Magnetic Force Equations based on Computer Simulation and the Effect of Load Line

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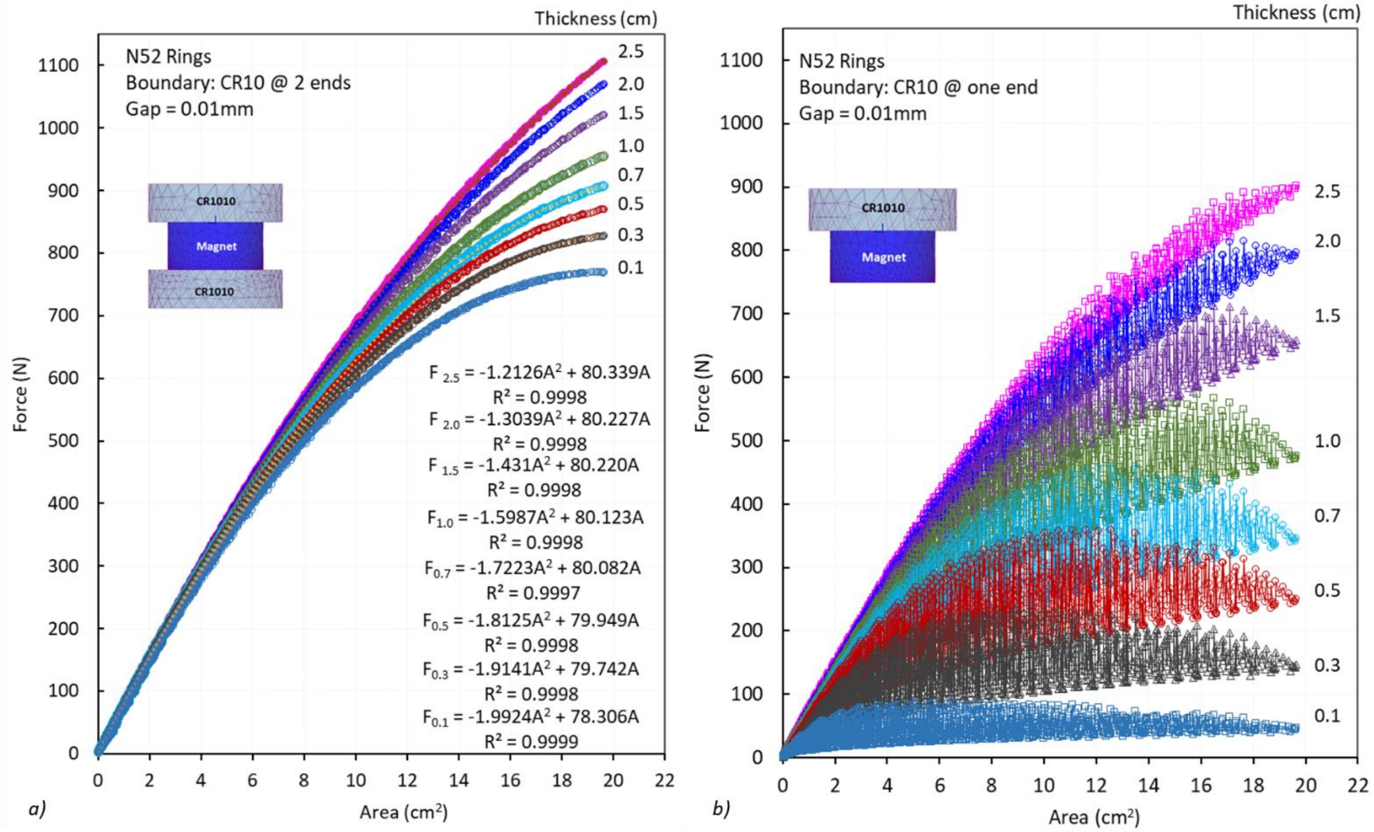
Digest

