Longitudinal and Circumferential Cracks in a Ferromagnetic Bar Detected Simultaneously

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Abstract. In ferromagnetic materials it is possible to detect surface cracks using two principles. One is the magnetic leakage test that is very often applied with the testing by D.C magnetic fields. Magnetic particle methods are based on this principle. The second principle is testing by eddy currents that can be applied for ferromagnetic and for non-ferromagnetic materials. The aim of our investigation is to construct a universal arrangement of coils that could be used for ferromagnetic bars for detecting surface cracks of any orientation.

1. Magnetic particle methods

It is very often explained that magnetic leakage fields can be used for detecting surface cracks in ferromagnetic material. The part must be magnetized in the direction being perpendicular to the length of the expected surface crack. Usually a strong D.C. magnetic field is used and magnetic particles (in the form of powder or suspension) are spread over the surface being investigated.

From the Maxwell equations it is evident that when crossing the boundary between two materials the normal component of the magnetic field density (B) must be conserved and the tangential component of the magnetic field strength (H) must be conserved too. Since the magnetic permeability of a ferromagnetic material is considerably bigger than 1 the flow of the magnetic field is different from the flow in a non-ferromagnetic material. In the defective places a part of strong magnetic flux comes out of the material and can be registered by a suitable instrument.

The principle of the magnetic particle method is in concentration of the field in the vicinity of the crack that influences the magnetic particles in the suspension so that they get concentrated in the spots of emerging field of both sides of the crack.

Sometimes it is possible to observe the change of the magnetic particle distribution on the surface by naked eye sometimes it is better to use a fluorescent suspension and to make a good photo of the part. The surface cracks being oriented *along* the field cannot be detected in this way.

The method is very practical and there are several procedures available for changing the orientation of the field accordingly. It has however some drawbacks. It does not tell much about the crack depth. When the magnetic leakage fields are measured it is possible to connect the measurements with the depth of the crack [1].

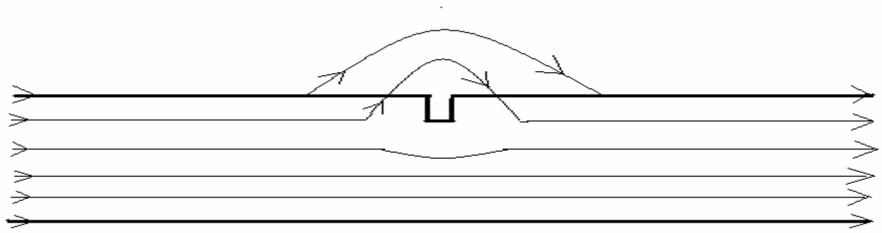

Fig.1: Magnetic leakage fields in the vicinity of a surface crack in the cross-section of a ferromagnetic plate.

2. Eddy Currents

2.1 Primary and secondary coil

The basis of the eddy current method is often explained by a simple example of detecting surface cracks in a metal bar:

A long metal bar of circular cross-section is supposed to be put in a homogenous A.C. magnetic field oriented along the bar. Because of the demagnetizing effect of eddy currents flowing in circular direction in the cross-section (skin effect) the magnetic field in the cross-section is not uniform. It is much stronger close to the surface than in the middle and there are also phase differences in the field among different parts of the cross-section. This effect depends on frequency and on physical properties of the material.

