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Overview on Amorphous Alloy Electrical Machines and Their Key Technologies

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Abstract: Amorphous alloy (AA) is attracting more and more attention in electrical machines due to its excellent low loss characteristics. This paper overviews advances on AA electrical machines over the last 30 years, with particular reference to new and novel topologies and processing techniques of AA electrical machines and their key technologies. These include current states and trends for radial-flux AA electrical machines, axial-flux AA electrical machines, influences of processing techniques on electrical performance of AA iron cores, the characteristics of loss and vibration and noise of AA core and AA machines, optimum design of AA electrical machines, etc. The paper highlights the application prospects of the AA electrical machines.

Keywords: Amorphous alloy, electrical machine, radial flux, axial flux, topologies and processing techniques, loss, noise and vibration.

1 Introduction

Along with the increasing shortage of energy and the pollution problems, electrical machines which are key parts in manufacturing and daily life, and spend more than 50% of the electric power generated throughout the world, have attracted great attention for the demand of reducing losses and increasing efficiency. Normally, the application of high-performance soft magnetic materials for machine cores, especially those with high frequency and high speed in which the iron loss is a majority, has become an efficient way for loss reduction[1].

Amorphous alloy(AA) materials are obtained through the fast solidification of the liquid alloy. Inside them, the atoms are joined together randomly and disorderly, and form the amorphous state. The special inner structures build up the excellent electromagnetic performances[2-6], and make them possible replacements of silicon steel(SS) materials. The main advantages are as below:

(1) Since the material is with low coercivity force and low remnant flux density, the area of hysteresis loop is much smaller than that of the SS material. The magnetic hysteresis loss is lower[2].

(2) The AA lamination can be made extremely thin in depth. The thickness is only about 1/20 of that of SS lamination. As a result, the eddy-current loss is lower[3].

(3) Within the increase of the working frequency, the flux density of SS materials drop greatly while that of AA materials can hold and even ignore the decreasing amplitude[6].

It can be seen that the good use of AA materials can better conserve the energy in those high-frequency machines such as electric vehicle(EV) motors, high-speed motorized spindle motors, high-speed aviation dynamotors, and mobile power station generators. AA materials will have broad prospects in those applications in which iron loss plays a major role[7-8]. However, the AA lamination is always thicker, more brittle and harder than normal SS electrical sheets, it is of vital importance to analysis the proper topological structures of the machines and seek high efficient and low cost manufacturing techniques[2,4]. Furthermore, stresses inside the sheets can greatly affect the magnetic performance. These stresses are easily introduced during the fabricating process, weakening the operating properties[2-3,9-10] and making the magnetic performance of the core assembled different from that of a separate AA sheet. As well, the magnetostriction property of an AA sheet is more significant than a SS one, together with the loose structure caused by low lamination factor, the vibration and acoustic noises of an AA motor under operation are louder than the noises generated by a SS machine. Finally, due to the changes in topological structures and characteristics, the optimization process differs.

Based on the issues above, this paper reviewed and summarized the research works of the AA motors presented by researchers domestically and abroad. Firstly, the topological structures and the processing methods of the machine cores are analyzed starting from the perspective of topological structures and manufacturing techniques. The main data of existing AA machines are then summarized. Secondly, influences on the electro-magnetic performances of the AA cores caused by different processing techniques are concluded and summarized. The losses and acoustic noises of the machine and their optimization methods are analyzed. Finally, the development and analysis directions and the application prospects of AA machines are expected.

2 Topologies and processing techniques of AA electrical machines

Since the 1970s, the research and development

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works of AA machines have continued with increased intensity. Within the developments and applications of the transducers, the work frequency of the machines changed from 50, 60 Hz in the initially to hundreds or even thousands Hz recently. The processing techniques, topological structures, optimization methods, and the machine performances are developed with the development of the AA materials.

2.1 Radial flux AA electrical machines

The most common technique in processing SS sheets for iron cores is the punching to the sheets based on their designed shapes. The shaped sheets are then overlaid and make up the axial lengths of the cores. In the beginning period of designing and developing AA machines, the AA cores were still assembled by the AA sheets slotted[11-15], as shown in Fig.1. The AA sheets could be slotted by corrosion and wire cutting[12-13,16].

Limited by the processing techniques, the widths of AA strips are generally less than 300mm. As a result, the cores of large-size machines are often assembled by smaller parts[17-18]. Each layer of the core consists of several modularized sheet elements, and the ports are often staggered for minimizing the end effect, as shown in Fig.2. Take the AA machine (rated power 250W, core length 75mm) presented in paper[14] as an example, each piece of the AA sheets stacked is made up by 14268 smaller pieces to follow the size limit in manufacturing, causing a large amount of work in preparing the laminated core of the machine. As could be summarized, the cost of the work in making a AA core is generally 10 times that for an SS one. Furthermore, the AA material is much harder than SS, resulting in the massive attrition in the patterns and higher costs. The traditional processing techniques in making an SS core are no longer suitable for an AA one.

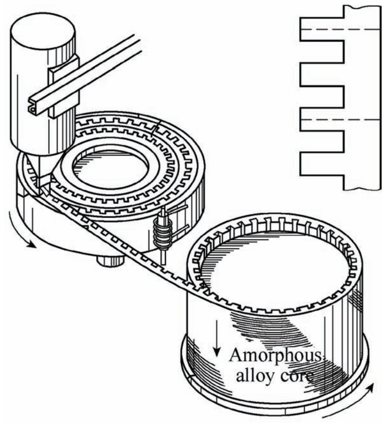


Fig.1 Manufacturing process of stator core of radial flux AA motor

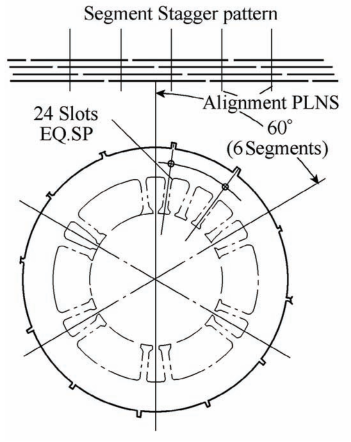


Fig.2 Combination type manufacturing process of amorphous alloy core

In order to simplify the complicated means for the slotting process, the AA sheets could be laminated or wound before the process, and then be slotted together. By this means, the work and costs introduced by slotting process can be greatly reduced and thus the method has been widely used by researchers and manufacturers[19-31]. The AA strips are cut into square slices and then been laminated to form the cuboid-shaped AA core blocks as shown in Fig.3. Finally, the blocks are annealed and vacuum-dipped to finish the preparation.

