The Magnetic Dipole Theory for Non—Destructive Testing in China

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Abstract A survey of the generai situation and progress of the magnetic dipole theory research in China is given in this paper. These include the following contents: 1) Magnetic field of a magnetic dipole, a linear magnetic dipole of finite length and a strip magnetic dipole of finite length; 2) Magnetic force acting upon a magnetic particle; 3) The effect of magnetizing field orientation on the revelation of defects by magnetic particles; 4) Longitudinal magnetization of a rod, tube and cuboid steel component; 5) Magnetic leakage field yielded by a slot on the workpiece surface; 6) The analytic expressions for some results of classical experiments (made by Japanese Society for NDI and Dr. F. Förster) ; 7) Theoretical explanation of some strange magnetic particle patterns (around a square hole, near corners of a keyslot and over cylindrical surface of a pin with throughout hole) and abnormal phenomena in magnetic NDT (reversing of magnetic poles in a slot after discontinuation of magnetization, non - relevant magnetic particle indications along the lateral edges of a cuboid steel component magnetized longitudinally and along the base apex lines of a workpiece magnetized circumferentially); 8) Seeking new electromagnetic law and conception for NDT; 9) The distribution of magnetic charges in a region on the plane; 10) Approximate theory for the ring standard specimens (magnetic leakage field from a subsuface flaw) and so on.

Keywords: Magnetic dipole，Theory，NDT，China

The magnetic non-destructive testing started in 1868. The British S.M. Saxby searched for flaws and other irregularities in gun barrels by making use of a magnetized compass needle[1]. In 1876, A. Hering obtained a U.S. patent for detection of discontinities in railroad rails by using similar techniques[2]. In 1922, a patent was granted to American W.E. Hoke in respect of fault detection by magnetic means[1, 2]. About the end of 1923 in England the method was applied with success to turbine blades and traction pinions under production condition and was quickly extended to other components[1]. From then on magnetic particle inspection became an important means of non-destructive detection for steel, iron products, and has lasted up to now. For recent decades there have appeared new magnetic leakage flux techniques[3].

Although the magnetic leakage field yielded by a spherical and a cylindrical hollow cavity in magnetic medium had been studied in 1938[4], the understanding of magnetic NDT principle still remained long on the sweeping qualitative statement. It was until 1966 that the first article[5] analysing magnetic leakage field of defects was published in USSR. Thence, scholars of USSR, Japan, USA, Germany and England compete with research in this filed. Two main schools of thought have been formed. One is the classical theoretical school with USSR as its leader, of which the major method is magnetic dipole, and another is the technological approximate school with USA and Japan as its chiefs, of which the major method is Finite Element Method[3,6]. For last 42 years both sides carried out a large number of investigations, but either met with his difficulty respectively. Therefore to this day neither side has gained any theoretical results wholly coinciding with the experiments.

This investigation programme got off to a late start in China. In 1979, there appeared the first introductive paper[7] reporting partial foreign research condition. Before 1984 only one article[8] introduced the application of this theory in the Japanese MPI standard pieces. After that the study of magnetic dipole theory in China began to be active[9], its general situation and progress are as follows:

1. Magnetic field of a magnetic dipole

The magnetic field strength yielded by a magnetic dipole was analysed, and all its typical spatial distribution characteristics were plotted[10～13].

2. Magnetic field of a linear magnetic dipole of finite length

The traditional model of linear magnetic dipole of infinite length was replaced with a model more close to reality, which the length of the linear magnetic dipole was finite. The analytic expression of the magnetic field yielded by the latter was derived. A series of typical curves of its spatial distribution were plotted through digital calculation[14].

3. Magnetic field of strip magnetic dipole of finite length

The analytic expression of the magnetic field strength from a strip magnetic dipole with finite length was given in reference[15]. And it has been discovered that this theory didn't totally conform with the experiment of deep cracks made in USSR[16]. Thereby it concludes that the traditional physical model——the hypothesis of constant polarity isn't true, and the correct distribution of magnetic charges on the slot must be reseeked for.

Besides, there were studies on the original model of strip magnetic dipde with infinite length[17～20].

4. Magnetic force acting upon a magnetic particle

The magnetic force acting upon a magnetic particle of finite length in the magnetic field of a magnetic dipole or a linear magnetic dipole of finite length were analyzed[10,11,14]. Further, shape and dimension of magnetic particle pattern on point - type defects of workpiece surface were discussed[21,22].