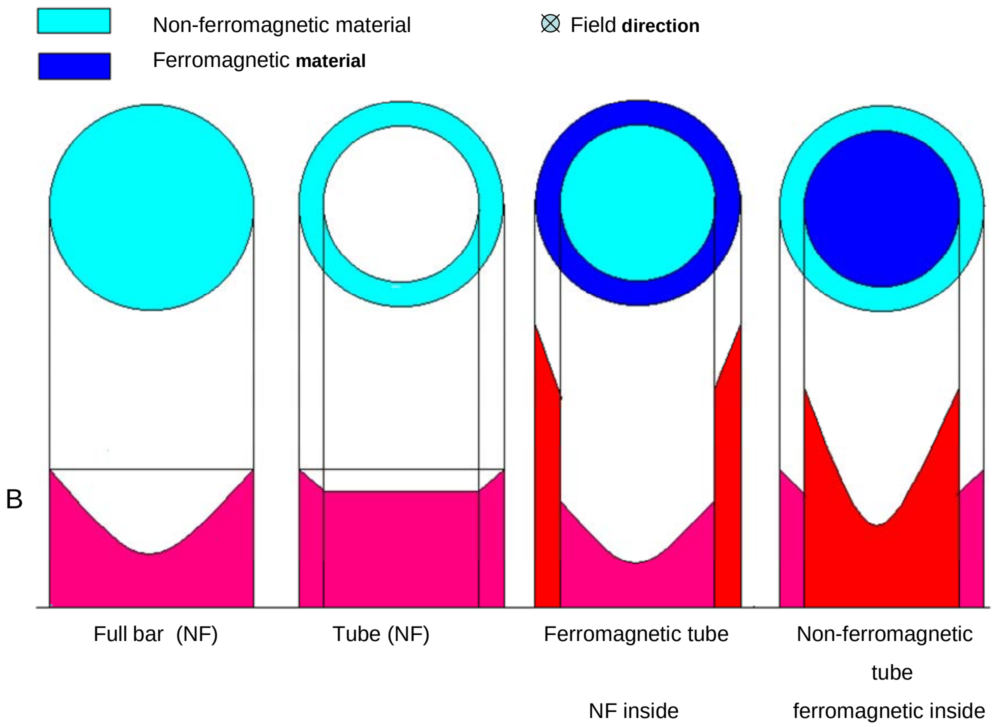

Fig. 2: Magnetic field density in circular cross-sections of different materials in longitudinal homogenous magnetic A.C. field.

In Fig. 2 it is schematically shown how skin effect influences the magnetic flux distribution for different combinations of the material. In a secondary coil wound around the bar the induced voltage would be directly proportional to the magnetic flux in the cross-section of the bar. Some examples are shown in Fig.3.

The situation in the secondary coil changes if there is a surface radial crack being oriented along the length of the bar. The demagnetizing influence of eddy currents in the cross-section is diminished because eddy currents cannot flow across the crack. The net magnetic flux in the cross-section is increased in the vicinity of the crack and so is the induced voltage increased in the secondary coil. The difference between two induced voltages is the indicator of the crack in a metal bar. Fig. 4 schematically shows the magnetic field in the cross-section of a metal bar with a radial crack and without a crack. The two outer regions of the defective cross-section are increased and indicate the increase of the field caused by the crack. The darker regions belong to smaller phase difference and to stronger magnetic field. According to these explanations it would not be possible to detect difference in the induced voltage if the surface crack is not hindering the flow of eddy currents. It would not be possible for instance to detect very thin surface cracks in the direction perpendicular to the axis of the bar. In the case mentioned above the eddy currents namely would not be forced to change their direction at all.

There are several explanations given in the literature how to distinguish among voltage differences caused by different position and forms of cracks [2].

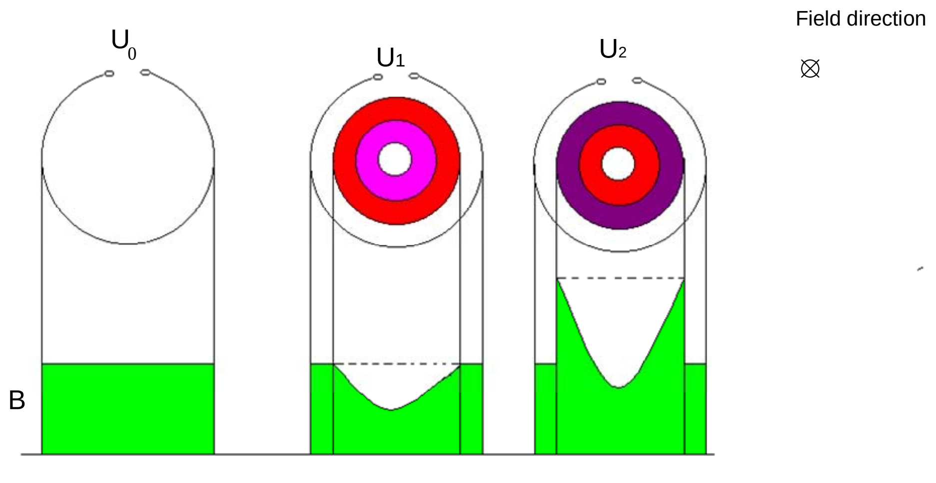

Fig. 3: The induced voltage is proportional to the encircled magnetic flux in free space (U_0), in a non-ferromagnetic (U_1) and in a ferromagnetic (U_2) cross-section.

