Evaluation of a Motor with an Amorphous Iron Core Punched by a Die

Yuji Enomoto** Senior Member, Keisuke Suzuki** Non-member
Seiji Okita** Non-member, Kohei Eto** Non-member
Eiji Katayama** Non-member

We have been studying the application of amorphous metals, which have a significantly lower loss than electrical steel sheets, to motors. Thus far, we have studied simple-shaped iron cores that can be machined only by shearing for radial motors. However, it is considered that the loss can be further reduced if the iron core is entirely made of amorphous metal. Here in this report, we report the results of a trial evaluation of a motor in which an amorphous metal is punched using a press die to form a stator core.

Keywords: radial gap type motor, permanent magnet synchronous motor, iron-based amorphous metal, motor efficiency, iron loss, magnetic field analysis

1. Introduction

Engagements in SDGs (Sustainable Development Goals) to resolve environmental issues are gaining urgency (1). Among such engagements, the development of energy-saving motors, which currently account for approximately half of power consumption, and the electrification of automobiles for the reduction of CO₂ emission are being accelerated (2). The Chinese automobile market, in particular, is seeing a remarkable rise in sales, and the polluting effect on the environment has come to the forefront. Thus, in China, regulations promoting the adoption of environmentally friendly NEVs (New Energy Vehicles) were implemented in January 2019 (3). The vehicles that are covered under the NEV regulations are EVs (Electric Vehicles), PHVs (plug-in hybrid vehicles), HEVs (Hybrid Electric Vehicles), and FCVs (Fuel Cell Vehicles) and each of these drive-sources uses a motor.

The authors of this study are promoting research on amorphous iron-core motors, as the adoption of iron-based amorphous metal as the iron core has proved to raise the efficiency of motors (4-8). Traditionally, iron-based amorphous metals were considered too thin and hard to be molded into the shape of a conventional motor stator using the pressing method. Therefore, the authors have thus far proposed a manufacturing method for the iron core where the amorphous metal is punched using a press die and formed into a simple stator iron core and a structure for such a stator core. In making such proposals, the authors have prototyped and evaluated axial gap type and radial gap type motors to verify their effect on the improvement of motor efficiency (9-10). However, while the authors were able to verify that it is possible to manufacture the teeth core of a multi-slot radial gap type motor as a simple form using the shearing method, issues such as the assembly process was laborious due to the number of pieces, the management of the segment gaps’ precision, an increase in high-frequency loss of the rotor surface due to the slot opening remained as issues. Therefore, it was decided that in this study, a motor using the same form and manufacturing method of the stator that is currently available on the market should be examined. Up till now, evaluation of prototypes of motor stator iron core formed from amorphous laminated blocks using wire electrical discharge machining (EDM) has been considered (11), but this method has been deemed impractical for commercialization as its production cost would be too steep. There is an example that managed to fabricate a core by punching amorphous metal sheets using a press die (12). This study aims to consider the stator iron core structure that will be suitable for press punch manufacturing and to create the said prototype to then evaluate the motor. In this paper, the authors report iron loss evaluation results wherein magnetic field analysis was used on a motor whose stator core is entirely made of amorphous metal, as well as the evaluation results of the loss reduction effect the application of amorphous metal iron core has on the working prototype of such a motor.

2. Motor Structure that Has an Amorphous Metal Iron Core

2.1 Considerations on Punch-pressing Amorphous Metal

Table 1 shows the comparison of representative characteristics of electromagnetic steel sheets and iron-based amorphous metal (13). Furthermore, Fig. 1 shows the comparison of magnetic properties of electromagnetic steel sheets and iron-based amorphous metal. While iron-based amorphous metal has an advantage over electromagnetic steel sheets as its iron loss is 1/10th of the latter, its difficulty in
using it as an iron core of a motor due to its hardness, brittleness, and thinness compared to electromagnetic steel sheet remains an issue. The key issues, therefore, are the following three: 1) Due to its thickness, the number of metal strips to process increases; 2) As it is hard, the life of the die press is reduced; 3) As the material comes in only three widths (142, 170, and 213 mm), it is not possible to manufacture stators with larger diameters.

