Defect separation considerations in magnetic flux leakage inspection

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The magnetic flux leakage (MFL) method is used for assessing the corrosion integrity of oil and gas pipelines. The interpretation of defect-induced magnetic signals has to take into account the inspection tool and pipeline steel characteristics. The MFL signals are very sensitive to the stress state and magnetisation level of the specimen. The presence of a material-loss defect influences both the stress and magnetisation distributions in the material. Moreover, clustering of the corrosion defects complicates this situation by superposition of the local stresses and by magnetic shielding in the region between defects. In this paper, the degree of interaction between two adjacent metal-loss defects is analysed as a function of the defects’ centre-to-centre separation, residual and applied stresses, and magnetic flux density. The necessary centre-to-centre separation for two defects to be considered interacting is evaluated by extrapolation of the magnetic signal features of known defect geometries.

Introduction

Structural integrity and reliability of pipelines are of paramount importance for preventing environmental catastrophes and human losses. Depending on the defect geometry and frequency of occurrence, pipeline operators have to decide on the time intervals for periodic inspections. Subsequent measures can be taken to extend the pipeline lifespan by repairing, sectional replacement, or by simply lowering the operating pressure.

The MFL method has the advantage of being able to inspect the ferromagnetic pipelines while in service, without the need of shutting down its operation. The technique relies on calibration runs for correct interpretation of the leakage signals in terms of defect location, size, and depth. Calibration of the corrosion-induced MFL signals as a function of the test object and inspection tool properties had been previously studied\(^{(3,4)}\). Although the effect of stress on the magnetic properties cannot be determined with certainty for field inspections, the most efficient method for reducing stress influences on the MFL response is by magnetically saturating the pipe wall, minimising in this way local variations of the magnetic permeability of the steel\(^{(3,4)}\).

Oil and gas pipelines are operated at high pressures, corresponding to about 70% of the material yield strength\(^{(5)}\). This line pressure generates circumferential (hoop) stress in the pipe wall. Furthermore, much higher stresses are generated in the vicinity of corrosion defects, since defects act as stress raisers\(^{(6,7)}\) in the material. Three types of stresses are usually developed in a pipeline\(^{(8)}\): (i) bulk stress, occurring in the volume of the specimen, as a result of the pipeline operating pressure; (ii) residual stress, that develops in the sample after the removal of the applied load; and (iii) local stress, generated in the neighbourhood of metal-loss defects. Although the applied stress does not exceed the yield strength of the material, the stress concentration developed in the vicinity of a corrosion defect often introduces loads surpassing the yield strength. This fact, in conjunction with successive loading and unloading cycles of the pipeline, results in the creation of residual stress regions.

When clustering of the corrosion defects occurs - regions of stress superposition\(^{(9,10)}\) and magnetic flux shielding further complicates the defect-induced MFL signal calibration\(^{(19)}\). A formal definition of interacting defects, according to code Z662 of ‘Oil and Gas Pipeline Systems’ is given as follows: ‘Corroded areas in close proximity shall be considered to interact if the distance between them is less than the longitudinal length of the smallest defect’\(^{(11)}\). We consider an extreme situation of this definition - two holes that are sufficiently close to influence both stress and flux distributions in the region between them.

Figure 1 presents the interacting situation most often encountered in practice: two corrosion pits, aligned along the pipe axis. Most field inspections use a magnetisation of the pipe wall in the same direction\(^{(12)}\). In Figure 1, the shaded zone experiences lower flux density than the bulk of the material, since the defects mutually shield one another from the applied magnetic field. It was previously shown that when the defects are not aligned perpendicularly to the applied stress direction the interaction is negligible\(^{(4,10)}\), such geometry allowing for more magnetic flux to enter the area between defects and less stress superposition.

Experimental technique

Two through-wall circular defects were drilled on mild steel plates. The mild steel represents a lower strength laboratory substitute for pipeline steel, with an yield strength of 291 MPa and Young’s modulus of 219 GPa. The plates were 500 mm long, 216 mm wide, and 2.8 mm thick. The defects were introduced by an electrochemical milling procedure while the samples were uniaxially loaded along their length at 135 MPa, or 46% of the yielding stress. The electrochemical drilling of the holes was preferable to mechanical drilling because this defect introduction
method does not induces residual stresses and it simulates a real corrosion process.

