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ARTICLE

Electromagnetic and Microwave Absorption Properties of Flake Nd1$Ni_{5-x}C_x$ Alloy Powders

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Abstract: Flake $Nd_1Ni_{5-x}C_x$(x=0.0, 0.1, 0.3, 0.5) alloy powders were prepared by arc smelting and planetary grinding. X-ray diffractometer (XRD), scanning electron microscopy (SEM), vibrating sample magnetometer (VSM), vector network analyzer (VNA) etc were used to detect the structure, morphology and electromagnetic characteristics. The results show that with the increase of C content, M_s and H_c of the sample tend to decrease. The absorption peak of electromagnetic wave moves to high-frequency, and two effective bandwidths (RL≤–10 dB) at 8.28~9.82 and 11.17~12.03 GHz appear when the additive amount of C is x=0.5, which increase the applicable frequency band of the powder. In addition, with the change of the powders thickness, the frequency band with great impedance matching changes greatly, so the reflection loss can be adjusted in the larger frequency band. These changes make the powders have the possibility of wide application.

Key words: electromagnetic parameters; reflection loss; Nd_1Ni_5; magnetic material

With the rapid development of electronic communication technology, electromagnetic wave is widely used. Especially in the microwave frequency band, electromagnetic interference is more serious[1, 2]. Therefore, with the deepening of the research, different requirements have been put forward for the properties of absorbing materials in order to meet the requirements of various complex environments.

Magnetic absorbing materials have both magnetic loss and electrical loss. Because of the complex loss mechanism, researchers have paid much attention to it. For example, the Ni/C nanocapsules prepared by Wu et al[3] can obtain a large reflection loss at a relatively thin thickness. Liu et al[4] fabricated hierarchical $NiCo_2O_4/Co_3O_4/NiO$ composites through hydrothermal method, which makes the reflection loss up to –57 dB. At present, magnetic absorbing powder mainly consists of Fe, Co, Ni and their alloys. Their electromagnetic parameters can be easily improved by adding different components. As a typical soft magnetic material, Nd_1Ni_5 has obvious loss effect on electromagnetic wave. The purpose of this research is to study the electromagnetic characteristics and wave absorption performance through adding non-magnetic element C to Nd_1Ni_5 to change its electromagnetic parameters.

1 Experiment

$Nd_1Ni_{5-x}C_x$(x=0.0, 0.1, 0.3, 0.5) flake alloy powders were prepared by arc smelting and planetary grinding. The raw materials were Nd (99.9wt%), Ni (99.9wt%) and C (99.9wt%). Allocate the material in atomic fraction. Smelting was carried out in an atmosphere of argon. Homogeneous annealing was carried out in vacuum for ten d. Annealing temperature was 800 ℃. Annealed alloys were ball milled for 20 h with a rotation speed of 300 r/min and alcohol as protective. The structure and composition of the alloy were detected by X-ray diffractometer (XRD, Empyrean PIXcel 3D) and the morphology of the powder was observed by scanning electron microscopy (SEM, SM-5610LV). The saturation magnetization of the powders was measured by vibrating sample magnetometer

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(VSM, PPMS-8).

The powders after ball milling were mixed with paraffin at a mass ratio of 4:1 and pressed into a ring with an inner diameter of 3 mm, an outer diameter of 7 mm and a thickness of about 3.5 mm. The electromagnetic parameters of the ring were measured by vector network analyzer (VNA, HP8722ES).

2 Results and Discussion

2.1 Powder structure and particle size distribution

Fig.1 shows the XRD patterns and cell volume of $Nd_1Ni_{5-x}C_x$ alloy powders. It is clear that the sample consists entirely of Nd_1Ni_5. The addition of C has no effect on the phase structure. Meanwhile, the calculated cell volume (V) according to the Debye-Scherrer formula decreases with the increase of C. This situation is caused by the C atoms replacing Ni atoms and C atoms have a smaller atomic radius[5].

