

DESIGNING WITH HIGH PERFORMANCE RARE EARTH PERMANENT MAGNETS

JINFANG LIU AND MICHAEL WALMER

Electron Energy Corporation, 924 Links Ave., Landisville, PA 17538, USA

Corresponding author e-mail: jfl@electronenergy.com

Abstract

Rare earth permanent magnets have the widest range of magnetic properties and are used in an extensive variety of applications. Sintered NdFeB magnets have the highest maximum energy product $(BH)_{\max}$ but are limited to applications with relatively low temperatures. Sintered $\text{Sm}_2\text{Co}_{17}$ -type magnets have the best thermal stability with high magnetic performance at temperatures up to 550°C. Bonded magnets offer some design flexibility at the expense of magnetic properties. In view of these complexities, it is very important to understand the critical factors when designing the magnetic circuit. The magnetic properties, maximum operating temperature, reversible temperature coefficient of B_r of permanent magnets will be discussed from a design standpoint. Design examples on travelling wave tubes and magnetic couplers will be discussed based on finite element analysis (FEA).

Introduction

There are many critical factors that need to be considered when designing with high performance rare earth permanent magnets. Those factors include (1) the magnetic properties; (2) thermal stability; (3) reversible temperature coefficient (RTC) of residual induction B_r ; (4) corrosion resistance and coating; (5) maximum operating temperature; and (6) the application environment. Currently there are three primary categories of rare earth magnets to choose from, namely SmCo_5 , $\text{Sm}_2\text{Co}_{17}$ and $\text{Nd}_2\text{Fe}_{14}\text{B}$ type magnets.

The outstanding magnetic properties of SmCo based magnets — particularly, excellent stability over the widest range of environmental conditions — led to an exciting variety of applications. Prior to 1983, sintered Sm-Co based magnets dominated the field of advanced permanent magnet applications. A few examples include *travelling wave tubes* for commercial and military radars, space exploration, satellite communications, missiles, and combat aircraft, *inertial devices* for guidance and stabilization of military spacecraft, *power tools for medical applications* to withstand autoclave conditions, and *motors and generators* for aircraft engines and missiles [1]. Funded by the US Air Force, EEC and UDRI developed a series of high temperature SmCo magnets that can be used up to 550°C, which opened a new window for designers [1].

Sintered $\text{Nd}_2\text{Fe}_{14}\text{B}$ type magnets developed in 1980s have the highest maximum energy product $(BH)_{\max}$ but are limited to applications with relatively low temperatures. Bonded rare earth magnets offer some design flexibility at the expense of magnetic properties [2].

Using design examples based on finite element analysis (FEA), we will discuss design trade-offs and the selection of magnet materials for various applications. Examples will include periodic permanent magnet arrangements for travelling wave tubes and magnetic couplers for mixers and pumps. The magnetic properties -- maximum operating temperature and reversible temperature coefficients -- of permanent magnets will be discussed from a design standpoint.

1 Maximum operating temperature of permanent magnets

1.1 Overview

Table 1 lists some of the choices of rare earth permanent magnets with various maximum operating temperatures.

Table 1. Room temperature magnetic properties and maximum operating temperatures (T_{op}) of various permanent magnets

Material	Grades	B_r	H_{ci}	$(BH)_{max}$	T_{op}
		kG	kOe	MGOe	$^{\circ}C$
Sintered NdFeB magnets	N48	14.0	>12	48	80
	N45H	13.5	>17	45	120
	N42SH	13.0	>20	42	150
	N33UH	11.5	>25	33	180
High energy Sm_2Co_{17} type magnets	EEC2:17-31	11.5	>20	31	250
Standard Sm_2Co_{17} type magnets	EEC2:17-27	10.8	>25	27	300
	EEC2:17-24	10.1	>25	24	300
Patented high temperature SmCo magnets (U.S. patent number 6,451,132 B1)	EEC24-T400	10.1	>25	24	400
	EEC21-T400	9.5	>25	21	400
	EEC20-T500	9.3	>25	20	500
	EEC18-T500	8.7	>25	18	500
	EEC16-T550	8.5	>20	16	550
	EEC15-T550	8.0	>20	15	550

