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FIBER REINFORCED ALUMINUM ALLOY FOR THE MOVING PARTS OF ROTARY COMPRESSOR

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ABSTRACT

To meet with the high speed rotary compressor demand, highly reliable light weight materials have recently been needed for moving parts such as vane as well as other mechanics. A special carbon material has successfully been applied for vanes in mini split heat pump rotary compressors. However, more reliable light weight materials with greater strength for vanes were expected to develop for the high powered and high speed rotary compressor. In this paper we discuss both the investigation progress of Metal Matrix Composite (MMC) as a high strength and reliable light weight material and the development result of Fiber Reinforced Aluminum (FR-Al) alloy for moving parts.

INTRODUCTION

Recently , rotary compressors with a variable speed features have been increasingly demanded to create precise temperature control and also to achieve plural room air conditioning with one compressor unit. To develop high speed rotary compressors there was a need for reliable light weight moving parts as well as design improvements. A special carbon material has been applied for vanes in our 180Hz inverter rotary compressor. However , a more reliable light weight material with greater strength for vanes was expected to develop the high powered and high speed rotary compressor. Therefore we have continued to study aluminum based Metal Matrix Composite (MMC) , which have been vigorously investigated, to provide a reliable light weight material with greater strength for vanes.

The results of this study led us to select Fiber Reinforced Aluminum (FR-Al) alloy manufactured by squeeze casting process because it provided us with a high Volumetric Fraction (Vf) of reinforcement fibers. We then decided to use SiC whisker as the reinforcement fiber and high silicon aluminum alloy as the base matrix because of their excellent features when used in FR-Al alloy. Consequently we selected the optimum Vf of SiC whisker (SiCw) in our experiment. This FR-Al Alloy was excellent in the properties such as wear resistance, bending strength, dimensional stability and compatibility with Halocarbon, and it fully satisfied the criteria for vane materials in high powered and high speed rotary compressers.

REQUIRED PROPERTIES FOR MOVING PARTS MATERIALS

The Structure of Rotary Compressor Pump Parts

As a sectional view shown in Fig. 1 , rotary compressor pump parts consist of cylinder, vane which performs reciprocating motion, roller which performs rotational motion and crankshaft which transmits the rotational motion of the rotor. When the rotary compressor with such a structure is put into high speed operation, the following problems are presumed by the increasing inertia of moving parts and by the increased sliding speed on bearing parts.

① Decrease in compression efficiency caused by the insufficient pursuit motion to the roller.

② Raise of friction loss and wear caused by the increased bearing pressure and sliding speed.

③ Raise of friction loss and wear caused by increased deflection of the crank shaft.

④ Raise in noise caused by the increased bearing pressure and sliding speed.

To apply light weight materials in moving parts is one of the most effective ways to solve these problems.

Particularly it is difficult to improve pursueing ability of the vane to the roller motion without light weight materials.

Fig. 2 shows a comparison of vane loads to the roller both from a casting iron vane and a carbon vane. In case of a casting iron vane, it becomes negative according to inertia raise and as a result the vane can not pursue the roller motion.

The Main structural materials for Rotary Compressors

Table. 1 shows the main structural materials for rotary compressors both of commercial power specifications and 180Hz inverter specifications. We selected the carbon vane for the 180Hz inverter rotary compressor because this special carbon is light in weight and also excellent in properties such as wear resistance and coefficient of thermal expansion. We also selected a higher grade material for shaft and journal bearing in the 180Hz inverter rotary compressor to reduce wear. However, in case of the high powered inverter rotary compressor the carbon vane became insufficient in strength when liquid compression occured during the starting operation. Accordingly, we started to research for more reliable light weight materials with greater strength and higher wear resistance. Table. 2 shows the required properties for vanes used in high powered inverter compressors in comparison with the representative materials used in compressors. Among them the coefficient of thermal expansion plays an important role in maintaining proper clearance for the moving parts in a pump chamber made of ferrous materials when the temperature rises.