After the processes mentioned above, wire-electrode cutting is often used to slot the blocks[23-24]. However, wire-electrode cutting is very time consuming and can hardly meet the need of quantity production. Therefore, a new method that separates the tooth parts and yoke parts to reduce the processing time is presented by some scholars abroad. The basic idea of the method is to make the tooth parts and yoke parts respectively through the laminating or winding of the AA strips and then joining them together[32-41]. The joining modes include jointing[32-33], pasting[34], and fastening by dove tail slots[35], as shown in Fig.4. By using amorphous alloy to build the stator teeth of radial-field surface PMSM, a core loss reduction of 40% at 5500r/min can be attained compared to the same permanent magnet motor made of conventional SS sheet[35]. The method mentioned above is a simplified way of making up the cores. However, it still has some disadvantages as the introduction of air-gaps and the instability of connection. In order to address the disadvantages, a modified method is implemented to gather the AA strips with different lengths and make the C-type modules. These modules are then pasted by resin as shown in Fig.5. By this method, the cores are made with good stability[34]. Beyond that, no-slot structures are implemented to reduce the influence introduced by the slotting process[42-45]. As shown in Fig.6 and Fig.7, the winding coils are distributed in the air-gap directly. But for the no-slot structures, it’s still facing the problems of the low power density of the machine and the complicated process of placing the windings. As a reult, a simplified circular recess structure is analyzed and solved the placing problem to some degree[44], as shown in Fig.8.

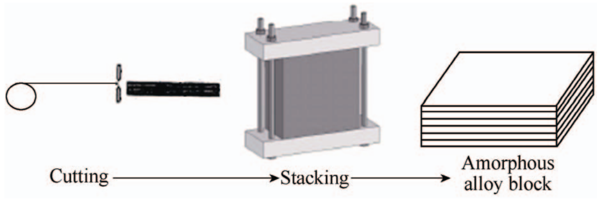
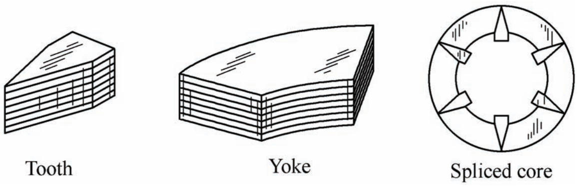
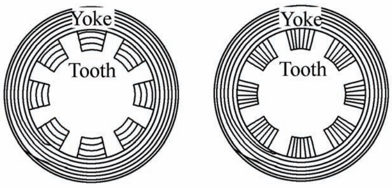


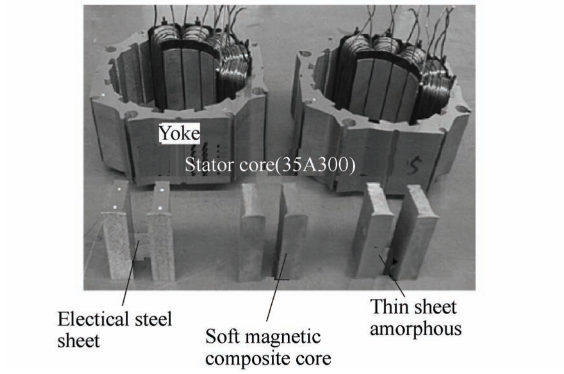
Fig.3 Manufacturing process of laminated AA block



(a) Spliced AA core



(b) Bonded AA core



(c) Inlaid AA core

Fig.4 Teeth-yoke connection method of radial flux motors

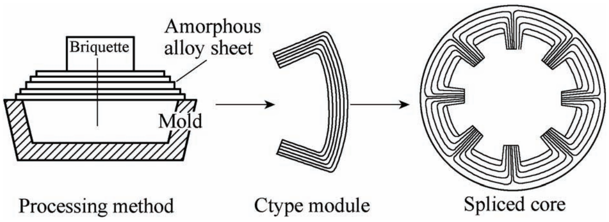


Fig.5 C type AA block connection method

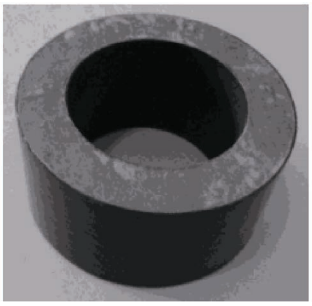


Fig.6 Slotless radial flux AA core

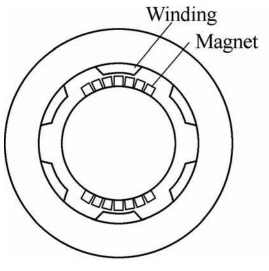


Fig.7 Arrangement windings and permanent magnets

Fig.8 Radial flux AA core with circular slots

2.2 Axial flux AA electrical machines

The axial flux (AF) AA machines were first analyzed and published by the GE company with the pre-slotted process that cut slots in the AA strips with different intervals. The pre-slotted strips were then wound up and made up the whole core as shown in Fig.9. The piecework process is very complicated.