The authors have proposed a motor structure that uses amorphous metal in part of the iron core, using only shearing as shown in the literature (7) and (8). However, as indicated earlier, motor manufactures have expressed their anticipation for a motor structure that their present facilities could be utilized to manufacture as well as such structures that would have fewer steps in assembly. Therefore, it was determined to consider an amorphous metal stator iron core that has an equivalent structure to that of the current radial gap type motor stator. First, regarding the width of the materials, it was determined that we should approach the creation based on the premise that the core will be constructed using the split core method. As we consider the fact that for the time being, the rotor would be comprised of other materials, the split-core method is ideal from the perspective of material utilization rate as well. Furthermore, smaller punch dies would be more suitable compared to large dies since the clearance between the mold and the punch die becomes very narrow when thin materials are punch-pressed. Based on these considerations, the amorphous metal will be punch-pressed in the shape of a portion of an annular stator which is divided in a circumferential direction to create a laminated block, as shown in Fig. 2.

Since amorphous metal sheets are thin and hard, riveting methods would be deemed difficult; it was thought that the use of lamination bonding method within the mold would be suitable. To assemble, the core blocks will be cascaded and stacked as though they were bricks.

### 2.2 Consideration of the Cost-effectiveness of the Amorphous Metal Stator

Table 2 shows comparison results of the productivity of the above-mentioned split core structure of a stator iron core that is formed through punch-pressing amorphous metal in relation to the electromagnetic steel sheet. Considering that there are no limitations in the supply of electromagnetic steel sheet materials, and as the rotor is also fabricated using the same core through pressing, it is common for the structure of an electromagnetic steel sheet stator to be fabricated as a single unit. Furthermore, since the current target machine is structured in a way that the coils are inserted through a coil inserter, a split core would not be able to withstand the strain as the coil is inserted. For this reason, it was decided that the representative motor using an electromagnetic steel sheet that would be used for comparison would have a stator core that would be fabricated as a single unit. While the labor it takes to create the rotor core as a separate unit should also be considered, here, the cost comparison is limited to the overall cost of obtaining the stator core. First, the material cost of amorphous metal ($K_2$) is assumed to be approximately twice that of the material cost of electromagnetic steel sheets ($K_1$). In the case of the

| Table 1. Comparison of electromagnetic steel sheet and iron-based amorphous |
| --- |
| **item** | Electromagnetic steel sheet | Iron-based amorphous metal |
| Material | 35A300 (JIS) | 260SHB1M (Metglas) |
| Appearance | Strip condition | |
| Density | 7.65 g/cm³ | 7.33 g/cm³ |
| Thickness | 0.35 mm | 0.025 mm |
| $B_s$(100A/m) | 0.95T | 1.47T |
| $B_{50}$(5000A/m) | ≥ 1.64T | 1.63T |
| Resistivity | 0.52 Ω·m | 1.3 Ω·m |
| Loss $W_{(0.4)}$ | 18 W/kg | 1.5 W/kg |
| Hardness | 100～200(HV) | 900(HV) |

![Fig. 1. Comparison of magnetic properties](image)

![Fig. 2. Stator structure composed of pressed amorphous metal](image)

| Table 2. Productivity comparison by stator structure |
| --- |
| **Item** | Electromagnetic steel sheet core | Amorphous stator core |
| Appearance | | |
| Core weight: W kg | | |

### Material utilization rate

(Material cost)

| Material utilization rate | (W×$K_1$×100/40) | (W×$2K_1$×100/60) |
| --- | --- | --- |
| $K_1$ | 3.25(WK$_1$) | 3.3(WK$_1$) |

### Material price

$K_1$ /$kg$ | $K_2$ /$kg$($K_2$×2$K_1$)

### Jig tool costs

$K_4$ /unit | $0.8×K_3$ /unit

### Number of shots until re-polishing the mold (Polishing cost)

| Number of shots | 2,000 shots | 200K shots |
| --- | --- | --- |
| (K$_4$/unit) | ($0.8×10×K_4$ /yen) | ($K_4$ /yen) |