THE PROGRESS AND RESULT OF FR-AL ALLOY DEVELOPMENT

Manufacturing Process of FR-Al Alloy Parts

Aluminum based MMC is generally produced by the manfacturing process shown in Fig. 3. There are two processes to produce a billet, powder metallurgical process and the squeeze casting process. There are also two procedures in making a vane from a billet, direct mechining and machining after plastic work.

We have researched the feature of each process and consequently selected the squeeze casting process and subsequent mechining process without plastic work because it provided us with the excellent features of FR-Al alloy such as high Vf of reinforcement fibers.

Squeeze casting process

Squeeze casting process is to pour molten aluminum into a tightly closed mold and let it solidify under high pressure by press work. Squeeze casting process for FR-Al alloy consists of the following two processes.

① Process for the pre-formed fiber body with precise Vf for FR-Al as shown in Fig. 4.

② Squeeze casting process for making FR-Al alloy by infiltration of aluminum into a pre-formed fiber body as shown in Fig. 5.

The Selection of Reinforcement Fiber for FR-Al Alloy

The followings are the required characteristics for reinforcement fiber used in FR-Al alloy.

① Inprovement in wear resistance by mixing the fiber.

② Reduction in coefficient of thermal expansion by mixing the fiber.

④ Excellent compatibility with the materials used in the refrigerant system.

⑤ High wettability and little reaction tendency with molten Aluminum based alloy.

We have looked for a fiber to meet the above requirements. Table. 3 shows representative fibers and their properties. The reaction tendency of carbon fiber with molten aluminum was reported to be difficult to control and Al_2O_3 fiber was found to be insufficient in wear resistance as FR-Al alloy in our experiment. Finally we arrived at a decision to select β-SiCw for reinforcement fiber.

The Selection of Aluminum Alloy for Matrix

Properties of aluminum casting alloy varies considerably in accordance with the silicon content. We, therefore, researched the relationship of the silicon content of aluminum alloys with wear resistance, mechanical properies and the coefficient of thermal expansion. Fig. 6 shows the relationship between the silicon content and each of the properties[1] and it was found that the optimum silicon content is 15 to 20%. As a result, we decided to adopt ALCOA A390 or its equivalent which contains 17% silicon. The chemical composition of the A390 is shown in Table. 4.

Selection for Vf of SiCw

To select the optimum Vf of SiCw we researched the effect of the Vf of SiCw on wear resistance, the coefficient of thermal expansion and strength in FR-Al alloy.

(1) The relationship between the Vf of SiCw and wear resistance

An Amsler wear tester was used to evaluate wear resistance. We furnished a block of FR-Al alloy as a vane and a ring of casting iron as a roller. Fig. 7 shows the wear quantity of the block with varying Vf of SiCw. As shown in Fig. 7, Vf of SiCw increased up to 25% the wear width of block becomes less than that of the carbon vane. Beside this fact it is found that even if the Vf of SiCw is increased more than 25% the wear quantity is kept almost same.

(2) The relationship between the Vf of SiCw and the coefficient of thermal expansion

The coefficient of thermal expansion of FR-Al alloy was measured with varying Vf of SiCw, and the result of the measurement is shown with a solid line in Fig. 8 in comparison with calculated values from Schapery's equation[2] applied for a composite material with fibers aranged in one direction. As shown in Fig. 8, the experimental value is in the middle of the calculated values, each from equation-1 for direction of fiber and equation-2 for right-angled direction of fiber. It was acertained from this result that SiCw is arranged at random in FR-Al alloy and Vf of SiCw at 20% to 40% can achieve the required coefficient of thermal expansion.

(3) The relationship between the Vf of SiCw and bending strength

Fig. 9 shows the results of the bending strength measured with varying Vf of SiCw. The values shown with a solid line are given from our experiment. The values shown with a broken line are given from the calculation by Fujii's equation[3]. It is found that measured values are closer to the calculated values and it is also known to us that when the Vf of SiCw is 30% bending strength is secured 500 MPa.

(4) Determination of the Vf of SiCw

From the above results (1) to (3), as far as bending strength is concerned the required values can be satisfied by any Vf of SiCw, but for wear resistance 25% or more Vf of SiCw is required. On the other hand, the required Vf of SiCw for coefficient of thermal expansion is 20 to 40%. By considerings these data we determined the 30% Vf of SiCw.

