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Low Cost Manufacturing Process of Titanium Matrix Composite Ring

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ABSTRACT

Continuous fiber reinforced titanium matrix composites (TMCs) are attractive as high potential materials to reduce the weight of fan rotor ring. In this study, manufacturing process and over speed test of TMC ring have been reported.

As a cost-effective process for fan rotor ring, monotape preform producing technique has been adopted. TMC ring with a dimension of 130-114mm in diameter and 26mm in width MMC was manufactured. The cost of TMC ring could be reduced by 60%, compared with conventional methods.

Over speed tests of TMC ring has been carried out. For comparison, Ti monolithic ring with the same shape of TMC ring was manufactured and put to the over speed test. For deformation which arises from rotational accelerated velocity, TMC reinforced specimen is less deformable than Ti monolithic one. TMC ring was taken for X-ray radiograph to examine whether the fibers fracture of the TMC occurred or not by the over speed test. From the X-ray radiography after over speed test, dark lines that are not recognized before over speed test are observed. Inner side of a quarter segment of the TMC ring was immersed into hydrofluoric acid to dissolve the matrix, fibers fracture is observed. When TMC ring was examined by means of X-ray radiography, the fracture was detected. The stress distribution of the specimens during over speed test was calculated by finite element method. Analysis results are similar to the ring specimen shapes after over speed test.

INTRODUCTION

In the midst of enhancing movement for environment-conscious, responses to environmental standards are critical for next-generation SST. In the ESPR (Environmentally compatible Propulsion system for next-generation supersonic Transport) project supported by government, CO_2 reduction technologies, NOx reduction technologies, and noise reduction technologies are especially focused as environmentally compatible technologies. Among them, we are researching and developing the light weight designs adopting the advanced materials, which are effective for CO_2 reduction.

Continuous fiber reinforced titanium matrix composites (TMCs) are attractive as high potential materials to reduce the weight of rotor parts, due to their high specific mechanical properties and improved high temperature capability. Particularly, when the fan rotor ring is reinforced by TMCs in the hoop direction, weight saving of more than 30% has been expected. Fig.1 shows cross section of ESPR turbofan engine demonstrator. The target of applying TMC is determined to the compressor in the second stage of the ESPR engine, and research and development have been conducted.

The main barrier of using TMCs is high cost in processing. To lower the material and manufacturing cost, fan rotor ring was designed to be partially reinforced. When fan rotor parts are rotated, high stress in the hoop direction are loaded in the area near inside diameter. It is thought that they are reinforced in the needed volume of TMC in this area. In this paper, manufacturing cost development and over speed test of TMC ring has been reported.

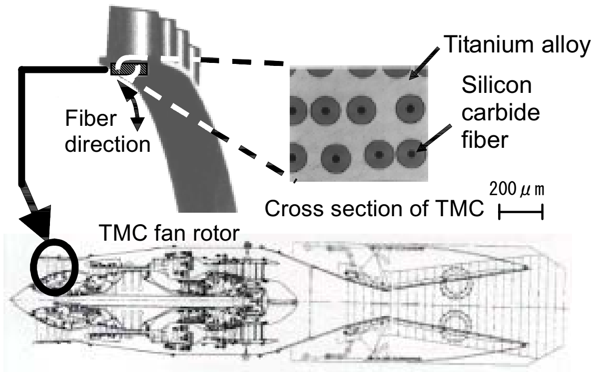

Fig.1 Cross section of ESPR turbofan engine demonstrator

MANUFACTURING PROCESS

There are several methods of manufacturing TMC ring components, such as a foil-fiber-foil method and a coated fiber method. If these methods are applied to manufacture fan rotor parts in which TMCs are partially reinforced near inside diamter, the manufacturing cost couldn't be reduced. Because these methods are stacked silicon carbide fiber and titanium foil in the width direction, a large number of layer increases the manufacturing cost. To make TMCs practicable, it is necessary to develop the new manufacturing process which is laminated in the radial direction.

As a cost-effective process, monotape preform producing technique has been proposed and developed. Fig 2 shows schematic illustration of monopate preform producing technique. Woven-fabric (continuous SiC fibers interwoven with Titanium ribbon) sandwiched by two matrix foils were moved into the hot press die in the vacuum chamber, then they were hot pressed until the opposite surface of matrix foils was diffusion-bonded. Repeating this route continuously, monotape preforms with 2-10 m in length were made. The monotape was rolled up like a ring to fabricate the multi-layered preform. The preform was then encapsulated in a metal container, degassed and sealed. The capsule was consolidated into full dense ring using hot isostatic pressing. The ring was then machined to the required ring dimension. With the use of the monotape perform producing technique, TMC ring specimen for over speed test were manufactured. Configuration of TMC ring is shown in Fig.3. TMC has a dimension of 130-114mm in diameter

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and 26mm in width. Actually the manufacturing cost of TMC ring has been demonstrated to be reduced by 60% by applying monotape preform process, compared with conventional foil-fiber-foil process.