### Stator core cost

$2.5W_K_1+K_4$, $3.3W_K_1+0.8K_3+8K_4$
amorphous metal iron core in the divided core, material utilization can be improved, and its usage decreased; the material cost increase can be limited to 1.3 times. In comparing the die cost (K1), split cores allow for smaller dies, and thus tooling related costs are expected to be lower. Here, the tooling cost is assumed to be approximately 20% lower than its comparison. Next, to the maintenance cost of the die for punch-pressing, the viable number of shots the die can punch press amorphous metal before the die needs re-polishing is assumed to be 1/10th of the die used for punch-pressing electromagnetic steel sheets. Also, even though the die itself could be conceivably smaller, the cost of re-polishing could cost approximately eight times more. Generally, the die cost (K2) and the re-polishing cost of the die (K3) per component would be hovering a few yen over 10 yen or so; hence, its impact is actually not that significant compared to that of material cost. Based on these assumptions, it is expected that if the stator core was to be manufactured using a punch press, though it will add a few procedures, the manufacturing cost difference should be less than the difference of the material cost.

3. Predicted Performance of the Motor Using Magnetic Field Analysis

3.1 The Specification of the Target Machine

The targeted motor’s specification is shown in Table 3, and the motor’s cross-sectional form of the motor in the target machine and its N-T characteristics are shown in Fig. 3. The target motor is an IPM (Interior Permanent Magnet) motor with distributed winding, which has a rotor structure with generic magnets placed in a V-shape.

Figure 3(a) shows the schematic diagram of the stator and the rotor. The coil is comprised of 11 generic round wires. The wires are wound six turns, and it uses distributed winding. While the form is such that it could be manufactured using a coil inserter, the coil end section becomes bigger, which would lead to an issue of having greater coil resistance. The motor efficiency of the target machine is approximately 95% at the rated operating point, which is equivalent to the IES efficiency standard as set by IEC (International Electrotechnical Commission) 60034-30-2. Figure 3(b) shows the rated and maximum output characteristics. Maximum torque is 2.5 times the rated torque, and the speed at which maximum torque can be obtained is up to approximately 4,000 r/min.

3.2 The Characteristic Calculation of the Target Machine based on Magnetic Field Analysis

The characteristic calculation of the target machine was conducted using magnetic field analysis, and the relationship between the current and torque as well as the N-T characteristics were calculated. The calculation result of the rated current is shown in Fig. 4. Figure 4(a) shows the relationship between the current phase and torque. At a 33-degree current phase, the sum of the reluctance torque and the magnet torque reached its maximum and reached approximately the rated torque of 24 Nm. Figure 4(b) shows the N-T characteristics. In short, we were able to achieve the characteristics that roughly match the target specification. Using this magnetic field analysis model, the motor efficiency was calculated.

As to motor loss, \( W_{\text{cu}} \): copper loss, \( W_{\text{eddy}} \): iron loss (eddy current loss), \( W_{\text{hy}} \): iron loss (hysteresis loss), \( W_{\text{mag}} \): magnetic eddy current loss, \( W_{\text{coleddy}} \): the eddy current loss that occurs in the coil, \( W_{\text{mech}} \): machine loss were considered, and the efficiency was calculated based on the equation (1) as shown below. As to machine loss, we used the fitted value based on the measured value, which was obtained through spinning the non-magnetized rotor, which was then plugged into equation (2).

\[
\eta = \frac{\text{Output } P_{\text{out}}(W)}{\text{Input } P_{\text{in}}(W)}
\]

\[
\text{Mechanical loss } W_{\text{mech}} = 1.2 \times 10^{-6} \times \text{Speed } N^2
\]