For this purpose, the method that incises slots after the cores have been solidified is implemented. The AA strips are firstly wound up based on the designed structures, as shown in Fig.10. Secondly, the solid wound up is annealed and dipped, and then cut slots by wire-electrode cutting or a milling machine[25-26], as shown in Fig.11. Furthermore, new methods are analyzed and designed for the slotting process such as cutting two cracks by the doubled rotating cutters and then drilling for the slot bottom[27-28], as shown in Fig.12, and the usage of the jet machining with abrasive water[29-31], as shown in Fig.13.

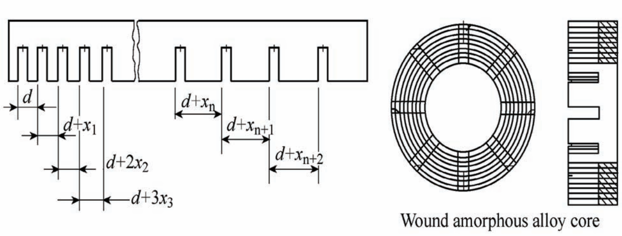


Fig.9 Manufacturing process of wound stator core for axial flux AA motor

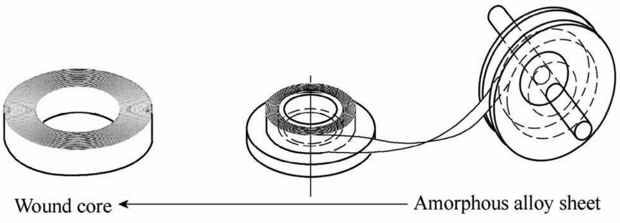


Fig.10 Manufacturing process of wound AA block

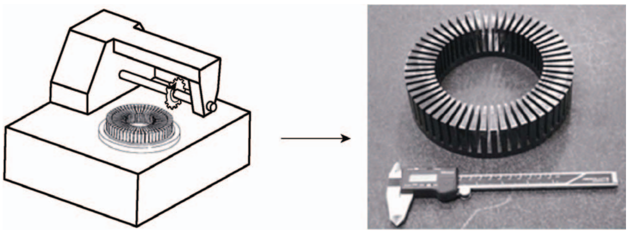


Fig.11 Milling slotting process

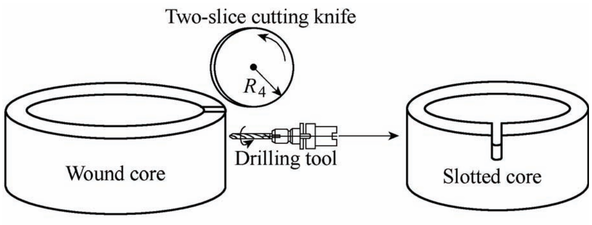


Fig.12 Cutting slotting process

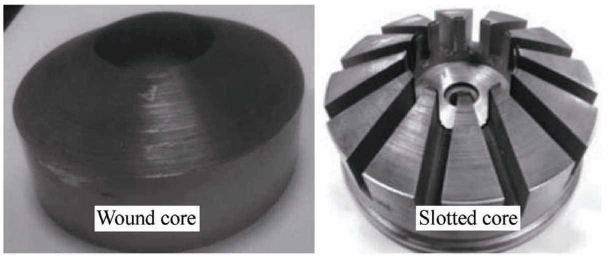


Fig.13 AA core manufactured by abrasive water jet method

Work can be saved by those methods since the slots can be formed one time, together with the reduction of costs. However, as the slotting process is carried out after the anneal process, the stresses introduced by cutting cannot be eliminated and thus weaken the magnetic performance of the cores. In order to conquer this problem, the slotless structures are implemented in machine designing process. Fig.14 illustrates an axial flux AA machine with no-slot structure. The winding coils of the machine are enwound across the annular core[46] which is made by wound AA strips. The difficulties of cutting slots is eased, meanwhile the costs are reduced and the noises of the machine are suppressed since the cogging torque is eliminated. In addition, the iron loss of the machine is reduced by this no-slot structure. Nevertheless, the machining precision during manufacturing is very demanding since the coils are directly located in the air gap. On the other hand, the existence of coils greatly enlarges the air gap, resulting in the increase of costs and the reduction of air gap flux density. For these reasons, this structure is more suitable for the high-frequency and low magnetic load machines.

In addition, some special processing techniques of making up the cores can also be implemented based on the characteristics of AFAA machines. For instance, the whole core can be pasted[36-38] by tooth parts and yoke parts made by AA sheets separately, as shown in Fig.15. However, the cores pasted up also suffer from the instability problems. For this purpose, the single-stator and double-rotor structure can be implemented since the yoke part of the stator can be left out, and thus avoid the influence caused by the connections of yoke part and tooth parts. The stator core can be joint by several wound modules and pasted by resin[39], as shown in Fig.16. In order to minimize the eddy-currents and reduce the iron loss, each module is often narrowly slotted or translated into a laminated one[40-41], as shown in Fig.17. Beyond that, there are some other novel processing techniques[47-49], and the main purpose of these methods is to reduce the work introduced by slotting.

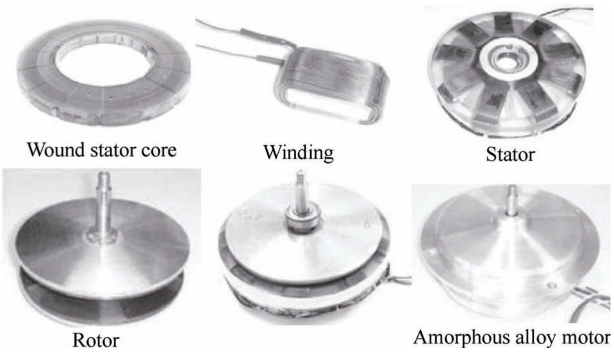


Fig.14 Axial flux slotless AA motor

2.3 Summary of AA electrical machine prototypes

The basic parameters of the AA machine prototypes and the machine products are summarized for the sake of research and analysis, and shown in Table 1.

