Optimal structural design evaluation of magnetic attachments using three-dimensional finite element method

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Abstract

Magnetic attachments are designed to exert an attractive force at clinically useful levels. However, improvement of the attractive force is necessary, in order to deal with complexed clinical conditions. The present study analyzed and investigated magnetic attachments from the point of a magnetic circuit using a three-dimensional finite element method to enhance the performance of magnetic attachments.

An analysis model was constructed based on a dental magnetic attachment (GIGAUSS D 600, GC). Round non-magnetic material was embedded in 1) the disk yoke only , 2) the keeper only and 3) both the disk yoke and keeper in the analysis model. Magnetic flux density distribution and attractive force were analyzed by changing the diameter of non-magnetic material by 0.05 mm.

An increase in magnetic flux density on the attractive surface was confirmed by embedding non-magnetic material to the magnetic assembly and the keeper. However, magnetic flux density was oversaturated when it exceeded a certain value. A similar tendency was observed in attractive force.

Introduction

Magnetic attachments have been continuing to improve. Various magnetic circuits have been designed so that the minimal size of magnetic attachment can exert high attractive force.

A magnetic attachment consists of a magnet assembly and a keeper. A magnet in the magnetic assembly is encapsulated by magnetic and non-magnetic materials. Magnetic flux can penetrate a magnetic body, but cannot penetrate non-magnetic material. Magnetic flux is the magnetic line of forces. It penetrates magnetic materials and forms the closed magnetic circuit that exerts attractive force when a magnetic assembly and a keeper come into contact[1)].

Attractive force is affected by attractive surface area of a magnetic assembly and a keeper, and magnetic flux density. Since the size of a magnetic attachment should be minimal, it is impossible to increase the attractive surface area of a magnetic assembly and a keeper[2)] . Attractive force of a magnetic attachment can be effectively increased by increasing magnetic flux density. A magnetic circuit changes by incorporating non-magnetic material in the inner structure of a magnetic assembly and a keeper, and this may increase a magnetic flux density. In other words, clinically-feasible magnetic assemblies and keepers can be developed by introducing an optimal magnetic circuit. Finite element method is considered the most effective method to optimize the magnetic circuit as it can visualize the dynamic behavior of the magnetic circuit inside a magnet, and simulation can be performed by changing the conditions.

Objective

Three-dimensional finite element method was performed to analyze the influence of differences in the magnetic circuit on the attractive force, and to optimize the magnetic circuit by changing the internal structure of magnetic attachment.

Materials and Methods

1. *Analysis model*

The size of a magnetic assembly was 1.8 mm in radius and 1.3 mm in height, and a magnet inside the magnetic assembly was a round shape, and was 1.3 mm in radius and 0.5 mm in height. The size of a ring was 0.2 mm in width and 0.2 mm in height. A disk yoke was 1.1 mm in radius and 0.2 mm in height. A keeper was a round sharp, and was 1.8 mm in radius and 0.7 mm in height. Considering the model was axial symmetry, 1/4 model was set as a basic model (Fig. 1).

Analysis range was 2.0 mm around a magnetic assembly and a keepe. Marc mentat 2010 (Multi-Purpose Finite Element Pre and Post Processor, MSC) was used for model construction, and μ-MF (electromagnetical field analysis system, μ-TEC) analysis software was used. Element type was three-dimensional pentahedron and hexahedron elements. The element count was 53,802, and nodal point count was 57,784.

The components of a magnet were Nd-Fe-B (Neodymium, Ferrum, Boron), and its magnetic properties were calculated based on the thermal property of GIGAUSS D 600 and values provided by a manufacturer[3)]. The component of a yoke and a keeper was measurement of magnetic properties of SUSXM27, and the B-H curve of the magnetic properties was calculated by the approximation formula (Table 1).