Loses other than machine loss were calculated using the results of the magnetic field analysis. The copper loss was calculated using the current value given at the time of analysis and from the coil resistance. As to iron loss, the calculation method utilized Steinmetz’s equation, where each of the

| Table 3. Specifications of the target machine |
|---------------------------------------------|
| Rated power | 15 kW |
| Rated speed | 6,000 r/min |
| Motor type / poles, slots (Winding method) | IPM motor / 8P-48S (distribution winding) |
| Rated torque / Rated current | 24 N·m / 39 Arms |
| Maximum speed | 15,000 r/min |
| Peak power | 25 kW (15 s) |
| Peak torque / Peak current | 60 N·m / 104 Arms |
| Voltage | DC-518 V |
| Volume of motor | 4.130 x 1.80 mm |
| Number of conductors in slot | 66 (6 Turn : ø 0.6mm x 11 parallel) |
| Winding resistance (phase) | 0.06Ω |
| Motor efficiency (Rated point) | ≥ 94.5% (IE5 : IEC60034-30-2) |
elements’ magnetic flux density and frequency from the magnetic field analysis result was used. The BF (Building Factor) of electromagnetic steel sheets was set at 2.0, and hysteresis loss and eddy current loss were determined by multiplying this value to the above-mentioned calculation results. The eddy currents that are generated on the magnet and on the coil were directly calculated through magnetic field analysis based on setting each of the materials’ electroconductivity. The eddy current loss of the coil includes the influences such as the skin effect, proximity effect, and the leakage flux from the rotor magnets. An efficiency map was created using these loss calculation results. Figure 5 shows the efficiency map of the target machine. The rated output region shows the highest efficiency, and its maximum efficiency is approximately 95%. The result also shows that the high-speed region and low-speed-high torque region show low efficiency, leaving much to be desired with improved efficiency in these regions.

3.3 Torque Characteristics based on the Application of Amorphous Metal The predicted motor characteristics of the target machine where amorphous metal is applied were calculated using magnetic field analysis in the same manner as the previous section. The magnetic properties of the amorphous metal were calculated based on setting the direct current magnetization property of 2605HB1M, which was shown in Fig. 1, and calculating the current torque characteristics. Figure 6 shows the comparison of current torque characteristics. When amorphous metal is used for the stator, it can output approximately the same torque until the rated current; it was found that the torque was on a declining trend the larger the current value became. This is due to the low saturation magnetization of the amorphous metal; thus, this result was as expected. The current value that is capable of producing the maximum torque of 60 N·m as output is 130 Arms, which is to say approximately 1.25 times more current would be necessary. The maximum output (25 kW) of the target machine is set at 15 seconds, and unless the temperature rise at the time of maximum output is made equivalent, it is not possible to assure the same performance. For this reason, the maximum output performance was determined to be equivalent by making copper loss equivalent. When the current value reaches 1.25 times higher, copper loss occurs at the square of that. When setting copper loss to be equivalent, it is necessary to reduce the coil resistance by approximately 36%. Therefore, it was determined to increase the slot space factor using flat wires and to use high-density mounting of the coil ends using a wave-winding structure. Furthermore, it was determined that the assembly method should be to use conductors without enamel coating, inserting them into thin-walled, insulated bobbins to increase the slot space factor. Figure 7 shows the cross-section of the stator core and the schematic diagram of the coil assembly structure. As the thickness of the enamel coating changes per manufacturing lot, there is a chance for its space factor to decline when the assembly clearance is taken into consideration. On the other hand, bare conductors can have stability in their dimensions based on the manufacturing precision, which makes it possible to assure the space factor. In this manner, the slot conductor’s cross-section area can be calculated as 1.8 × 2.6 mm, and the coil resistance value can be determined to be 50 mΩ per phase, which is 2/3 of the current machine.

3.4 The Predicted Efficiency of the Suggested Machine, which Employs Amorphous Metal Figure 8 shows the magnetic field analysis results with the amorphous metal employed and the motor efficiency map based on calculating the coil resistance when flat coils are used. Here, the iron loss of amorphous metal on the rotor side of the electromagnetic steel sheet and the BF (Building Factor) of the stator side are each calculated as 2.0. Since the BF of punch-pressed amorphous metal has not been evaluated in the past, it was evaluated along with the BF that is typically used with electromagnetic steel sheets. Figure 9 shows the difference compared to the efficiency map as shown in Fig. 5. The results demonstrate that by employing amorphous metal, there has been an improvement in efficiency, mainly on the high-speed side. Furthermore, with the reduction of coil resistance, the reduction in efficiency in the larger torque region was suppressed, which verifies its ability to maintain not only the specifications but also improve its efficiency in all regions.
4. Prototyping a Motor with Punch-pressed Amorphous Metal