The power level of the AA machines can change from several watts to several hundred kilowatts as can be derived from the table. However, most of the rated powers of the machines are below 10 kW. LE company declared that the rated power of their AFAA motor product used for the EVs can reach 170kW with the peak power of 230kW. The AA machines are mostly with high rotation speeds. The rotation speeds of LE products can range from 2000r/min to 4000r/min mostly, and these AA machines are almost traction motors for EVs or used as the small mobile generators.

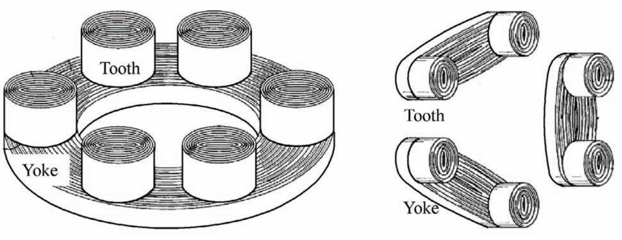


Fig.15 Teeth-yoke connection method of axial flux motors

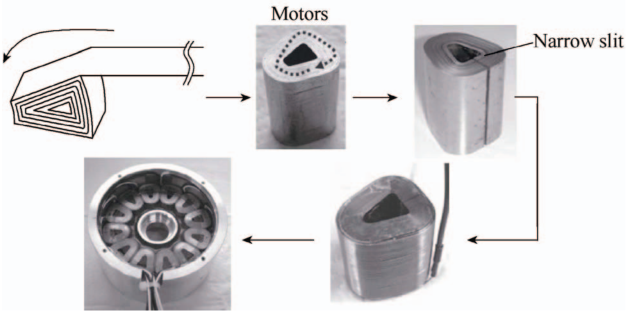


Fig.16 Splicing core of wound AA blocks

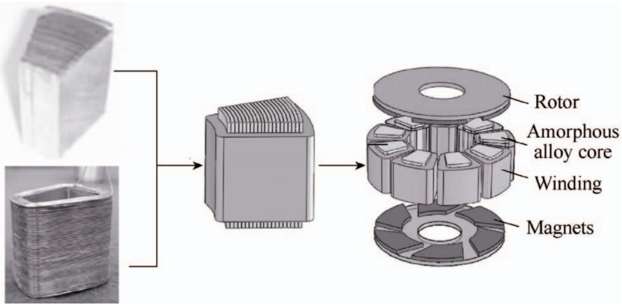


Fig.17 Splicing core of laminated amorphous blocks

Table 1 Specifications of representative AA machines

Year Institution	Motor type	Power/ kW	Speed/ (r/min)	Poles/ slots	Type of PM	Dimension/ mm	Efficiency (%)	Efficiency with SS(%)	Torque density/ (N·m/L)	Application
2008 TUS	SRM	2.4	8500	4/6		$\Phi139\times L70$	95.1	89 (35A300)	2.54	
2005 Hitachi	RF-PMSM	0.4	3000	10/12	NdFeB	$\Phi70$	90.5	88.5 (35A300)		
2010 Hitachi	AF-PMSM	0.2	2000	8/12	Ferrite	$\Phi100\times L60$	85		1.36	Home appliances
2011 Hitachi	AF-PMSM	0.4	15000	6/-	Ferrite	$\Phi100\times L25$	93		1.38	
2012 Hitachi	AF-PMSM	11		-/12	Ferrite		93			
2011 Hitachi	AF-PMSM	0.15	2000	6/9	Ferrite	$\Phi95\times L43$	90		2.35	
1992 UW-M	AF-PMSM	0.375	1800	4/-	Ferrite	$\Phi159\times L78$	90		1.002	
2005 UAD	AF-PMSM	2.9×10^{-3}	6000	2/3	NdFeB	$\Phi32$				
2004 UTS	RF-PMSM	0.15	13300	2/-	NdFeB		96			
2012 LTU	IM	0.402	1500	4/24	No	$\Phi118\times L102$	77.1	About 76	2.330	
		0.88	3000				86.5	About 84.5	2.511	
2013 INFM	RF-PMSM	1	70000	2/-	NdFeB	$\Phi57\times L40$	73		0.98	
2011 CISRI	RF-PMSM	5	8000	-/6	NdFeB		90.1	85.5		
2013 IEECAS	RF-PMSM	20	2500	12/36	NdFeB	$\Phi210\times L65$	95.9	94.3	33.77	EV
2015 UAD	AF-PMSM	1.5	7000	10/12	NdFeB	$\Phi110$	90			Generator
2016 SUT	RF-PMSM	15	30000	4/18	NdFeB	$\Phi130\times L70$	93.8	92.2	5.06	Spindle

※ SRM: switched reluctance motor; RF-PMSM: radial flux permanent magnet motor; AF-PMSM: axial flux permanent magnet motor; IM: induction motor.

3 Influences of processing technics on electrical performance

3.1 Annealing

From the micro perspective, the atom arrangement of AA material is random, and the power for impeding the motion of magnetic domains is quite low, which means the coercive force is low, and consequently low hysteresis loss. During the production of the AA material, some internal stress exists, and will lead to a deterioration of the performance. In order to eliminate the influences of internal stress, annealing could be used to release the stress[50-51].

The characteristics of AA material will be changed a lot by the annealing parameters, such as annealing temperature, annealing time, temperature rise speed and so on. These annealing parameters should be chosen properly, which are shown in Table 2[51-53]. It should be noted that, when the AA cores are used in high frequency motors, core loss will decrease when the annealing temperature is higher than that in low frequency motors[50].