Understanding the application environment is essential for satisfactory performance of the device and is an important step in the design process in which selection of appropriate magnetic parameters is incorporated in the design models [3]. As seen in Table 1, sintered NdFeB magnets offer high magnetic properties at room temperature, but can be only used at relatively low temperatures. In comparison, standard SmCo magnets have impressive magnetic properties at elevated temperatures up to 330 $^{\circ}C$. The new series of patented high temperature magnets can be used up to 550 $^{\circ}C$ [4]. Figure 1 shows the trade-off between maximum operating temperature and the maximum energy product, $(BH)_{max}$, of various magnetic materials.

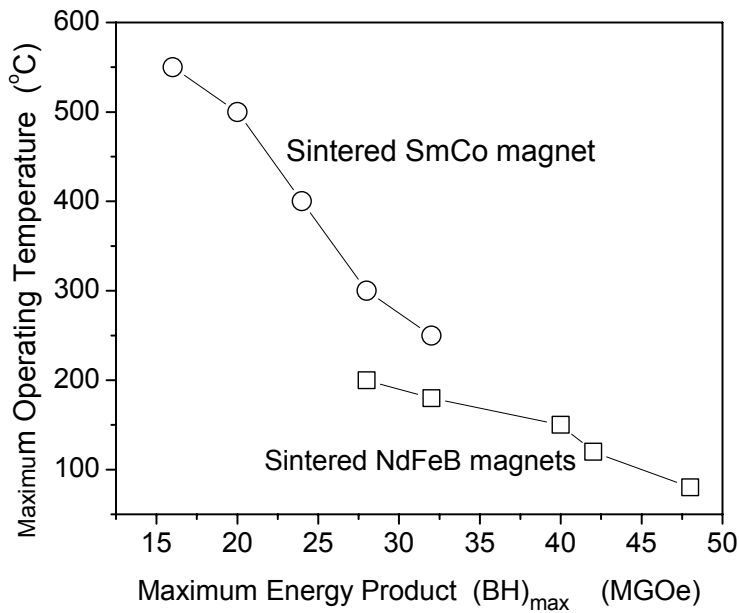


Figure 1. Sketch showing the maximum operating temperature versus maximum energy product of sintered SmCo and NdFeB-type rare earth permanent magnets

1.2 Maximum operating temperature and permeance coefficient

The maximum operating temperature is normally defined as the maximum temperature to which the magnet may be exposed with no significant long-term instability or metallurgical changes [5]. For EEC SmCo magnets, the second quadrant extrinsic demagnetisation curves are straight lines up to the maximum operating temperature. This offers design flexibilities for critical applications. But for high-energy sintered NdFeB magnets, the extrinsic demagnetisation curves are not linear, which must be taken into consideration in the magnetic design.