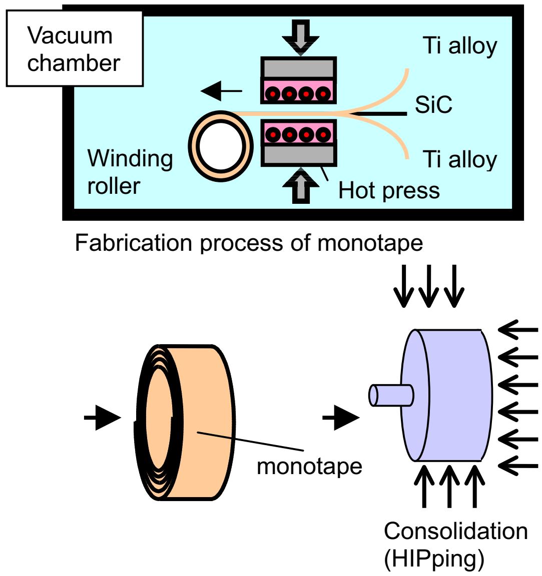


Fig2. Schematic illustration of monotape perform producing technique

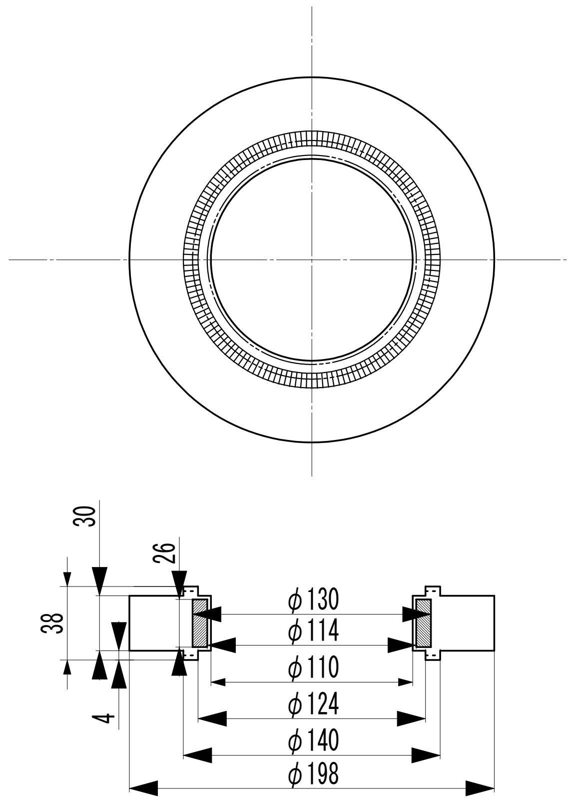


Fig.3. Configuration of TMC ring specimen for over speed test

EXPERIMENT AND ANALYSIS

Over Speed Test of TMC Ring

Over speed tests of TMC ring has been carried out. For comparison, Ti monolithic ring with the same shape of TMC ring was manufactured and put to the over speed test. To curb unbalance during the over speed test, the convex parts of the specimens were attached to the adapter parts of the rotating equipment. Specimens were tested in the following rotation condition. Revolution speed was run up from 0 to 20000 rpm, held for 50 seconds and increased up to 30000rpm. And then, it was repeatedly gone up at the constant cycle that it was held for the 50 seconds and mounted up in increments of 5000rpm. Specimens have been kept rotating until the shaft vibration had started to increase rapidly.

Out-of-plane Distortion of the Specimen after Over Speed Test

Specimens were put on the three points of the support jigs, and planes of the ring surfaces were defined where the points at the angles of 0, 120, and 240 degrees were the same height, as shown in Fig.4. Displacement of a certain point from the defined surface was measured by use of a dial gauge. Points as shown Fig.5 on both sides of the Ti monolithic and TMC ring were measured. The thicknesses at the points as shown Fig.5 were also measured by the micrometer.

