Advanced Materials for Motor Laminations: Past, Present and Future

John Petro
Petro and Associates (Consultants)

Abstract

Traditional iron-based, soft magnetic materials have been used for laminations in electric motors for over 100 years. Such materials provide excellent manufacturability and adequate magnetic performance, but exhibit more losses than are ideal when greater efficiency is also a design goal. The demand for higher motor efficiency is therefore a catalyst for research into better performing lamination materials. A number of material choices exist, such as Nickel-Irons and Cobalt-Irons, but these materials are generally expensive, compared with traditional silicon iron materials. However, there are other candidate materials with costs more in line with standard motor lamination materials. Two of these are amorphous iron and nano-crystalline iron formulations. These materials exhibit superior magnetic performance combined with reasonable cost. While cost-effective in their “as cast” form, these materials are challenging to manufacture into traditional motor structures because currently they are only readily available in a thin (25 micron) ribbon format and exhibit very high hardness. This creates an issue of how to design and construct a cost-effective motor utilizing these advanced materials. This paper will outline past and current efforts to build commercial motors with these materials and will also project potential future paths for developing cost-effective motor structures that utilize these high performance magnetic materials.

Introduction

This paper reviews the history of the use of amorphous and/or nano-crystalline metals in electric motor applications and examines possible new methods of utilizing these advanced magnetic materials to improve electric motor performance in the future.

The history of amorphous metals started in the 1960’s with a number of researchers formulating metal alloys and casting them with extremely fast cooling rates so that the formation of normal metal crystals was inhibited. The typical cooling rates utilized are in the range of one million degrees per second [1]. This is usually achieved by casting very thin strips of ribbon-like material on a refrigerated rotating drum.

While there are numerous amorphous metal combinations that exhibit unique magnetic properties, the commercial focus has been on iron-boron-silicon (FeBSi) formulations. The most pervasive formulations are 85 to 95 percent iron, 1 to 5 percent boron and 5 to 10 percent silicon. While many companies make some amorphous or nano-crystalline materials, most only sell very small volumes. Only two companies sell amorphous materials in high volume. The largest of these companies is Metglas [2], which is part of Hitachi Metals. The other is a Chinese company, Advanced Technology & Materials Co., Ltd (AM&T) [3].

Because the material does not contain any expensive elements and can be produced at high speeds via a continuous casting process, the base cost of the material is very reasonable for large volume applications. The main use of magnetic amorphous metal is in electrical distribution transformers, which can range from small residential pole-mounted transformers to megawatt substation transformers (Figure 1). While such amorphous transformers do cost somewhat more than traditional lamination transformers, the life cycle costs are significantly lower (Figure 2). This range of transformer applications validates the low loss performance of the amorphous materials used in them.

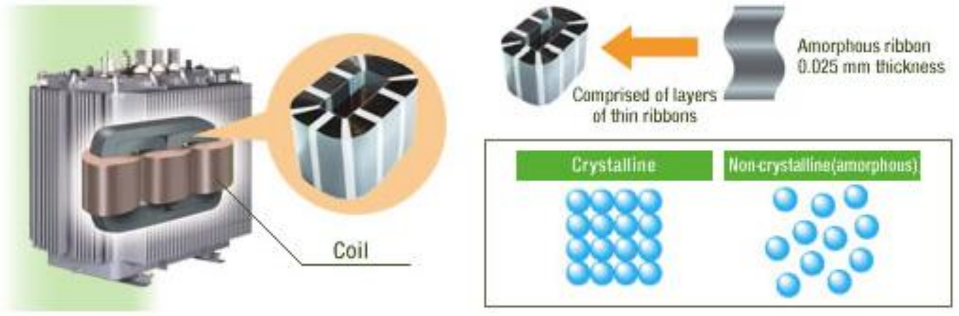

Figure 1: Amorphous metal in transformer applications (courtesy of Hitachi Metals [2])

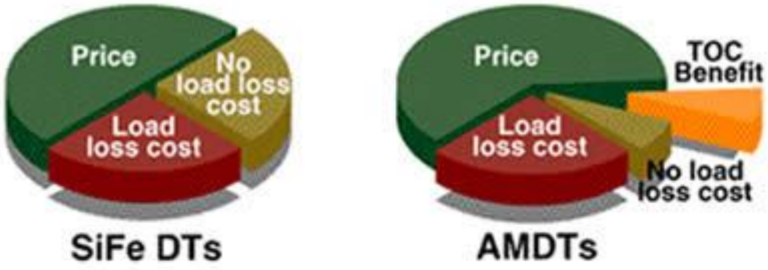

Figure 2: Cost and benefits of amorphous metal transformers (courtesy of Hitachi Metals [2])

Material Properties

The three properties that make these materials highly attractive for magnetic applications are:

- Very high permeability,
- A square hysteresis loop, and
- An oxide layer on the surface of the material that provides electrical insulation.