Fig.2 reveals the SEM images of $Nd_1Ni_{5-x}C_x$ alloy powders. Fig.3 is the normal particle size distribution curves obtained from the SEM image of Fig.2. As can be seen from Fig.2 and Fig.3

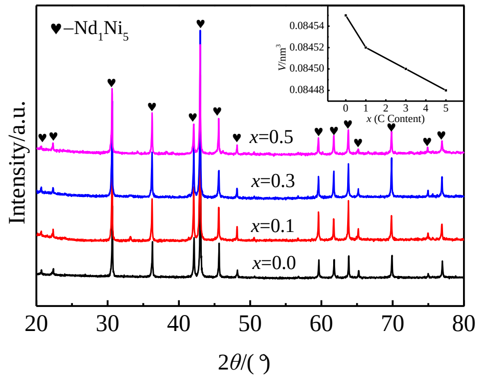

Fig.1 XRD patterns of $Nd_1Ni_{5-x}C_x$ powders

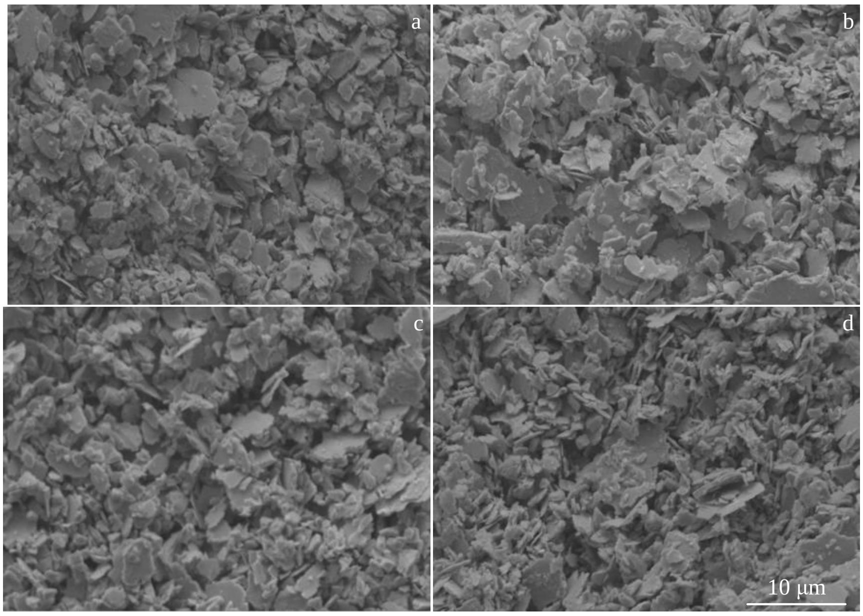

Fig.2 SEM images of $Nd_1Ni_{5-x}C_x$ powders: (a) x=0.0, (b) x=0.1, (c) x=0.3, and (d) x=0.5

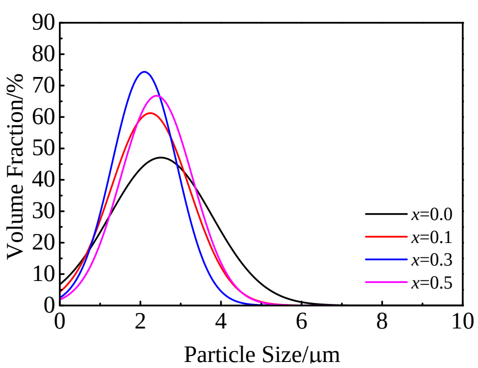

Fig.3 Particle size distribution curves of $Nd_1Ni_{5-x}C_x$ powders

that the powder has a flaky structure and with the increase of C content, the flakes become smaller and thinner. It is reported that the lamellar structure and high aspect ratio (length to thickness) are conducive to exceeding snoke's limit and improving the ability of absorbing EMI[6-8].

2.2 Electromagnetic characteristic

The magnetic properties of $Nd_1Ni_{5-x}C_x$ powder are shown in the Fig.4. Obviously, with the increase of C addition, the saturation magnetization (M_s) and the coercive force (H_c) decrease gradually. As the non-magnetic element C gradually replaces the magnetic element Ni, the decline of magnetic polarization intensity is inevitable, which leads to a decrease of M_s[3]. Additionally, the situation may be related to reduction

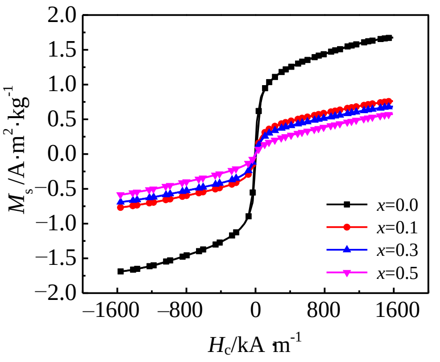

Fig.4 Magnetic hysteresis loops of $Nd_1Ni_{5-x}C_x$ powders

in magnetic anisotropy and grain size[9,10]. With the decrease of M_s and H_c, the reflection loss peak is inclined to the high-frequency direction[10,11].

