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Study on Effect of Electromagnetic Characteristics of Deformed 304 Stainless Steel on Eddy Current Testing

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Abstract. The induced ferrite and other high magnetic microstructures content changes are studied when 304 austenitic stainless steel stripe specimens are tested under different uniaxial tension deformation, namely its deformation less than 50%. Furtherly, the correlation is plotted between the resulting magnetic permeability or coercivity caused by these microstructures and deformation. Meanwhile, the optimal eddy current excitation frequency under different deformation was obtained, which was consistent with 3-D finite element analysis (FEA). Besides, other various factors affecting the quality of eddy current testing (ECT), such as temperature and conductivity, are also considered comprehensively during the tensile test. The results of the experiment and simulation calculation show that when the deformation is within 50% that necking deformation has occurred, the magnetic permeability of specimens increases with deformation, and gradually begin to have the magnetic properties of weak ferromagnetic materials, which also changes the optimal excitation frequency, which varies from 60 kHz to 110 kHz. Because of the electromagnetic response noise increase, the impedance plane diagrams of defects distort simultaneously, which leads to the quantitative evaluation error of defects.

Keywords. 304 austenitic stainless steel, deformation, eddy current testing, the optimal frequency

1. Introduction

304 austenitic stainless steel is widely used in different branches of the industry, covering from daily life to complex industries (chemical, oil, nuclear, etc.).[1] However, due to its structural characteristics, the typical failure mode of this type of stainless steel is stress corrosion cracking (SCC), which often occurs on the surface of the component and is very suitable for ECT. Meanwhile, these steels may become ferromagnetic when the martensite phase is produced by cold work deformation, hydrogen charging, or ion irradiation. [2] Cold working deformation is ubiquitous in the service of industrial equipment. It changes the electrical and magnetic properties of 304 stainless steel, especially the magnetic properties, which affect the implementation of ECT. Therefore, it is essential to study the effect of deformation on ECT for the safety of industrial equipment made of 304 stainless steel.

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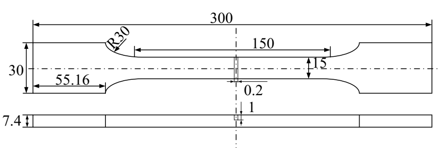
S. H. Khan [3] pointed out in his research that austenite transformation results in changes in electromagnetic properties of the material, causing variation in eddy current impedance, but didn't make a profound study. Maher Shaira [4] used eddy current probes for local measurements that were proved to be sensitive to austenite transformation and even quantitatively after calibration. A Lois [5] developed a standard curve for ECT of martensitic magnetic structure content for 304 austenitic stainless steel, but it is not clear how to select the permeability. In practice, Li Xiaoting [6] found that the best frequency of ECT for stainless steel pressure vessel was 100 kHz, but the effect of phase transformation was not taken into account.

In this paper, the relative content of micromagnetic structure after austenite transformation at different stretching stages and the change of magnetic properties of specimens are measured by experiments. On this basis, the optimal frequency of ECT for 304 stainless steel surface cracks under two typical deformation conditions was calculated by the 3-D FEA method. Furthermore, the optimal frequency under different deformation is also obtained by experiments, which is in agreement with the simulation results. Finally, the source of magnetic noise affecting ECT and the mechanism are analyzed preliminarily. The above research is expected to guide stainless steel inspection.

2. Specimens processing and measurement

Two sets of 304 stainless steel strip specimens were prepared. One group was used to measure magnetic properties, and the other group was used to fabricate artificial grooves (representing crack-like defects). EDM processed the surface opening grooves located in the middle of each specimen after specified deformation, and their sizes were all 0.2×1×15mm, as illustrated in Figure 1.



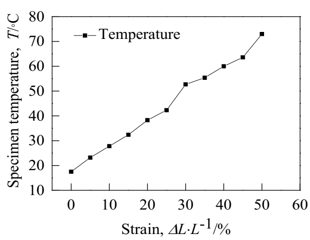


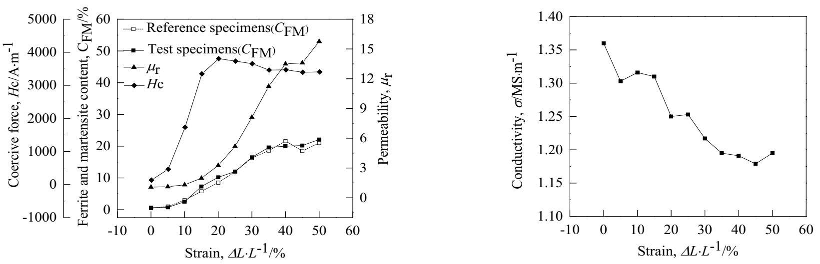
Figure 1. Specimens with grooves (unit mm). **Figure 2.** Temperature variation of specimens with deformation.

The specimens are stretched at a rate of 60 mm/min, and the ambient temperature is 17.5°C. Because these become hot during the stretching process, the temperature variation curve of the specimens under different stretching ratios in the actual test process is as shown in Figure 2. When the maximum deformation is 50%, the temperature is 73°C. A slow process of deformation occurring during the operation of actual industrial equipment can be considered that the temperature does not change.