Properties of FR-Al Alloy

Consequently we developed the FR-Al alloy which consists of SiCw pre-formed body with 30% Vf and A390 matrix alloy. This newly developed FR-Al alloy has the properties as shown in Table. 5 and fully satisfied with our required properties.

EFFECT WHEN APPLIED TO ROTARY COMPRESSOR

Effect on Application for Vane

We evaluated the new FR-Al alloy vane in the high powered inverter rotary compressor for our unitary air conditioner and the new FR-Al alloy passed all the examinations for performance, durability, etc. We also confirmed that there is no problem as to pursuing ability and wear resistance. Fig. 10 shows the calculated value of vane load to the roller. The data proved that there was no problem with regard to pursuing ability of FR-Al vane to the roller motion.

Effect on Application for Roller

When the new FR-Al alloy is applied to the roller material, it is possible not only to lighten the roller weight itself but also to reduce the mass of the upper and lower balancers. Fig. 11 shows the calculation results of bearing pressure at the journal for both casting iron roller and the new FR-Al alloy roller. As shown in Fig. 11, if the new FR-Al alloy roller is applied, pressure at the journal bearing goes down and efficiency can be expected to increase by the reduction of friction loss.

CONCLUSION

We have found the high strength and light weight material for moving parts to apply for the high powered and high speed rotary compressor. This newly developed FR-Al alloy for moving parts consists of 30% Vf of SiCw pre-formed body and aluminum containing 17% silicon and compounded together by squeeze casting process. This material is of a high strength and light weight material with excellent wear resistance and high chemical stability. When this new FR-Al alloy is applied for a rotary compressor, the vane's high speed operation can be realized because it can pursue the roller motion and bearing pressure is reduced due to the light weight roller, then high efficiency and good reliability of the rotary compressor can be expected. In the future, However, we will continue the further studies for developing a lower cost fiber and for rationalizing the manufacturing process for the FR-Al alloy.

ACKNOLEDGEMENT

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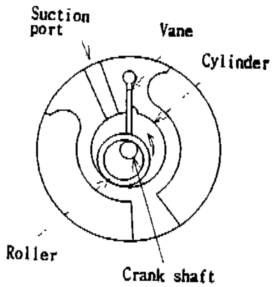


Fig.1 Sectional view of pump.

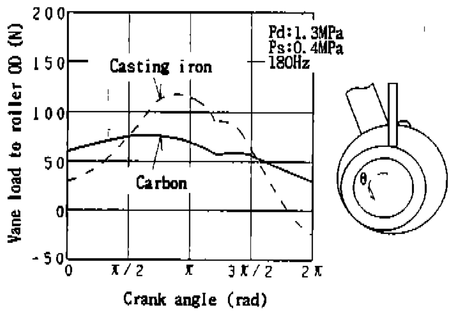


Fig.2 Comparison of vane load.

Table.1 Main structural materials for rotary compressor.

Compressor	Materials			
	Vane	Roller	Cylinder	Crank shaft
Commercial power (50/60Hz)	Wear resistant casting iron	Continuous casting iron	Permanent mold casting iron	Gray casting iron
180Hz inverter	Carbon	Continuous casting iron	Permanent mold casting iron	Wear resistant gray casting iron

Table.2 Required properties for rotary compressor moving parts.

Item	Coefficient of thermal expansion ($\times10^{-6}$/K)	Density (g/cm³)	Bending strength (MPa)	Wear resistance	Charpy impact strength (N-m/cm²)
Required value	11-13 (20-100℃)	3 Max.	300 Min.	to exceed carbon	1 Min.
Casting aluminum (ASTM B108-85a 336.0 Solution heat treatment)	22	2.72	448	——	2
Casting iron (ASTM A48-83 N040)	11	7	300	——	2.5
Carbon	11.3	2.15	170	——	0.35