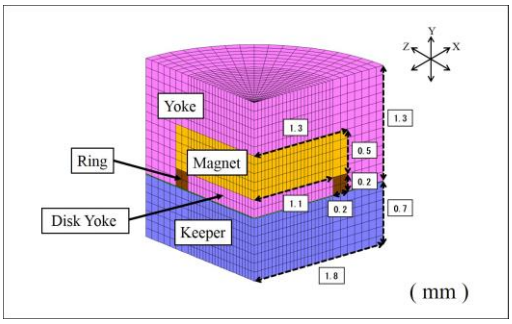

Fig. 1 Basic model

Table 1 Analysis conditions

Magnet		
Nd-Fe-B	(BH) max = 46 MGOe Residual magnetic jnduction = 1. 22 T	
Keeper & Yoke		
SUS XM27	Saturation magnetic induction = 1. 35 T	
B-H curve	$B = Bs \{ 1 - \exp (-\mu_r \cdot \mu_0 \cdot H / Bs) \}$	

2. *Analysis items*

(1) The disk yoke only

Non-magnetic material was embedded in the center of the disk yoke of a magnetic assembly and center of the attractive surface of a keeper. The radius of non-magnetic material was changed by 0.05 mm increments from 0.05 mm to 1.0 mm in the center of a disk yoke (20 patterns in total)(Fig. 2).

(2) The keeper only

In the center of the attractive surface of a keeper, the radius of non-magnetic material was changed by 0.05 mm increments from 0.05 mm to 1.0 mm, and the depth was changed by 0.1 mm from 0.1 mm to 0.6 mm (120 patterns in total)(Fig. 3).

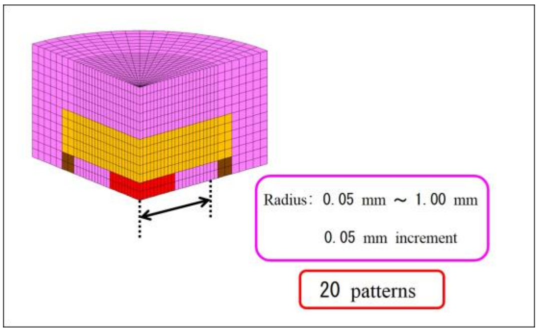

Fig. 2 Analysis item

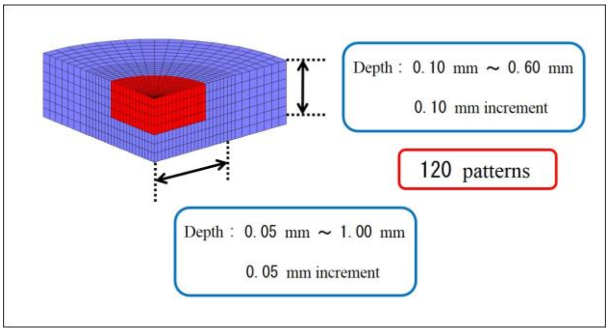

Fig. 3 Analysis item

(3) Both the disk yoke and keeper

Part of (1) and (2) were respectively combined, and a total of 1,200 patterns were analyzed (Fig. 4).

Analysis result was evaluated as magnetic flux density and attractive force.

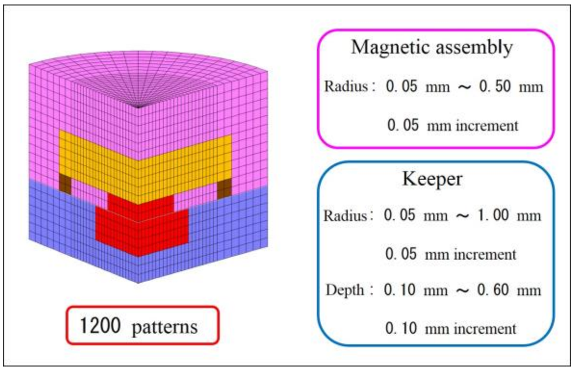

Fig. 4 Analysis item

Results

Attractive force and Magnetic flux density distribution

(1) The disk yoke only

A graph of the attraction force of the analysis result is shown (Fig. 5). Gradual increase in the attractive force was observed. The attractive force reached the maximum of 560 gf when a radius of non-magnetic material in the center of a disk yoke was 0.3 mm, but decreased thereafter with an increase of a radius of non-magnetic material.