2.1. Measurement of electromagnetic characteristics

All specimens tested are from the same batch of raw materials, using the same heat-treatment process. The total content of ferrite and martensite in standard 304 stainless steel after reliable solution treatment is generally less than 3%, measured by Fischer

FERITSCOPE FMP30, according to the magnetic induction method. The content of the magnetic microstructure at different deformation stages corresponded to Figure 3. The average error of two sets of specimens was less than 5% to ensure repeatability. Indirectly, the measured electromagnetic properties of reference specimens were considered the same as defective specimens. The experimental device can refer to the previous work[8].



(a) Magnetic properties variation.

(b) Conductivity variation.

Figure 3. Electromagnetic characteristics variation with deformation.

2.2. Test results analysis

The measurement results from Figure 3 show that the surface conductivity measured by the four-probe method decreases with deformation, and the maximum change is 13%, which is little effect on eddy current distribution compared with permeability variation. The permeability and coercivity measured by FE-2100SD [8] increase during plastic deformation, as illustrated in Figure 3. Non-ferromagnetic 304 stainless steel begins to possess some magnetic properties of weakly ferromagnetic materials because of deformation. When the deformation reaches 15%, permeability increases significantly, and there is even hysteresis. These changes inevitably affect eddy current distribution in the specimen, such as detectable depth reduction at the same frequency and higher magnetic noise. Besides, it also causes a change in the optimum detection frequency.

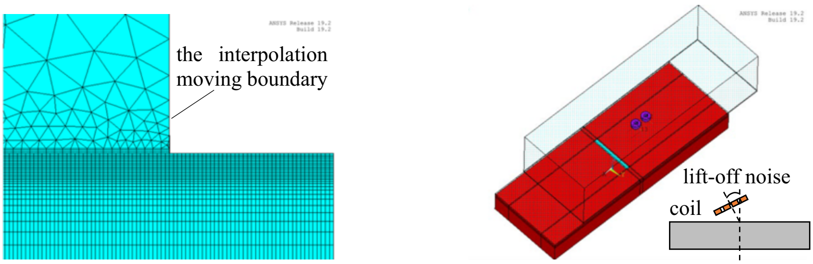
3. Finite element simulation

The electromagnetic parameters of materials in two critical stages of deformation are selected for FEA. One is the deformation of 15%, and stress has exceeded the yield limit; the other is the deformation of 35% when the uniform deformation stage of specimens is terminated. There are key points that affect the eddy current distribution of specimens.

Table 1. Simulation parameters

Coil parameters						Flat specimen material		
						Permeability		
Inner radius	Outer radius	Height	Interval	Turns	Strain	Initial	Maximum	Electrical conductivity
r_1/mm	r_2/mm	h/mm	d/mm	n	$\Delta L \cdot L^{-1}$/%	μ_i	μ_m	σ/MS·m^{-1}
0.500	1.25	1.00	1.00	150	15	1.397	1.974	1.310
					35	3.274	11.230	1.195

When the differential eddy current probe is used, the plate specimen, size 61×22×6mm, is large enough to cause no edge effect. However, the defect size in the 3-D FEA model is quite small, and the other model size is massive, which leads to too large tolerance in mesh generation to be solved accurately or even not convergent. Air, specimen and coil part can be meshed reasonably by using the interpolation moving boundary method [7]. In this way, the lift-off layer can be meshed effectively, as showed in Figure 4.

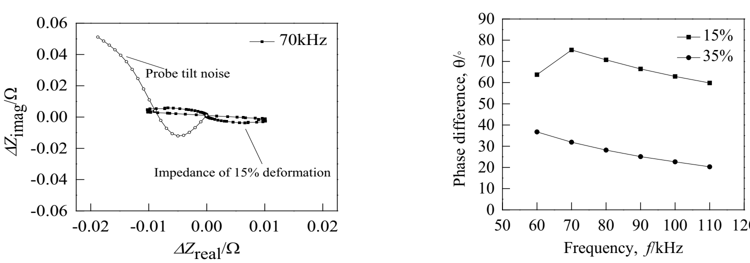


(a) FEA mesh (b) FEA model

Figure 4. Simulation model and mesh.

Because the primary interference of differential probe is the probe tilt, it is necessary to calculate the coil impedance phase caused by the probe tilt and the coil impedance caused by defects at different frequencies in the simulation calculation. Since the detection frequency of 304 stainless steel without deformation is 100 kHz, 60 kHz~110 kHz is chosen as the frequency range of simulation calculation, and simulation parameters can be obtained from Table 1. The magnetic field produced by the coil is fragile; the initial permeability obtained from the test is substituted into the calculation.

From Figure 5, it can be seen that the amplitude of the lift-off signal may be much larger than that of defect signal when the probe tilt angle is large. The phase difference should be as significant as possible in the range of 0° to 90° as a reference to optimal frequency selection. According to the above principles, the following conclusions can be drawn. When the deformation is 15%, the optimal frequency is 60 kHz, and the phase difference is about 40°. When the deformation is 35%, the optimal frequency is 70 kHz, and the phase difference is about 80°.