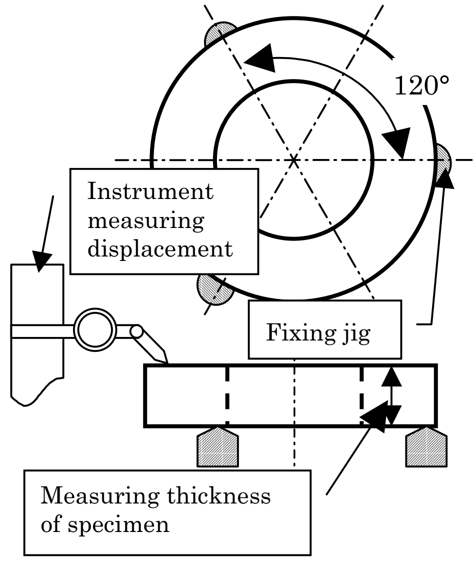


Fig.4 Measurement method of the out-of-plane distortion of the specimen

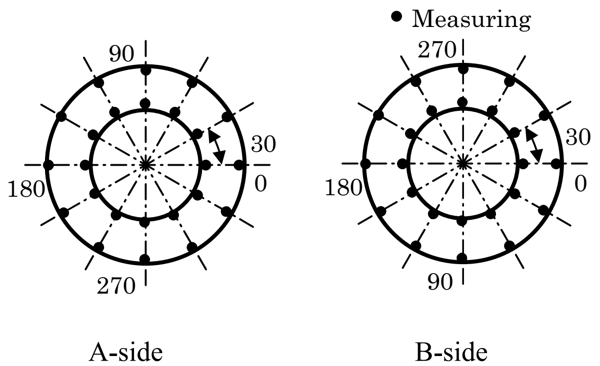


Fig.5 Measuring point of the specimen

X-ray Radiography of the Specimen after Over Speed Test

Convex parts of the both sides of TMC ring specimen were removed by machining, which is intended to improve accuracy of inspection in the TMC reinforced area. It was cut into three segments as shown Fig.6. Three fourths were taken for X-ray radiograph to examine whether the fibers fracture of the TMC occurred or not by the over speed test.

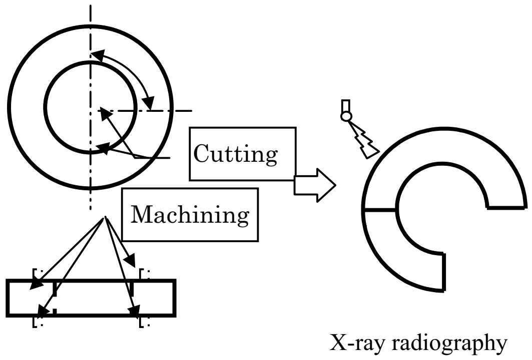


Fig.6 Measurement method of X-ray radiography of the TMC specimen

Examination of Fibers Fracture in the TMC Ring after Over Speed Test

TMC ring specimen was cut into three segments as shown Fig.6; of which the quarter was used to investigate fibers fracture. Inner side of quarter segment of the TMC ring was immersed into hydrofluoric acid to dissolve the matrix, and the fibers fracture of the TMC with over speed test was examined.

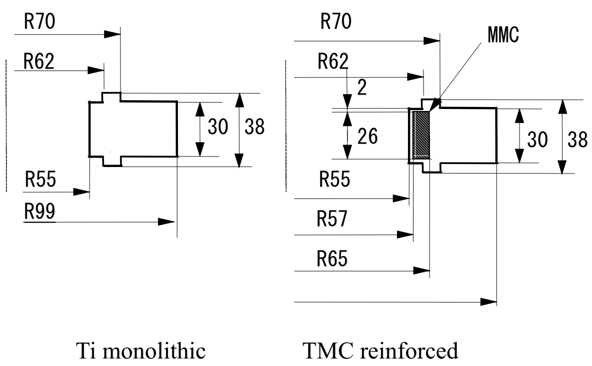


Fig.7 Configurations of FEM analysis model

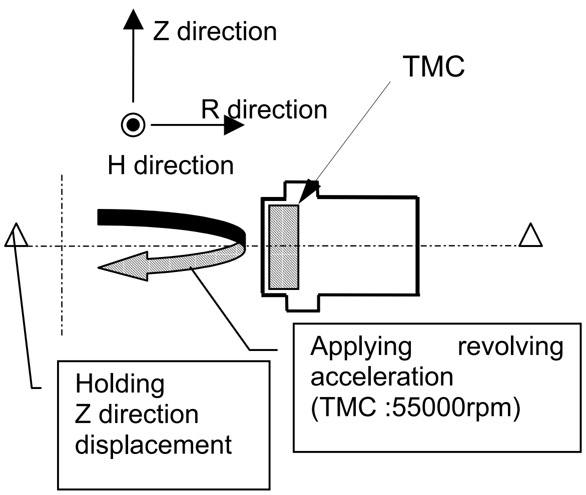


Fig.8 Analysis parameter

Analysis of Spin Test

The stress distribution of the specimens during over speed test was calculated by finite element method, using MSC.MARC program. Fig.7 shows configurations of FEM analysis. Axis symmetric models were used to reduce the analysis time. The parameter used in this analysis is shown in Fig.8. Material data used in this analysis is shown in Table.1.