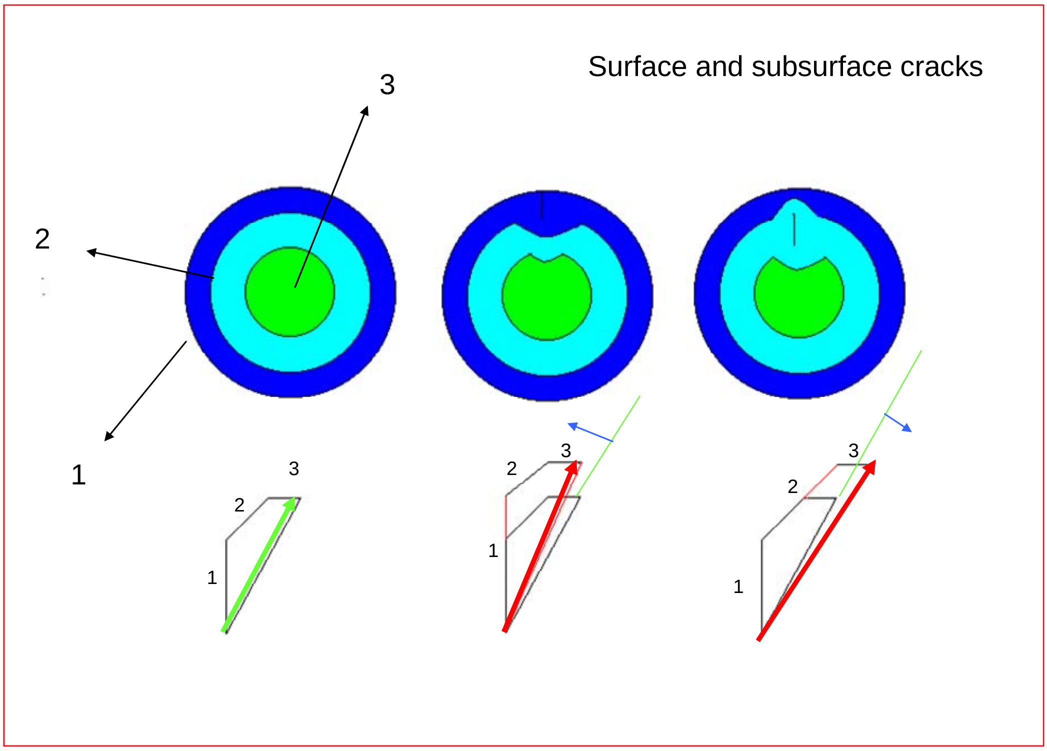

Fig. 4: Cross-section of a metal bar with a radial crack and without a crack. Surface cracks rotate the signal in the opposite direction than do the subsurface cracks.

It is not so convenient to measure the induced voltage of a secondary coil and to look for small changes in the induced voltage. Much more useful is the so called differential arrangement of secondary coils. Two equal parts of the secondary coil are wound in opposite directions and connected serially so that the induced voltages are subtracted. Any measured value is proportional to the difference of the magnetic flux in both parts of the secondary coil (Fig. 5).

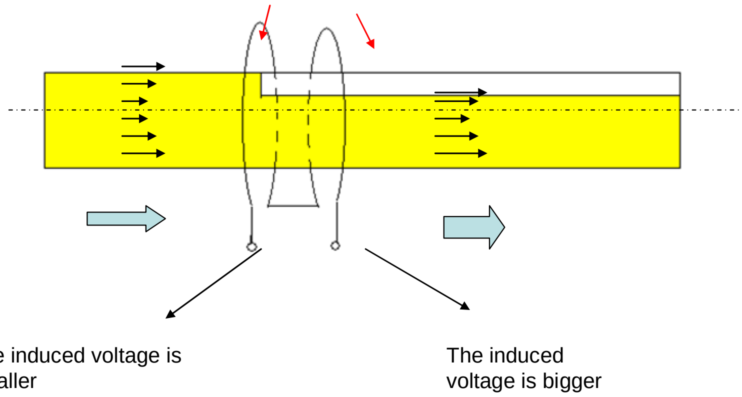

Fig.5: Differential arrangement of coils.

