Experimental research on the residual magnetization of a rare-earth permanent magnet for a cryogenic undulator*

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The magnetic properties of commercial polycrystalline $Nd_2Fe_{14}B$ (N50M, N45H, N40SH, N35EH) and Sm_2Co_{17} (XG30/20, XG26/25, XG22/20) magnets at cryogenic temperatures were tested by using a comprehensive physical properties measurement system (PPMS). The results show that the spin tilt temperature T_{st} of $Nd_2Fe_{14}B$ magnets is closely related to intrinsic coercivity H_{ci}, N50M and N45H with smaller H_{ci} show a residual magnetization jump at 235 K and 225 K, respectively. For Sm_2Co_{17} magnets, in 50–300 K, with temperature decreasing, residual magnetization M_{rc} shows a nearly linear increase, while in 10–50 K, M_{rc} has little change. The research results provide a reference for cryogenic undulators and other high-precision cryogenic devices.

Keywords: $Nd_2Fe_{14}B$ and Sm_2Co_{17}, spin reorientation, residual magnetization, intrinsic coercivity

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1. Introduction

Permanent magnet undulators are key insertion devices in synchrotron radiation facilities and free electron lasers.[1] They use an anisotropic a rare-earth permanent magnet $Nd_2Fe_{14}B$ or Sm_2Co_{17} as the magnetic field source. One important development direction of permanent magnet undulators is to obtain a higher magnetic field. $Nd(Pr)_2Fe_{14}B$ and Sm_2Co_{17} magnets show excellent magnetic properties at cryogenic temperatures, the corresponding cryogenic undulator (CPMU) will obtain a higher magnetic field,[2,3] and can break the limitation caused by the use of vacuum undulators.[4,5] In recent years, Japan's Spring-8, France's ESRF, and the United States's NSLS have studied the magnetic properties of anisotropic $Nd(Pr)_2Fe_{14}B$ and Sm_2Co_{17} magnets at cryogenic temperatures, with the research results and data, CPMU prototypes were developed.[6,7]

In China, the Shanghai Synchrotron Radiation Facilities have been built, the synchrotron radiation has also been broadly used, the demand for high brightness X-rays shows a substantial increase, and cryogenic undulators will be able to meet this demand.[8] The II-period construction of the Shanghai Synchrotron Radiation Facilities will start in 2013, and a number of cryogenic undulators will be developed, the magnetic properties of domestic magnets at cryogenic temperatures should be studied. In this study, the residual magnetization M_r of domestic typical commercial polycrystalline anisotropic $Nd_2Fe_{14}B$ and Sm_2Co_{17} magnets are tested at cryogenic temperatures, and the results are analyzed.

2. Experiment

Anisotropic $Nd_2Fe_{14}B$ (N50M, N45H, N40SH, N35EH) and Sm_2Co_{17} (XG30/20, XG26/25, XG22/20) magnets are developed by Zhejiang Innuovo Magnetics Co., Ltd and Chendu Magnetic Material Science & Technology Co. Ltd, respectively. For $Nd_2Fe_{14}B$ magnets N50M, N45H, N40SH, and N35EH, remanence B_r and induction coercivity H_{cb} gradually reduce, intrinsic coercivity H_{ci} and coercivity H_k at the bending point of the B–H curve gradually increase, Sm_2Co_{17} magnets show similar behaviors. The room temperature (300 K) magnetic properties of the magnets are listed in Table 1.

Table 1. Magnetic properties of domestic $Nd_2Fe_{14}B$ and Sm_2Co_{17} magnets.

Category	Product	B_r/T	H_{cb}/kA·m^{-1}	H_{ci}/kA·m^{-1}	H_k/kA·m^{-1}
$Nd_2Fe_{14}B$	N50M	1.420	1078.9	1137.8	1105.9
	N45H	1.352	1046.2	1359.9	1321.7
	N40SH	1.276	993.7	1609.1	1562.9
	N35EH	1.200	940.3	2399.0	2325.7
Sm_2Co_{17}	XG30/20	1.126	843.2	1742.1	1184.7
	XG26/25	1.074	805.0	2026.3	1300.2
	XG22/25	0.987	744.5	2051.0	1328.9

For measuring residual magnetization M_r of the magnet (in the orientation direction and the perpendicular to orientation direction) at cryogenic temperatures, sample magnets were processed into rectangles of sizes 2.0 mm×2.0 mm×2.5 mm, and the length along the orientation direction was 2.5 mm. The residual magnetization along the orientation direction is M_{rc}, and that perpendicular to the orientation direction is M_{ra}. Sample magnets were saturation magnetized. The M–T curves of the magnets at cryo-

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genic temperatures were obtained by using Quantum Design Company's comprehensive physical properties measurement system (PPMS±9T: EC-II) at Shanghai Jiaotong University. The PPMS system has the following parameters: temperature range 10–300 K, temperature control accuracy ±1.0%, and temperature stability ±0.02%, no background magnetic field ($H = 0.0$).