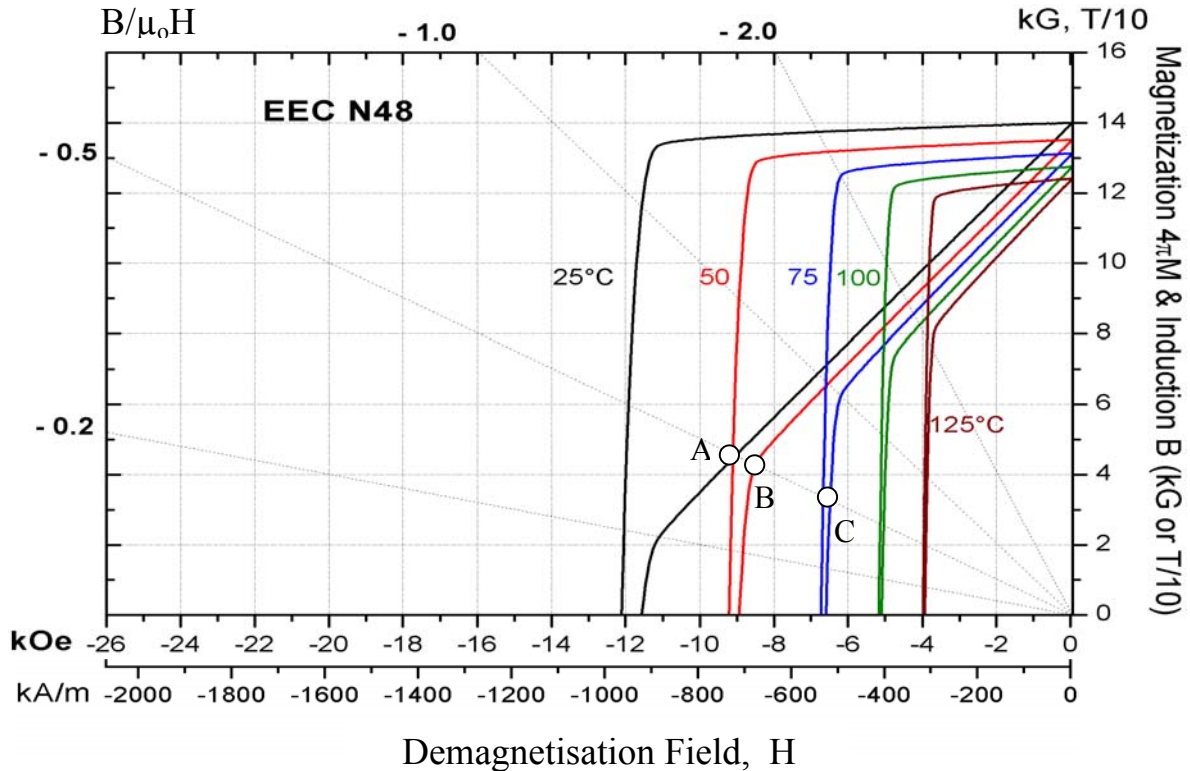


Figure 2. Typical demagnetisation curves of N48 sintered NdFeB magnets

The maximum operating temperature for sintered NdFeB magnets is related to the permeance coefficient (P_c), which is also known as the load line or the operating point of a magnet. The permeance coefficient is related to the dimensions of the magnet and its associated magnetic circuit. Figure 2 shows the typical demagnetisation curves of N48 sintered NdFeB magnets. Assuming the permeance coefficient $P_c = -0.5$, sintered N48 magnet can be only used at room temperature because it would be too close to the knee even at temperatures as low as 50°C. N48 sintered NdFeB magnet is rated with a maximum operating temperature of 80°C in most of the literature, however, this applies only to geometries with P_c below -1.5 . Room temperature applications are not even recommended if the permeance coefficient P_c is greater than -0.2 .

With a linear extrinsic demagnetisation curve up to the maximum operating temperature as shown in figure 3, EEC SmCo magnets do not have the above-mentioned problem. This is true for all EEC sintered SmCo magnets, including the high temperature series as evidenced in figures 4, 5 and 6 [6].

The rated maximum operating temperature for permanent magnets in most literature provides only guidelines. The communication between magnet design engineers and magnet producers is important for successful new system design.

