

Received April 20, 2020, accepted April 28, 2020, date of publication May 6, 2020, date of current version May 15, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.2991718

Effect Model of Stress and Plastic Deformation on Conductivities of Various Magnetic Materials

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This work was supported by the National Natural Science Foundation of China under Grant 51367001 and Grant 51507005.

ABSTRACT In order to study the effect of stress/plastic deformation on electrical conductivity of various magnetic materials, the electrical conductivity of silicon steel, carbon steel and aluminum alloy of different resistance coefficients at the stage of elasticity deformation and plastic deformation were studied by measuring the resistance, fitting-models were established through theorization and measuring data, and corresponding parameters are given. The results show that: ① At the stage of elasticity deformation, the electrical conductivity of the material increases rapidly first, and then slowly increases with the increase of stress. ② At the stage of plastic deformation under stress unloading conditions, the electronic conductivity decreases approximately linearly with the increase of plastic deformation. ③ At the stage of plastic deformation under stress loading conditions, the electronic conductivity decreases approximately linearly with the increase of plastic deformation. As the result of stress, electrical conductivity in the superposition state is higher than that in the corresponding plastic deformation state.

INDEX TERMS Effect model, magnetic materials, stress, plastic deformation, conductivity.

I. INTRODUCTION

Because of their effectiveness and convenience, electromagnetic Non Destructive Testing (NDT) methods, such as magnetic flux leakage testing [1], eddy current testing [2], [3], magnetic memory testing [4], magnetic Barkhausen noise testing [5], current field testing [6] and current potential drop testing [7], have been widely used to detect metal-loss defect [8], [9], crack [10], [11] and especially some mechanical damages induced by stress, such as stress concentration [12]–[15], plastic deformation [16], [17], etc. The electromagnetic nondestructive testing of mechanical damage mainly depends on a physical phenomena that the mechanical stress and the dislocations induced the plastic deformation can change the magnetic and electric properties of the testing materials, which were described as the Magneto-Mechanical Effect (MME) [18] and the Electro-Mechanical Effect (EME) [19], respectively. MME and EME are very interesting cross-coupling physical phenomena with great research value, but the mechanisms of stress's actions on the magnetic and electric properties of testing materials are

often complicated and intangible. It is also possible that the MME and EME are related not only just to the magnetic and electric properties of the testing materials, but also to some other factors not yet known. Anyway, even if MME and EME are coupling results of multiple factors, studies on each factor correlating with stress are necessary and vital.

Being two key parameters that are frequently used for characterizing the electromagnetic properties of the testing materials, the conductivity and permeability of materials have important effects on the results of electromagnetic nondestructive testing [20], [21]. Vice versa, the detectability of the stress-induced mechanical change by using electromagnetic nondestructive testing methods also suggests the possibility that stress has effect on the conductivity and permeability of the testing materials, thus affect the results of electromagnetic nondestructive testing, which in turn results in the stress-induced mechanical damage being identified and characterized by the electromagnetic nondestructive testing methods. Therefore, the effects of stress on the conductivity and permeability of the testing materials are critical factors that will affect the tested results of the stress-induced mechanical damage. Furthermore, the studies on the correlations between the mechanical stress and the conductivity and permeability

The associate editor coordinating the review of this manuscript and approving it for publication was Guijun Li.

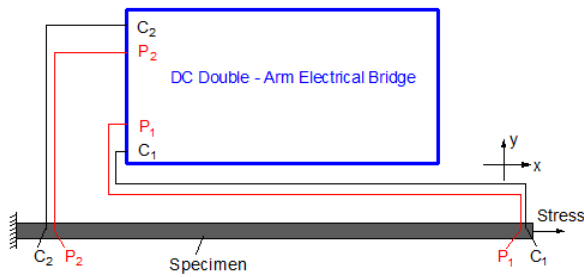


FIGURE 1. Experiment system.

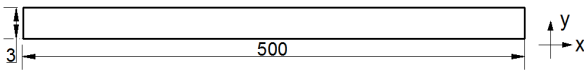


FIGURE 2. The shape and sizes (mm) of the specimen.

of materials are also important ways to further reveal the mechanism of MME and EME.

