Application of anhysteresis residual magnetization method to evaluate distribution of additional plastic deformation in ferromagnetic metals

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Received 5 May 2016

Abstract
After a huge earthquake, it is important to evaluate additional plastic deformation induced by the disaster to identify damage to important structures such as nuclear power plants, tall buildings, or high-pressure hydrogen infrastructure. As residual magnetization takes on anhysteresis characteristics during plastic deformation, the “law of approach” based on the magnetomechanical functional property can be used as a non-destructive test, termed anhysteresis residual magnetization method, to determine additional plastic deformation beyond that of the last instance of magnetization or demagnetization. The mechanism of this property can be explained by the interactions between dislocations and magnetic domain walls. Furthermore, the experimental results of demagnetization under tensile or compressive stress are provided for the anhysteresis residual magnetization method under a non-magnetic field. The advantages and limitations of the method are discussed.

Key words: Additional plastic deformation, Non-destructive test, Residual magnetization, Anhysteresis curve

1. Introduction

Most structural materials are safe when stressed within their elastic limits. However, after being subjected to plastic deformation, they sometimes become dangerously weak with reduced fatigue limits. In the case of unpredicted strong earthquakes, structural materials must be checked for damage in important facilities, as plastic deformation can easily occur from the large forces that accompany the disaster.

For instance, if a large earthquake strikes a nuclear power plant with excessive acceleration, the reactor core structures must be checked to verify that they did not undergo plastic deformation during the impact (Nonaka, et al., 2010). Similarly, if a tall building suffers a strong earthquake, its residual seismic capacity should be evaluated before continuing to use the construction (Kusunoki, 2006). Moreover, high-pressure iron vessels for hydrogen gas in fuel cells should be constantly monitored to ensure their stress falls within the elastic region, as a single occurrence of unexpected plastic deformation would induce delayed fracture and subsequent hydrogen embrittlement (Kotake, 2013).

As a typical example, during the Niigata prefecture Chuetsu earthquake on July 6, 2007, nuclear power plants were shaken with excessive acceleration. At the ground floor of the No.3 turbine building, the acceleration was recorded to be 2058 gal, which is far beyond the maximum allowable acceleration of 834 gal. Furthermore, the electric transforming equipment caught fire. After the earthquake, the important structures within the power plant had to be evaluated for damage, especially with regard to plastic deformation, prior to restarting power generation.

In 2008 at the conference of materials and mechanics division in the Japan society of mechanical engineers, there was a special session to discuss methods used to evaluate the damage of important structures following an earthquake (Nakasone, et al., 2008). At the conference, specialists and scholars of material mechanics were asked how to measure the amount of plastic deformation induced by the disaster. Without any innovative solutions, people had selected Vickers hardness test to evaluate the amount of plastic deformation, although this method merely estimates total dislocation density of the structures.
Since then, there have not been many discussions on the evaluation of plastic deformation resulting from a certain traumatic event. One reason is that strict requirements have not been established, except for in a few special cases such as the above-mentioned earthquakes. Another reason is that most nondestructive tests for plasticity evaluate total hysteresis of plastic deformation or dislocation density, but not necessarily additional damage resulting from a specific disaster. Conversely, because of the Great East Japan earthquake in March 11, 2011, people have recently taken a greater interest in disaster prevention and disaster management. Although the evaluation of additional damage induced by a certain disaster has become essential for important social infrastructure, nondestructive tests to estimate it have not yet been developed.

As most structural materials are made of steel, which has ferromagnetic properties, such as permeability, coercivity, and residual magnetization (remanence), people have tried to use these properties for nondestructive testing of the material. Pitman (1990) reported sudden changes in residual magnetization of iron, which shifts towards an anhysteresis curve after applying mechanical stress. Schneider et al. (1992) discussed using the magnetoelasticity of ferromagnets under large stress. Jiles (1995) and Jiles and Li (2004) studied the magnetomechanical effect and discovered the existence of the “law of approach” in residual magnetization, in which the hysteresis converts to an anhysteresis curve under applied stress. Although the effect of mechanical stress on magnetic properties of ferromagnets has been studied for a long time, it has been discussed primarily in the field of electric devices, and has not been applied to the field of nondestructive testing.