Fig.5 shows the relationship between electromagnetic parameters and frequency. As can be seen from Fig.5a and 5c that the real parts (ε') and imaginary parts (ε'') of relative complex dielectric constant tend to decrease with the increase of C content. With the increase of C instead of Ni, the suspension key (unsaturated key) connects to C at the surface of flake $Nd_1Ni_{5-x}C_x$ to discretize the conducting band, resulting in the decrease of conductivity [12]. The decrease of ε' may be caused by the decrease of conductivity[13]. As reported, the main mode of dielectric loss is relaxation loss, and the enhancement of polarization is beneficial to the relaxation loss[6,10,13]. There- fore, the addition of C will inevitably lead to the enhancement of dielectric loss. Fig.5b and 5d show the real parts (μ') and imaginary parts (μ'') of the complex permeability, and the resonances correspond to μ' and μ'' in 10~12 GHz. This change can be caused by spin resonance[14]. As is known to all, the change of μ' and μ'' has an important effect on the magnetic loss of absorbing material[15]. Therefore, the optimal frequency band of magnetic loss of the powder should appear in 10~12 GHz.

According to the electromagnetic loss theories, the magnetic loss is composed of natural resonance, domain wall resonance, exchange resonance and eddy current effect[16]. Since domain wall resonance only occurs in low-frequency region, its influence can be excluded[16,17]. Eddy current coefficient can be used to check the existence of eddy current effect[18]:

$$C_0 = \mu''(\mu')^{-2} f^{-1} = 2\pi\mu_0 d^2 \delta \quad (1)$$

where μ_0 is the vacuum permeability, f is frequency, δ is electronic conductivity, d is thickness of the sample. If magnetic losses are caused only by eddy current losses, C_0 should not vary with frequency. The eddy current data C_0 of the powder is shown in Fig.6. As C increases, conductivity decreases, skin depth increases, and C_0 increases. On the whole, C_0 does not change a lot in 6~10 GHz, but change greatly in 10~12 GHz. Therefore, natural resonance and exchange resonance are main absorption modes in the range of 6~10 GHz, while eddy current loss is the main absorption mode in the range of 10~12 GHz.

2.3 Reflection loss

According to the transmission line theory, the reflection loss

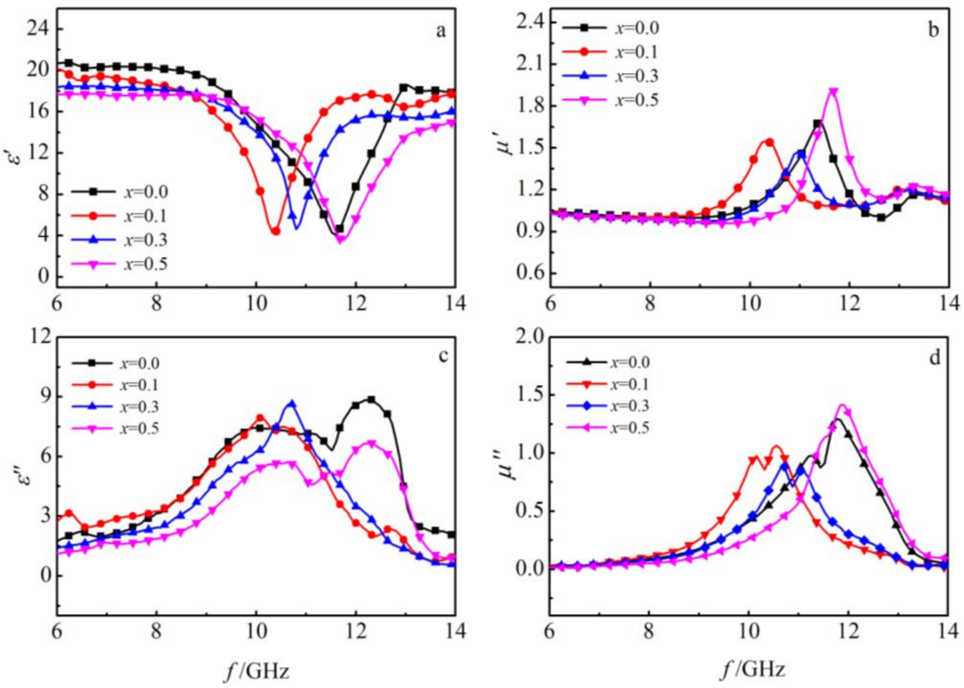

Fig.5 Electromagnetic parameters of $Nd_1Ni_{5-x}C_x$ powders: (a) ε', (b) μ', (c) ε'', and (d) μ''