2.2 Magnetic leakage fields due to eddy currents

At the WCNDT in Moscow [3] the interpretation of the eddy current testing was made in some different way.

If namely the magnetic flux in the cross-section of the defective bar is increased it means that an additional magnetic flux had to enter from the outside. Another secondary coil (sensor) was used to detect radial flux as shown schematically in Fig.6. A sharp peak in radial flux could be calculated and also experimentally proved. In this way a new idea was given to use the magnetic flux flowing in radial direction instead of change of the magnetic flux in axial direction.

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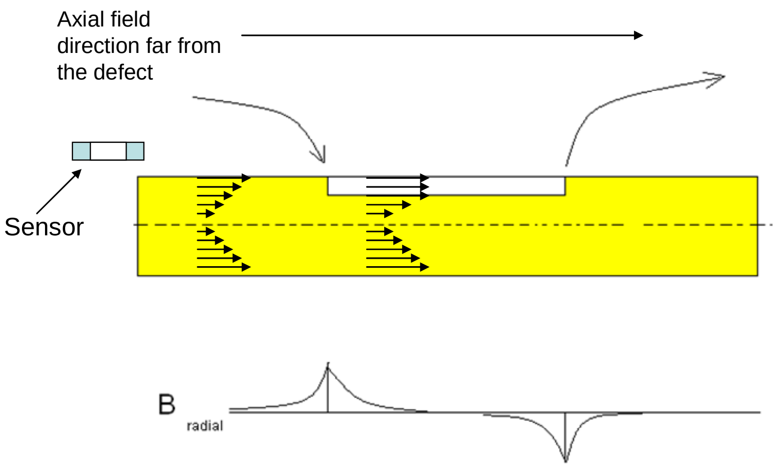

Fig. 6: Sensor for registration of the radial field.

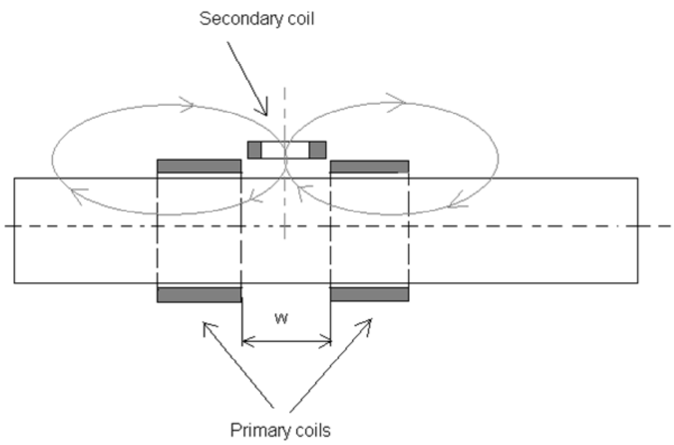

Fig. 7: Two parts of primary coils and the secondary coil measuring radial field.

3. Arrangement of coils with two parts of one primary coil and a secondary coil between them (Fig.7).

The idea is being studied at the Faculty of Mechanical Engineering of the University of Ljubljana (Slovenia). [4, 5]

Two parts of primary coil are magnetizing the bar in longitudinal direction. The coils are rather short and so it is not possible to assume, that the magnetic field in this direction is homogenous. The separation between both parts (w) according to Fig.7 is very important.

There are two fluxes flowing in radial direction, one part enters the bar and one leaves the bar. If both parts of the primary coil are equal and if the material is homogenous there is no induced voltage in the secondary coil if it is placed precisely in the middle position. If however there is some defect in the material being situated in one part of the primary coil the flux in axial direction is changed and also the induced voltage in the secondary coil is not equal zero any more.