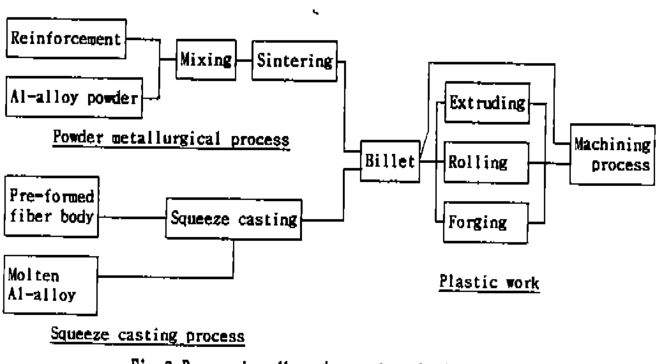


Fig.3 Processing flow charts for aluminum MMC.

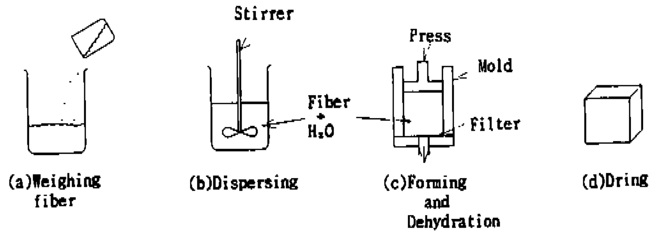


Fig.4 Process for pre-formed fiber body.

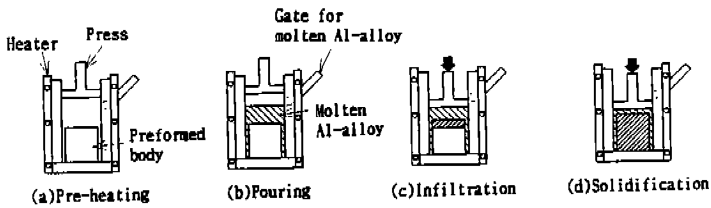


Fig.5 Squeeze casting process for FR-Al alloy.

Table.3 Properties of fibers.

Fiber	Diameter (μm)	Length (μm)	Density (g/cm^3)	Tensile strength (MPa)	Young's modulus (MPa)	Crystal system	Coefficient of thermal expansion ($\times 10^{-6}$/K)
β-SiC whisker	0.1-1.0	30-100	3.2	3-14 $\times 10^3$	4-7 $\times 10^5$	Cubic system	4.3
Al_2O_3 short fiber	3	500	3.3	2 $\times 10^3$	3 $\times 10^5$	Polycry-stalline	5.0
Carbon fiber	7	1300	1.7	3 $\times 10^3$	3 $\times 10^5$	Polycry-stalline	-1.1

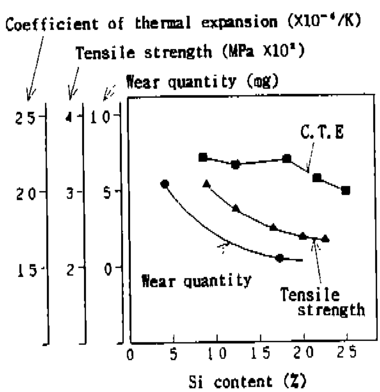


Fig.6 Relationship of wear characteristics, tensile strength and coefficient of thermal expansion vs Si content of aluminum alloy.

Table.4 Chemical composition of aluminum alloy.

Cu	Si	Mg	Fe	Mn	Ti	Al
4.0 ~ 5.0	16 ~ 18	0.5~0.65	0.20 Max.	0.01 Max.	0.01 Max.	Remain

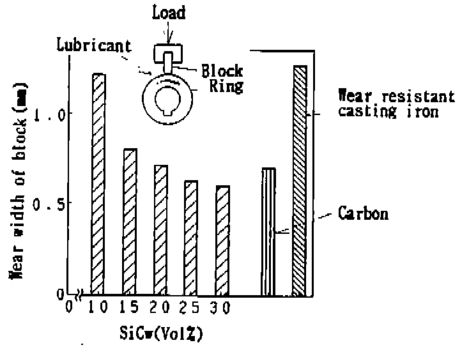
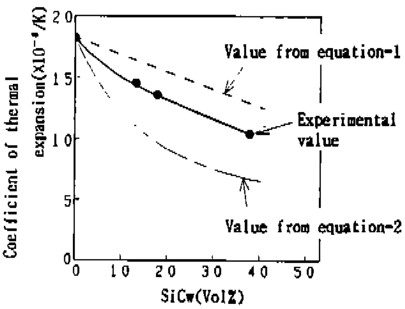


Fig.7 Relationship of wear characteristics vs SiCw content of FR-Al.