Table.1 Material data used in this analysis

Ti monolithic	
Young Modulus E (Gpa)	110
Yield Stress σ (MPa)	918
Poissons ratio γ	0.33
Density ρ (kgf/mm^2)	4.5×10^{-10}
TMC	
Young Modulus E_h (Gpa)	202
Young Modulus $E_{r(z)}$ (GPa)	128
Young Modulus G (Gpa)	77.4
Yield Stress σ (MPa)	1608
Poissons ratio γ_{hr}	0.31
Poissons ratio γ_{rz}	0.16
Poissons ratio γ_{zh}	0.26
Density ρ (kgf/mm^2)	4.03×10^{-10}

RESULTS AND DISCUSSION

Spin Test of TMC Ring

The shaft vibration of the Ti monolithic specimen at various revolution speeds during over speed test is shown in Fig.9. When revolution speed was run up from 55000 to 60000 rpm, the shaft vibration had started to increase rapidly. The maximum rotating speed of Ti ring was 56600rpm. The shaft vibration of the TMC reinforced specimen is shown in Fig.10. When revolution speed

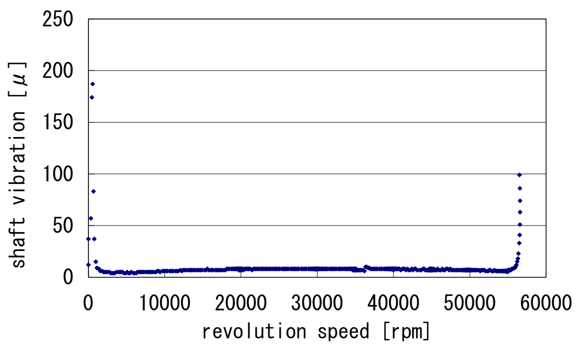


Fig.9 Revolution speed and shaft vibration during over speed test of titanium specimen

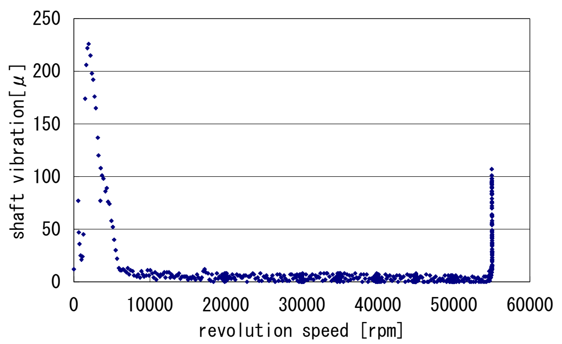
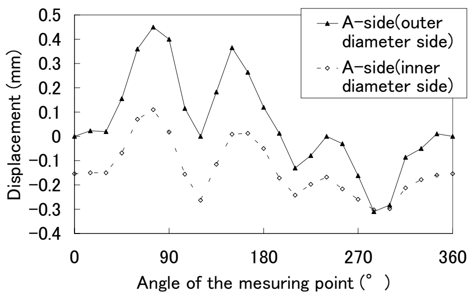


Fig.10 Revolution speed and shaft vibration during over speed test of TMC specimen

was run up from 50000 to 55000 rpm, the shaft vibration had startedto increase rapidly. The maximum rotating speed of TMC ring was 55000rpm. Both specimens were not broken. Deformation of these specimens was not recognized in a macroscopic scale.

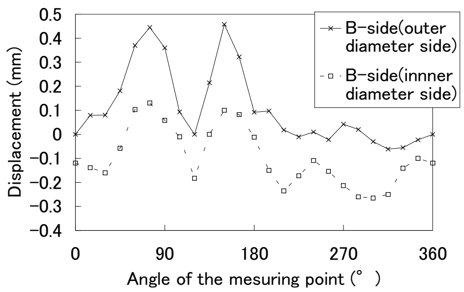
Out-of-plane Distortion of the Specimen after Over Speed Test

Displacement of the defined surface of the Ti monolithic and TMC reinforced specimen is shown in Fig.11 and 12, respectively. In case of Ti monolithic specimen, displacement ranges from 0.468 to -0.31mm. The variation of the displacement for Ti specimen is larger than that for TMC reinforced specimen, which varies from 0.160 to -0.252mm. Fig.13 shows the thickness of the over speed test specimens. The thickness ranges from 30.03 to 28.98 for Ti specimen, and from 30.03 to 29.63 for TMC. The thickness for Ti specimen at inner side is thinner than at outer diameter side. On the other hand, the thickness for TMC specimen at inner diameter side is almost the same as at outer diameter side. Both distortion and thickness for Ti specimen vary larger than those for TMC. In case of Ti specimen, plastic deformation extends over Ti ring due to the stress which arises from rotational accelerated velocity. So, outer side of Ti ring is wholly distorted especially at inner side. On the other hand, variation for TMC ring is slight in distortion and thickness. Outer side of TMC ring has the same distortion and thickness as inner side. These results indicate that the TMC reinforced specimen is less deformable than Ti monolithic one, because TMC reinforced area receives the revolving stress and keeps ring shape less deformable.