According to reference [22], the effect of uniaxial stress on the effective mass of electronic conductivity of Si materials is different under different crystal directions. Under uniaxial tensile stress, the effective mass of electronic conductivity along the 45° direction decreases with the increase of stress, while that along the 0° and 90° directions increases with the increase of stress. Maybe because of the dislocation, slip and twin in the crystal, the electronic conductivity of SUS304 stainless steel decreases with the increase of plastic deformation [23]. However, these studies only are the relationships between conductivity and stress/plastic deformation of specific materials, lacking universality and corresponding theoretical models and experiment data. According to the reference [24], the conductivity decreases with the increase of plastic deformation. But these studies are the conclusion under stress unloading of plastic deformation. Under stress loading, the relationship between plastic deformation and conductivity is rarely studied. Moreover, there is lack of a simple method to determine the quantitative relationship between electrical conductivity and stress/plastic deformation.

Based on this, this paper uses a simple method to research the relationship between the electronic conductivity and stress/plastic deformation of the silicon steel, carbon steel and aluminum alloy of different initial electronic conductivity under three different stage, which are the stage of elasticity deformation, the stage of plastic deformation under stress unloading conditions, and the stage of plastic deformation under stress loading conditions. Moreover, we give the corresponding relationship model based on fitting method. This method has a certain reference for studying the effect of stress/plastic deformation on the electronic conductivity and the magnetic output. And it has certain practical significance and value for nondestructive testing of equipment by extracting the change information of material electronic conductivity.

TABLE 1. Chemical compositions (wt%) of (a) Silicon steel B35A440; (b) Carbon steel Q195 and (c) Aluminum Alloy 2A12.

(a)							
Si	C	Mn	P	S	Al		
3~5	0.06	0.15	0.03	0.25	5.1~5.8		
(b)							
C	Mn	Si	S	P			
0.06~0.12	0.25~0.50	≥0.3	≤0.04	≤0.035			
(c)							
Si	Fe	Cu	Mn	Mg	Zn	Ti	Ni
0.06	0.19	4.72	0.61	1.65	0.06	0.03	0.04

II. EXPERIMENTS

The experiment system of electronic conductivity and the specimen are shown in Fig. 1. The experiment system consists of a resistance testing instrument and some electrical conducting lines. The resistance testing instrument is used Double – arm electrical DC bridge. The specimen is fabricated with a 3mm-thickness plane, its shapes and sizes are shown in Fig. 2. Specimens are used silicon steel of B35A440, carbon steel of Q195 and aluminum alloy of 2A12. The chemical compositions of the specimen are listed in Table 1, where Table 1(a) is the material of silicon steel B35A440, Table 1(b) is Q195 steel and Table 1(c) is aluminum alloy of 2A12. The tensile stress was introduced into the specimen along the x axis of the specimen, as shown in Fig. 2. Stress–strain curves of specimens were tested by pulling standard samples, and shown in Fig. 3, where Fig. 3(a) is the curve of silicon steel of B35A440, Fig. 3(b) is carbon steel Q195, and Fig. 3(c) is Aluminum alloy 2A12. Fig. 3 shows the yield strength of tested specimens, which means they are in the elastic deformation stage ($O-O'$) when stress of the specimen is below yield point (O) and they are in the plastic deformation stage ($O-F$) when the applied stress is above yield point. Series of tensile elastic stress is loaded into specimen and up to yield point, with interval of 10MPa. At each interval and with stress loading, we measured the resistance by the Double – arm electrical DC bridge while stress loading.

Series of tensile stress are loaded into the specimen and made the plastic deformation up to 12%, with interval of 2%. At each interval and with stress loading as $O-F$, we measured the resistance. At each interval and with stress unloading as $O'-F'$, we measured the resistance too.

According to the relationship between the resistance and the resistivity $R = \rho l/A$, we can obtain: $\rho = RA/l$, where R is the resistance, ρ is the resistivity, l is the length of the specimen, A is the cross-sectional area of the specimen. So we can obtain: $\sigma_e = 1/\rho$, where σ_e is the conductivity. Therefore, we can obtain the conductivity of the material by measuring the resistance.