The combination of an insulating layer with such thin material results in very low eddy current loss characteristics and enables higher frequency operation. The core loss for typical amorphous metals is about one-tenth the loss for normal non-oriented electrical steels (Figure 3) [2]. Such low iron loss makes this material especially attractive at this time because in recent years electric motors have become more efficient primarily by reducing losses in the rotor and secondarily by reducing copper losses with better winding techniques. Thus, the remaining stator iron losses have become a much larger percentage of the total loss remaining in modern efficient motors. This means that reducing the iron losses is now the greatest opportunity for further increasing motor electrical efficiency.

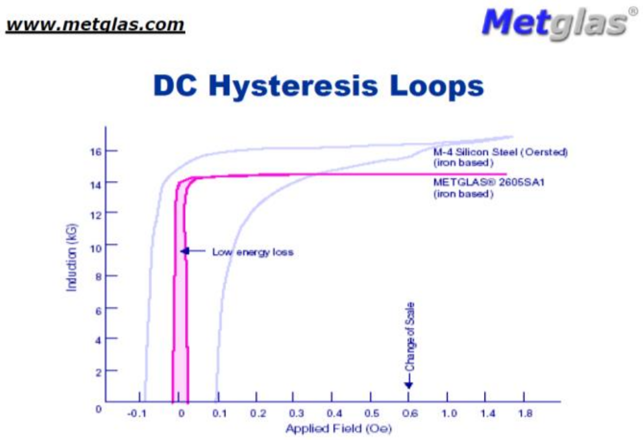

Figure 3: Hysteresis curves of amorphous metal and M-4 Silicon Steel (courtesy of Metglas [2])

While the basic magnetic properties of this amorphous material are attractive, there are several major disadvantages to this material. These include the fact that this material is very thin, very hard, and difficult to handle. In addition, the insulation layer is not very robust. A further disadvantage of the standard amorphous formulations is that their saturation flux density is typically about 1.5 to 1.6 Tesla. This limits the overall flux carrying capability, resulting in a need for more material to carry equivalent flux levels when compared to standard silicon iron lamination material.

The major manufacturing disadvantage of amorphous metals is that the production method for this material limits the thickness to a very thin (approximately 25 micron) ribbon. The extreme thinness of the material, combined with its high degree of hardness, makes processing amorphous metals into structures useful for electric motors extremely difficult. In fact, while there have been many attempts to make motors out of amorphous metals, no significant commercial success has ever been achieved.

The thin nature of this material also results in a lower packing factor, leading to less useful magnetic material for carrying flux. Given the large number of layers needed to make a useful motor structure, even small gaps between layers lead to lower packing factors.

The extremely thin oxide insulation layer is also easily damaged, and such damage can lead to shorting conditions between layers. Some of these shorts may be in the center sections of the ribbon material, but most will form at the edges of laminations where ribbon cutting methods often expose conducting edges. Shorts such as these lead to stray current paths around the material, creating their own magnetic flux paths. These sometimes can create flux paths that are orthogonal to the plane of the lamination, resulting in much higher eddy currents than would be anticipated in such a thin structure [4]. Again, due to the high number of thin layers, it is far easier for shorts to develop at the edges of a stack of this material during handling, stacking or wrapping. These edge shorts can lead to much higher losses than would be expected in a material that has such low intrinsic loss.

Methods of Motor Production

Four major approaches have been pursued to construct electric motors from amorphous ribbon coils. The first method is to cut the desired lamination shape from the material while it is a single ribbon and then assemble these laminations into the desired motor structure. The second approach is to wind the amorphous ribbon into the overall shape of the desired motor structure and then cut away the unwanted portions. The third method is to wind material into partial shapes of the desired motor and then assemble and magnetically connect these shapes into a final motor configuration. The fourth approach is to cut the desired shape into a strip of material and then wind it into the desired shape of the overall motor structure. This fourth method was one of the first tried [5] and is also described in one of the newest patents [6] on constructing motors from amorphous material.