In this study, we propose a nondestructive test to evaluate the amount of additional plastic deformation from certain instance by using the “law of approach” of magnetomechanical phenomena in ferromagnetic metals. We refer to it as the anhysteresis residual magnetization method for additional plastic deformation. To clarify the effect of the method, we introduce the concept of total plastic deformation versus additional plastic deformation (Kotake, 2012, Kotake, 2014). Furthermore, we explain the mechanism of the method by considering the effects of elastic or plastic deformation to residual magnetization. Moreover, we provide experimental results to illustrate the advantages and disadvantages of the method. Although this technique is merely applicable to ferromagnetic materials, it can be practically useful in many cases, as most mechanical structures contain ferromagnetic steel, nickel or cobalt.

2. Additional plastic deformation and total plastic deformation

2.1 Total plastic deformation

In the following section, we will discuss two new concepts regarding plasticity, total plastic deformation and additional plastic deformation, in order to clarify the features of the proposed nondestructive test method. Total plastic deformation is total amount of plasticity from the perfect crystal structure to the current state of a test material. From a mesoscopic point of view, total plastic deformation is reflected from total dislocation density, which always increases with plastic deformation below recrystallization temperature. In many cases, x-ray diffraction is used to evaluate dislocation density, as the development of dislocation density during plastic strain increases the lattice constants of the material. However, lattice constants can also be increased with elastic strain, thus we cannot distinguish one from the other. To merely evaluate the amount of dislocation density, a hardness test has been used because of the work hardening effect of metals. In practice this method had been applied to investigate damage to important structures in Kashiwazaki-Kariwa nuclear power plants after the Chuetsu earthquake as previously mentioned. However, as a large dislocation density has already been introduced into the structures during the manufacturing process and the method only evaluates total plastic deformation, it is difficult to detect slight increases in dislocation from disaster-induced damage (Shimotomai, 2008).

2.2 Additional plastic deformation

Additional plastic deformation, a concept newly introduced by the author, indicates additionally increased amount of plasticity beyond a certain instance. Of course, the amount of additional plastic deformation can be evaluated from the finite increase of total plastic deformation. However, in case in which the increase of total plasticity is not sufficiently high and previously introduced plasticity is much higher, signals of additional plastic deformation are too small to be evaluated against the background noise of total plasticity. Therefore, certain physical quantities of the material can be initialized at any moment and proportionally increased with additional plastic deformation following initialization.
In this study, we utilize the magneto-mechanical effect of ferromagnetic materials, called law of approach, which indicates a gradual change in residual magnetization from hysteresis to anhysteresis with additional plastic deformation. The residual magnetization can be initialized with magnetization or demagnetization under an external field. In the following section, we explain the mechanism of this effect.

3. Mechanism of the law of approach in residual magnetization

3.1 Residual magnetization under elastic deformation

As ferromagnetic materials have the property of spontaneous magnetization, submicron-sized magnetic domains can be created within a crystal grain. Boundaries of these magnetic domains are called magnetic domain walls, which have nanometer-sized widths (Kittel, 2004). Residual magnetization appears because of the pinning effect of magnetic domain walls against obstacles such as dislocations. The dislocations are also pinned against the domain walls as they interact with each other (Takahashi, 2006). If pinning sites among dislocations and magnetic domain walls were not moved and recovered, the ferromagnetic property would not be changed after applying mechanical strain. It should be noted that this elastic property exists not only mechanically but also magnetically.

It has been well known that ferromagnetic materials are subject to the phenomenon of magnetostriction, which is caused by the anisotropy of spontaneous magnetization. Although α-iron of ferrite has a body-centered cubic structure, it is slightly stretched along its magnetic orientation because of the magnetic field energy. Therefore, when the specimen is pulled, magnetic domains, whose magnetization vectors are perpendicular to the tensile stress, increase their volumes. Conversely, they decrease their volumes if their magnetization is parallel to the stress. In other words, the coefficient of magnetostriction is negative in ferrite.

As two opposite magnetic domains are parallel/perpendicular to the tensile stress, opposite magnetization vectors increase/decrease simultaneously, as far as the specimen is deformed in elastic region. After unloading, the volume of each domain returns to its initial state. Therefore, we expect that macroscopic residual magnetization will not change after elastic deformation. Figure 1 expresses this phenomena schematically.