3. Results

Figure 1(a) shows the M_{rc} versus T (M_{rc}–T) of N50M, N45H, N40SH, and N35EH magnets. In 10–300 K, M_{rc} of the four grade magnets first increases with the decreasing temperature, while it decreases after the spin reorientation transition (SRT). The spin tilt temperatures (T_{st}) of the four grade magnets are 115 K, 105 K, 100 K, and 90 K, respectively. Compare to that at 300 K, M_{rc} at T_{st} increases by 12.2%, 12.3%, 9.9%, and 9.7%, respectively. For N50M, N45H, N40SH, and N35EH magnets, H_{ci} gradually increases, while T_{st} gradually declines. Figure 1(b) shows the M_{ra} versus T (M_{ra}–T) of N50M, N45H, N40SH, and N35EH magnets. For N50M and N45H magnets with smaller H_{ci}, in 235–300 K and 225–300 K, respectively, M_{ra} varies gently, but it shows an obvious residual magnetization jump at 235 K and 225 K, respectively. For N40SH and N35EH magnets with larger H_{ci}, in 220–300 K and 230–300 K, respectively, the M_{ra}–T curves are not as smooth as those of N50M and N45H magnets, the curves begin to show jags at 220 K and 230 K, respectively, and have no significant jump.

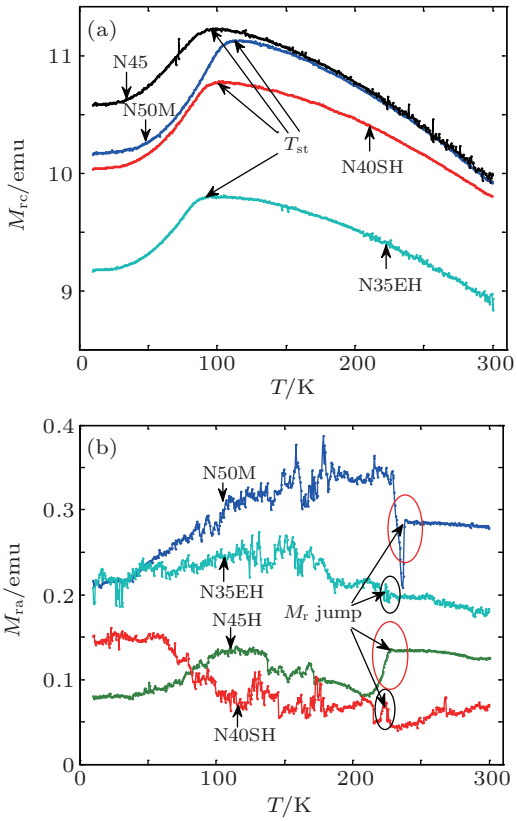


Fig. 1. (color online) The $M-T$ for $Nd_2Fe_{14}B$ magnets: (a) orientation direction, (b) perpendicular to orientation direction.

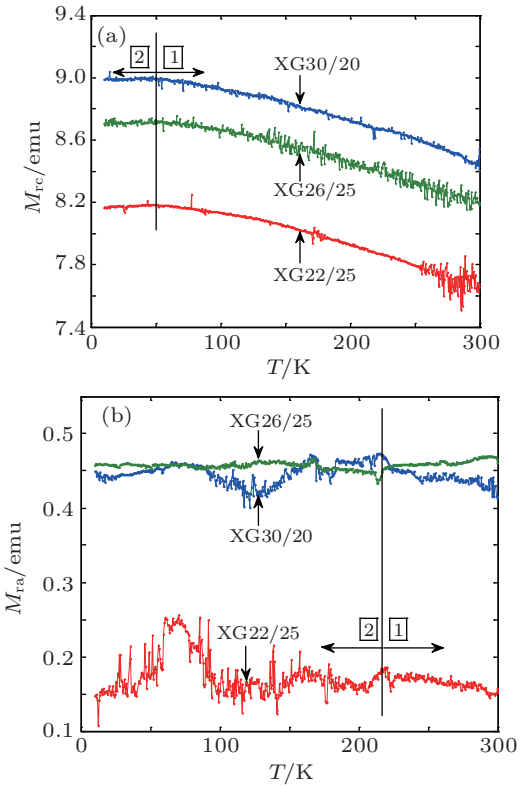


Fig. 2. (color online) The M–T for Sm_2Co_{17} magnets: (a) orientation direction, (b) perpendicular to orientation direction.

Figure 2(a) shows the M_{rc} versus T of XG30/20, XG26/25, and XG22/20 Sm_2Co_{17} magnets. We can see that there are two stages. At the first stage (50–300 K), M_{rc} of the three grade magnets presents nearly linear increases. At the second stage (10–50 K), M_{rc} has no substantial change. Sm_2Co_{17} magnets also have no spin reorientation transition. Compared to that at 300 K, M_{rc} of the three grade magnets at 50 K increases by 5.3%, 6.4%, and 6.9%, respectively. Figure 2(b) shows the M_{ra} versus T of XG30/20, XG26/25, and XG22/20 Sm_2Co_{17} magnets. We can see that there are also two stages. At the first stage (220–300 K), M_{ra} of the three grade magnets changes gently. At the second stage (10–220 K), the curves are smooth.

