# EXPERIMENTAL STUDY OF MAGNETIC PROPERTIES FOR MAGNET MATERIAL IN CYCIAE-100

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*Abstract*

The magnetic property of magnet material is one of the key factors that influence the distribution of magnetic field in large scale cyclotron, especially embody on the vertical focusing of field and the first harmonic field in cyclotron. According to the requirements of the physics design of CYCIAE-100, we have studied the key factors effect the magnetic properties and tested the magnetic property of materials for magnet in CYCIAE-100, including the cooling rate during magnetic annealing and residual stress influence on the magnetic properties. The study and test result will be shown in this paper.

## INTRODUCTION

The main magnet of 100MeV cyclotron consists of top/bottom yoke, 4 sectors and yokes. We investigated the metallurgical and machining ability of domestic industries, and adjusted the magnet structure design again and again. The construction project of main magnet for100MeV cyclotron was selected as below [1]: The magnetic properties of AISI1008 steel was used as reference in theoretical design of the magnet; The characters of magnet comprise compact overall structure, the fan-shaped poles with straight edge and the variety gap; The industrial forging pure iron will be selected for the material of poles and centre plugs; The upper/down covers will adopt an integral structure in CYCIAE-100, and the china 8# casting low carbon steel will be considered for the material of the upper/down covers and yokes; The diameter and thickness of covers are 6160mm and 775mm, and the radius and height of poles are 2000mm and 785mm. Many processes such as pure iron smelting, forging and heat treatment will affect ingredient segregation, internal stress, the grain size of material, and thus will impact on the magnetic properties of the material. Therefore we must test the magnetic properties of the materials for 100MeV cyclotron magnet, and study some key factors that affect the magnetic properties to ensure that the materials of the main magnet meet the requirements of the theoretical design.

## THE STUDY OF MAGNETIC PROPERTIES IMPACT THE DISTRIBUTION OF THE MAGNETIC FIELD IN MEDIAN PLANE

If the magnetic permeability of material for CYCIAE-100 has large difference with that of AISI1008 steel, it will induce the departure from ideal distribution of magnetic field. In order to maintain isochronous field, the ampere-turns and the angular of shimming bars width will be changed, and which will weaken the axial focusing frequency. We assume the magnetic permeability of material are 97%, 93% and 90% of that of ANSI1008 steel in FEM simulation, respectively, and the axial focusing frequency are shown in figure 1. As we know from figure 1, when the magnetic permeability μ (H) of the material is less than 90% of reference steel, the axial focusing frequency of CYCIAE-100 will fall down in large radius, and the harmful walkinshaw resonance will be induced. The non-uniform magnetic permeability will bring the imperfection field in median plane. If the first harmonic field will be controlled less than 10 Gauss, the deviation of magnetic permeability between magnetic poles should not exceed 1.5%, and the deviation between top/ bottom yokes should not exceed 15%.

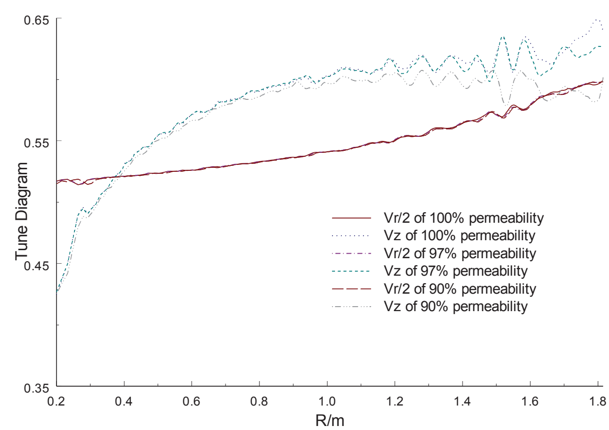


Figure 1: The axial focusing frequency of different magnetic permeability.

## EXPERIMENTAL STUDY OF MAGNETIC PROPERTIES FOR CYCIAE-100

The magnetic properties of the magnet can be influenced by the chemical composition and structure of the material. The higher the carbon content is, the higher the carbide content will be; meanwhile, the magnetic reluctance is greater and the magnet will be more difficult to be magnetized; the grain size is larger and the maximum permeability is higher. Some studies have shown that the heat treatment will improve the magnetic properties of pure iron material [2]. Because the final goal of the magnetic heat treatment is to obtain a large ferrite grain, the cooling rate will be controlled during the grain of the austenitization transforming to ferrite in order to have sufficient time for the grain growth. For industrial pure iron, the start temperature is 910 º C when the ferrite grain will be precipitated from the austenitization start

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temperature of the ferrite grain growth, while the grown of grain will stop at about 600 º C.