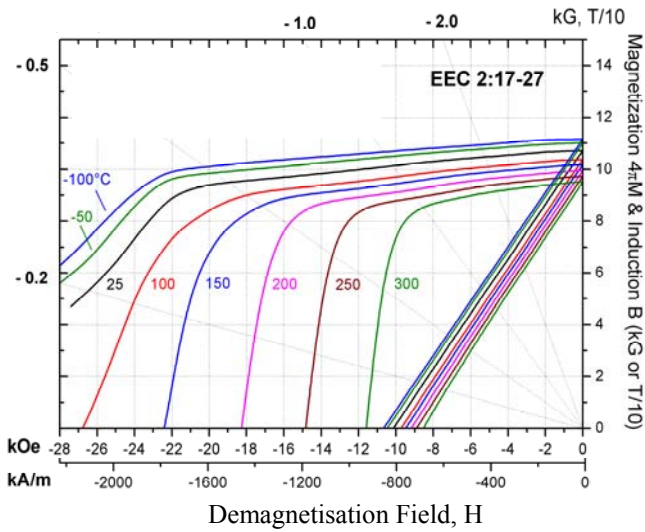


Figure 3. Typical demagnetisation curves of SmCo 2:17 magnets

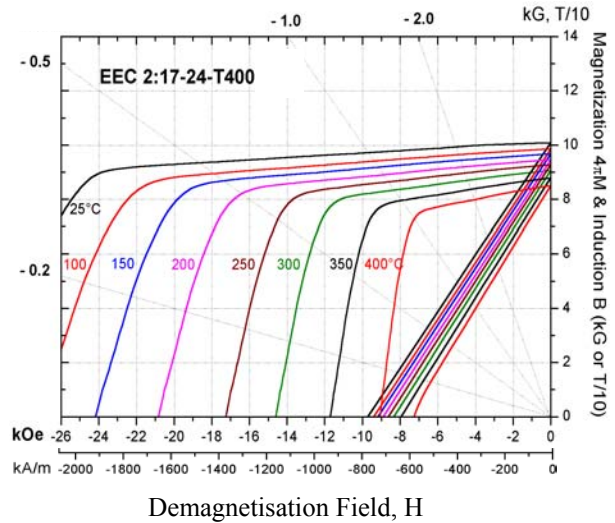


Figure 4. Typical demagnetisation curves of EEC24-T400 high temperature magnets

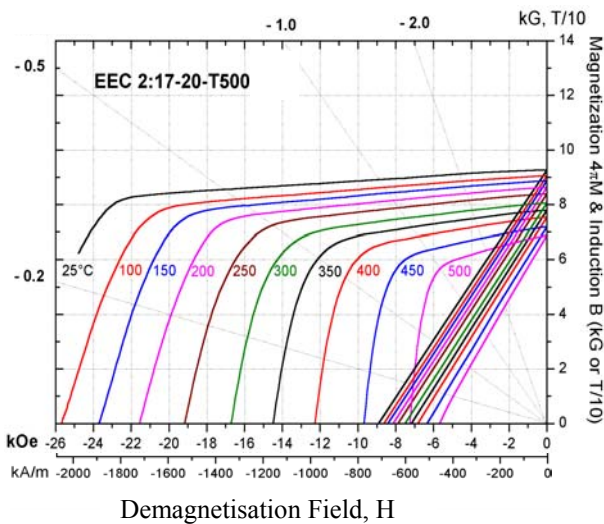


Figure 5. Typical demagnetisation curves of EEC20-T500 high temperature magnets

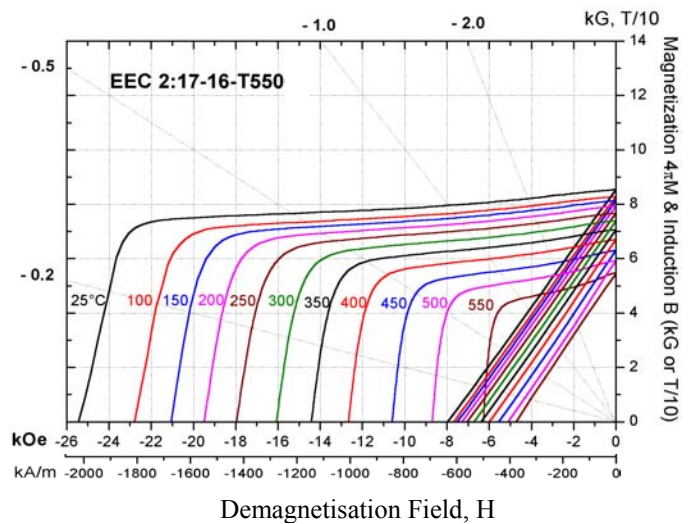


Figure 6. Typical demagnetisation curves of EEC16-T550 high temperature magnets

2 Reversible temperature coefficient of B_r

For the standard grades of SmCo_5 and $\text{Sm}_2\text{Co}_{17}$ type magnets, the reversible temperature coefficients (RTC) of B_r , α , are -0.04 and $-0.035\%/^\circ\text{C}$, respectively. For applications in inertial devices, constant field strength as a function of temperature is required. In response to that need, EEC developed a series of magnet grades that are temperature compensated by substituting gadolinium for a portion of the samarium in the alloy. This series of magnets, which includes 1:5TC-9, 2:17TC-15 and 2:17TC-16, are widely accepted by the inertial device industry for applications in accelerometers and gyroscopes. Design engineers in the travelling wave tube, TWT, industry has also embraced the benefits of these “near zero” temperature coefficient grades. Table 2 listed the options for temperature compensated magnets.

Table 2. Typical magnetic properties of temperature compensated SmCo magnets