Outer diameter side : maximum value 0.450 minimum value -0.310
Inner diameter side : maximum value 0.110 minimum value -0.303

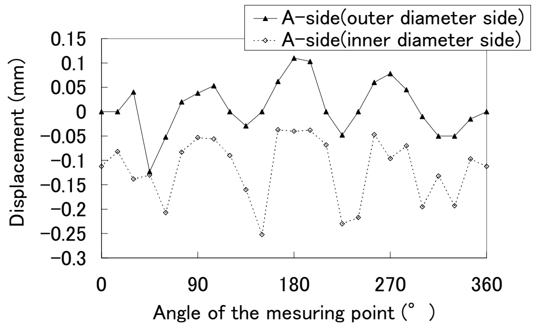
A-side



Outer diameter side : maximum value 0.458 minimum value -0.061
Inner diameter side : maximum value 0.130 minimum value -0.265

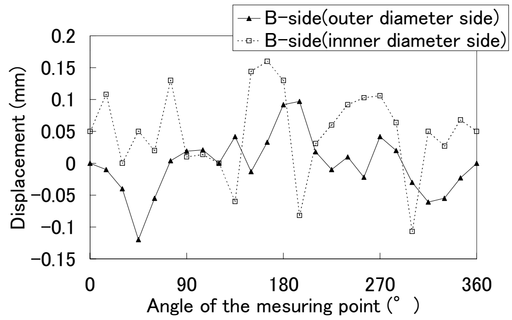
B-side

Fig.11 Displacement of the measuring point from the definition plane with titanium monolithic specimen



Outer diameter side : maximum value 0.110 minimum value -0.123
Inner diameter side : maximum value -0.037 minimum value -0.252

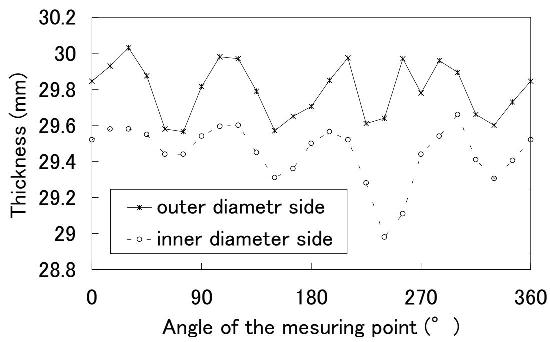
A-side



Outer diameter side : maximum value 0.097 minimum value -0.120
Inner diameter side : maximum value 0.160 minimum value -0.107

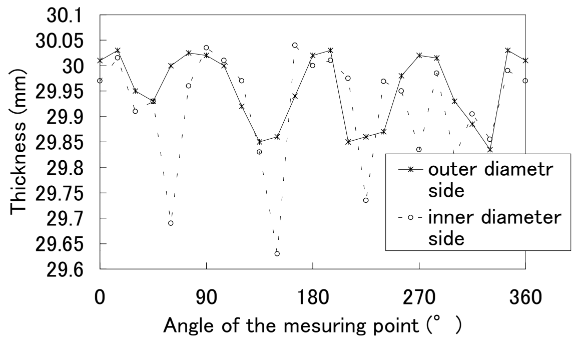
B-side

Fig.12 Displacement of the measuring point from the definition plane with TMC specimen



Outer diameter side : maximum value 30.03 minimum value 29.565
Inner diameter side : maximum value 29.66 minimum value 28.98

Titanium monolithic specimen



Outer diameter side : maximum value 30.03 minimum value 29.835
Inner diameter side : maximum value 30.04 minimum value 29.63

TMC specimen

Fig.13 Thickness of the measuring point of Ti monolithic and TMC specimen

X-ray Radiography of the Specimen after Over Speed Test

X-ray radiography of the TMC ring after hot isostatic pressing (before over speed test) is shown in Fig.14. Over all picture of X-ray radiography of the TMC ring after over speed test is shown in Fig.15. Black area in the innermost layer is a lead sheet which curbs radio scattering around boundary of ring. Gray area is titanium alloy, white area is TMC. Fig.16 shows the radiography on larger scale. Dark lines across the TMC ring are observed as indicated by red arrows. They are not recognized from the radiography after hot isostatic pressing. It is guessed that empty space is generated by fibers fracture, because it resembles area where there is nothing in color.