3.2 Residual magnetization under plastic deformation

Pitman (1990) and Jiles (1995) reported that the residual magnetization of ferromagnetic metal approaches to an anhysteresis curve after applying external stress to the specimen, which is called the “law of approach” by Jiles. As elastic deformation does not change macroscopic residual magnetization, we attribute its change to plastic deformation of the ferromagnetic metal with compressive stress, and (c) elastically deformed demagnetized ferromagnetic metal with tensile stress under non-magnetic field (In this case ferromagnetic metal has negative magnetostriction coefficient, such as pure Fe).
specimen mechanically or magnetically. Here, we mainly discuss mechanical plastic deformation, as the applied stress causes dislocation flows in the specimen initially. The flow of the unpinned magnetic walls causes magnetic plastic change as a result.

When a metal is plastically deformed, many dislocations are unpinned and move along the plastic deformation flow. In the same manner, when magnetized ferromagnetic metal is plastically deformed under a non-magnetic field, moved dislocations unpinned some magnetic domain walls. As unpinned magnetic walls transfer into a stable state, the “law of approach” is realized to produce an anhysterisis curve. Therefore, the volumes of magnetic domains will become equivalent to make the residual magnetization vanish, when plastic deformation occurs under a non-magnetic field. Figure 2 expresses this phenomena schematically.

Fig. 2 Microscopic image of magnetic domains under a non-magnetic field in (a) magnetized ferromagnetic metal whose magnetic domain walls are pinned at dislocations to retain residual magnetization, or in (b) after plastic deformation where the magnetic domain walls are unpinned from dislocations to lose residual magnetization, and (c) schematic image of a $B$-$H$ curve under a non-magnetic field, where residual magnetization approaches an anhysterisis curve to be demagnetized.

Fig. 3 Microscopic schematic of magnetic domains under a magnetic field in (a) magnetized ferromagnetic metal whose magnetic domain walls are pinned at dislocations to retain demagnetization, (b) after plastic deformation whose magnetic domain walls became unpinen from dislocations to gain residual magnetization, and (c) schematic image of a $B$-$H$ curve under a magnetic field, where the residual magnetization approaches an anhysterisis curve to be magnetized.
In the case that the specimen is deformed under a magnetic field less than the coercive force, unpinned magnetic walls move into a stable state of the anhysteresis curve, where the volumes of magnetic domains along the external field increase. Therefore, residual magnetization increases if the demagnetized specimen is plastically deformed under a certain magnetic field.

From the above considerations, the residual magnetization of ferromagnetic metals will change during plastic deformation. Therefore, if the important structure was initially magnetized, then we can predict the distribution of additional plastic deformation after the instant by measuring the residual magnetization distribution. We can use the “law of approach” of residual magnetization as a nondestructive test. Therefore, we termed it as an anhysteresis residual magnetization method to detect additional plastic deformation. Figure 3 expresses this phenomena schematically.

4. Specimens and experimental apparatus

4.1 Specimens

To investigate the effect of plastic deformation to residual magnetization, we selected several ferromagnetic metals, such as pure Fe, pure Ni and carbon tool steel SK95M. All the specimens were t0.1mm thin plates, which came from Nilaco Co. Ltd. or Japan special metals Co. Ltd. The shape of all the specimens for tensile test is shown in Fig. 4(a). For the compression test, a carbon steel pipe of JIS G3452 was used. The pipe had an outside diameter of 6.3mm; the thickness and length of the pipe were 1mm and 26mm, respectively.

4.2 Magnetization and magnetic measurement

At first all the specimens were magnetized under 0.6T for 1 min by using an electric magnet of WS24-40SV-5K-N1 by Hayama Co. Ltd. Magnetic flux vectors from the electromagnet were oriented perpendicular to the surface of the plate or parallel to the longitudinal direction of the pipe. After magnetization, distributions of residual magnetization were measured for all specimens. After the following tensile tests or remagnetization, the distributions of residual magnetization were also measured. To evaluate whole leaked magnetic flux density, the measurement area of 20×20mm was set much larger than the size of the specimen as shown in Fig. 4(a). During measurement the sample plate was placed at the center of a magnetic shielding, which consisted of three-layered permalloy pipes. Inside the shielding, the magnetic flux density was less than 1 μT without the specimen.