Considering the circumstance of heat treatment for yokes, we simulated the cooling rates of upper/down covers under air-cooled, and get the maximum cooling rate 180 ºC/h and minimum cooling rate 37 ºC/h. In order to obtain the relationship between cooling rate and magnetic properties of the top/bottom yoke in CYCIAE-100, we have carried out the test with some annular samples, for which the inner and outer diameter and height of the test samples are selected 32mm, 40mm, and 9mm respectively. The heat treatment of the samples was processed in a vacuum oven to avoid the sample from being oxidized at high temperature. Meanwhile, in order to get large austenite grains, after the temperature of samples heats up to 800ºC with the furnace, the rate of heat will be controlled from 50ºC per hour to 920±10ºC, and then will be kept at 920ºC for 4 hours. In the end the temperature will be cooled to 600ºC with different cooling rate, which will be selected for 180ºC / h, 30ºC/h and 10ºC/h.

The annealing temperature curve and B-H curve of sample with different cooling rates are shown in Figure 2 and Figure 3. The maximum permeability, remanence and coercive force under different cooling rate are shown in Table 1, in which samples Numbered R12 and 4R are of the same chemical composition.

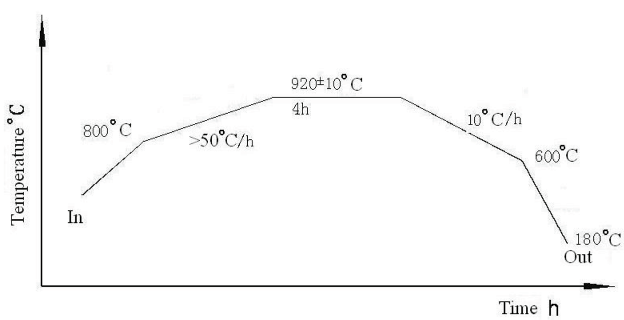


Figure 2: The annealing temperature curve.

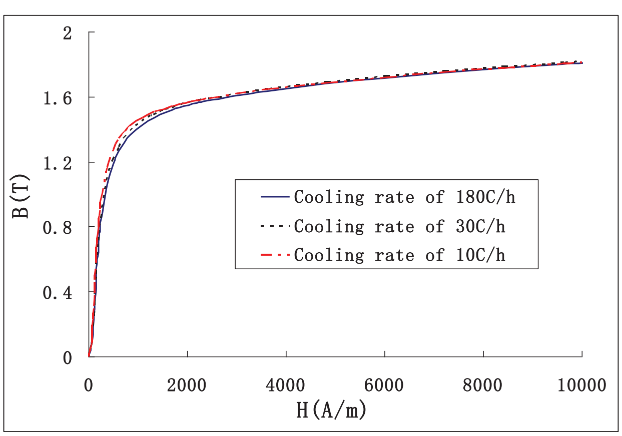


Figure 3: The B-H curve with different cooling rates.

Table 1: The Magnetic Properties and Different Cooling Rates

| Number of sample | Cooling rate | μm(k) | Hc(A/m) |
|---|---|---|---|
| | 10ºC/h | 3.216 | 110.9 |
| R12-3A | 30ºC/h | 2.913 | 118.9 |
| | 180 ºC/h | 2.529 | 131.4 |
| | 10ºC/h | 3.217 | 108.5 |
| 4R-3A | 30ºC/h | 2.891 | 117 |
| | 180 ºC/h | 2.675 | 127.2 |

As we know from the above results, the maximum permeability, the coercive force and the maximum magnetic flux density will be impacted by the cooling rate, especially for the maximum magnetic permeability and coercive force. When the magnetic induction is greater than 1.6T, the magnetic permeability μ (H) of the sample will not be significantly changed with the cooling rate.

## RE-CALCULATION OF MAGNETIC FIELD IN CYCIAE-100

To get the magnetic properties of rough pieces for main magnet in CYCIAE-100, we tested the B-H curves of some samples taken from rough pieces for all parts of the main magnet. The deviation of magnetic permeability between magnetic poles doesn't exceed 1.3%, and the deviation between top/ bottom yokes should not exceed 5%. The magnetic property comparison between all parts in CYCIAE-100 and 1008# steel is shown in Table2.

Table 2: The Magnetic Properties Comparison

| H(A/m) | Covers/T | yokes/T | Poles/Bars(T) | 1008# /T |
|---|---|---|---|---|
| 110 | 0. 24 | 0. 22 | 0. 59 | 1. 0 |
| 300 | 1. 0 | 1. 06 | 1. 10 | 1. 44 |
| 500 | 1. 29 | 1. 35 | 1. 33 | 1. 5 |
| 1000 | 1. 45 | 1. 48 | 1. 52 | 1. 55 |
| 4000 | 1. 66 | 1. 68 | 1. 68 | 1. 69 |
| 7000 | 1. 75 | 1. 77 | 1. 76 | 1. 77 |
| 9000 | 1. 79 | 1. 81 | 1. 80 | 1. 82 |
| 12000 | 1. 85 | 1. 87 | 1. 86 | 1. 88 |

In order to verify that the properties meet the requirement of CYCIAE-100, the properties of upper/down cover, yokes and poles have been taken in re-calculation of magnetic field. Taking account of the complexity of the main magnet model and the magnetic flux distribution, the high density mesh has been produced in the region of median plane, round region of vacuum holes and shimming bar, and meanwhile the centre region has been simplified. In order to reduce the influence of meshing on simulated results, the same meshing size has been applied to all parts of model under both the 1008# steel and real steel [3].