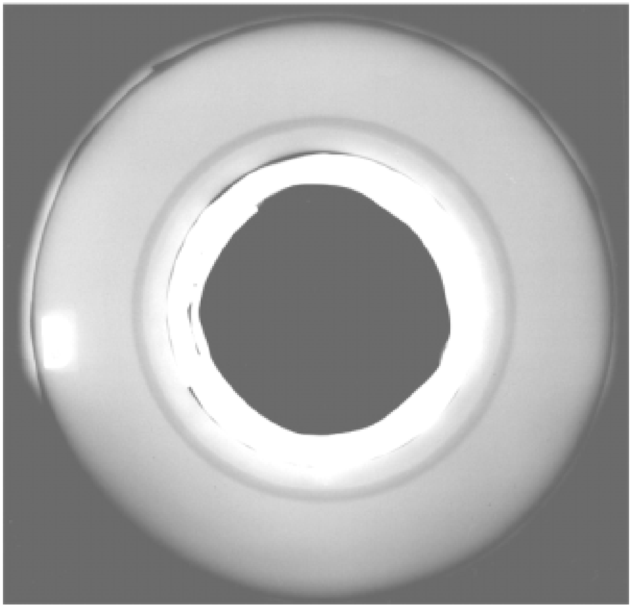


Fig.14 X-ray radiography of the TMC ring after hot isostatic pressing

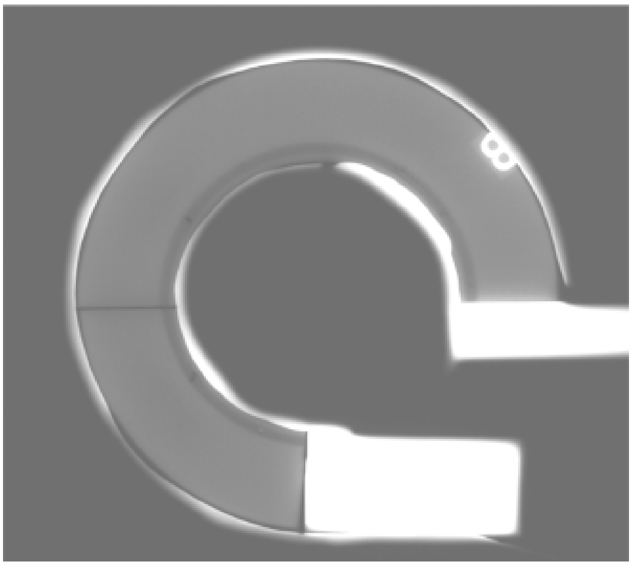
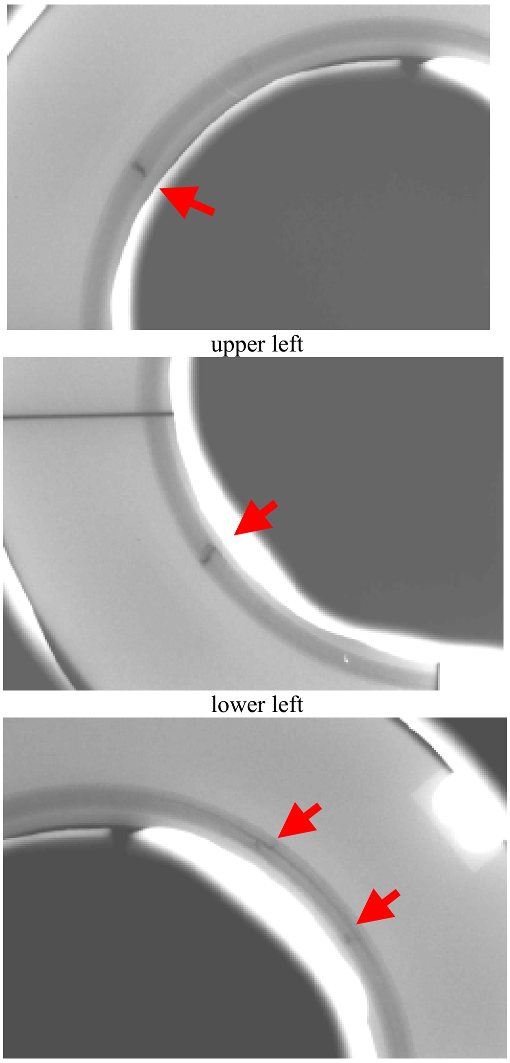


Fig.15 Over all picture of X-ray radiography of the TMC ring after over speed test



upper left

lower left

upper right

Fig.16 X-ray radiography on larger scale of the TMC ring after over speed test

Examination of Fibers Fracture in the TMC Ring after Over Speed Test

Fig.17 shows outlook of the TMC ring after inner side of quarter segment of the TMC ring was immersed into hydrofluoric acid. Fig.18 shows fibers fracture of the TMC specimen. Fibers fractures are observed at A and B site. Shapes of fiber fracture are almost parallel in the direction of rotation axis. All layers of fibers are fractured in the radial and rotation axis direction. When TMC ring was examined by means of X-ray radiography, this area was detected as a result of gathering void space.