To evaluate the residual magnetization, leaked magnetic flux from the specimen was measured by a Hall magnetometer (HGM-8900S ADS Co. Ltd.) with a magnetic probe (TS-1, ADS Co. Ltd.). In the probe, a Hall effect sensor having a size of 7×7μm was set perpendicular to the plate surface. The sensitivity of the magnetometer was 10nT. The whole area of each specimen was scanned with the magnet probe by using a computer-controlled XY stage in steps of 200μm. The gap between the probe and specimen was 1mm. The set-up of the measurement apparatus is shown in Fig. 4(b).

Fig. 4 Schematic figure of (a) the shape of the ferromagnetic metal specimen for tensile test whose measurement area was 20×20mm, and (b) schematic figure of the measurement apparatus used to evaluate the distribution of leaked magnetic flux vectors from the specimen.
4.3 Tensile test

After magnetization, tensile stress was applied to all specimens by using a tensile testing machine (UTM-4-100, A&D Co. Ltd.). Wider parts of the specimen at the both side comprised the grip sections during tensile test. The strain rate was set to $2 \times 10^{-2}/s$. The mechanical load cell was ZPH-5000N, Imada Co. Ltd. As the maximum load of the testing machine was as small as 1kN, our specimen required a thin plate configuration. Elongations were measured from the distance between the grip bodies of the tensile testing machine. Around the tensile testing machine, the magnetic field was as small as terrestrial magnetism of 0.4mT.

4.4 Compression test

After magnetization, a carbon steel pipe was applied uniaxial compression stress of 500 MPa by mechanical pressing. Surrounding the hydraulic press, the magnetic field was as small as terrestrial magnetism of 0.4 mT. In this study, such a small terrestrial magnetism can be ignored; thus, we express the magnetic circumstance during tensile or compression test as having no external magnetic field.

5. Experimental results and discussions

5.1 Stress-elongation curves of tensile test

Figure 5 shows the stress-elongation (S-E) curves of each specimen under the tensile tests; (a) pure Ni, (b) pure Fe and (c) carbon tool steel SK95M. As the size of the tensile-test specimen was much shorter than the JIS standard (JIS Z 2241) for special thin plates having a thickness of 0.1 mm, the elongation was short because of Barba’s law. Moreover, as slant fractures occurred based on fracture mechanics for a tensile-stressed thin plate, large plastic elongations were not observed (Knott, 1977).

In most cases, each material showed a couple of small shifted elongations during the tensile tests in the early stage, as marked in Fig. 5. In pure Ni, they were observed under 162 MPa and 331 MPa. In pure Fe, they occurred under 158 MPa and 321 MPa. In SK95M, they were observed at 270 MPa and 640 MPa. As the strains during these shifts were larger than 0.1% as they were not caused by magnetostriction, which saturates on the order of $10^{-5}$ (Gray, 1972). They could be caused from plastic deformation. We are unsure whether they fall within the easy glide region, for which linear hardening occurs afterwards (Jaoul, 1969). As these plastic deformations were accompanied by sudden magnetic changes inside the specimens, they resemble the magneto-plastic effect discovered by Hayashi et al. in 1971. Same shifted elongations, called Portevin-Le Chatelier effect, were observed in the other tensile tests (Min et al., 2014).

5.2 Temporal change of residual magnetization

Apart from discussing the effect of plastic deformation, we must check the temporal change of the residual magnetization. Of course, if there is strong external magnetic field greater than the coercive force of the specimen, the residual magnetization will be affected. However, under these experimental conditions, DC magnetic field having a terrestrial magnetism of 0.4mT existed. In addition, there was a weak AC electromagnetic field from the commercial...
power supply.

As pure ferromagnetic metal has a small coercive force, we selected a pure Ni plate to study this phenomenon. At first, we magnetized the specimen only once. After placing the Ni plate under a terrestrial magnetic field for the following period, we measured the distribution of residual magnetization. We repeated these measurements under various intervals.