(a) Impedance plane at 70kHz (b) Phase difference at different frequencies

Figure 5. Impedance analysis under 15% and 35% deformation.

4. Result

The optimal frequency is not entirely determined by the phase difference but also related to other factors such as impedance amplitude and detection sensitivity. Further experimental analysis is made to consider as many factors as possible, affecting ECT. Before a 5% deformation, the phase difference does not change much between different frequencies, roughly between 10° and 20°. When the deformation is between 10% and 35%, the phase difference varies greatly, and the optimal frequencies range from 60 kHz to 110 kHz, as illustrated in Figure 6. The results are consistent with the theoretical calculation [8]. When the deformation exceeds 35%, the optimal frequencies approach 110 kHz and do not change much. The impedance amplitude increases with the deformation, which has similar trends at different frequencies, as illustrated in Figure 7.

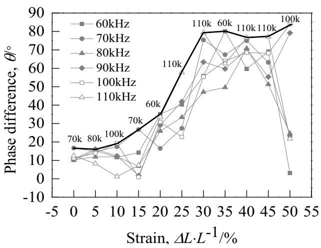


Figure 6. Phase different variation by experiment

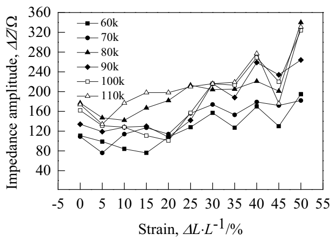


Figure 7. Impedance amplitude variation by experiment

It can be concluded that if the optimal frequency is selected according to the phase difference, there is a certain correlation between the stress-strain curve of 304 stainless steel and the coercivity variation rule under different deformation. If it is selected according to amplitude, it is related to the change rule of the micromagnetic structure or its permeability under different deformation. The region with the greatest change in the optimal frequency occurs in the plastic uniform variation region corresponding to the yield point and the tensile strength. If some areas of in-service equipment are just at this stage, eddy current exciting frequency should be carefully selected.

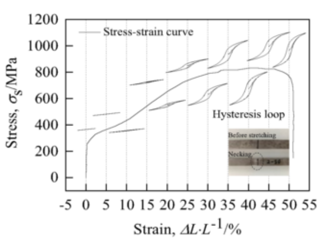


Figure 8. Hysteresis variation with deformation

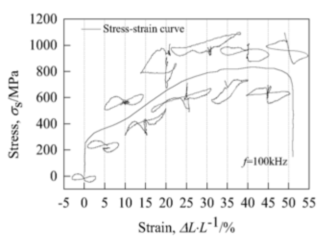
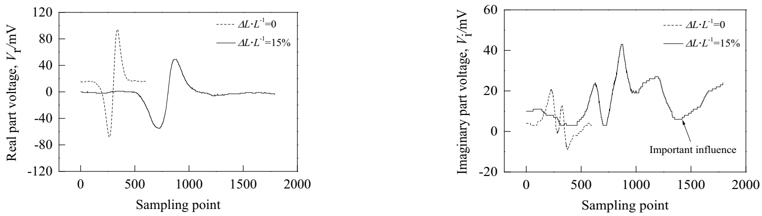


Figure 9. Impedance plane diagrams with deformation

The magnetic properties are not only characterized by permeability, but also by hysteresis loops. It can be seen from Figure 8 that the area of the hysteresis loop increases gradually along the stress-strain curve. The magnetic noise of the probe is not only caused by the inhomogeneous permeability of the tested material but also affected by the hysteresis loop. It is considered that the micromagnetic structure is homogeneous under uniaxial tensile strain, so the magnetic noise is mainly related to the different working points of the hysteresis loop. Usually, this noise is reduced by magnetic saturation.

From Figure 9, it can be seen that the area with the greatest magnetic noise is the deformation range corresponding to the yield point to the tensile strength. Thus, the changes of real and imaginary parts of impedance (voltage in the device) with 15% deformation are studied separately. It can be found that the distance between the peak value and its value in the real part of the impedance varies slightly, but the shape remains unchanged. The imaginary part of impedance varies greatly; not only the amplitude and position of peak value change, but also it has a small additional range of variation compared with the specimen without deformation from Figure 10. It can be concluded that the influence of micromagnetic structure on defect detection is mainly caused by the influence of coil impedance imaginary part after 304 stainless steel deformation.



(a) Real part (b) Imaginary part

Figure 10. Change of coil inductance by deformation

5. Conclusion

In the process of ECT of industrial equipment made of 304 stainless steel in service for a long time, the high magnetic microstructures by deformation have a dominant effect on the eddy current coil impedance imaginary part, which leads to the distortion of impedance plane of defects and its quantitative evaluation error. Besides, the optimal detection frequency should be selected in the range of 60 kHz~110 kHz according to the ferrite content measured at that time or obtained by multiple ECT experiments in this range. The quantitative evaluation of 304 stainless steel defects under inhomogeneous tension will be further studied in the future.

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