Representative magnetic flux density distribution (Fig. 6). An increase in the magnetic density was confirmed in the magnetic assembly and attractive surface of a keeper. When the radius of non-magnetic material in the center of a disk yoke exceeded 0.3 mm, the magnetic flux density in the magnetic assembly and on the attractive surface of a keeper became oversaturated, and a decrease in the magnetic flux density in the magnetic assembly and inside a keeper was observed.

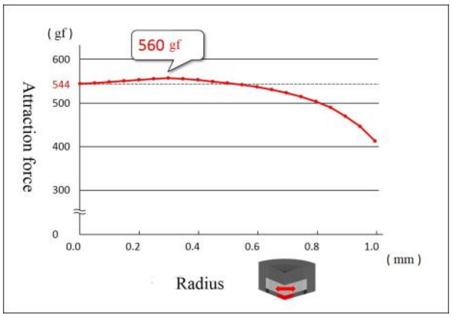

Fig. 5 Attraction force

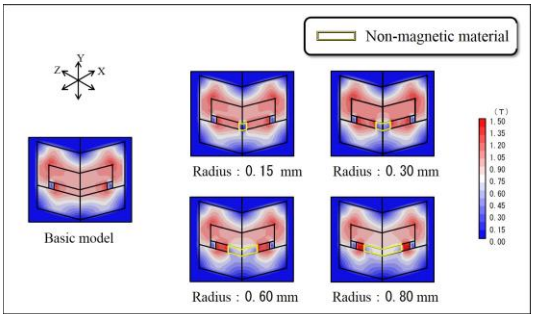

Fig. 6 Magnetic flux density distribution

(2) The keeper only

A graph of the attraction force of the analysis result is shown (Fig. 7). Gradual increase in the attractive force was observed. The attractive force reached the maximum of 582 gf when a radius of non-magnetic material in the center of a keeper was 0.6 mm, but decreased thereafter with an increase of a radius of non-magnetic material. There was a little influence of the depth of non-magnetic material until the radius of non-magnetic material in the center of a keeper attractive surface reached 0.6 mm where attractive force continued to increase.

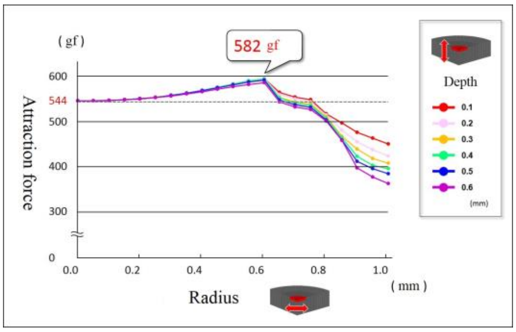

Fig. 7 Attraction force

Representative magnetic flux density distribution (Fig. 8). An increase in the magnetic density was confirmed in the magnetic assembly and attractive surface of a keeper. When the radius of non-magnetic material in the center of an attractive surface of a keeper exceeded 0.6 mm, the magnetic flux density in the magnetic assembly and on the attractive surface of a keeper became oversaturated, and a decrease in the magnetic flux density in the magnetic assembly and inside a keeper was observed.