4.1 Prototyping a Motor Utilizing Amorphous Metal

The amorphous metal shown in Table 1 was punch-pressed using a die to create a laminated stator core and prototype a motor. Figure 10 shows the photographs of each part’s structure of the prototyped motor. Figure 10(a) shows the structure of the laminated amorphous metal block of the eight-way split-core in the circumferential direction. The core was fabricated to have an axial length of 20 mm. Figure 10(b) shows the amorphous core block as seen in Fig. 10(a) stacked like bricks with 0.2 mm thick resin bobbin made by LCP inserted into the slot area in the axial direction. The stator comprised of a four-layered block core is thus bound together in the circumferential direction by inserting the bobbins. With all the bobbins inserted, its integrity can be maintained temporarily while the coil is being assembled. In the end, the structure of the core will be fixed and maintained by its insertion into the housing. Figure 10(c) shows the rotor. The rotor was created by inserting magnetized magnets into the slot groove in the axial direction of the laminated electromagnetic steel sheets. The photograph shows a brass end plate on one side, but the prototype has the brass end plates on both sides, and by machining them, a balance equivalent to Class G1.0 has been achieved and maintained. Figure 10(d) shows the assembled stator. The structure is such that only the coil end section has an insulated coating. Figure 10(e) shows the exterior of the motor characterization test bench. The evaluation was conducted while the housing surface was cooled using cooling water.

The estimate of the cost of materials used for the stator in the proposed prototype is shown. As to the stator core, as stated in Section 2.2, the production device will cost approximately 1.3 times higher. In terms of the stator coil, since the cross-sectional area of the conductor would be 1.5 times greater, the weight is also approximately 1.5 times greater. However, since with the suggested machine, we are proposing a structure that does not use enamel-coated wire, the cost for enamel coating magnet wires (approximately 30%) can be reduced, and thus the increase in material cost will be minimal. As to the resin bobbin manufactured by LCP, the cost is equivalent to that of conventional insulating aramid paper. Hence, the proposed stator’s total material cost is not expected to come with a significantly higher price tag.

4.2 Evaluation of the Motor Utilizing Amorphous Metal

Figure 11 shows the measurement results of the no-load induced voltage waveform. The electromagnetic steel sheet machine and the amorphous machine both returned waveforms that matched what was predicted for the most part in magnetic field analysis. While the induced voltage constant is slightly higher with the amorphous machine, this may include gaps and other variations introduced during the assembly process. Figure 12 shows the evaluation results of no-load iron loss evaluation. The no-load iron loss was measured and plotted by measuring the torque of each prototype driven from the outside, and for each speed (rpm) setting, the machine loss shown in equation (2) was subtracted. Compared to the iron loss obtained by a magnetic field analysis,
they both showed higher loss than the calculated values but the trends in both prototypes matched for the most part. It was found that the no-load iron loss of the prototype using amorphous metal was approximately half to a quarter of the electromagnetic steel sheet motor.

Figure 13 shows the current torque characteristics. While the torque constant of the amorphous machine shows a slightly higher number, the results are nonetheless consistent with the differences in the induced voltage constant. Figure 14 shows a comparison of motor loss at low- and high-speed in the low torque range where the effect of copper loss is minimal. Here, the loss is based on separating the copper loss calculated by the current and resistant values and the mechanical loss calculated by equation (2), defining the difference between the input and output evaluated by actual measurement as the total loss. That is to say, iron loss includes rotor loss and the coil’s eddy current loss as well. The amorphous machine has reduced iron loss at both low- and high-speed, showing an improvement in motor efficiency.

Figure 15 shows the result of loss comparison at the rated operating point. With the target machine made of electromagnetic steel sheet, the copper and iron loss is approximately the same at the rated operating point. By employing amorphous for the stator, the iron loss of the prototype was reduced by nearly 50%, and there is about 2.7% improvement in the efficiency. Near the rated operating point, the copper loss showed results that were lower with the prototype as well.