Figure 6 shows the distributions of residual magnetization of the Ni plate just after magnetization or after leaving it for several periods. From these results, we determined that the distribution of residual magnetization in pure Ni was not affected by the terrestrial magnetism. As coercive forces of the other specimens were larger than Ni, they also were unaffected. Therefore, if residual magnetization of the specimen changed under stress, it was not because of the temporal change. As residual magnetization is used to predict the periods of archaeological sites in paleomagnetism, it can be applied to several hundreds of years.

5.3 Residual magnetization after tensile test

5.3.1 Pure Ni specimen

Figure 7 shows the distribution of the residual magnetization of the pure Ni plate immediately after magnetization or after applied tensile stress. The upper figures have the same scale and the lower side figures reflect an intensity normalization. In the following figures, the residual magnetic distributions were depicted in a similar manner. From the upper figures, the residual magnetizations show reduced values immediately after applying small tensile stress of 229 MPa. Furthermore, continued to decrease as tensile stress increased, which coincides with the “law of approach” from the hysteresis to the anhysteresis curve under stress.

According to the results of the S-E curve in pure Ni, the specimen was first plastically deformed at 162 MPa. Therefore, we think the plastic deformation reduced the residual magnetization at the first tensile test under 229 MPa. As more plastic deformation moves more dislocations, unpinned magnetic domain walls were shifted into stable conditions of demagnetization under no external magnetic field.

As shown in the lower half of Fig. 7, the distributions of residual magnetizations were inhomogenously changed after each tensile test. The reason for this change will be discussed in section 5.4.

5.3.2 Pure Fe specimen

Figure 8 shows the distribution of residual magnetization of the pure Fe plate just after magnetization or after applied tensile stress. From the upper half, we found the residual magnetizations to suddenly decrease after applying tensile stress and continued to decrease by increasing the tensile stress, which also coincides with the “law of approach.” As the pure Fe specimen was first plastically deformed at 158 MPa in the S-E curve, the plastic deformation reduced the residual magnetization when subjected to the first tensile test at 208 MPa.

5.3.3 SK95M specimen

Figure 9 shows the distribution of residual magnetization of the SK95M carbon tool steel plate just after magnetization or after applied tensile stress. From the upper half of the figures, we found the residual magnetization was kept constant at a tensile test of 194 MPa, and started decreasing by increasing the tensile stress past 407 MPa, which...
also coincided with the “law of approach.” According to the results of the S-E curve in SK95M, the specimen first plastically deformed at 270 MPa. Therefore, the threshold of this phenomenon indicated the yield strength of the SK95M specimen. As the residual magnetizations did not drastically decrease under the small tensile stress, the specimen was mostly elastically deformed at the first tensile test.

Fig. 7 Distribution of residual magnetization of a pure Ni plate, which is (a/a’) just after magnetization, (b/b’) after tensile test of 229 MPa, (c/c’) after tensile test of 347 MPa or (d/d’) after tensile test of 311 MPa under terrestrial magnetism condition. Figures of (a), (b), (c), and (d) are expressed under the same graduation. Figures of (a’), (b’), (c’), and (d’) are expressed with intensity adjustment.

Fig. 8 Distribution of residual magnetization of a pure Fe plate, which is (a/a’) just after magnetization, (b/b’) after tensile test of 208 MPa, (c/c’) after tensile test of 416 MPa or (d/d’) after tensile test of 589 MPa under terrestrial magnetism condition. Figures of (a), (b), (c), and (d) are expressed under the same graduation. Figures of (a’), (b’), (c’), and (d’) are expressed with intensity adjustment.
5.4 Residual magnetization of remagnetized specimen after tensile test

In this experiment, we repeated the tensile test and remagnetization alternatively on the same specimen. After each operation, we measured the distribution of residual magnetization. Figure 10(a) shows the distribution of the residual magnetization of a pure Ni plate after initial magnetization. Figure 10(b) shows the distribution of the residual magnetization after the first tensile test of 241 MPa. Figure 10(c) shows the distribution of the residual magnetization after the first remagnetization. Figure 10(d) shows the distribution of the residual magnetization after the second remagnetization. All figures are expressed with intensity adjustment.
after the first remagnetization. Figure 10(d) shows the distribution of the residual magnetization after the second tensile test of 440 MPa. Figure 10(e) shows the distribution of the residual magnetization after the second remagnetization. We omitted the figures of the distribution just after the tensile tests, as they similarly reduced the residual magnetization.