The Maxwell magnetic force equation $F = B^2A/(2\mu_0)$ [1-6] can be used for determining the magnetic force of magnetic components, where F is the force in newton (N), B is the flux density in tesla (T), A is the area of cross-section in square meter (m^2), and μ_0 is the permeability of the vacuum ($4\pi\times10^{-7}$ H/m). The formula can be converted to an easy to remember expression of $F = 40B^2A$, in which the unit of A is cm^2. This equation says that if the field is 1T, and the area is $1cm^2$, then the magnetic force is 40N or 4kgf. However, it is somehow difficult to determine the B value in many practical cases, and the accuracy is usually not satisfactory. Computer simulation using finite element method can determine the magnetic forces with various boundary conditions, but usually it is not convenient for industrial users. In this paper, we report several simple equations, which are established based on the large database generated by using 3D computer simulation. The users can use the equations to obtain the force by simply inputting the magnet's B_r, area and thickness. The effect of load line is also analyzed in this paper.

Infolytica's MagNet software was chosen for the simulation. Parameterization function with newton tolerance 0.1% was used to systematically solve the problems for NdFeB cylinders, rings, and rectangular blocks interacting with CR1010 steel. The steel plates are both thicker and larger than the magnets. The maximum sizes for the magnets are shown in Table 1. The result database for each gap in a single boundary condition includes 62500 data points for rectangular blocks, 30625 data points for rings, and 1250 data points for cylinders. The gaps between the magnets and steel plates are in the range of 0.01 – 15mm with 23 unequal intervals. The itemized data were then plotted and analyzed to establish the force equations for the magnets with relative high load lines.

Figure 1 shows the magnetic force vs the area of N52 magnet rings with gap = 0.01mm to steel plates. Fig. 1a and 1b have different boundary conditions: 1a has CR1010 steel on both ends of the magnets, and 1b has the steel only on one end. The load line of a standalone magnet can be estimated by using the equations described in Parker's book [7], but the magnets in this project have much higher load lines compared to the standalone magnets since steel plates are associated with these magnets. Boundary condition 1a obviously gives much higher load line compared to boundary condition 1b. For these ring magnets with higher load line in condition 1a, the force value vs area for each thickness can generate 2nd degree polynomial formulas, which has R-squared R2 >0.9997 as shown in Figure 1. (R^2 of 1.0000 was obtained for all the thicknesses of rectangular blocks). These formulas were then analyzed to establish a general equation $F = B_r^2(aA^2+bA)$. Using the equation, the magnetic force for any B_r value can be determined by inputting magnet's B_r, area, and thickness. As shown in Table 1, the factor a is a function of thickness in 2nd degree polynomial, and the factor b is also a function of thickness but in power form.

The effect of boundary condition is tremendous. Condition1b has much lower load line compared to condition 1a, hence the magnetic force values vs the area cannot generate satisfactory equations. As shown in the Fig. 1b, for the same magnet area, the magnetic force values are in a range with various values due to different load lines. For example, the ring magnets with exact the same thickness 0.1cm and area $2.8cm^2$, the force values range from 18.4N to 74N for ID/OD values from 0.1/1.9cm to 4.3/4.7cm. Details for all the magnet shapes with two boundary conditions will be reported in this paper, and the effect of load line will be analyzed.



a) Steel plates on both ends; b) Steel plate on one end

Figure 1 Magnetic force vs magnet area for N52 Rings with gap = 0.01mm to steel

Table 1 Magnetic force equations for magnets of any Br with steel plates on both ends (gap = 0.01mm)

$F = Br^2 (aA^2 + bA)$			$a = cT^2 + gT + h,\ \ b = d(T-p)^n$					
Shape	**Maximum size (cm)**		***a***			***b***		
	OD/width/length	**Thickness**	***c***	***g***	***h***	***d***	***p***	***n***
Cylinders	**5**	**2.5**	**-0.0356**	**0.2495**	**-1.0129**	**38.902**	**0.098**	**0.005**
Rings	**5**	**2.5**	**-0.0365**	**0.2515**	**-0.9765**	**38.090**	**0.097**	**0.004**
Blocks	**5**	**2.5**	**-0.0172**	**0.1499**	**-0.7604**	**38.874**	**0.093**	**0.007**
F - force (N); A - area ($\leq$ 25 cm^2); T - thickness (cm); Br - magnet's remanence(T)								

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