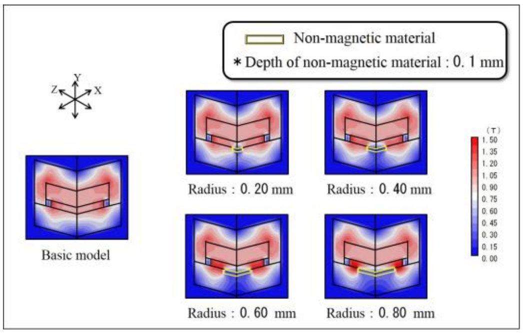

Fig. 8 Magnetic flux density distribution

(3) Both the disk yoke and keeper

A graph of the attraction force of the analysis result is shown (Fig. 9). This is the influence of the radius of non-magnetic material embedded in the keeper attractive surface on the attractive force for the depth where the radius of non-magnetic material in the center of a disk yoke was 0.15 mm. There was no influence of depth until the radius of non-magnetic material in the attractive surface of a keeper reached 0.5 mm. Attractive force was the highest at 0.5 mm in radius. When the radius exceeded 0.55 mm, attractive force started to decrease and was affected by the depth.

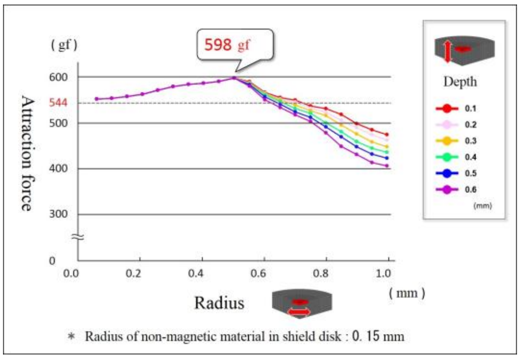

Fig. 9 Attraction force (Influence of the depth)

A graph of the attraction force of the analysis result is shown (Fig. 10). This is the influence of a change in radius of non-magnetic material in the attractive surface of a keeper on attractive force in the center of a disk yoke. Since there was a little influence of the depth of non-magnetic material until the radius of non-magnetic material in the center of a keeper attractive surface reached 0.5 mm where attractive force continued to increase (Fig. 9), the depth of non-magnetic material was set at 0.1 mm. Attractive force

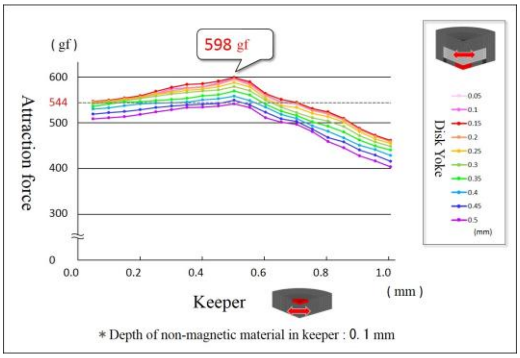

Fig. 10 Attraction force

(Influence of disk yoke and keeper)

increased with an increase of a radius of non-magnetic material in the center of a keeper attractive surface. The attractive force reached the maximum of 598 gf when a radius of non-magnetic material was 0.15 mm and that of a keeper was 0.5 mm, but decreased thereafter with an increase of a radius of non-magnetic material on the attractive surface of a keeper.

Representative magnetic flux density distribution (Fig. 11). This is the radius of non-magnetic material in the center of an attractive surface of a keeper was changed when the radius of non-magnetic material in the center of a disk yoke was 0.15 mm and the depth of non-magnetic material in the center of an attractive surface of a keeper was 0.1 mm.