Whereby the principle of MPI for a point - type defect and a shallow crack - type flaw on the workpiece surface were explained[10,11,14].

Otherwise, the magnetic force acting upon a magnetic particle with infinitesimal length in the magnetic field of a strip magnetic dipole with infinite length were also discussed[17,23～25].

5. Effect of magnetizing field's orientation on the revelation of defects by magnetic particles

Through analysis of magnetic dipole theory the function of magnetizing current I and the angle between this current and the defectθhas been discovered as:

$$I \propto 1/\cos^2\theta \quad (\theta_{s1} \le \theta \le \theta_{s2}\ ;\ \theta \le \theta_t) \qquad (1)$$

$$I \propto 1/\cos^3\theta \quad (\theta_t \le \theta \le \theta_{s1}\ ;\ \theta \ge \theta_{s2}) \qquad (2)$$

or approximately

$$I \propto 1/\cos^4\theta \quad (\theta_t \le \theta \le \theta_{s1}) \qquad (3)$$

$$I \propto 1/\cos\theta \quad (\theta \le \theta_t) \qquad (4)$$

The physical meanings of these rules, initial magnetizing current I_o (θ = o°), turning point θ_t, landing point θ_{s1}, taking up point θ_{s2} and limited orientation of detection θ_L have explained not only theoretically, but also have been verified by experiment of MPI[26～28].

6. Longitudinal magnetization of bars and tubes

According to the traditional opinion, that magnetic charges will distribute uniformly on the two bases of a bar or a pipe magnetized longitudinally, the demagnetizing field and demagnetizing factor on the surface of a steel bar or a pipe were calculated, and some demagnetizing factor curves were plotted. It provides theoretical basis for selecting longitudinal magnetizing criterion[29].

Since there is Coulomb's repulsion between the like magnetic charges[30], after longitudinal magnetization of a right circular cylinder of magnetic medium the magnetic charges will distribute in the two circular bases (at the center of circle or not) and uniformly along the two base apex lines[31～34]. So the demagnetizing field of a cylinder must be superimposed by two parts: one is the demagnetizing field of the magnetic charges along the base apex circles, the other is in the circular bases. The former has been deduced, calculated and plotted[31,35].

7. Longitudinal magnetization of a cuboid steel component

The references [36]～[38] from both cases of interaction force and interaction energy between magnetic charges, demonstrated that after longitudinal magnezition of a cuboid magnetic medium the magnetic charges will uniformly distribute along all the edges of the cuboid. Whereby the reason has been explained theoretically, why the non - relevant (stray) indications will occur after longitudinal magnetization of a rectangular parallelepiped along its lateral edges.

Besides the demagnetizing field for an arbitrary point in the cuboid steel component magnetized longitudinally at the initial transient moment of magnetization and the net magnetic charges were derived, calculated and plotted[39]. As the first approximation, the linear magnetic charges density along all edges of a cuboid and its demagnetizing field were respectively given.[40～42].

8. Strange magnetic indications along the base apex lines of a workpiece magnetized circum - ferentially

The reference [43] proves that after circumferential magnetization of the workpieces (including cylinder, cuboid, parallelipiped and triangular prism etc.), the same lineal magnetic charges will uniformly distribute along not only the edges of the lateral faces but also the base apex lines, so both the former and the latter must adsorb magnetic particles, and non - relevant magnetic indications may also be formed along the latter.

9. Magnetic leakage field yielded by a slot on the workpiece surface

The reference [44] proved that there will be approximate linear law or exponential law between slot depth in the workpiece surface and the magnetic leakage field yielded from the slot respectively due to differences of testing block’s figures, magnetizing types and slot depths. The theoretical result coincides with the Japanese experiment [44].

The analytic expression for the magnetic leakage field inside and outside a slot on the cylindrical surface of a disc is given in reference [45]. Its theoretical characteristic curves basically conform to the Japanese experimental result, which has been known for at least 23 years and any theoretical explanation about this classical experiment has never bee seen since then[45,46].

The references [47～49] give the analytic expression for the classical experiment made by Dr.F. Förster in 1985, of which the analytical solution has never been seen since then. The characteristic curves from this theory basically conform to that experimental result[50].

In addition, the following relations have been studied: between the magnetic leakage field and the depth of a surface - breaking defect[51,52], between magnetic leakage field and the dimensions of a rectangular through slot on surface of a steel cubold [53], between magnetic leakage field and the section shape[54] and between magnetic leakage field and slot width or lifting off[55].