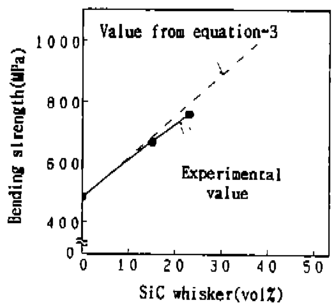
Equation-1 $\alpha c_T = (1-Vf) \times \alpha m + Vf \times \alpha f$

Equation-2 $\alpha c_L = \dfrac{(1-Vf) \times \alpha m \times Em + Vf \times \alpha f \times Ef}{(1-Vf) \times Em + Vf \times Ef}$

αc_T:Coefficient of thermal expansion for a right-angled direction of fiber
αc_L:Coefficient of thermal expansion for the fiber direction
Vf :Volumetric fraction of fiber (%)
αm :Coefficient of thermal expansion of matrix
Em :Young's modulus of matrix (MPa)
αf :Coefficient of thermal expansion of fiber
Ef :Young's modulus of fiber (MPa)

	α (1/K)	E(MPa)
Al alloy	18.3×10^{-6}	7×10^{4}
β-SiCw	4.3×10^{-6}	49×10^{4}

Fig.8 Relationship of coefficient of thermal expansion vs SiCw content of FR-Al.



Equation-3 $\sigma c = K\{B \times Vf \times \sigma f + (1-Vf) \times \sigma m\}$

σc: Bending strength of FRM (MPa)
K : 1.6(Coefficient from tensile strength to bending strength)
Vf :Volumetric fraction of fiber (%)
B : Constant(3/8) for disposition of fiber
σf: Tensile strength of fiber (3×10^{3} MPa)
σm: Tensile strength of matrix (3×10^{2} MPa)

	Tensile strength(MPa)
σf	3×10^{3}
σm	3×10^{2}

Fig.9 Relationship of bending strength vs SiCw content of FR-Al.

Table.5 Properties of FR-Al in comparison with required value.

Material	Density (g/cm^3)	Bending strength (MPa)	Charpy impact strength $(N\text{-}m/cm^2)$	Coefficient of thermal expansion $(\times 10^{-6}/K)$	Wear resistance
New FR-Al	2.85	500	3	12.25	better than carbon
Required value	3 Max.	300 Min.	1 Min.	10-13	to exceed carbon

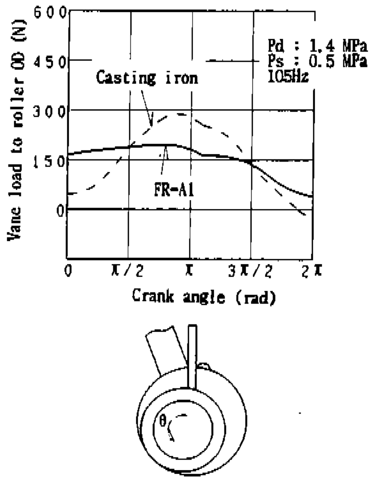


Fig.10 Vane load improvement by using FR-Al vane.

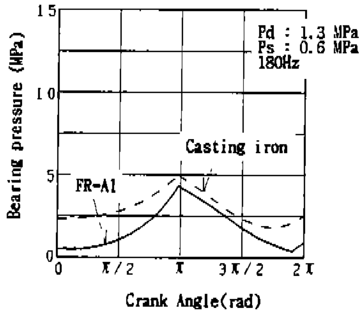


Fig.11 Bearing pressure improvement by using FR-Al roller.