Figure 16 shows the efficiency map of the rated output region based on actual measurement. As the authors do not possess a control device to drive the target machine, for the time being, the evaluation was limited to the extent of the rated output. Furthermore, the inverter used for evaluation was driven without sensors; thus, the condition is such that the control at the optimal phase is not possible. While some
5. Conclusion

Using the stator iron core with the punch-pressed amorphous metal, the effectiveness of motor efficiency improvement was examined against a stator made entirely of the amorphous metal motor. By applying a small-sized, punch-pressed form using the circumferential split method, the issue of the limited width of the amorphous metal supply was overcome, indicating the potential to reduce the manufacturing cost. Furthermore, through performance prediction using magnetic field analysis, prototyping of an actual machine, and its evaluation, the authors could successfully prove an improvement in the efficiency due to utilization of amorphous metal. On the high-torque side, a problem was confirmed that the current would increase due to low-saturation magnetization, and it was proven using the prototype that a reduction in the coil resistance value would be effective in compensating for this. The details of the findings obtained in each of the items that were to be considered are shown below.

(1) When amorphous metal is used to construct a stator iron core of a motor, it was demonstrated that by splitting the amorphous metal in the circumferential direction, it is possible to improve the material utilization rate when punch-pressing amorphous metal while simultaneously resolving the issue of the material supply range. Additionally, if we were to estimate the die cost and its maintenance cost could be reduced by 20% since the dies become smaller, even if the number of shots that could be performed before re-polishing is required is reduced down to 1/10th of that of electromagnetic steel sheet core, the production cost could be estimated to be held at approximately 1.3 times.

(2) As a result of predicting the motor properties through calculations using magnetic field analysis, a reduction effect of iron loss on the high-speed side was verified. On the other hand, on the high-torque side, it was verified that when the stator iron core is made of amorphous metal, the current value increases due to low saturation magnetism. The authors have demonstrated that when the copper loss which occurs due to increased current is made equivalent to that of a motor comprised of electromagnetic steel sheets, and when the stator iron core made of amorphous metal is combined with a structure that reduces the coil’s resistance, efficiency increases in all its regions.

(3) In building a prototype of a motor that employs amorphous metal, an actual machine was built by stacking amorphous laminated blocks that were split in the circumferential direction, and the motor was then evaluated. As a result, it was found that even when press-dried amorphous metal iron core was to be used, there was no significant increase in iron loss, and the authors were able to demonstrate with a prototype that there are improvements in efficiency compared to the motor that uses electromagnetic steel sheets.

Based on the above findings, we were able to demonstrate that the amorphous metal, which has thus far been considered to be too thin and too brittle to be aggressively pursued for usage in motors, could indeed be used as a stator iron core of a common radial type motor. Reduction of energy use in industry, home appliances, automotive fields must be continuously pursued going forward, and the results of this study are applicable for a wide variety of such fields.

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Evaluation of a Motor with an Amorphous Iron Core Punched by a Die (Yuji Enomoto et al.)

Keisuke Suzuki (Non-member) joined Hitachi High-Technologies Corporation (currently Hitachi High-Tech Corporation) in April 2008. He is engaged in sales of resin, non-ferrous and metal materials. Currently, he is in charge of sales and marketing of special steel to domestic and overseas electric and automobile related manufacturers.

Kei Suzuki

Seiji Okita (Non-member) joined Hitachi High-Technologies Thailand in May 2005. After that, he joined Hitachi High-Technologies Corporation (currently Hitachi High-Tech Corporation) in April 2012. He is mainly engaged in resin and non-ferrous metal sales, and is currently engaged in non-ferrous sales coordinating work.

Seiji Okita

Kohei Eto (Non-member) joined Hitachi High-Technologies Corporation (currently Hitachi High-Tech Corporation) in April 2014. He is engaged in the sales of metal materials. Currently in charge of sales and marketing of non-ferrous metals and special steels to domestic and overseas electric and automobile related manufacturers.

Kohei Eto

Eiji Katayama (Non-member) joined Nissei Sangyo Co., Ltd. (currently Hitachi High-Tech Corporation) in April 1992. He is engaged in coordinating the metal materials business. Currently, he is in charge of new business development and BI (Business Integrator).

Eiji Katayama