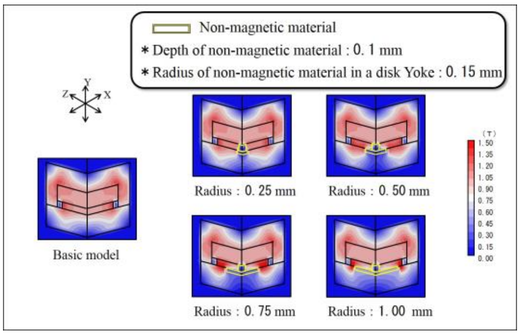

Fig. 11 Magnetic flux density distribution

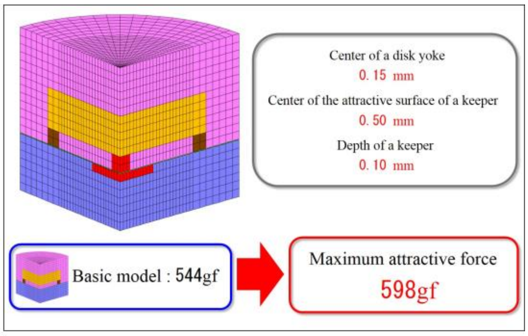

Fig. 12 Optimal structural design model

An increase in the magnetic density was confirmed in the magnetic assembly and attractive surface of a keeper. When the radius of non-magnetic material in the center of an attractive surface of a keeper exceeded 0.75 mm, the magnetic flux density in the magnetic assembly and on the attractive surface of a keeper became oversaturated, and a decrease in the magnetic flux density in the magnetic assembly and inside a keeper was observed.

From the analysis result so far, when attractive force of the basic model was defined as 100%, the attractive force was increased to approximately 110% at 0.15 mm radius of non-magnetic material in the center of a disk yoke, 0.5 mm radius of non-magnetic material in the center of an attractive force of a keeper and 0.1 mm the depth of non-magnetic material in a keeper where attractive force reached the maximum (Fig. 12).

Discussion

1. Efficiency of finite element method

It is difficult to measure and observe the detail of behavior of attractive and repelling force created by a magnet. This is because the magnetic field has a gradient in all directions, and, therefore, simple calculation formula cannot be established. Finite element method allows visualization and simulation of the inner behavior of the magnetic circuit by adding various conditions. It is considered time-efficient and cost-effective to search optimal magnetic circuit using a finite element method.

2. The relationship between the attractive surface area and magnetic flux density

The attractive force of a magnet can be expressed as $F = (1/2\mu_0) \cdot S \cdot B^2$ {μ_0: space permeability, S:attractive surface area, B: magnetic flux density}[4)]. The attractive force of a magnetic attachment is affected more by magnetic flux density than attractive surface area[5)]. Therefore, attractive force can be increased efficiently by increasing the magnetic flux density. The magnetic circuit changes by replacing part of a keeper of a magnetic attachment with non-magnetic material, resulting in an increase in the magnetic flux density on the attractive surface. The attractive force was affected more by an increase in the magnetic flux density than a decrease in the attractive surface area, resulting in an increase in the attractive force. However, there is a limit of magnetic flux density in the magnetic body called “saturated magnetic flux density”. When the magnetic body reaches that point, an increase in the magnetic flux density stops even with the continuous increase of the size of non-magnetic material. As a result, the attractive force decreases due to an influence of the attractive surface area. The relationship between the attractive surface area and magnetic flux density is extremely important for the optimization of the magnetic circuit.

3. Inference of the depth

The attractive force is affected by an increase of the magnetic flux density on the attractive surface, and is rarely affected by the depth of non-magnetic material. However, when the radius of non-magnetic material in the center of an attractive surface of a keeper exceeds 0.5 mm, the magnetic flux density on the attractive surface becomes oversaturated. The magnetic flux that could not penetrate the attractive surface flows into non-magnetic material. The magnetic flux is hard to penetrate non-magnetic material, but a small amount of magnetic flux can flow. The deeper non-magnetic material gets, the more difficult the magnetic flux can penetrate non-magnetic material. It is considered that a decrease in the attractive force is caused by the depth of non-magnetic material.

Conclusion

Optimal structural design evaluation of magnetic attachments was analyzed and investigated using a three-dimensional finite element method, and the following results were obtained:

1. An increase in the attractive force was confirmed by setting non-magnetic material inside the magnetic attachment and changing the magnetic circuit.
2. It was confirmed that the increase in the attractive force was greater when the non-magnetic material was set at the center of an attractive surface of a keeper than the center of a disk yoke of the magnetic assembly.
3. The influence of the depth of non-magnetic material in the center of an attractive surface of a keeper was small compared to the size of the radius.

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