10. Reversing of magnetic poles in a slot on the workpiece surface after discontinuation of longitudinal magnetization

This unusual phenomenon surprised Dr. Förster[50] and other NDT personnel, but they didn't gain a satisfactory explanation. And not only a simple qualitative interpretation[56], but also a quantitative calculated result basically conforming with the experiment[49] have been given in China.

11. Strange magnetic particle pattern around a square hole on the workpiece surface

In the summer of 1995, Chinese NDT personnel surprisingly discovered that the magnetic particle pattern around a little square hole ($0.6\times0.6mm^2$) was four long straight lines staring from the four corners of the square hole and spreading out along the extension lines of the two diagonals of the hole. And the calculating result from magnetic dipole theory just like this[57]. Then it has bee proved that similar magnetic particle patterns will appear around the corners of a large square hole, a rectangular hole and a parallelogram hole under a certain condition. This deduction was verified not only by magnetic particle testing experiments, but also by some experiences of magnetic particle inspection in production[58,59].

12. The introduction and application of the concept of magnetic dipole chain

After a magnetizing field is applied in a magnetic medium, the magnetic dipoles orienting irregularly in origin must form a lot of magnetic dipole chains, in which every positive and negative magnetic poles connect head to tail[30,60]. Their varieties and characters (transversal repulsion, changing direction, connection, increasing of length, breaking and rearrangement etc.) were investigated[61,62]. With which, not only the theoretical difficult problems in paragraph 6, 7, 8, 9 and 10, were solved, but also the reasons of following unexpected phenomena were explained:

1) Abnormal magnetic leakage field appears over a steel ball with surface crack on, at the spot opposite the crack[63].

2) The strange magnetic particle pattern over the cylindrical surface of a cylinder magnetic medium with a circular or a square through hole[64].

3) Sometimes longitudinal (circumferential) magnetization of a workpiece can also reveal longitudinal (circumferential) defects[65].

13. Seeking new law in electromagnetism for magnetic NDT

1) The influence of a needle - like magnetic medium on the magnetic force between two point magnetic charges——an amplifying effect[66].

2) When a cuboid steel component is magnetized longitudinally, there will appear two different stages of magnetization (sub - stable and stable condition) with the increasement of the magnetizing field strength[67].

3) In the stable condition of magnetization of a magnetic charges system, the equilibrium between magnetic forces is equivalent to the minimum magnetic interaction energy. If there are non - magnetic forces in the system, these two are irrelevant[68].

14. Magnetic charges distribution on a plane

The magnetic charges uniformly distributing in a any - shaped region on a plane at the initial transient moment of magnetization must be divided into two parts: one remains in the planar region and the other deposits upon the edge of the region due to Coulomb's repulsion[30,32]. So there will appear point magnetic charge at the geometrical center of the region (or not) , non - uniform areal magnetic charges and uniform linear magnetic charges [33,34,69,71]. The watershed of magnetic forces is similar to the watershed of magnetic charges on the two end surfaces of a rectangular steel componet magnetized longitudinall[72].

15. Theoretical exploration for the standard steel ring specimen (magnetic leakage field caused by sub - surface defects)

Through the analysis of Betz's ring[73,74], an approximate theory was proposed[75, 76] on the basis of a hypothesis, that the electric current in the ring is uniform[77]. The tendency of the calculated and plotted curve is identical with the experimental result [76,73]. It was discovered that only three between four geometrical dimensions of a ring specimen are independent, the fourth must be decided by electromagnetic law[78]. In adition, the difficult problem, why a ring revealing 5 holes can reveal 9 holes after anneal in the same testing condition [74,79,80] has been theoretically solved [75].

16. Other studies on or by magnetic dipole theory

1) Magnetic field strength at any point in ferromagnetic material [81].

2) Magnetic leakage field detected by the metal magnetic memory testing and diagnostic technique [82,83].

3) The zero value line of the normal component of magnetic leakage field in the metal magnetic memory testing and diagnostic technique [82,84].

To sum up, it isn't difficult to see that magnetic dipole theory is unusually convenient to solve the unresolved theoretical questions in magnetic NDT and has distinctive effect. In recent 20 years China has obtained some progress in this region. For the real realization of quantification and automatization of magnetic NDT, the NDT personnel of China and the whole world must continue to study hard and solve the outstanding theoretical problems in this respect.

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