The first approach, cutting shapes and stacking layers, has been attempted with a number of cutting methods. The cutting has been done with precision stamping, laser cutting, chemical etching and electric discharge machining (wire EDM). With all of these cutting methods, the major drawback is the large number of lamination layers that need to be cut and then assembled. From the pictures that are available, Hitachi has attempted to use this method in some prototypes to construct their 11 kilowatt high efficiency amorphous motor [7].

The second approach is to wind a coil of this material into a structure that resembles the final shape of the motor structure and then cut away the sections of this coil that need to be removed. The cutting methods for this approach are more limited, but include electric discharge machining (EDM) -- both wire EDM and plug EDM -- and water jet cutting. Lasers have been tried, but at this time can only cut relatively small structures. Work is currently being conducted in Adelaide, Australia [8] that uses a water jet cutting method to construct a motor.

The third method is being pursued by RADAM [9] and essentially is adapting the radial cut core or segmented core method to amorphous material. Here the amorphous material is wound into the desired sub-shapes and then connected into a final motor assembly [10].

The fourth method is both one of the oldest production methods tried and is the subject of some of the newest patents. Back in the early 1980's, General Electric (GE) attempted to directly cast concentric shaped ribbon with integral pole shapes to construct radial motors [5]. This very interesting and challenging approach was moderately successful, but was never carried to commercial production. As far as can be determined, no other attempts at direct casting have been made.

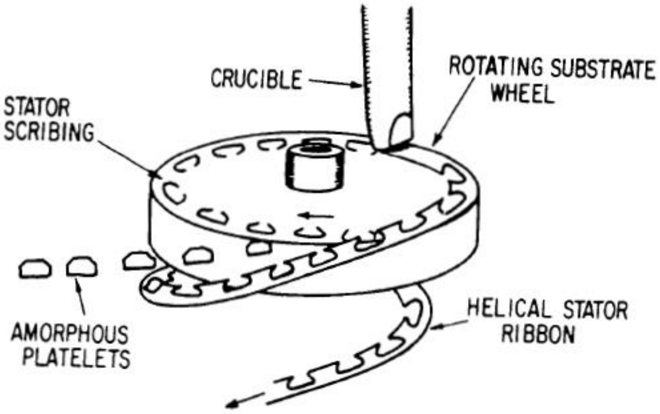

Figure 4: Early direct casting of helical ribbon for radial motor stator [5].

History of Use in Motors

There are a number of research examples of amorphous metals being used in electric motors, but very few commercially available motors. General Electric (GE) was issued a patent on amorphous motors in 1986, near 30 years ago [11]. The most prominent commercial amorphous motor is the Light Engineering [12] motor. Early designs of this motor were done in the mid 1980's. In the late 1980's, prototypes were produced. This motor used an axial motor design and was made available for sale in the early 1990's and stayed on the market for many years. It was made in a number of versions, from a few kilowatts to many tens of kilowatts. Light Engineering was moved from California to Indianapolis in 1998 and much later formed a partnership with XEMC Motors [13] from China. However, sales of this motor never reached high volumes, and now it is sold only to special purpose applications.

The performance of this motor was excellent, but it never established much market penetration. The primary market that valued the very high efficiency performance was small, fossil fuel-powered generators, where the higher generator efficiency was a significant benefit because of the high cost of fuel to operate the internal combustion drive engine. Over the years, these motors were sold mainly as components for high efficiency generators.

One of the early engineers working on the Light Engineering motor was Andrew Hirzel, who later worked on radial amorphous motor designs with his company RADAM, using the third construction approach described above. His designs are based on a radial motor concept and use wound sections of amorphous material that are linked together to form a complete motor flux path. This segmented core design has become popular for standard radial permanent magnet applications, and the use of amorphous materials enhances the overall motor efficiency. Prototypes have been tested and run for many thousands of hours to prove reliability.