Magnet grades	B_r	H_{ci}	$(BH)_{max}$	RTC of B_r^*
	kG	kOe	MGOe	%/°C
EEC2:17TC-16	8.3	>25	16	-0.001
EEC2:17TC-15	8.0	>25	14.5	-0.001
EEC1:5TC-9	6.1	>25	9.2	-0.001

(* Reversible temperature coefficient of residual induction B_r , between -50°C to 150°C)

3 Case study #1: Magnetic design of travelling wave tubes

The permanent magnet is one of the most important components in the travelling wave tubes (TWT). Magnetic circuit design is critical for the TWTs. The magnets of choice are the temperature compensated magnets, such as 2:17TC-16, 2:17TC-15 and/or 1:5TC-9 grades. The recently developed high temperature SmCo magnets, such as EEC24-T400, also resulted in improved tube performance.

Magnets with various magnetic properties are placed in appropriate positions of the periodic permanent magnet (PPM) structure to obtain the desired axial field profile. A finite element analysis (FEA) of a PPM structure with 45 individual magnet rings was conducted to obtain a stack axial field of 4400 G. Figure 7 shows the 2D FEA plot of the axial field of the PPM structure. The magnetic properties of each magnet position can be adjusted precisely to get the accurate field profile.

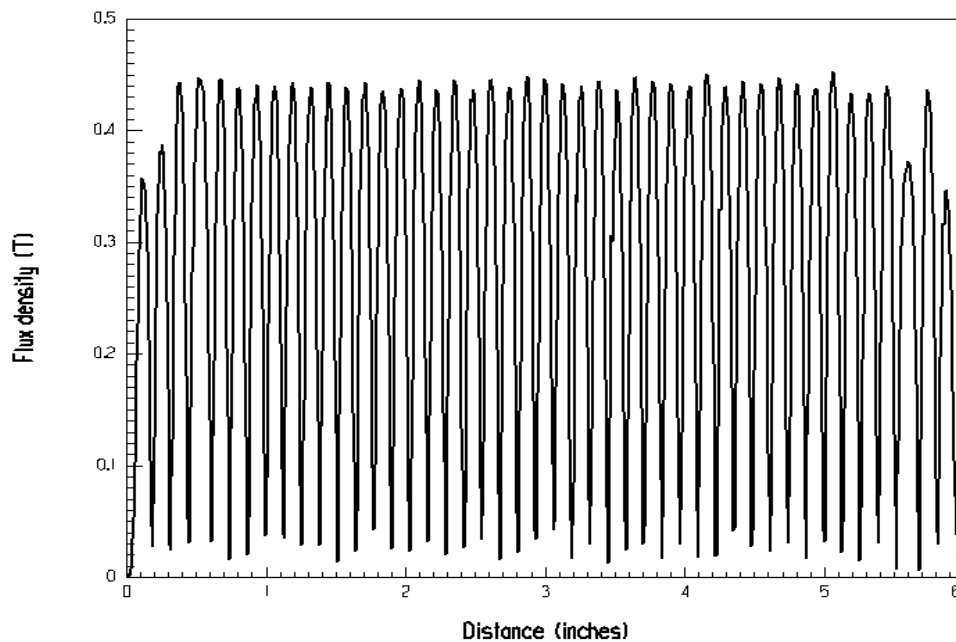


Figure 7. A 2D FEA plot of the axial field of a PPM structure

Finite element analysis proved to be a very useful tool for the magnetic design of travelling wave tubes. Without the FEA data, development must be done empirically – a tedious process.