III. RESULTS

A. AT THE STAGE OF ELASTICITY DEFORMATION ($O'-O$)

At the stage of elasticity deformation which is the stage of $O'-O$ below yield point O shown in fig.3, we measured the

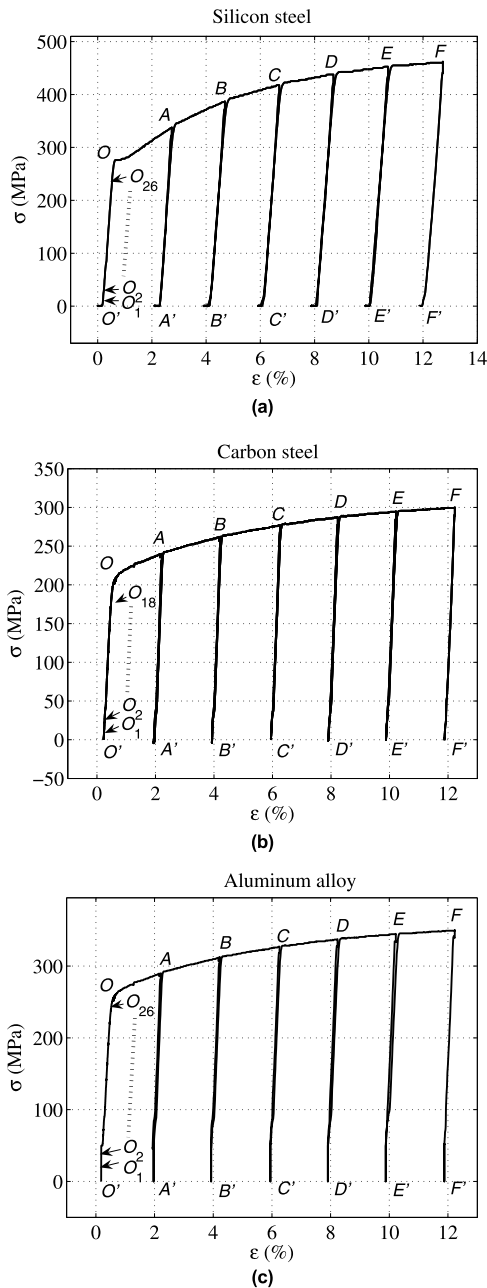


FIGURE 3. Stress (σ)-strain (ϵ) curves of tested materials. (a) Silicon steel B35A440; (b) Carbon steel Q195; (c) Aluminum alloy 2A12.

point O_1 — O_{26} for the specimen of silicon steel, O_1 — O_{18} for carbon steel, and O_1 — O_{26} for aluminum alloy. We measured the resistance under stress loading, and then we obtain relationships between the conductivity σ_e and the stress σ are shown in Figure 4, where Fig. 4(a) is the specimen of silicon steel, Fig. 4(b) is carbon steel, and Fig. 4(c) is Aluminum alloy. As you can see from Fig.4, the conductivity goes up dramatically with the increase of stress, and then keeps approximately the same. It shows that the effect of stress on conductivity is greater at the initial stage than at the later stage.

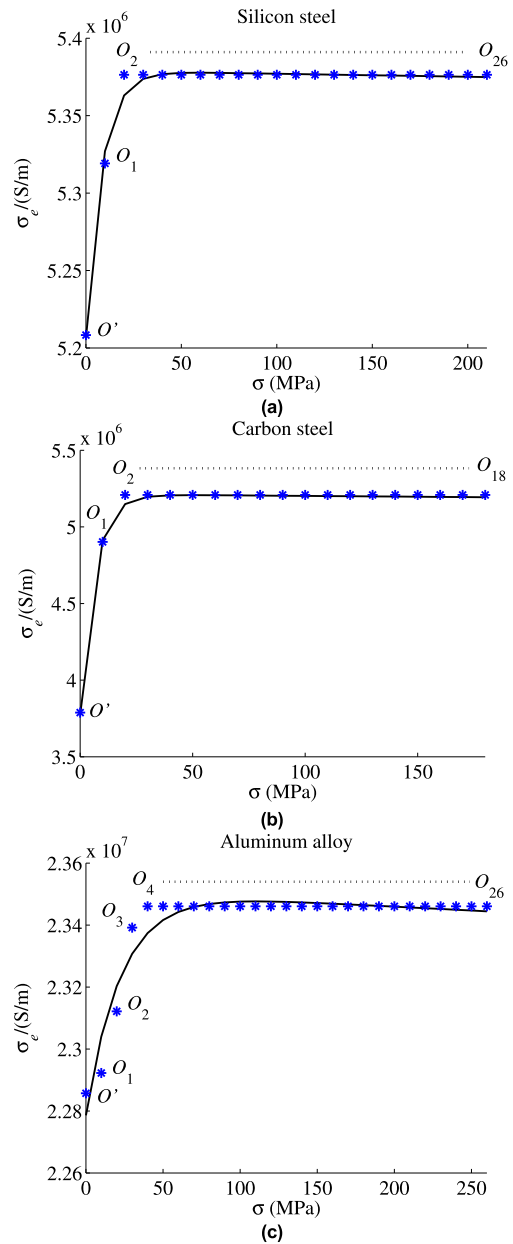


FIGURE 4. Relationship between the conductivity σ_e and the stress σ (a) Silicon steel of B35A440, (b) Carbon steel of Q195, (c) Aluminum alloy 2A12, where \blacklozenge = experimental data, solid lines = fitting lines.