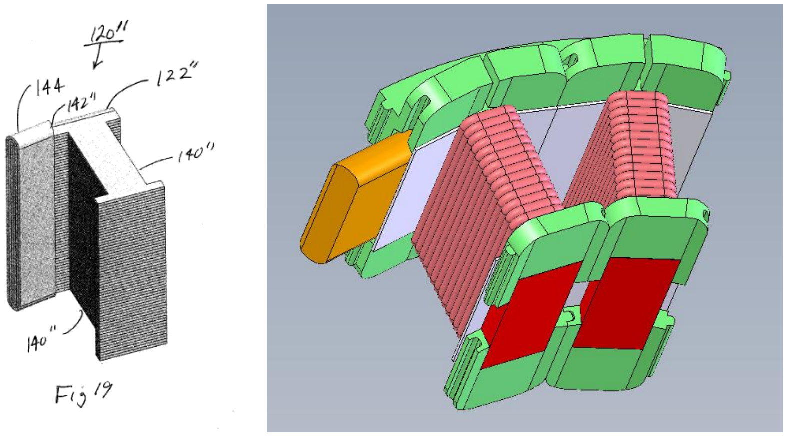

Figure 5: RADAM segmented core radial motor construction [10]

There has been substantial work at the University of Adelaide in forming axial motor stators by first forming a coil of amorphous metal into a wound conical form and then waterjet cutting slots into this coil [8] [14]. This forms an axial motor stator that, when combined with coils and a permanent magnet rotor, forms an electric machine that can be used as either a motor or a generator. This motor was designed as an axial motor with a single stator and single rotor. One unique feature is that this is a conical air gap motor, which creates a larger air gap surface area for a given motor diameter.

The waterjet technique has been perfected so that cuts of at least 5 cm deep can be accomplished. Of course, cuts that are shorter result in faster cutting times, and cutting time is an issue with respect to manufacturing cost. However, motor designs can be adapted to minimize the cutting depth by trading off other parameters such as overall motor diameter.

The waterjet cutting method has an advantage of being very flexible with respect to the shapes that it can produce. It allows the production of a single piece axial motor stator with pole shoes. This capability gives axial motor design the same flexibility enjoyed by radial motor designs This author, as well as others, have been looking for this type of design flexibility for axial motors for many years.

Waterjet cutting can result in some shorting of the individual laminations, but several techniques can be employed to reduce this shorting problem. This issue is being researched in more detail at the present time.

Figure 6: Water jet cutting of wrapped amorphous core [8]

Some results from this University of Adelaide motor development effort have recently been published and, while the motor's efficiency is not outstanding, it is still reasonably good. Examination of the motor design by this author indicates that there are a number of areas that could easily be improved to create a motor with much better efficiency performance.

Hitachi has been working on a commercial line of industrial motors based on the use of amorphous materials for a number of years. These motors are of an axial design with a single stator and dual rotors. The permanent magnet rotors use low-cost ferrite magnets to keep the total motor cost lower. Hitachi presented a paper on the first version of this motor, which is an 11 kilowatt motor at EEMODS in Rio de Janeiro, Brazil, in 2013 [7]. At that time the results were good, but not outstanding. Recently, a second version of the motor has been announced that has substantially improved over those initial results, making it one of the most efficient motors in that power range. My understanding is that they are currently sampling motors to potential customers and are working on expanding the product line to additional power levels.