Table 2 Process parameters of annealing

Annealing method	Nitrogen protection
Annealing temperature/℃	380
Annealing time/min	120
Temperature rise speed(℃/min)	10
Cooling method	Natural cooling

3.2 Immersion and solidification

On the one hand, the solidification of insulation will leads to internal stress, on the other hand, the magnetostriction coefficient of AA is high, and the magnetostriction is limited after solidification, which will also lead to internal stress. Both of these stresses lead to deterioration of magnetic and loss performances. So AA laminators should be bonded firmly without suffering too much stress[54]. After solidification, general insulator almost cannot stretch, so people are seeking of other insulators to solve the problem. Reference[52-53] show that epoxy resin and acetone could be formulated as a insulator by a certain percentage, and it is better to use vacuum impregnation method. In order to uniform the thickness of solidified insulator, a painting device is used as shown in Fig.18[23,27-28,55], but its manufacturing process is more complicated.

The loss density performance of two AA cores are researched by Shenyang University of Technology (SUT), one of them is immersed and solidified after annealing(C1), the other is done without annealing (C2). The results show that loss densities increase a lot after solidification, and the loss density of C1 is lower than C2.

3.3 Wire cutting

After impregnation, the eddy current circuit between laminations is cut down because of the interlaminar insulator. But when the AA cores are slotted by wire cutting process, the original phase structure of AA material is changed, and most of the adjacent laminations are melted together as shown in Fig.19, which means the eddy current circuits are rebuilt, and more eddy current losses will be produced in the AA core. It should be noted that not only does the loss performance change after wire cutting process, the magnetization performance is also deteriorated a lot, but the saturated flux density of AA changes little after wire cutting process[56].

The conductive ability of solidified AA cores are low because of the existence of interlaminar insulators, what is more, AA laminations are thin and fragile, large scale of burrs will be produced by wire cutting process. In order to avoid them, the solidified AA core could be sandwiched by two thick steel plates, and both of the AA core and steel plates are processed by wire cutting together[52-53].

In [57], three kind of AA core samples are manufactured, and the loss performances are also measured and compared as shown in Fig.20. The results show that the highest specific core losses are present for the ring-shaped sample made of discs, the lowest specific core losses values are observed for the frame sample in the Epstein apparatus. It may be explained by the presence of short-circuits between particular discs. They are the effect of the wire cutting that may cause corrosion. The roll ring shaped sample was not processed, and it results in lower values of specific core losses. The higher values of specific core losses measured for the roll sample may have their origin in stresses observed during the rolling the strips in the discs.

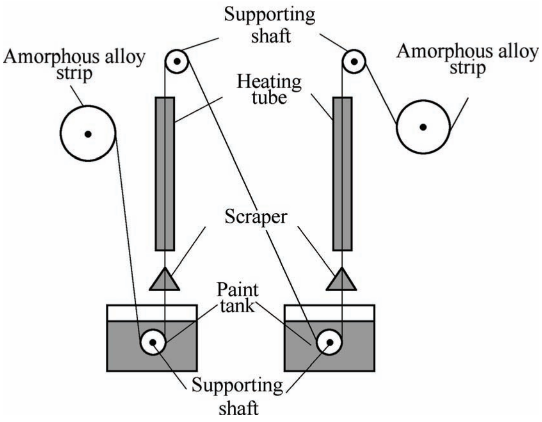
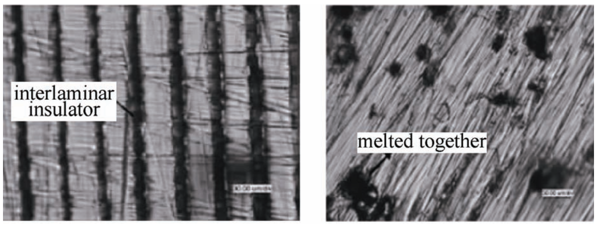


Fig.18 The device of insulator painting

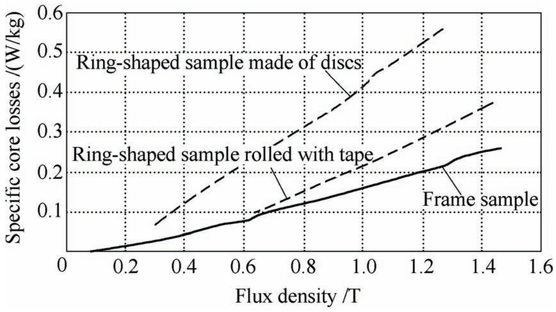


(a) before wire cutting process (b) after wire cutting process

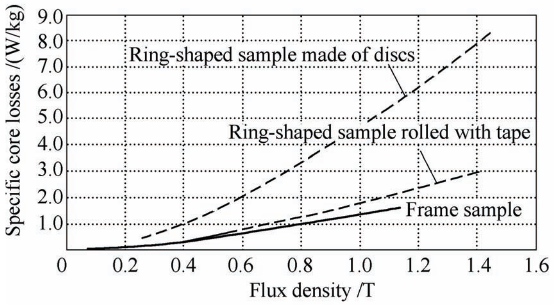
Fig.19 The AA cores before and after wire cutting process

3.4 Shrink fitting

The loss performance of AA core will deteriorate because of the yoke stress caused by shrink fitting process. The influences of shrink range to the loss density of AA core are quantitatively researched by SUT using experimental methodology. The results show that when the shrink range increases, loss density of AA core increases too, but the raising speed is getting lower as shown in Fig.21. The shrink fitting process should be avoided in casing AA motors.