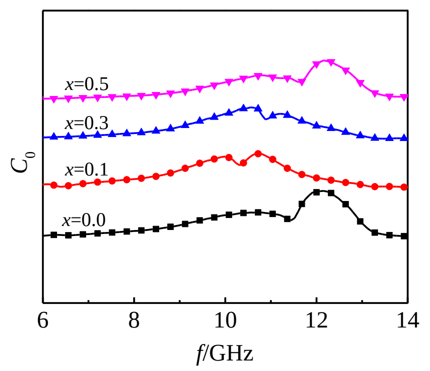

Fig.6 Eddy current data C_0 of the $Nd_1Ni_{5-x}C_x$ powders

(RL) at different thicknesses can be calculated by electromagnetic parameters[5,19]:

$$\mathrm{RL} = 20\lg\left[\frac{Z_{\mathrm{in}} - Z_0}{Z_{\mathrm{in}} + Z_0}\right] \tag{2}$$

$$Z_{\mathrm{in}} = Z_0\sqrt{\frac{\mu_{\mathrm{r}}}{\varepsilon_{\mathrm{r}}}}\tanh\left[\mathrm{j}\frac{2\pi fd}{c}\sqrt{\mu_{\mathrm{r}}\varepsilon_{\mathrm{r}}}\right] \tag{3}$$

where Z_{in} is the impedance matching of materials; Z_0 is free space of impedance matching; μ_r, ε_r stand for relative permittivity and relative dielectric constant, respectively; f is the frequency of electromagnetic wave; c is wave propagation velocity in free space (or the speed of light); j is the imaginary unit.

Fig.7 shows the relationship between RL and frequency when powder thickness is 2.1 mm. It can be seen that the powder has two absorption peaks, which appear in 6~9 and 10~12 GHz. As C content increases, the reflection peak appears at x band (8~12 GHz) and moves toward the high frequency. This phenomenon is consistent with the decrease of M_s and H_c. In addition, it may be related to the increase of magnetic anisotropy and electrical conductivity[20,21]. The peak of reflectivity occurs at x=0.3 which reaches to −39.59 dB. It is worth mentioning that two effective bandwidths (RL≤ −10 dB) appearing at x=0.5 are 8.28~9.82 and 11.17~12.03 GHz. This change makes the powder have the possibility of wide application.

Fig.8 is a 3D figure of relationship among reflection loss, frequency and thickness of $Nd_1Ni_{4.7}C_{0.3}$ powder. It can be seen that with the increase of thickness, the reflection peak tends to move towards to low-frequency. Moreover, when the thickness is low, the reflection loss of high- frequency band is enhanced, while that of low-frequency band is weakened. By comparing Fig.8 and Fig.9c and 9d, the change of reflection loss frequency band is closely related to impedance when the thickness of powder is relatively low. Moreover, the appearance of two reflection peaks of the powder is also caused by uneven impedance matching. This phenomenon indicates that the powders can be applied to different frequency bands by adjusting the thickness.

Impedance matching determines the ability of electromagnetic wave to enter the material, so impedance matching is very important for the RL[10]. In this research, impedance matching is evaluated with $|1-Z_{in}/Z_0|$, and the closer the $|1-Z_{in}/Z_0|$ is to 0, the better the impedance matching. Fig.9 shows the RL versus frequency and thickness of $Nd_1Ni_{5-x}C_x$ powder. The blue area is the smallest area of RL. Fig.10 shows the $|1-Z_{in}/Z_0|$ versus frequency and thicknesses of $Nd_1Ni_{5-x}C_x$ powders. Similarly, the blue areas in the figure represent the best impedance matches. With the increase of C, the magnetic loss increases and the electrical loss decreases, thus the matching of electromagnetic parameters is enhanced[15]. In addition, it is worth mentioning that the peak of the RL always appears at the optimum impedance matching, illustrates that the reflection loss and impedance match reflect excellent consistency.