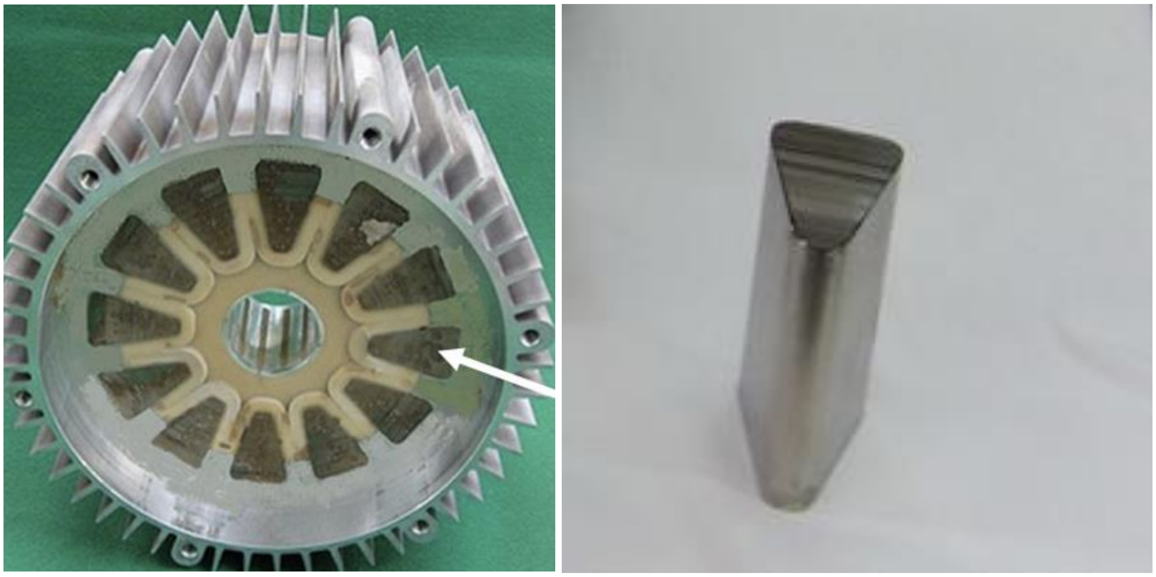

Figure 7: Hitachi axial amorphous motor and individual stator pole [7]

Hitachi has attempted several manufacturing approaches. One approach was to wind individual cores as shown in a paper from 2010 [15]. The construction method of the final motor has not been disclosed but the pictures they have shared illustrate that the approach is one of cutting and stacking lamination layers together to form individual stator pole pieces. These stator pole pieces are then assembled into a complete stator structure and a molding compound is used to secure them in place within the stator housing. This author is very familiar with this approach to constructing an axial motor, given his experience in creating the NovaTorque axial motor, which also uses this construction method.

The Future

Superior Materials

There is substantial research work being conducted into improved formulations of amorphous metals, with the major focus on increasing the saturation flux density of these materials. One such material that has been announced by the Materials Solutions Center at Tohoku University in Japan is NANOMET [16]. This formulation adds copper and phosphorus to the iron-boron-silicon melt, which allows the iron percentage to be increased above 90 percent. However, phosphorus tends to oxidize rapidly, which creates problems with melting and casting that need to be solved before mass production of this material is available. However, the mere fact that this material exists, and uses inexpensive component elements, is a powerful incentive to continue work towards commercial formulations that have extremely attractive magnetic properties and can be produced in volume at competitive prices. There are many other efforts looking at other additives to achieve similar results of higher flux saturation values and high permeability.

Motor Production Methods

Clearly, none of the methods tried so far has achieved the goal of simple, low-cost production of motors with amorphous materials. However, that is not to say that these methods could not be improved upon in order to achieve that goal in the future. For instance, the ability to stamp thin, hard materials has greatly improved in the last 20 years. New die materials and the ability to hold higher precision between die and punch have greatly improved. Robotic stacking and other pick and place machines have also greatly increased in speed. Similarly, waterjet and laser cutting have increased in capabilities and precision. This has increased both the speed and the penetration distance that can be cut with these techniques. The cost of waterjet and laser cutting equipment has also dropped dramatically in recent years. Such improvements could lead to economical production in the future.

While laser cutting has been done for prototype laminations for many years, this type of cutting has been done by melting the material and using a gas assist to eject the melted material. This process is limited in speed by the need to physically move the laser head and gas nozzle. Much more recently, it has been shown that fiber lasers with an optical scan head can cut metal laminations and do so at much higher speeds. This then enables production processes to be envisioned using lasers as the lamination production method. A 100 watt fiber laser cost nearly $60,000 in 2006. A 100 watt laser with even better beam characteristics now can be purchased for under $20,000. This makes using multiple stations of this type of equipment feasible for production environments.

NovaTorque’s unique axial motor with a conical lamination geometry is, in fact, produced in this manner, with a single fully automated machine that cuts, stacks, and welds laminations into completed production pole pieces.

While direct shape helical casting and roll-to-roll shaping and processing have not been implemented yet as production processes, the concepts have interesting theoretical possibilities, even though they are difficult to implement. This is an area where additional research could yield significant progress.

Alternative Motor Designs

While radial induction motor design has dominated the motor industry for many years, recently a number of alternative technologies and motor geometric configurations have entered the market or have at least been proposed. These innovations open up the possibility of developing motor configurations that are particularly suited to using amorphous metals. One particularly interesting design area is in the use of axial motor configurations. An axial motor stator can be wound around a mandrel and built up in layers. One interesting patent in this area is U.S. 8,505,351, where an axial motor stator is constructed in a rolled-up assembly. While such manufacturing methods are not yet commercially available, work on such schemes is progressing.