From these results, we noticed the distribution of residual magnetization just after each magnetization was inhomogeneous and could be changed drastically. It is interesting to see that the more demagnetized areas during tensile testing were higher when remagnetized afterwards. As dislocations can be pinning sites of magnetic domain walls, more dense dislocation areas can experience higher coercive forces (Ogura, et al., 2010). Therefore, these results might indicate various distribution of dislocations density or total plastic deformation, which affects the inhomogeneous distribution of magnetization. However, as the inhomogenous demagnetization and magnetization were observed merely in pure Ni specimens, and not in pure Fe or SK95M specimens, more precise analysis of the inhomogeneity should be discussed. Moreover, as the residual magnetization was inhomogeneous even immediately following magnetization, we could not predict the amount of additional plastic deformation that occurred without measuring the initial distribution of magnetization. Disadvantages from the above properties will be discussed in the following section.

5.5 Residual magnetization after compression test

To understand the “law of approach” under applied stress, the results of the compression stress were also important, in addition to the above tensile tests. Figure 11(a) shows the distribution of residual magnetization at the cross section of the pipe just after magnetization. Figure 11(b) or (b’) shows it after compression. Figure 11(c) shows the distribution of residual magnetization at the longitudinal section of the pipe just after magnetization. Figure 11(d) or (d’) shows it after compression. From the results, the residual magnetization was found to be vanish after compression tests at the cross-section or longitudinal section of the specimen, which also is consistent with the “law of approach.” Although the two sections of the pipe were applied with stresses having opposite signs, this was independent of the “law of approach.”

![Fig. 11 Distribution of residual magnetization of the carbon steel pipe, of the cross sectional view (a) after magnetization or (b/b’) after compression tests of 500 MPa, or longitude sectional view (c) after magnetization or (d/d’) after compression tests of 500 MPa under terrestrial magnetism condition. Figures of (a) and (b) are expressed under the same scale, as are (c) and (d). (b’) and (d’) depict intensity normalizations.](image)

5.6 Profile of residual magnetization of each test

To understand the “law of approach” under applied stress in a more quantitative way, profiles of the residual magnetization of each experiment are shown in Fig. 12. There are certain positional deviations resulting from the error
of the each measurement. Figure 12(a) depicts the temporal change of the residual magnetization of the pure Ni plate in Fig. 6. Considering the measurement error, the residual magnetizations did not change under the terrestrial magnetism. Figure 12(b) shows the residual magnetization of the pure Ni plate just after magnetization or after applied the tensile stress of Fig. 7. Figure 12(c) is that of the pure Fe plate from Fig. 8. Figure 12(d) is that of the SK95M plate from Fig. 9. Figure 12(e) is that of the pure Ni plate applied magnetization and tensile stress repeatedly from Fig. 10. Lastly, Fig. 12(f) is that of the carbon steel pipe applied compressive stress from Fig. 11. From the figure, it can be seen that the residual magnetization suddenly decreased into the terrestrial magnetism under the first tensile stress and did not change much after the following tensile tests in pure metals. Conversely, it gradually decreased during several tensile tests using carbon steel.

Fig. 12 Profiles of residual magnetization in (a) Fig. 6 of the temporal change in the pure Ni plate, (b) Fig. 7 of the pure Ni plate under tensile stress, (c) Fig. 8 of the pure Fe plate under tensile stress, (d) Fig. 9 of the SK95M plate under tensile stress, (e) Fig. 10 of the pure Ni plate under tensile stress or magnetization repeatedly, (f) Fig. 11 of the carbon steel pipe under compressive stress.

6. Anhysteresis residual magnetization method as nondestructive test

6.1 Advantages of anhysteresis residual magnetization method

From the above discussions, we can understand the anhysteresis residual magnetization method has the potential to detect the occurrence of additional plastic deformation in ferromagnetic specimen after certain initial magnetization or
demagnetization. The initialization process is easy with an electromagnet. Moreover, evaluation is also easy with a Hall effect sensor, as fairly large magnetic changes were observed during this phenomenon.