(a) 50Hz



(b) 300Hz

Fig.20 Loss comparison of three kind of AA cores

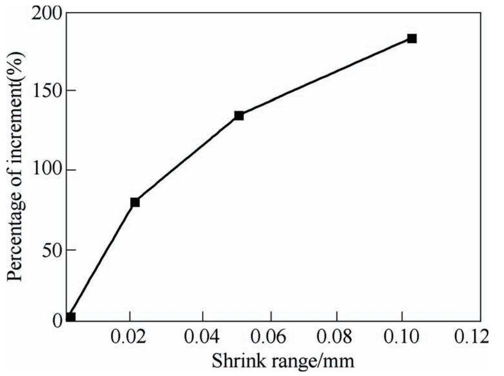


Fig.21 The increasing percentage of core loss with varietal shrink ranges

4 Key technologies of AA electrical machine

4.1 Losses of AA motor

Loss and magnetization performances of manufactured AA cores deteriorate a lot compared with that of AA strip. Errors may exist if the magnetic performance of AA strip is used for analyzing the AA motors. One way to solve this problem is researching the manufactured AA cores by measurement, by using Epstein frame and single sheet measuring system, but for AA cores, method of measurement of ring specimens is more convenient. Some results could be deduced by the measurement as follows:

(1) Compared with AA strip, the saturated flux density of manufactured AA core decreases[58], the loss density of manufactured AA core increases a lot[59].

(2) Compared with 35W270 SS strip, loss density performance of AA core is superior[58,60-61], but the saturated flux density of AA core is lower than SS strip as shown in Fig.22, and what is more, the permeability in the common use core flux density range is lower than SS strip as shown in Fig.23[61-63].

Based on the measurement results of AA cores, finite element method could be used to analyze the losses of AA motors. Two motors are always produced with the same specifications, but the cores are made of AA and SS material respectively. Then losses of these two motors are compared, and the results show that, because of the excellent loss density characteristics, core losses of AA motor are quite lower than that of SS motors[58,61,66-68], especially when it is used in high frequency motors[64-65,69].

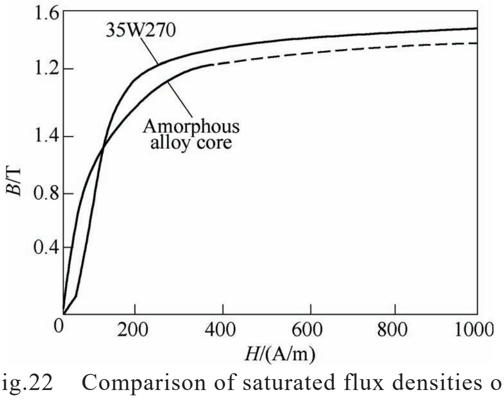


Fig.22 Comparison of saturated flux densities of AA core and SS

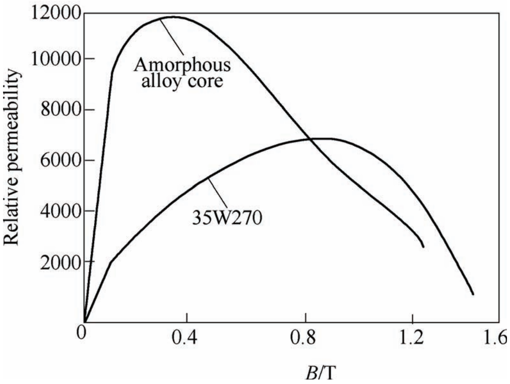


Fig.23 Comparison of permeability of AA core and SS

With the increasing of loading rate, the flux density of cores of AA motor are more easily saturated than SS motor, which means the winding current of AA motor will be larger than that of the SS motor. Losses of a 55kW AA motor are researched by ORNL, where it shows that the copper losses of AA motor are larger than SS motor when the loading rate is high[70]. The advantages of efficiency of AA motor may get weaker with the increasing of loading rate as shown in Fig.24[71].

In order to research the differences of losses between AA motor and SS motor, a 2.1kW 4000r/min SS motor is taken as a baseline motor, one other motor is produced by SUT with the same specifications, but the stator core is replaced by AA material, and the losses of these two motors are compared as shown in Fig.25.

In Fig.25, $p_{\mathrm{m\_\lambda}}$, $p_{\mathrm{m\_w}}$ and $p_{\mathrm{m\_a}}$ are the permanent magnet eddy current losses caused by slot opening, the harmonic of winding magnetic motive force and harmonic currents respectively. The $p_{\mathrm{s\_a}}$, $p_{\mathrm{s\_r}}$ and $p_{\mathrm{s\_b}}$ are the stator core losses caused by harmonic currents, armature reaction and fundamental respectively, p_{exp} is the measured motor losses. It is shown from Fig.26 5 that core losses of AA motor is lower than that of SS motor because the loss density of AA material is superior to SS material..

The value and distribution of no load losses in AA motor are studied under different supply modes, such as sinusoidal voltage supply, vector control inverter supply and direct torque control inverter supply[72].