The stress was applied by clamping the samples in a hydraulic single axis stress rig, procedure that was meant to simulate hoop stresses in an actual pipeline - developed as a result of pressurisation of the transported fluid. Consequently, the magnetic field used for MFL inspection was induced on a perpendicular to the mechanical load direction, which corresponds to the axial axis of a pipeline. The adjacent defects were also aligned along this axis, since this geometry allows for the highest stress superposition and magnetic flux shielding.

According to the Airy’s function analytical approach\(^{(6,7)}\), the stress level developed in the immediate vicinity of a hole is three times higher than the bulk stress, decreases quadratically with the axial distance from the defect edge, and is effective for a region equal to the hole diameter. After the holes were drilled at a stress capable of inducing local yielding at the defects’ edges tangential to the loading axis, the load was released and than reapplied for subsequent MFL testing.

Each circular defect has a radius of 18 mm. The degree of interaction was examined in two situations, one with a centre-to-centre distance between the adjacent holes equal to three times the radius, or 45 mm, and the other with the centre-to-centre distance equal to four times the radius of a hole, or 54 mm. The interacting defect geometries are schematically presented in Figure 2. The situation when the two holes were closer to one another was denoted as strongly interacting defects, while the case when they were further apart was identified as weakly interacting defects. This later situation corresponds to the limiting case of interacting defects as defined by code Z662\(^{(11)}\).

The magnetic field is applied with a C-shaped magnetic circuit, containing high-strength NdFeB magnets, and closed by the sample itself\(^{(12)}\). Two magnetic circuit arrangements were used in order to induce two different bulk flux densities in the sample, of 1.0T and 1.7T. MFL inspections of the plates were performed by scanning the area between the magnetic pole-pieces with a Hall element.

![Figure 2. Adjacent defects geometries differing by the separation between defects](image)

![Figure 3. Typical MFL scan output for two adjacent holes – surface and contour plots](image)

![Figure 4. MFL\(_{pp}^{(%)}\) variation with tensile stress in conditions of applied flux densities of 1.0T and 1.7T for both interacting defect geometries](image)

Experimental results

It is generally accepted that a close-to-saturation flux density applied to ferromagnetic samples minimises the bulk stress effect\(^{(3,5)}\). This situation is confirmed when plotting the percentage change in MFL amplitude, MFL\(_{pp}^{(%)}\), versus the applied ‘hoop’ stress, as seen in Figure 4. For a sample magnetisation of 1.0T, magnetisation away from the material saturation level, a decrease of 30-35% of the MFL\(_{pp}^{(%)}\) with the applied stress in the range 0-135 MPa was observed for both defect geometries. On the other hand, when the magnetisation is closer to the saturation of the material, here 1.7T, the same variation is less than 5%. However, this kind of the interpretation does not provide any information about the defect geometry and the degree of interaction between the two holes, the differences recorded between the strongly and weakly interacting defects being rather within the experimental error.
magnetisation curve (~1.0T); however, at close-to-saturation flux density (~1.7T), the coalescence of the magnetic domains and the disappearance of the domain walls results in an isotropic sample.

The differences in the absolute MFL amplitude, $M_{FL_{pp}}$, variations with applied stress can be observed from Figure 5. It is apparent that the $M_{FL_{pp}}$ amplitude, like $M_{FL_{pp}}(\%)$, has less stress dependence at high flux density. The strongly interacting defects are characterised by higher flux leakage, a tendency accentuated at close-to-saturation magnetisation.

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Other features of the MFL scans of adjacent defects examined in this study are related to their profiles. The magnetic field flow intersecting the defects’ centres along their direction of alignment has a normal incidence at the steel-air boundary; therefore, the magnetic induction is conserved between the two media. The wave-like pattern of the normal-to-sample surface (or ‘radial’) MFL scans is plotted for the two interacting defect geometries in Figure 6. These results correspond to the 1.7T flux density and 135 MPa applied ‘hoop’ tensile stress. The location of the extreme values of the profiles correspond to each defect boundary intersected by the magnetic field line. When the MFL profiles are normalised to their maximum positive value, as in Figure 6, it is observed that the intermediary peaks, corresponding to the hole edges facing the adjacent one, have smaller amplitude than that of the overall profile. The overall amplitude of an MFL profile is dictated by the outside edges of the holes. It was recently shown that the ratio of the intermediary to overall MFL profile amplitudes, in conditions of close-to-saturation flux density, is not affected by the level of applied stress. This ratio was found to be equal to 40% for strongly interacting defects and to about 60% in the case of weakly interacting holes.