4. Discussion

For $Nd_2Fe_{14}B$ uniaxial crystals, the spin reorientation transition is a temperature-induced magnetic phase transition that occurs at spin tilt temperature T_{st}, which is characterized by a change of the easy magnetization direction (c-axis). For $Nd_2Fe_{14}B$, at $T_{st} = 135$ K, the deviation of the c-axis goes from an easy axis anisotropy to an easy cone anisotropy, with tilt angle θ increasing from 0° at 135 K to 31° at 0 K,[9] see Fig. 3(a). But the results of the present experiments show that

T_{st} of the typical $Nd_2Fe_{14}B$ magnets (N50M, N45H, N40SH, N35EH) are less than 135 K and not the same, this indicates that for commercial polycrystalline $Nd_2Fe_{14}B$ magnets, T_{st} is related to the composition and the magnetic microstructure of the magnet.

The orientation direction of the magnets is defined as the z direction, see Fig. 3(b). For M_{rc} measuring, the orientation direction of the magnets is parallel to magnetic field H of the PPMS. For M_{ra} measuring, the orientation direction of the magnets is perpendicular to magnetic field H of the PPMS. The M_{rc} or M_{ra} are vector sums of residual magnetization components along PPMS magnetic field H of many grains for bulk sample magnets. At 10–300 K, at a certain temperature, when the temperature driving force reaches a certain level, the residual magnetization direction for single crystals will spin, this means that the residual magnetization for single crystals will show a jump phenomenon. Due to crystal structure differences, the residual magnetization spin directions of many crystals in bulk sample magnets are not strictly the same, the cryogenic temperature effect of the residual magnetization for different magnets is complex and diverse.

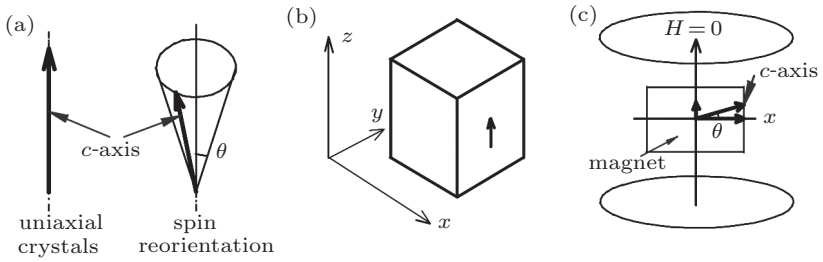


Fig. 3. (a) Spin reorientation transition, (b) sample magnet, (c) M_{rc} or M_{ra} measurements.

As shown in Fig. 1(b), N50M and N45H magnets show an apparent residual magnetization jump at 235 K and 225 K, respectively. A smaller H_{ci} shows that the resistance to the c-axis direction rotation is smaller, the c-axis directions of most grains in the $Nd_2Fe_{14}B$ magnet appear loose at this temperature. N40SH and N35EH magnets do not show a significant jump at about 220 K and 230 K, respectively, the larger H_{ci} produces a larger resistance to the c-axis direction rotation, only a small amout of grains appear loose at the temperature point. Comparing Figs. 1(a) and 2(a), we can find that the M_{rc}–T curve of the $Nd_2Fe_{14}B$ magnet is more smooth than that of the Sm_2Co_{17} magnet, that is because the Sm_2Co_{17} magnet has a complex phase ($SmCo_5$, Sm_2Co_{17}, etc) while the $Nd_2Fe_{14}B$ magnet has a single phase ($Nd_2Fe_{14}B$), each magnetic phase has a different magnetic effect at cryogenic temperature.

5. Conclusion

This test results show that T_{st} of $Nd_2Fe_{14}B$ magnets is closely related to H_{ci}, T_{st} of N50M, N45H, N40SH, and N35EH magnets are 115 K, 105 K, 100 K, and 90 K, respectively. Compare to that at 300 K, M_{rc} increases by 12.2%, 12.3%, 9.9%, and 9.7%, respectively. N50M and N45H with smaller H_{ci} perpendicular to orientation direction show a residual magnetization jump at 235 K and 225 K, respectively. For Sm_2Co_{17} magnets, in 50–300 K, with temperature decreasing, M_{ra} of XG30/20, XG26/25, and XG22/20 magnets shows nearly linear increases, at 50 K, M_{rc} increases by 5.3%, 6.4%, and 6.9% respectively. For $Nd_2Fe_{14}B$ and Sm_2Co_{17} magnets, the macroscopic residual magnetization M_r enhances, and the microscopic magnetic field uniformity deteriorates. The research results provide a reference for the physical design and development of Shanghai Synchrotron Radiation Facilities cryogenic undulators and the other high-precision cryogenic permanent devices.

Some issues need to be studied further. (i) For T_{st} of $Nd_2Fe_{14}B$ magnet at cryogenic temperature, what is the mechanism? (ii) Why do some $Nd_2Fe_{14}B$ magnets show a residual magnetization jump for perpendicular to orientation direction at cryogenic temperature and does this have a relation with H_{ci}? (iii) In Fig. 2(a), is the smoothness of curves related to the technical state of PPMS?

Acknowledgments

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