If a target structure has a ferromagnetic material, local sections of the target itself play roles of sensors and memories. Without preparing external sensors and memories, this nondestructive test has a high cost performance. If the target structure is a non-ferromagnetic material, we can glue ferromagnetic sheets to the target to evaluate its additional plastic deformation.

For example, to use this nondestructive test for residual seismic capacity judgment of high buildings, we should magnetize some of the steel components that are expected to be primarily deformed plastically immediately following the construction of a new building. For maintenance, we should check the amount of residual magnetization periodically, e.g. once per year. If the magnetic intensity is weaker than a certain threshold, then the components should be remagnetized. Through this, in the case of a strong earthquake, we can judge its residual seismic capacity from the amount of demagnetization.

Although we emphasize this nondestructive test as being useful for residual seismic capacity judgement, it can also be utilized for fatigue damage estimation of structures and aging diagnosis of infrastructures. As residual magnetization is sensitive to plastic deformation, it can serve as a unique and easy method to evaluate the dislocation dynamics of the specimen.

6.2 Disadvantages in anhysteresis residual magnetization method

In spite of the above merits, the anhysteresis residual magnetization method has several problems. To make the method a feasible candidate for nondestructive tests, these shortcomings much be addressed. At first, an inhomogeneous distribution of residual magnetization prevents the absolute prediction of additional plastic deformation without measuring the initial distribution. This requires us to compare the current measurement with the initial one. In order to implement the nondestructive test of residual seismic capacity judgment, we should measure the initial distribution of residual magnetization just after the magnetizing process. However, as a large decrease in residual magnetization occurs with small plastic deformation, we can measure it from the amount of decrease. Moreover, as pure Fe and carbon steel are magnetized homogeneously, we could have overcome this problem by selecting the proper target materials.

Another problem of the present method is the environmental magnetic field around the specimen, as the residual magnetization will approach an anhysteresis curve, which is the function of the external field. If the environmental magnetic field cannot be ignored, the residual magnetization will not dissipate. In case that the plastic deformed area is smaller than initially magnetized area, the residual magnetization in the undeformed area will affect that in deformed area. In the above experiments, as the area of plastic deformation is larger than or equal to the magnetized area, this effect does not have to be considered. To prevent this problem, we have to design the area of the initial magnetization for each specimen beforehand by predicting the area of plastic deformation under the expected conditions.

Moreover, if the external magnetic field is larger than the coercive force of the ferromagnetic material, the residual magnetization will be affected by the magnetic field, but not by the mechanical history. Therefore this method cannot be used under a strong magnetic field environment.

Furthermore, although the phenomenological results in this study indicate the existence of interactions amongst the magnetic domain walls and dislocations, clear experimental proof has not been obtained. Moreover, although the mechanism of the interaction has been discussed in previous studies (Takahashi, 2006), they have only been discussed within the context of strain energy. More precise studies within solid state physics and quantum mechanics are required.

Finally, as qualitative discussions primarily comprised this study, it is necessary to clarify this phenomenon more quantitatively and develop this method into a nondestructive tests.

7. Conclusions

In this study, we discussed the effect of plastic deformation on residual magnetization in ferromagnetic metals from a mechanistic perspective and through experimental results. The main conclusions were obtained as follows:

(1) If magnetized ferromagnetic metal is plastically deformed under no magnetic field, a sharp decrease in residual magnetization is observed. This coincides with the “law of approach” from a hysteresis to an anhysteresis curve under this stress.
(2) The decrease in residual magnetization can be understood by the unpinning effect of the magnetic domain walls against dislocations that move during plastic deformation. The residual magnetization is transferred into a stable state in an anhysteresis curve.

(3) After the initial magnetization, by measuring decrease of residual magnetization of the specimen under no magnetic field, we can detect the occurrence of additional plastic deformation under either tensile or compressive stress.

(4) The inhomogeneous distribution of residual magnetization could be related to the amount of dislocation density as total plastic deformation.

(5) Although the proposed anhysteresis residual magnetization method has several demerits, it has the potential to be a candidate for nondestructive evaluation of additional plastic deformation from beyond that of the initialization.

References