4.2 Vibration and noise of AA cores and motors

Magnetostriction is a property of magnetic metal

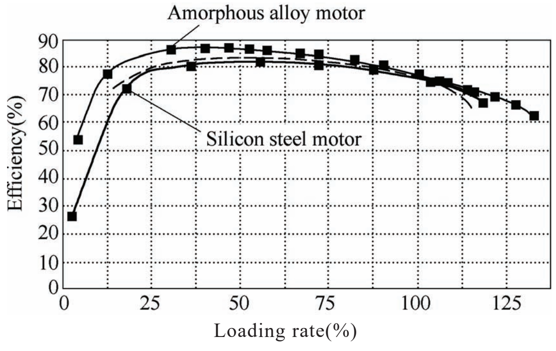


Fig.24 Comparison of efficiencies of AA motor and SS motor

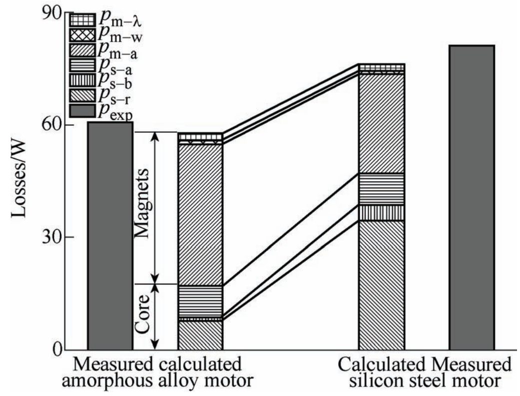


Fig.25 Separation and verification of losses

in which the material will exhibit strain in the presence of magnetic field and is recognized as one of the main causes of vibration and noise emissions for motor laminated cores, together with the Lorentz and reluctance magnetic forces[73-74]. For AA material, the magnetostriction coefficient is much larger than for the conventional SS sheet. Magnetostriction coefficient of conventional SS is 2×10^{-6}, and magnetostriction coefficient of amorphous magnetic metal is 26×10^{-6}. The magnetic characteristics of AA are greatly effected by stress, so lamination factor of AA cores which are applied to electrical machines is lower than SS cores. Hence, the vibration and noise in AA PMSMs is much larger than conventional SS PMSMs.

The vibration and noise of AA PMSMs are studied and compared with SS PMSMs by the academics from SUT. Two prototypes which have the same structure and size are shown in Fig.26. The parameters of the prototypes are listed in Table 3. The vibration and noise of the AA PMSM and SS PMSM which are under no-load running state with PWM voltage supply are tested under different working frequencies. Table 4 and Table 5 compare the test results of vibration acceleration and noise for the AA PMSM and SS PMSM. The comparison shows that the vibration acceleration of the AA PMSM is 2.4 to 4.4 times larger than that of the SS PMSM at some frequencies. The maximum increase of noise of the AA PMSM is 25% compared with the SSPMSM at some frequencies.

Fig.26 Two prototypes (AA PMSM and SS PMSM)

Table 3 Parameters of the AAPMSMs and SSPMSM

Item	Value
Rated power/ kW	2.1
Rated frequency/ Hz	267
Number of poles/slots	8/36
Stack length/ mm	54
Stator outer diameter/ mm	123
Stator inner diameter/ mm	81
Air gap/ mm	2

Table 4 Comparison between test results of vibration acceleration for the AAPMSM and SSPMSM

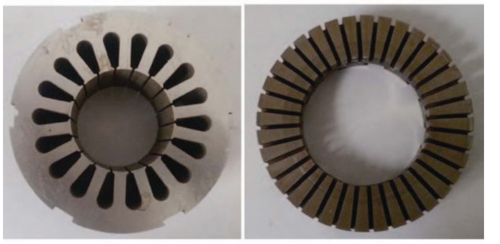
f/Hz	a_{AA}/(m/s^2)	a_{ss}/(m/s^2)	a_{ss}/ a_{AA}
67	0.876	0.257	2.41
133	3.01	0.72	3.18
200	6.56	1.43	3.59
267	11.6	2.15	4.40

Table 5 Comparison between test results of noise for the AAPMSM and SSPMSM

f/Hz	AAPMSM/dB(A)	SSPMSM/dB(A)	AAPMSM/ SSPMSM
67	66.8	56.2	1.19
133	74.4	60.3	1.23
200	77.2	61.7	1.25
267	78.6	62.9	1.25

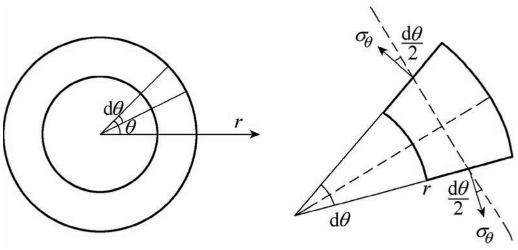
The effect of production processes on vibration and noise of AA cores is studied by the academics from SUT. An experimental method is set up to measure the vibration and noise in AA cores which is mainly generated by magnetostriction effects. The AA cores with different lamination directions and different producing processes are tested. The core in Fig.27(a) is a stacked core with axial direction lamination, and the core in Fig.27(b) is a tape wound core with radial direction lamination. The measured results show that the vibration and noise in wound AA cores is larger than stacked AA cores under the same conditions. The vibration of AA cores with immersion processes is increased by 68.2% and the noise by 4.7%. The vibration of AA cores with annealed producing processes is reduced by 27.8% and the noise by 2.5%. In reference [75], the vibration and noise of wound AA cores are measured under different power supply frequencies and different flux densities. Relationships of flux density versus vibration and noise in wound AMM cores caused by magnetostriction effect are obtained: the vibration of wound AA cores is in proportion to the square of flux density, and the noise in wound AA cores is logarithm function with respect to flux density.

In reference [76], an analytical model is developed to solve the vibration due to magnetostriction in AA PMSM. The analytical model for AA cores is set up based on piezomagnetic equation. The solution regions of the analytical model are divided into yoke and teeth subdomains. The yoke can be considered as a cylinder body. The illustration of yoke is shown in Fig.28(a). An element of unit thickness is defined by two radii r and $r+\mathrm{d}r$, and angle $\mathrm{d}\theta$, as shown in Fig.28(b). The tooth can be considered as a cuboid body. The cross-sectional dimensions of the tooth are shown in Fig.29. The analytical model is verified by using finite-element software. The analytical model is applicable to the radial flux AAPMSMs, which can be used to predict vibration displacement, vibration velocity, vibration acceleration and stress.



(a) Stacked AMM core (b) Wound AMM core

Fig.27 Configuration of AA cores



(a) Yoke (b) Mass element

Fig.28 Illustration of yoke and mass element

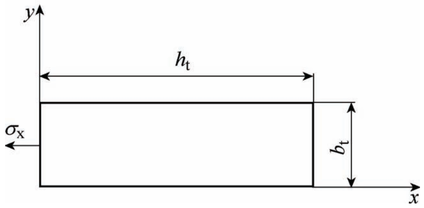


Fig.29 Cuboid shape of tooth with a cross-sectional view

4.3 Optimum design

As a new type of soft magnetic material, AA material has excellent electromagnetic properties of low hysteresis losses and eddy current losses. It is particularly suitable for iron core material of high-speed high-frequency machines. However, due to the characteristics of thin, brittle, hard, limited physical sizes (the standard available widths: 142mm, 170mm and 213mm), low saturation flux density (1.56T or 1.63T) and sensitive to mechanical stress, AA material use in electrical machines is restricted. The topology and design method of AA machines are different from SS machines.