B. AT THE STAGE OF PLASTIC DEFORMATION UNDER STRESS UNLOADING(O' - F')

At the stage of elasticity deformation which is the stage of O' - F' below yield point O shown in fig.3, we measured the point is A' - E' for the specimen. Relationships between the conductivity σ_e and the stress σ are shown in Figure 5, where Fig. 5(a) is the specimen of silicon steel, Fig. 5(b) is Q195 steel, and Fig. 5(c) is aluminum alloy. As you can see from Fig.5, the conductivity decreases approximately linearly with the increase of plastic deformation.

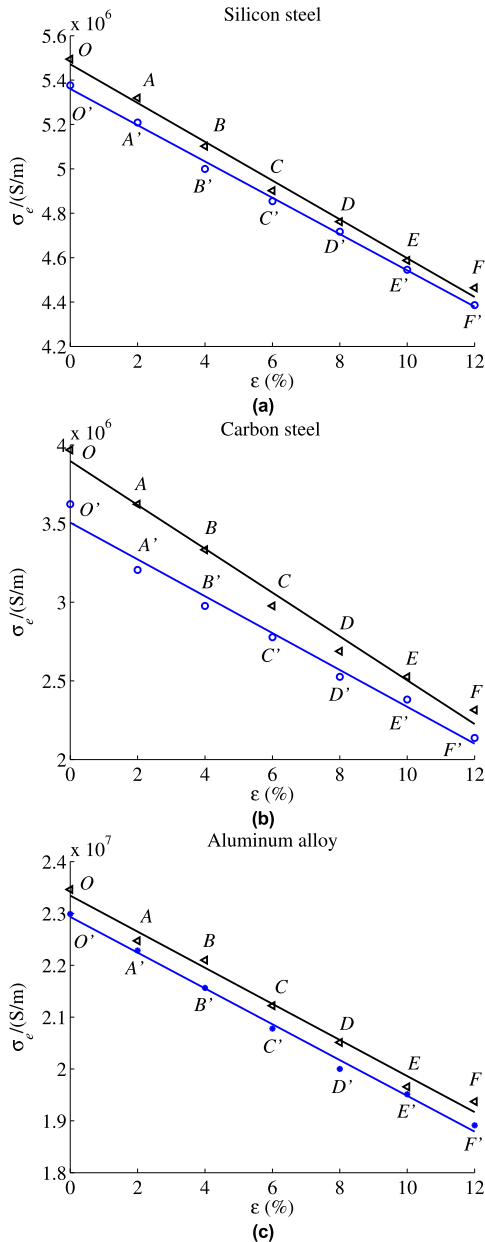


FIGURE 5. Relationships between the conductivity σ_e and the plastic deformation ϵ (a) Silicon steel of B35A440, (b) Carbon steel Q195, (c) Aluminum alloy 2A12, where [■] = experimental data, solid lines = fitting lines.

C. AT THE STAGE OF PLASTIC DEFORMATION UNDER STRESS LOADING (O–F)

At the stage of superposition state which is at the stage of plastic deformation under stress loading, the stage of O–F above yield point O shown in fig.3, we measured the point is A–E for the specimen. We measured the resistance and obtain the relationships between the conductivity σ_e and the stress σ are shown in Figure 5, where Fig. 5(a) is the specimen of silicon steel, Fig. 5(b) is carbon steel, and Fig. 5(c) is aluminum alloy. As you can see from Fig.5, the conductivity decreases approximately linearly with the increase of plastic deformation and stress.