In simulation of the magnetic field under real magnetic properties, the field distribution in median plane will be changed by adjusting the number of ampere turns of main coils and the angle of shimming bar. When the field distribution meets the requirement of beam dynamics, the number of ampere turns and the frequency of particle are 31000AT and 11.092MHz. However, under the magnetic properties of 1008# steel, the number of ampere turns and the frequency of particle are 29900 AT and 11.095MHz. Under the real magnetic properties and 1008# steel, the comparisons of integral phase shift and vertical focus are shown in Figure 4 and Figure 5, respectively. From the figures we know that the integral phase shift will be limited to ±6 º in corresponding to the optimum frequency of particle, but the phase shift under1008# steel is better than that under real magnetic properties. The vertical and radial focusing under real properties is approaching to that under 1008# steel, and in both cases the walkinshaw resonance has been avoided. The magnetic properties of material for CYCIAE-100 meet the requirements of physical design in the process of air cooling.

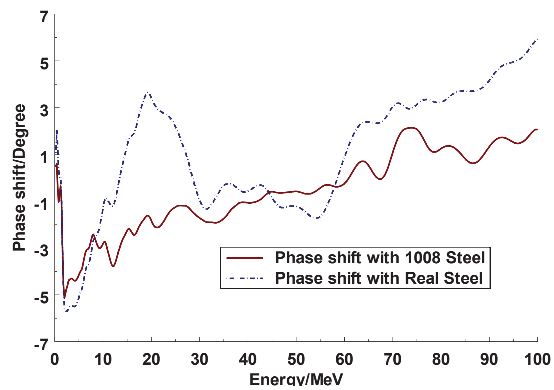


Figure 4: The comparison of integral phase shift.

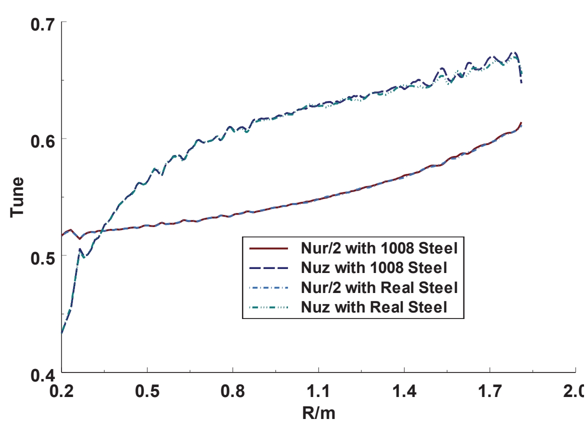


Figure 5: The comparisons of vertical focusing and radial focusing.

## STUDY OF RESIDUAL STRESS AFFECT ON THE MAGNETIC PROPERTIES

It should not be ignored that the residual stress influence the magnetic properties of material, and the stress includes the internal thermal stress and external applied stress [4]. The thermal stress is mainly concentrated at the grain boundaries, and restrains the movement of the magnetic domain walls. Further, the stress of machining will destruct and distort the lattice of the sample surface. Those stresses will lead to the deterioration of magnetic properties

In order to study the machining stress affect on the magnetic properties, we tested the properties under stress and without stress, and the B-H curves of sample are shown in Figure 6. As we know from Figure 6, the machining stress affects significantly on the magnetic properties of sample.

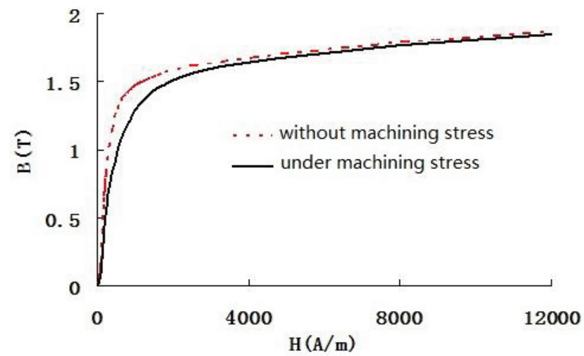


Figure 6: B-H curve of different machining stress.

## CONCLUSION

From the results of testing for B-H curves of samples and re-calculation of main magnet, we know the magnetic properties of rough pieces material meet the requirements of CYCIAE-100. The cooling rate will heavily influence on the maximum permeability, the coercive force. The machining stress affects significantly on the magnetic properties of sample. But the machining stress is only deposited on the surface of sample. When the volume with stress can be ignored in whole magnet, the influence of machining stress will not be considered.

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