This arrangement is similar to differential arrangement the only difference is that in this case instead of two voltages there are two magnetic fluxes subtracting.
In order to study the magnetic field distribution the mathematical model is used where there are simulations possible varying geometrical dimensions and physical properties of the material.

Maxwell equations for the magnetic field are being solved by numerical methods and the fields in the vicinity of the three coils are calculated [6].

3.1. Mesh points assumed in a simple example for numerical solution of differential equation

If two parts of primary coil are separated considerably as shown in Fig. 7 and if the problem is symmetrical it is possible to solve the system of Maxwell equations for one fourth of the cross-section as indicated in Fig.8.

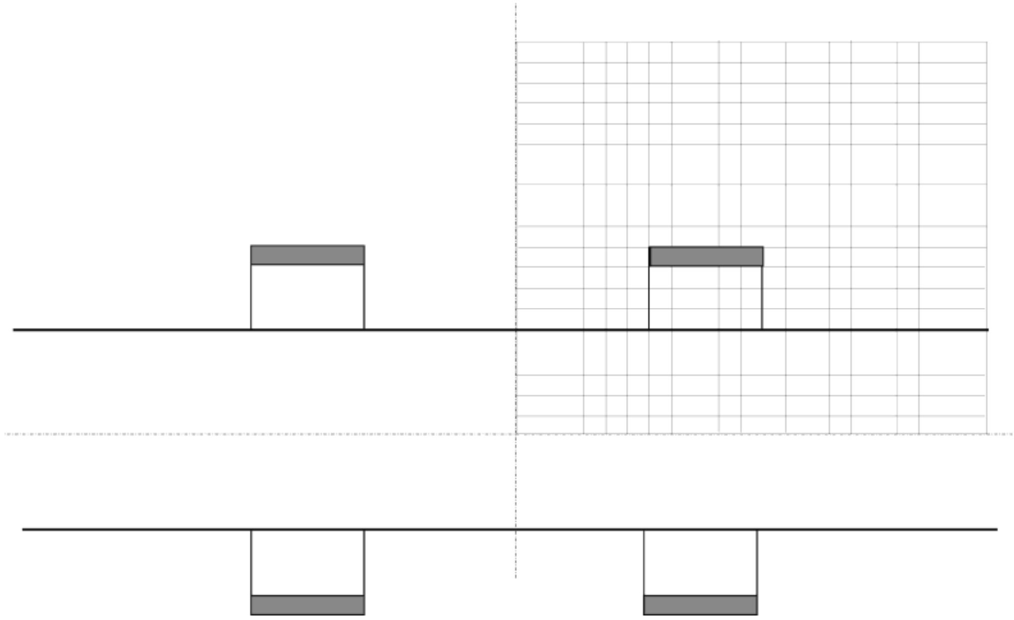

Fig. 8: Mesh of points where the magnetic field is calculated.

The mesh distance in two directions can be chosen deliberately if the method of finite differences is used. [7].

In Fig. 9 the magnetic field is represented by arrows indicating direction of the field, their length is somehow proportional to the magnetic field amplitude.