High intrinsic coercivity, H_{ci} , a measure of the resistance to demagnetisation, is always important for PPM structures due to their low working point. Precise control of residual induction, B_r , of each individual magnet is critical to obtain the field profile predicted by FEA.

Reversible temperature coefficient of B_r , α , has a great impact on the axial field of the PPM stacks. The variation of axial field of a PPM stack is almost zero between -50°C and 150°C in the temperature-compensated SmCo 0TC materials are used. In contrast, the axial field would vary by 7% for conventional SmCo magnet PPM stacks and 22% for NdFeB PPM stacks.

4 Case study #2: Design of magnetic couplers

Magnetic couplers are used to transfer torque between separated components, which have many different applications, including sealless magnetic drive pumps and mixers for chemical, biological and/or pharmaceutical industries. The magnetic coupling systems consist of two magnet assemblies -- the driver and the driven couplings. The torque of magnetic couplers is related to the magnetic properties of permanent magnets, magnet dimensions, number of poles and the air gap between the driver and driven components.

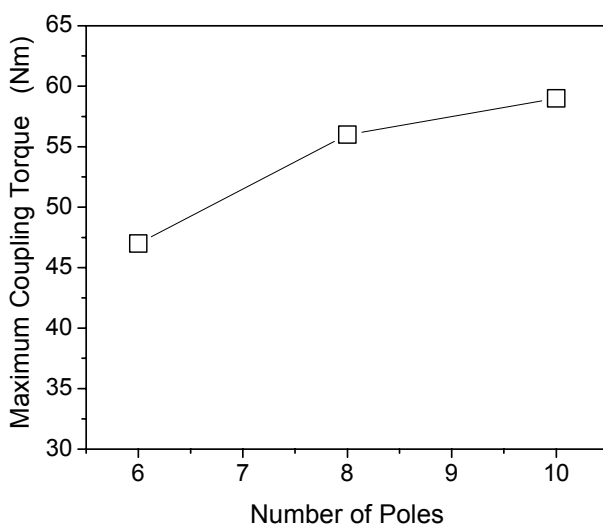


Figure 8. Torque versus the number of poles

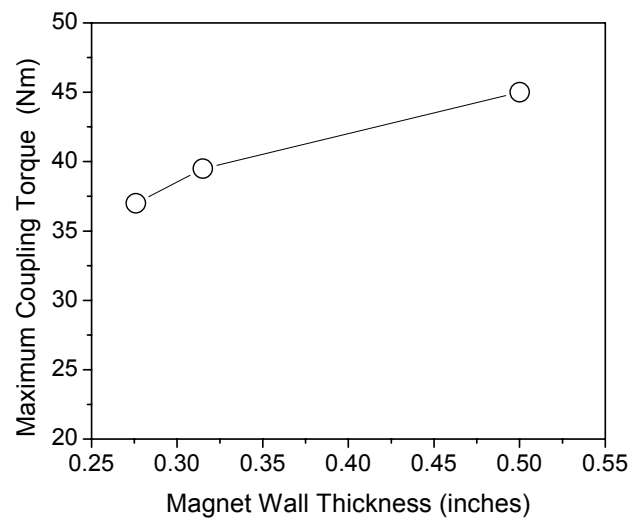


Figure 9. Torque versus magnet wall thickness

Considering a concentric coupling assembly of 2.75 inches long made of sintered NdFeB magnets, the inner assembly has an OD of 2.44 inches, and the outer assembly has ID of 2.913 inches. The magnetic properties of NdFeB magnets used in the FEA analysis is as follows: $(BH)_{\max} = 45$ MGOe, $B_r = 13.5$ kOe, $H_{ci} > 17$ kOe.

