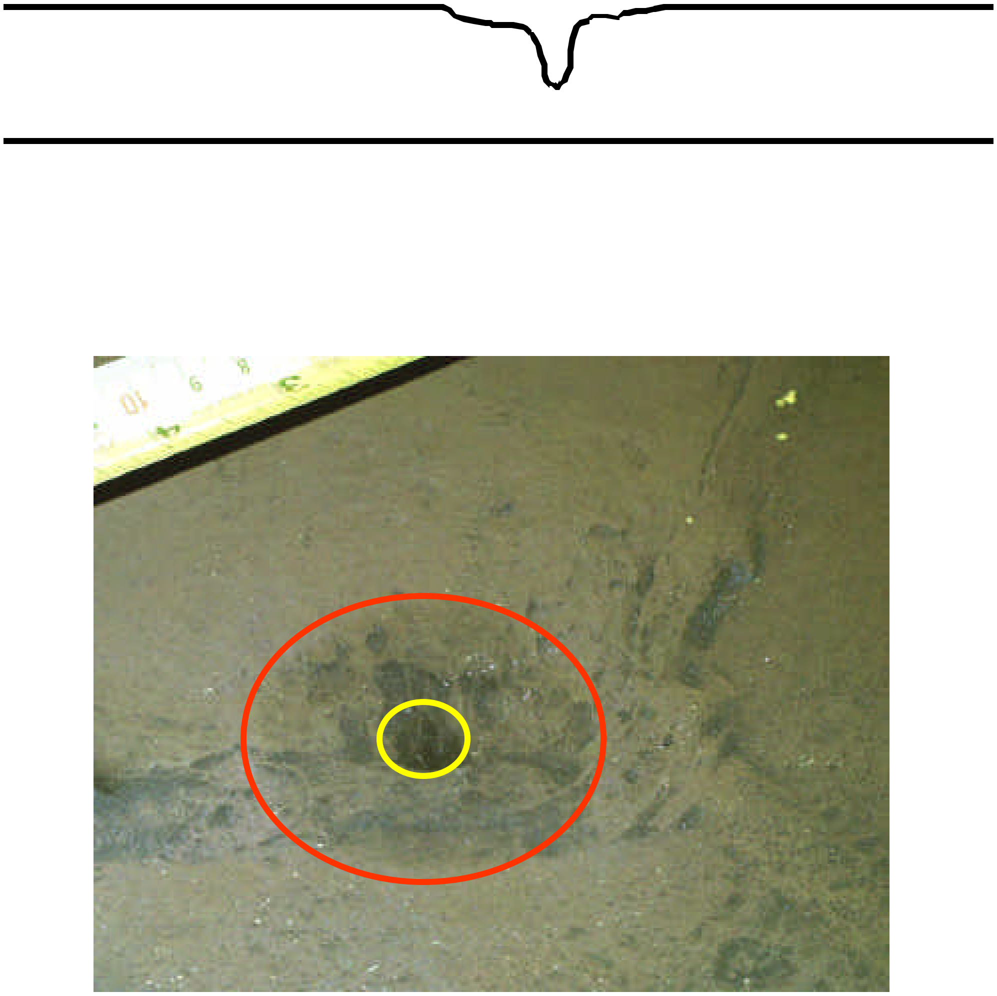


Fig. 10

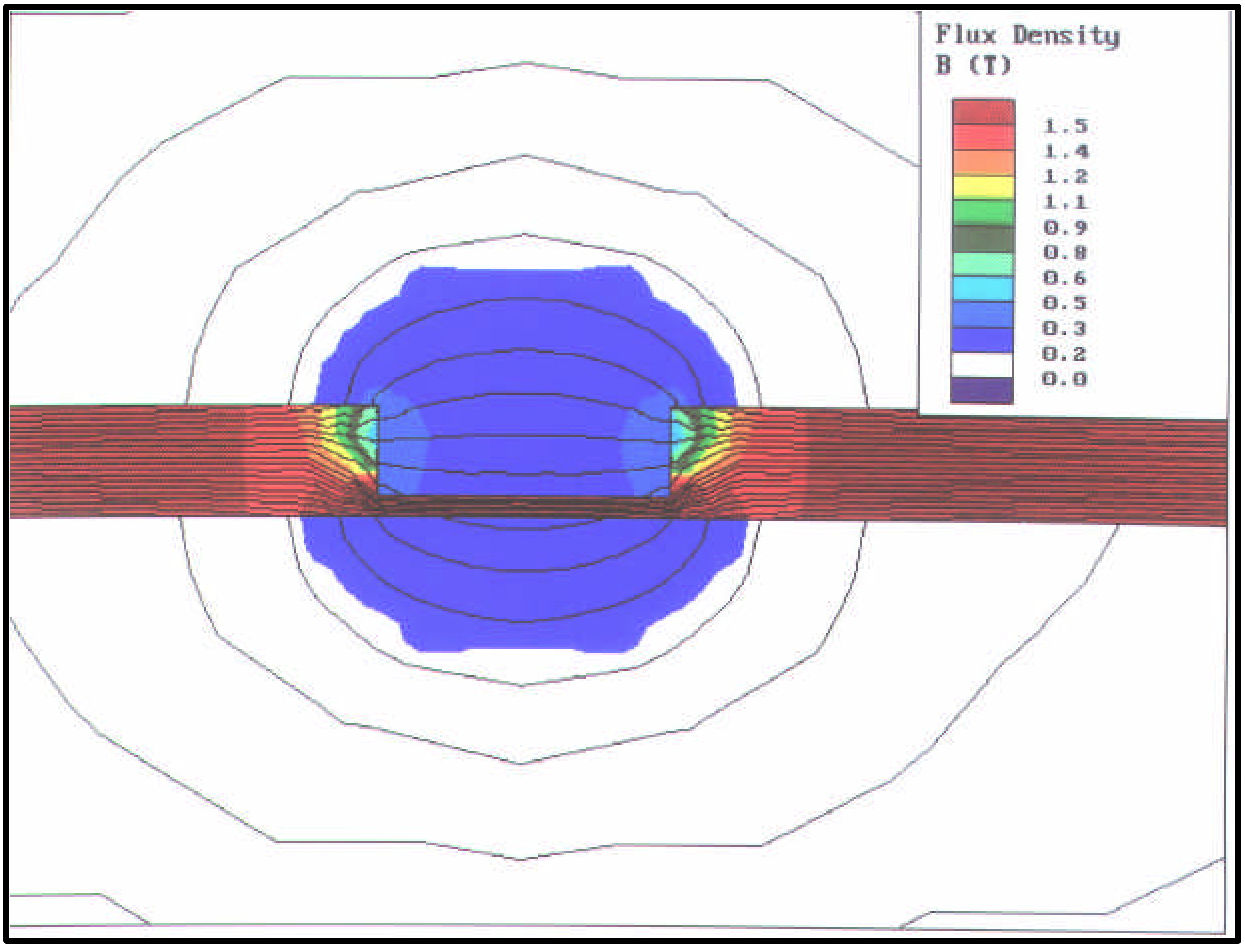
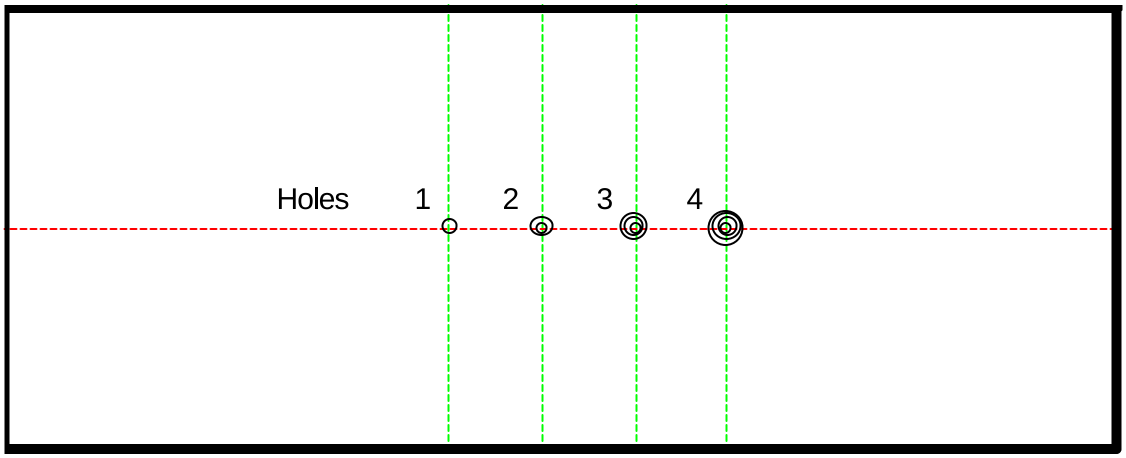
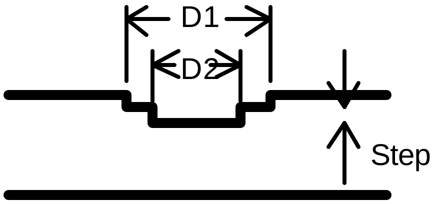


Fig. 11



Hole	Percentage loss
1	20%
2	40%
3	60%
4	80%



Typical 40% pit

Fig.12