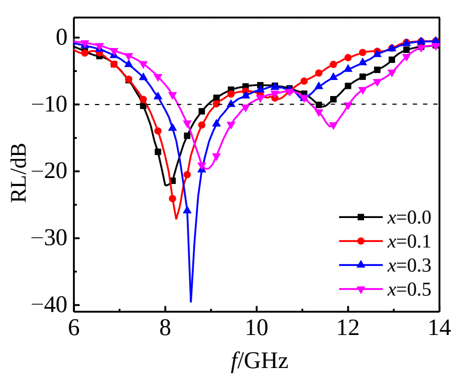

Fig.7 Relationship between reflection loss and frequency of $Nd_1Ni_{5-x}C_x$ powders (d=2.1 mm)

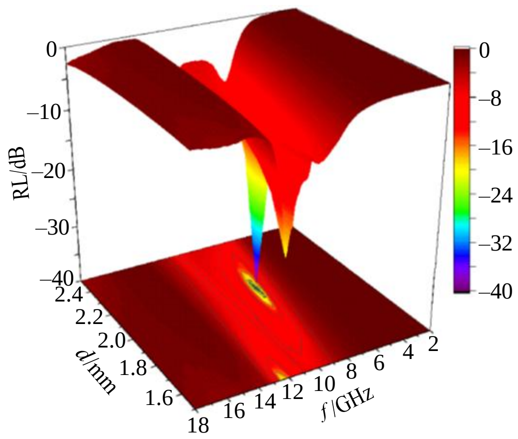

Fig.8 Relationship among reflection loss, frequency and thickness of $Nd_1Ni_{4.7}C_{0.3}$ powders

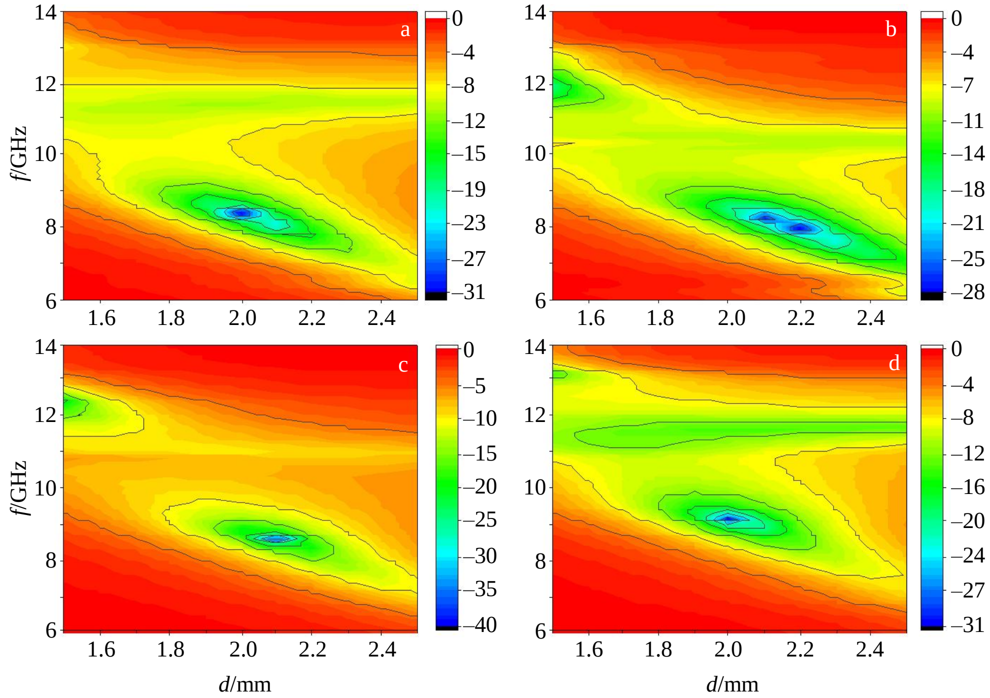

Fig.9 Reflection loss of $Nd_1Ni_{5-x}C_x$ powders versus frequency and thicknesses: (a) x=0.0, (b) x=0.1, (c) x=0.3, and (d) x=0.5