Fig.17 Outlook of the TMC ring dissolved metal matrix inner side

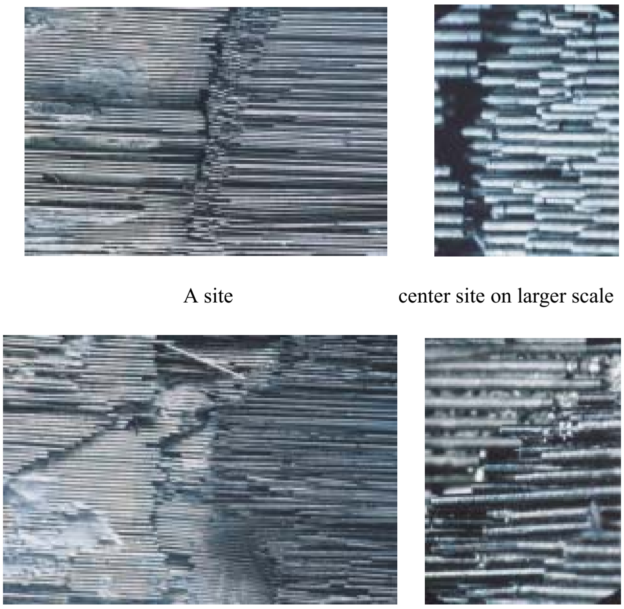


Fig.18 Fibers fracture of the TMC specimen

Analysis of Spin Test

A z-axial displacement at maximum rotating speed is shown in Fig.19. In the case of Ti monolithic ring, the upper area of inner side is deformed lower than outer side and the under area of inner side is deformed higher than outer side. So the thickness of inner side is thinner than outer side. On the other hand, in case of TMC ring, thickness in the area around the TMC is the thinnest. The distortion of Ti specimen vary larger than that of TMC. The maximum displacement of Ti ring is almost twice as large as that of TMC ring. So analysis results are similar to the ring specimen shapes after over speed test.

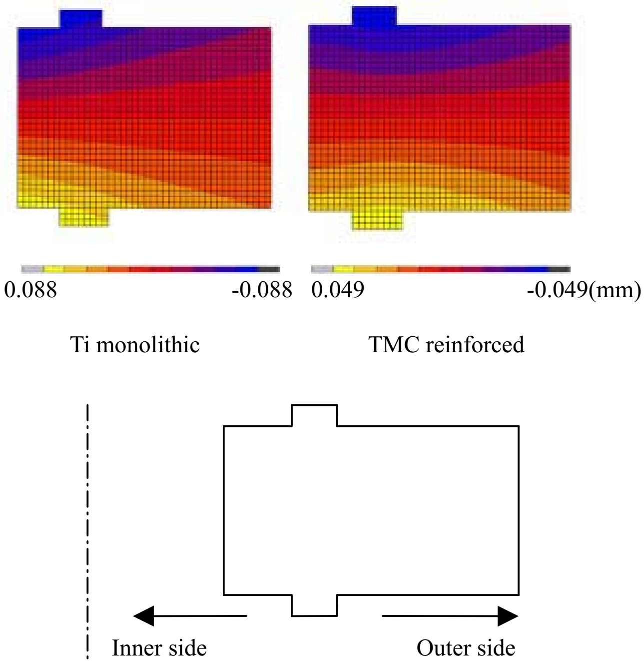


Fig.19 Z-axial displacements at maximum rotating speed

Fig.20 shows von-Mises stress of Ti monolithic specimen at each rotating speed. As shown Fig.20, plastic deformation occur the inner side of Ti ring at 48000rpm. The faster the rotating speed, the more the plastic deformation area expands. Fig.21 shows von-Mises stress of TMC reinforced specimen at each rotating speed. In case of TMC ring, TMCs are not fractured at 52000rpm yet. On condition that von-Mises stress of TMC specimen changes the same stress range as that of Ti monolithic specimen, stresses at the inner side of Ti ring are not yet to reach yield stress at 48000rpm, as shown Fig.22.

Based on these results, out-of-plane distortion of the specimen is looked as follows. In case of Ti specimen, plastic deformation occurs at the inner side of Ti ring at 48000rpm. Nonetheless, over speed test could be continued until the revolving speed had run up to 56600 rpm. On the ground that the ring is thick, it is hard to induce unbalance on the occasion when plastic deformation expands over Ti ring. As a result, out-of-plane distortion could be difficult to occur. However, once unbalance happens, Ti ring is easy to be distorted on a large scale because convex parts of the both sides have already yielded and could not be functioned to suppress unbalance. In case of TMC reinforced ring, because of TMC reinforced area receiving the revolving stress, convex parts are not yet to be yielded and be functioned, so TMC reinforced specimen is less deformable.