Another motor design that is potentially suitable for construction with amorphous materials is the transverse flux type motor.

Conclusions

While amorphous and nano-crystalline materials do offer superior magnetic properties and these properties can result in superior motor performance, especially in terms of motor efficiency, it will be a number of years before I expect to see these materials in commercial motors in any sizeable quantities. The manufacturing problems are still the main road block, and, until the manufacturing can be done on a high volume scale and with cost structures that are competitive in the marketplace, the current domination of the market by radial motors using conventional electrical steels will continue.

The other main obstacle to market adoption is the axial motor format, which is currently the motor geometry that is best suited for producing motors with these materials. While there are many academic papers illustrating the advantages of axial motors over radial motor designs, commercial motor manufacturers have not agreed. Until these barriers can be surmounted, amorphous metal motors will be specialty and niche market items. However, if and when the above issues are finally solved, a dramatic change in the commercial motor industry will occur.

References

[1] https://en.wikipedia.org/wiki/Amorphous_metal

[2] Metglas, a division of Hitachi Metals http://www.metglas.com/

[3] Advanced Technology and Materials Co., Ltd (AM&T) http://www.atmcn.com/en/

[4] Increase of Tape Wound Core Losses Due to Interlamination Short Circuits and Orthogonal Flux Components Proceedings of the 37th Annual Conference of the IEEE Industrial Electronics Society (IECON 2011), Melbourne, Australia, November 7-10, 2011. B. Cougo, A. Tüysüz, J. Mühlethaler, J. W. Kolar

[5] UTILIZATION OF AMORPHOUS METALS IN ELECTRIC MOTORS GE Technology Paper Oak Ridge National Labs, VOR N L/S~b-81/70519/ L. A. Johnson, October 1983, Prepared by: GENERAL, ELECTRIC COMPANY: CORPORATE RESEARCH AND DEVELOPMENT f o r OAK RIDGE NATIONAL LABORATORY Power Systems Technology Program, March 1984

[6] U.S. Patent 8,505,351 Product and method for manufacturing a three dimensional core mass and related inventions, Frederick Klatt, August 13,2013

[7] Highly efficient industrial 11-kW permanent magnet synchronous motor without rare-earth metals HIROOKI TOKOI, Hitachi Research Laboratory, Hitachi, Ltd., 29 October 2013, EEMODS'13

[8] A Novel Tapered Rotating Electrical Machine Topology Utilizing Cut Amorphous Magnetic Material, N. Ertugrul1, R. Hasegawa2, W. L. Soong1, J. Gayler3, S. Kloeden3 and S. Kahourzade1
1 University of Adelaide, School of Electrical and Electronic Engineering, Adelaide, Australia
2 Metglas Inc., 440 Allied Drive, Conway, SC 29526, USA
3 GMT Ltd., Adelaide, Australia

[9] Radam LLC http://www.radamllc.com/

[10] A History and Introduction to Amorphous Iron Motors, presented at Motors and Drives, January 2014 in Orlando, Florida, USA, Andrew Hirzel, Radam Motors LLC

[11] U.S. Patent 4,578,610 Synchronous Disk Motor with Amorphous Stator and Permanent Magnet Rotor and Flywheel, March 23, 1986

[12] Light Engineering http://www.lt-eng.com/

[13] XEMC motors – China http://www.xemc.com.cn/en/

[14] Analysis and Performance Investigation of An Axial-Field PM Motor Utilizing Cut AmorphousMagnetic Material, Gene S. Liew, Wen L. Soong and Nesimi Ertugrul, University of Adelaide, Adelaide, Australia Email: gliew@eleceng.adelaide.edu.au, John Gayler, Glassy Metal Technologies Ltd, Adelaide, Australia

[15] Development of a Permanent Magnet Motor Utilizing Amorphous Wound Cores, IEEE Transactions on magnetics, Vol. 46, No. 2, February 2010,Zhuonan Wang□, Yuji Enomoto□, Motoya Ito□, Ryoso Masaki_, Shigeki Morinaga_, Hiromitsu Itabashi_, and Shigeho Tanigawa_
Hitachi Research Laboratory, Hitachi, Ltd., Ibaraki, Japan
Hitachi Industrial Equipment Systems Co., Ltd., Tokyo, Japan
Hitachi Metals, Ltd.,Tokyo, Japan

[16] NANOMET http://nanoc.imr.tohoku.ac.jp/english/research.html