Assuming the coupling system has adequate thickness of the back iron sleeve, the maximum coupling torque is plotted against the number of poles in Figure 8 assuming the magnet wall thickness is 0.440 inches. The maximum coupling torque is also plotted against the magnet wall thickness in Figure 9 assuming there are 10 alternating poles. The 3D finite element analysis data was validated by prototypes.

Finite element analysis can help to optimise the magnetic coupling system, including the selection of materials, the dimensions of magnets and back iron sleeves, and the number of alternating poles.

If the couplers need to be operated at elevated temperatures, such as in autoclave conditions, the properties of permanent magnets at the maximum service temperatures can be used for the finite element analysis, which can help to predict the coupling system performance at the service temperatures.

A magnetic coupler designed using T550 high temperature magnets can operate up to 550°C . Room temperature properties of T550 magnets are as follows: $B_r = 8.55$ kG, $(BH)_{\max} = 16.91$ MGOe, $H_{ci} > 25$ kOe. The dimensions of the inner 8-pole magnet assembly are: OD: 2.440", ID: 2.000", Length: 2.755". The dimensions of the outer 8-pole magnet assembly are: OD: 3.353", ID:

2.913", Length: 2.755". Figure 10 shows the coupling torque for this 8-pole coupler at temperatures up to 550°C. The coupling torque is about 10 Nm at 550°C.

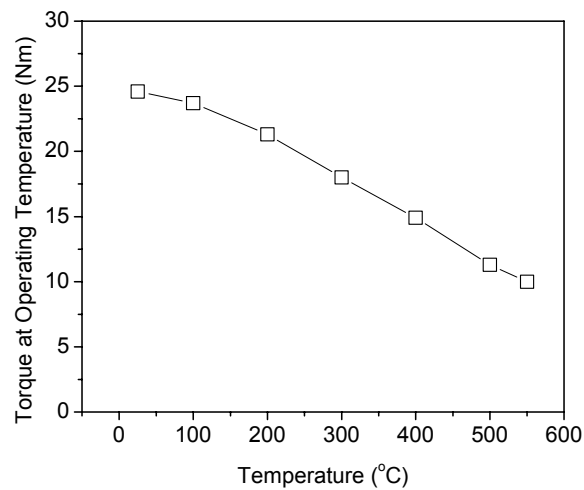


Figure 10. Torque at operating temperature for an 8-pole coupler made of T550 high temperature magnets

5 Summary

High performance rare earth permanent magnets offer many choices for design engineers. Sintered SmCo magnets can operate at temperatures up to 550°C with linear extrinsic demagnetisation curves and high magnetic performance, while sintered NdFeB magnets can be only used at relatively low temperatures although they exhibit the highest room temperature properties. The maximum operating temperatures of sintered NdFeB magnets rated in the literature can only serve as general guidelines due to their non-linear extrinsic demagnetisation curves.

Temperature compensated SmCo magnets are the designer's choice for inertial devices and travelling wave tubes. The newly developed high temperature SmCo magnets also show improved performance in these applications.

Finite element analysis is an extremely useful tool for the magnetic design of devices, such as travelling wave tubes and magnetic couplers.

References

- [1] Michael Walmer, *Proceedings of the 17th International Workshop on Rare Earth Magnets and Their Applications, August 18-22, 2002, Newark, Delaware, USA. Edited by G. C. Hadjipanayis and M. J. Bonder. P.37-51*
- [2] Jinfang Liu, *2001 Fall Technical Conference on Emerging Technologies for the Electric Motion Industry, October 3-5, 2001, Durham, North Carolina, USA.*
- [3] Jinfang Liu, *SMMA 2002 Technical Conference, November 6-8, 2002, St. Louis, USA.*
- [4] C. H. Chen, M. S. Walmer, M. H. Walmer, S. Liu, and G. E. Kuhl, *IEEE Trans. Magn.* **36** (2000) 3291
- [5] MMPA PMG-88, *Permanent Magnet Guidelines, December 1987.*
- [6] Electron Energy Corporation, *Product Literature, 2000*