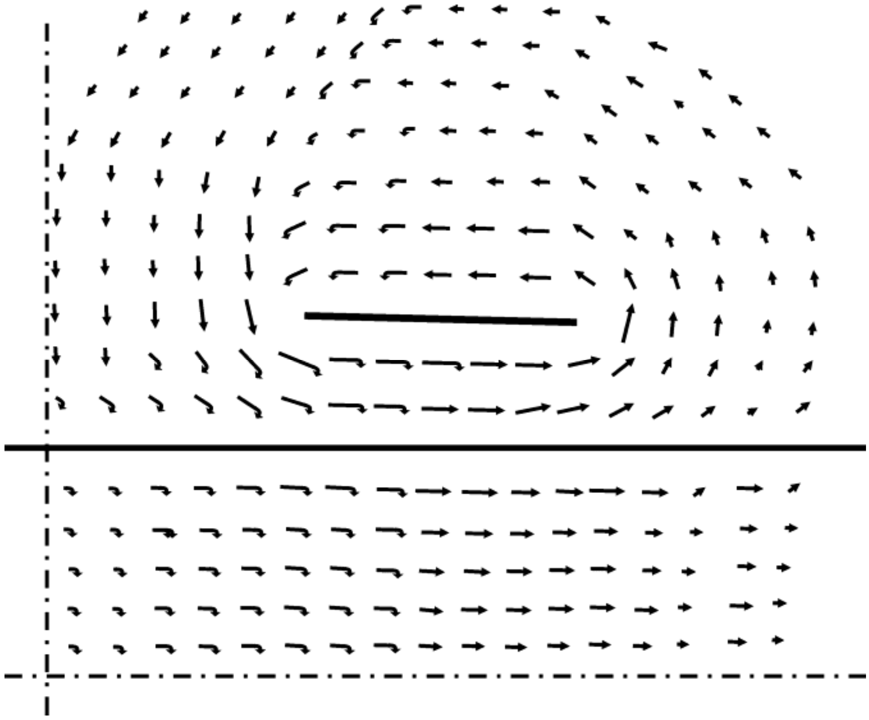

Fig. 9: Calculated magnetic field in the equidistant mesh points of Fig. 7. (F=1, μ=1)

3.2 Mathematical modeling

The appropriate dimensions of the primary coils and the secondary coils depend on how precise do we wish to detect the position of the crack. The sensitiveness is strongly dependent on the geometry. If the gap between the two parts of the primary coil is too small, the magnetic flux is flowing mostly in longitudinal direction and there is not enough flux flowing in radial direction. A compromise must be found between two fluxes flowing in longitudinal and in radial direction if the device is to be used for detecting defects in ferromagnetic bars. It strongly depends also on frequency and on practical limits for winding coils.

The mathematical modeling of the arrangement seems to be very helpful. By solving the Maxwell equation for the vector potential it is possible to simulate various situations concerning dimensions frequency and type of defects. Since the results of the mathematical model are more or less performed on simplified cases it is generally possible to calculate the main fields so that the most important parameters influencing the induced voltage can be assessed. It helps a lot with understanding mechanisms of detecting defects and gives ideas about practical limits of this NDT method.

4. Conclusion

The magnetizing coil is divided to two parts and in the gap between them a secondary coil is mounted. While the primary coil produces the longitudinal A.C magnetic field in the secondary coil the voltage is induced corresponding to the difference of magnetic fluxes from both parts of the primary coil. If the bar inside the coils is homogenous there is no induced voltage in the secondary coil. If however the defective part of the bar is placed in one part of the primary coils the eddy currents are different from the eddy currents in the sound part of the bar. Also the magnetic fluxes are different and the secondary induced voltage is different from zero. The radial component of magnetic flux has been changed accordingly and the longitudinal crack can be detected.

If however the surface crack is perpendicular to the axis of the bar the eddy currents are not affected but the magnetic leakage field can be detected in any way. Since the magnetic flux in the ferromagnetic material is avoiding surface defect some radial magnetic flux emerges that can be registered in the secondary coil. This holds naturally only for ferromagnetic materials.

By the arrangement of primary and secondary coils given above it is possible to detect longitudinal and circumferential surface cracks in ferromagnetic material simultaneously.

5. References

[1] Brudar B.: Magnetic Leakage Fields Calculated by the Method of Finite Differences, NDT International, Vol. 18, No.6, December 1985, p 353-357.

[2] Brudar B.: How to Distinguish Surface and Subsurface Cracks Using Electromagnetic NDT Methods, NDT International, Vol. 17, August 1984, p 221-223.

[3] Brudar B.: Proceedings of 10th WCNDT, Paper I-C6, Moscow, 1982.

[4] Brudar B.: Magnetic Field Around Two Separated Magnetizing Coils. The 8th International Conference of the Slovenian Society for Non-Destructive Testing, September 1-3, 2005, Portorož, Slovenia.

[5] Brudar B.: Magnetic Leakage Fields as Indicators of Eddy Current Testing, The 8th International Conference of the Slovenian Society for Non-Destructive Testing, September 1-3, 2005, Portorož, Slovenia

[6] Brudar B.: The Electromagnetic Field in the Neighborhood of a Defect in a Material, Research Techniques in NDT, Vol. V, Academic Press, London, 1982, 169- 238

[7] Smith G. D.: Numerical Solution of Partial Differential Equations, Oxford University Press, Oxford, 1971.