IV. DISCUSSIONS

A. AT THE STAGE OF ELASTIC DEFORMATION (O’–O)

According to the relationship between the conductivity and the stress shown in Fig. 4, we can get the experimental data σ_e induced by stress σ by fitting formula

$$\sigma_e = p_1 e^{p_2 \sigma} + p_3 e^{p_4 \sigma}, \tag{1}$$

where p_1, p_2, p_3 and p_4 are parameters. p_1 and p_3 are amplification factor, p_2 and p_4 are stress coefficient. In silicon steel, $p_1 = 5.379 \times 10^6, p_2 = -3.644e \times 10^6, p_3 = -1.723 \times 10^5, p_4 = -0.1202$; In carbon steel, $p_1 = 5.213 \times 10^6, p_2 = -2.086 \times 10^{-5}, p_3 = -1.437 \times 10^6, p_4 = -0.157$; In aluminum alloy, $p_1 = 2.351 \times 10^7, p_2 = -1.075 \times 10^5, p_3 = -7.24 \times 10^5, p_4 = -0.04372$.

It may because the conduction band structure of the material has changed and the electron mobility has enhanced under the action of stress [22], the electrical conductivity of the material increase rapidly first similar to step response with increase of stress, and then keeps approximately the same. The ratio k of maximum conductivity to initial conductivity of different materials is different. In silicon steel, $k = 1.0323$; In carbon steel, $k = 1.3750$; In aluminum alloy, $k = 1.0264$.

B. AT THE STAGE OF PLASTIC DEFORMATION UNDER STRESS UNLOADING (O’–F)

There existed a good linear correlation between the conductivity and the plastic deformation shown in Fig. 5, so the experimental data σ_e induced by the stress can be described as

$$\sigma_e = p_5 \epsilon + p_6, \tag{2}$$

where p_5 and p_6 are parameters, p_5 is amplification factor, and p_6 is additional items. In silicon steel, $p_5 = -8.74 \times 10^4, p_6 = 5.4717 \times 10^6$; In carbon steel, $p_5 = -1.393 \times 10^5, p_6 = 3.8972 \times 10^6$; In Aluminum alloy, $p_5 = -3.48 \times 10^5, p_6 = 2.3344 \times 10^7$.

The electrical conductivity of the material decrease approximately linearly with the increase of plastic deformation, which may because the electron transfer rate of the material has changed, and the crystal has undergone dislocation, slip, and twin under the action of plastic deformation [23].

C. AT THE STAGE OF PLASTIC DEFORMATION UNDER STRESS LOADING (O–F)

There existed a good linear correlation between the conductivity and the plastic deformation shown in Fig. 5, so the experimental data σ_e induced by the stress can be described as

$$\sigma_e = a_\sigma (p_5 \epsilon + p_6) + b_\sigma, \tag{3}$$

where a_σ is coupling coefficient of stress and plastic deformation, b_σ is additional item caused by stress. In silicon steel, $a_\sigma = 0.9357, b_\sigma = 2.4059 \times 10^5$; In carbon steel, $a_\sigma = 0.8407, b_\sigma = 2.2996e \times 10^5$; In Aluminum alloy, $a_\sigma = 0.9921, b_\sigma = -2.2602 \times 10^5$.

The electrical conductivity of the material decrease approximately linearly with the increase of the plastic deformation and stress, which may because the plastic deformation plays a major role at the stage of superposition state ($O-F$) under stress loading. However, as the result of stress, the electrical conductivity at the stage of plastic deformation under stress loading is higher than at the stage of plastic deformation under stress unloading.

V. CONCLUSIONS

It may because the conduction band structure of the material has changed and the electron mobility has enhanced under the action of stress, the electronic conductivity increases rapidly with the increase of stress, and then slowly increases with the increase of the stress. It also shows that the effect of stress on electronic conductivity is greater at the initial stage than at the later stage. It may because the electron transfer rate of the material has changed, and the crystal has undergone dislocation, slip, and twin under the action of plastic deformation, the electronic conductivity decreases approximately linearly with the increase of the plastic deformation. The plastic deformation plays a major role at the stage of superposition state under stress loading, the electronic conductivity also decreases approximately linearly with the increase of the plastic deformation and stress. However, by comparison, the electrical conductivity at the stage of plastic deformation under stress loading is higher than at the stage of plastic deformation under stress unloading, which is the result of stress.

According to the fitting model, the quantitative relationship between electronic conductivity and stress, and between electronic conductivity and plastic deformation can be explored. The research results provide the theoretical foundation and experimental data for studying the effect of mechanical effect on electronic conductivity. Moreover, it is valuable for non-destructive testing of materials by electronic conductivity.

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