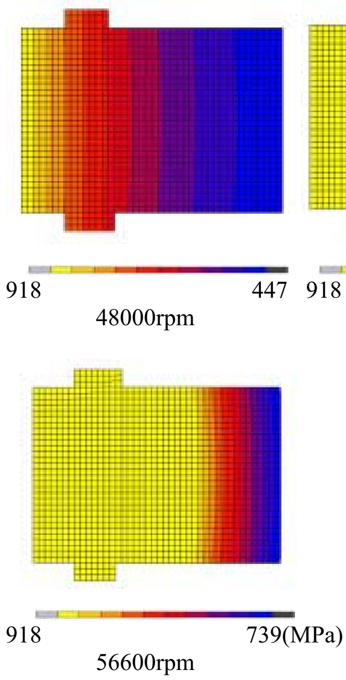


Fig.20 von-Mises stress of Ti monolithic specimen at each rotating speed

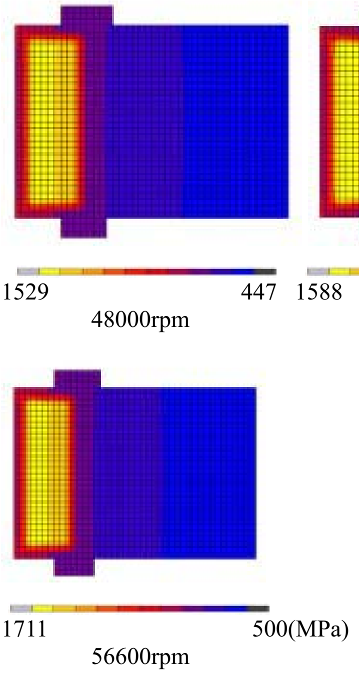


Fig.21 von-Mises stress of TMC specimen at each rotating speed

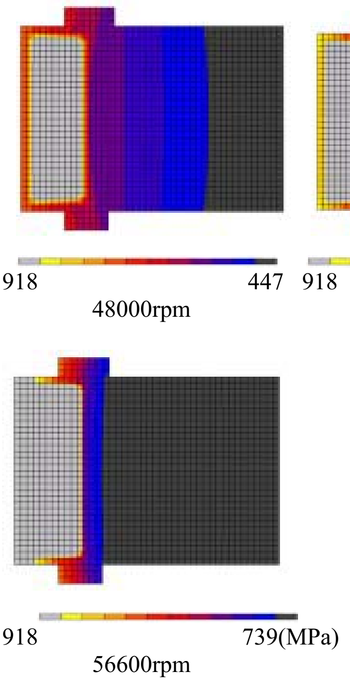


Fig.22 von-Mises stress of TMC specimen at each rotating speed changed the same maximum value of stress range as the yield stress of Ti specimen

CONCLUSION

With the use of monotape preform producing technique, TMC ring was manufactured. Over speed test of TMC ring has been carried out. For comparison, Ti monolithic ring with the same shape of TMC ring was manufactured and put to the over speed test. As a result, it become clear as follows:

(1) Although the maximum rotating speed of TMC ring was almost the same as that of Ti ring, both distortion and thickness of TMC specimen vary smaller than those of Ti monolithic, especially outer side of ring.

(2) TMC ring was taken an X-ray radiograph to examine whether the fibers fracture of the TMC occurred or not with over speed test. From the radiography after over speed test, dark lines which are not recognized before over speed test are observed.

(3) Inner side of a quarter segment of the TMC ring was immersed into hydrofluoric acid to dissolve the matrix, fibers fracture is observed. The shapes of fiber fracture are almost parallel to the direction of rotation axis. All layers of fibers are fractured in the radial and rotation axis directions. When TMC ring was examined by means of X-ray radiography, the area of fracture was detected as a result of void space.

(4) The stress distribution of the specimens during over speed test was calculated by finite element method. Analysis results indicate that the TMC reinforced specimen is less deformable than Ti monolithic one, because TMC reinforced area receives the revolving stress and suppresses that plastic deformation expands over ring specimen. These analysis results are similar to the ring specimen shapes after over speed test.

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BIBLIOGRAPHIC REFERENCES

S.Mall.T.Fecke., and M.A.Foringer., 1998 “Titanium Matrix Composites, ed.” by Shankar Mall and Theodore Nicholas, Thecnomic Publishing Co. Inc., pp.1-11

C.M.Ward-Close., and C.Loader, 1995, “Recent Advantage in Titanium Metal Matrix Composites,” ed. by F.H.Froes and J.Storer, TMS, Warrendale, PA, 1995, pp.19-32

Zheng Xiao Guo., 1997, “Processing of Ti / SiC Composites, A comparative study of the foil and the tape-casting techniques: Synthesis /Processing of Lightweight Metallic Materials Ⅱ, ed. by C.M. Ward-Close, F.H. Froes, D.J. Chellman, and S.S. CHO,” The Minerals, Metals & Materials Society, pp.195-206

K.Moriya, Y.Nojima, S.Nishibe., and K.Yasuhira., 1999, “Fabrication of Titanium Metal Matrix Composite Bling”, Proc. 12th Int. Conf. on Composite Materials (ICCM).