**Residual stress modelling**

From the in-situ defect drilling (at 135 MPa), local plastic deformation and residual compressive stress, induced at the defect edges tangential to the loading (hoop) axis, have an opposite effect on the magnetic permeability than tensile stress. Compared to a magnetically uniform sample, the stress-induced magnetic anisotropy indicates higher permeability along tensile stress direction and perpendicular to compressive stress axis. While the stress concentrations for through-wall defects are easily estimated by the use of Airy’s functions, residual stresses, which have an important effect on the magnetic flux flow in the vicinity of the defects, are almost impossible to be evaluated analytically or measured experimentally in field conditions.

We used specific finite element modelling software for visualising the local regions of residual stress developed in the defect vicinity. The residual stress distribution along the loading axis, ie hoop, for strongly and weakly interacting holes are shown in Figures 7 and 8, respectively. A two-dimensional representation of the plate subjected to uniaxial stress was modelled by using elements with four nodes (plane42), each having two degrees of freedom – translations on directions parallel and perpendicular to stress.

The regions of compressive stress were concentrated at the hole edges tangential to the load axis, and extended for a larger area in the case of strongly interacting defects than for weakly interacting ones. The highest compressive stress, of -13 MPa, was observed at the defect edges, in the region between the two strongly interacting holes.

**Discussion**

Under applied tensile load, because stress superposition and closeness of the holes, higher stresses are expected to develop in the area between them for the strongly interacting than for the weakly interacting defects. However, the compressive residual stresses have an opposite effect by reorienting the magnetic easy axis along the direction of defects’ alignment. Consequently, more
field lines are concentrated at the edge of the defect tangential to the ‘hoop’ axis. In these regions, the magnetic induction is normal to the defect edge and forced outside the sample.

The change in the MFL$_{pp}$ (%) with the applied stress at far-from-saturation flux densities (1.0T case in Figure 4) is attributed to the increased permeability along the loading axis. The tensile stress-induced anisotropy facilitates a path of lower reluctance around the defects region and consequently, the magnetic field lines flow around the defects, inside the sample rather than closing through the air. However, since the defects were drilled at 46% of the yield strength of the material and a stress concentration equal to 3 at the edge of the hole, local plastic deformation is introduced at the defect drilling stage. After the stress is released, this plastic deformation acts as residual compressive stress, as seen for the two defect geometries in Figures 7 and 8. Compressive stress has an opposite effect than the tensile load on the permeability, this time by lowering it. The residual stress has a permanent contribution to subsequent inspections and the applied stress superimposes over the local residual stress regions, at the edges of the defects tangential to the loading axis. Therefore, residual stress has a local effect on the flow of magnetic field lines - higher the residual stress, more field lines will intersect the defect boundary and leak into the air rather than spreading around the defects. This explains the higher MFL$_{pp}$ amplitudes for strongly interacting holes than for weakly interacting ones (Figure 5) for the same level of the applied stress, but regardless the flux density.

The limiting centre-to-centre separation for two axially aligned holes to be considered interacting is estimated by extrapolation of the ratio of intermediary to overall peak amplitudes of the MFL profile, as seen in Figure 9.

Three data points were used for this extrapolation: two from the strongly (centre-to-centre separation equal to 3 x hole radius), weakly interacting holes (centre-to-centre separation equal to 4 x hole radius), and the situation of a single hole, when, of course, the defects separation is equal to zero and there is no intermediary peak feature$^{9}$. It is understood that there is no interaction effect on the MFL signals when the ratio of the intermediary to overall MFL amplitude is equal to 100%. Graphically, it is found from Figure 9, that two axially aligned holes do not influence each other when their centre-to-centre separation is equal to at least 5.6 x hole radius.

**Conclusions**

This study investigated the effects of bulk applied stress, local compressive stress, and level of flux density on the MFL inspection of two adjacent holes geometries with the purpose of determining an appropriate axial defect separation in order for the defects to be considered independently or non-interacting. The experimental set-up tried to simulate realistic field inspections, but the defects considered were through-wall penetrating in order to mimic the most drastic situation in terms of local stress and magnetic flux distributions around them.

At high magnetic flux density (1.7T) a centre-to-centre separation of at least 5.6 x defect radius was found necessary for the MFL method to interpret the two holes independently. This contradicts existing standards$^{11}$, that, for the defects investigated here, required a centre-to-centre separation of only 4 x defect radius for two axially aligned holes to be considered non-interacting.

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References