As the most successful company of AA machines in the world, LE focuses on the design of axial flux AA machines. Based on the low core loss character-ristics of AA, the frequency is considered as a free variable in PMSM in effort to achieve optimal torque density. In order to achieve optimal torque density, the author give the design rules of motor dimension[77]. Also, to reach high efficiency, the choice of 0.5 slots/phase/pole(SPP) is used. This SPP minimizes winding end-turn length and the coil construction expense.

Simply replacing the stator core made of SS with AA is analyzed in [70], FEA simulation results show that the efficiency of AA motor is higher than the SS one only when the supplied current is lower than 100A. As the current increases, the AA motor is getting even worse in efficiency than the SS motor, due to the strong saturation effect. A useful criteria to judge direct replacement is presented in [78]. Also, an optimization software package is used to design the stator made of AA. The optimized AA motor is 31% smaller in volume than the baseline motor and 2.6 percentage points higher in efficiency.

5 Application prospect of the AA machines

5.1 AA generators used in the telecommunication base stations

With the swift development of the communication industry, the requirement of communication, especially the mobile communication, is highly increased, while the depth and width of the network coverage are the key points. The generator is the indispensable equipment for power supply in the mobile telecommunication base station, and should offer extremely stabilized power. Since the fuel used for generating electricity is sometimes hard to be transferred limited by the position of the station and the climate, the energy conservation problem is always a concern of researchers. Because of the high efficiency of the AA generator, it can work for a longer time with the same oil tank. Therefore, the power supply systems based on AA generators will no-doubt be more cost- effective and more reliable for the mobile telecommunication base stations. Meanwhile, the potential of for applications of AA machines in the emergency rush repair systems, the governing systems for the intelligent buildings, and as the portable power source in the vehicles can not be underestimated.

5.2 High-speed motorized spindle AA motors

The energy conservation problem is particularly important for machine tools as the basic instruments in manufacturing. Nowadays, the energy-saving machine tools are developing rapidly. The motorized spindle as the core part of the machine should be highly efficiency and with high reliability. As can be seen from extensive research work, when operating machine tools, especially high speed ones, the heat generated by the tools can affect the machining precision greatly. In high speed operations, the error caused by the load is much smaller than that introduced by heating, and the latter may occupy 40 % to 70 % of the whole error. Since the losses of AA motors are greatly reduced, the usage of AA motors can result in accuracy improve-ment and is promising. The AA motors also have many advantages in high-accuracy and low-loss servo applications as required by many companies.

5.3 High-frequency AA motors used in high-end fields such as aviation, shipping, and military usage

The biggest advantage of the AA motors is their low iron loss character. Based on this, the frequency limit of the motors in applications could be extended. In the aviation industry, the motor frequency is mostly set to 400Hz since it can satisfy both the limit of heat generated and the demand of power density. Since the AA motor could be operated under thousands Hz as its low iron loss property, it is suitable beyond the common frequency and be more advantageous in high- end fields such as aviation, shipping, and military usage than a SS one.

5.4 AA motor used as the EV traction machine

The popularization of electric vehicles is limited by their shortage in energy supply offered by the batteries. It is a promising way to conquer this problem by improving the efficiency of the traction system. Furthermore, the space used for maintaining the motors is always small, and thus challenges the sizes of the motors. Based on the report presented by the Machine Design Network, the SmartTorq^{TM} AA motor offered by LE company is only 60% weight and 55% the size of a SS motor while the efficiency of the motor could reach 95% during a wide speed range. As has been reported, the travelling distance could be increased by more than 30% if the traction motor is changed to an AA one, in other words, the power of the battery could be saved by 30%. Since the AA motor is with high-efficiency and high-power- density performance, it can be a new type of promising traction machine served for the high-performance EVs.

6 Conclusion

In this paper, an overview on AA electrical machines and their key technologies is presented. Firstly, topologies and processing techniques of radial flux and axial flux AA cores and machines are reviewed in detail. Secondly, the key technologies, such as iron loss characteristics, vibration and noise characteristics and optimum design are summarized. Thirdly, the application prospect of the AA electrical machines in the field of small generators, high-speed motorized spindle and other high-frequency AA motors used in high-end fields, EV, is described. Finally, the challenges and opportunities for promoting the technology development and the application of AA electrical machines are addressed:

6.1 Challenges

- Since the widths, the physical properties, and the saturated flux densities of the AA strips can hardly meet the needs of manufacturing machine cores, it’s of importance to analyze and develop the dedicated AA materials for electrical machines.
- The topological structures of electrical machines utilizing AA cores need to be analyzed on account of the lack of adequate understanding and sufficient studies. Furthermore, the economical, low consumption, and mass production techniques are also imperfect and need to be further investigated.
- Other than the well developed optimization design techniques of the SS electrical machines with more than 100 years of development, those of the machines with AA cores have just started. There exist many problems which limit the usage and the machine styles. Since the structural styles and performance indexes of the AA machines change with the power levels, the rotating speeds, and the applications, the analysis of the optimization design techniques need to be improved.
- The AA machines should be applied in the high frequency occasions for their performance advantages. However, the working frequencies of the machines are limited by the transducers.

6.2 Opportunities

The electrical machines with AA cores generally have better electromagnetic performance than traditional SS ones, especially in high-frequency applications. They meet the need of green development and are favorable from the market perspective. In the future, cost-effective applications of the AA machines can further developed, and thus open up generalization and adoption.

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