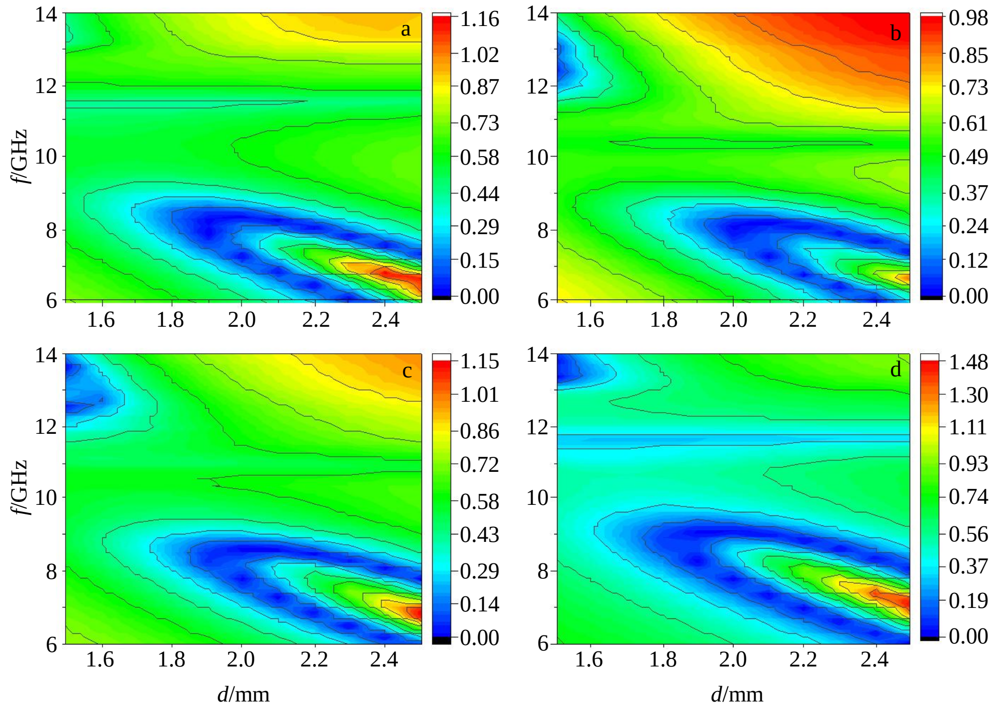

Fig.10 Impedance matching of $Nd_1Ni_{5-x}C_x$ powders versus frequency and thicknesses: (a) x=0.0, (b) x=0.1, (c) x=0.3, and (d) x=0.5

3 Conclusions

1) Addition of C has no effect on the phase structure but causes a decrease of lattice volume.

2) After ball milling, the powder has a flake structure, which increases the aspect ratio of the particles.

3) With the increase of C addition, the M_s and H_c of the powder decrease gradually. The powder has two absorption

peaks, which appear in 6~9 and 10~12 GHz, respectively.

4) As C content increases, the reflection peak appears at *x* band (8~12 GHz) and moves toward the high frequency.

5) Two effective bandwidths (RL≤−10 dB) appeared at x=0.5 are 8.28~9.82 and 11.17~12.03 GHz. The peak of reflectivity appears at x=0.3 which reaches to −39.59 dB.

6) With the increase of powder thickness, the reflection peak tends to move toward low-frequency. And when the thickness is low, the reflection loss of high-frequency band is enhanced.

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片状 $Nd_1Ni_{5-x}C_x$ 合金粉的电磁和微波吸收特性

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摘　要：利用电弧熔炼和行星球磨技术制备出片状 $Nd_1Ni_{5-x}C_x$(x=0.0, 0.1, 0.3, 0.5)合金粉。利用 X 射线衍射仪(XRD)、扫描电镜(SEM)、振动样品磁强计(VSM)、矢量网络分析仪(VNA)等仪器对其结构、形貌和电磁特性进行检测。结果表明，随着 C 含量的增加，粉体的饱和磁化强度和矫顽力逐渐减小，并且反射损耗的吸收峰向高频移动。在 C 添加量为 x=0.5 时出现 2 个有效带宽，分别为 8.28~9.82 GHz 和 11.17~12.03 GHz，有效改善了粉体的吸收带宽。另外，随着粉体厚度的变化，反射损耗可以在较大的频段内进行调整。可见该粉体有着广泛的应用前景。

关键词：电磁参数；反射损耗；Nd_1Ni_5；磁性材料

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