BepiColombo HGA ARA C/SiC Struts: A thermo - mechanical challenge for support structures in harsh environments

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Abstract
The BepiColombo orbiter, ESA's ambitious mission to Mercury, requires a lot of sophisticated solutions to succeed with the technical challenges resulting from the harsh environment in Mercury's orbit, with resulting component temperatures ranging from -196°C to 550°C.
Amongst others the structure of the High Gain Antenna of the orbiter, consisting of two times three struts, is a highly thermally loaded structure. Before exposure to the high temperature gradients the structure needs to be very stiff surviving the loads during launch. But not only withstanding the high temperature is a challenge, also a very low coefficient of thermal expansion is required to guarantee a permanent stable position of the sub reflector for high antenna pointing accuracy. ASTRIUM took the challenge and manufactured the struts out of ceramic matrix composites.

1. Introduction

The challenge of developing a strut able to withstand the high temperatures while expanding less as possible and surviving the high acoustic (vibration) and mechanical loads during launch led to the selection of carbon endless fiber reinforced silicon carbide as material for the struts. ASTRIUM's heritage and experience of manufacturing such ceramic matrix composite (CMC) material was the key factor to success. Besides the manufacturing the testing including mechanical testing of components (struts) in tensile and compression, measurement of coefficient of thermal expansion and vibration testing were a high effort to accept the struts for flight.

2. BepiColombo Mission

Named after the scientist Giuseppe "Bepi" Colombo (1920 - 1984) Europe's first mission to Mercury will be the third mission ever to the innermost planet of our Solar System. So far only NASA's Mariner 10 and MESSENGER provided close-up images of the planet when flying by in 1974/1975 and 2008/2009. Now BepiColombo will conduct the most extensive and detailed studies. This will be realized by orbiting Mercury for planned mission duration of one year. A second year is in principle possible [1].
In cooperation with the Japan Aerospace Exploration Agency (JAXA) the European Space Agency (ESA) is developing the spacecraft. Launched by an Ariane 5 rocket BepiColombo consists of three spacecrafts forming a single composite spacecraft during the voyage. Having reached Mercury JAXA's Mercury Magnetospheric Orbiter (MMO) will be deployed into its orbit. Finally ESA's Mercury Planetary Orbiter (MPO) will be separated from the Mercury Transfer Module (MTM) [1].
The artist’s view in Figure 1 shows the two BepiColombo orbiters (MPO and MMO) mounted on top of their transfer module (cruise configuration).

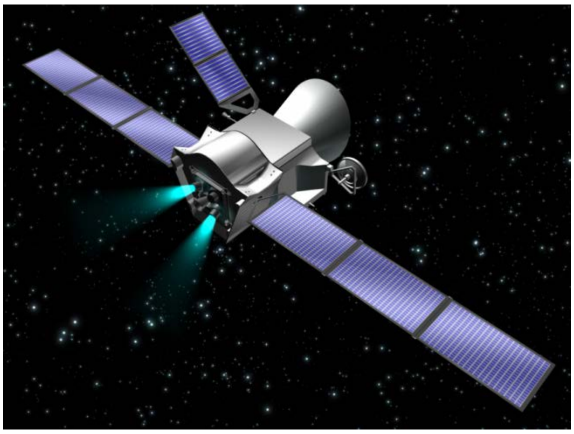


Figure 1: BepiColombo's cruise configuration [2]

The voyage to Mercury will last for 6.5 years. After being placed into orbit by the launcher, the composite spacecraft will be accelerated by solar-electrical propulsion and in total seven gravity-assistance maneuvers.
Having arrived Mercury BepiColombo's cruise-configuration spacecraft will separate. The transfer module will be ejected back into space and the remaining composite spacecraft with the Mercury Planetary Orbiter (MPO) and the Mercury Magnetospheric Orbiter (MMO) will use conventional rocket engines and the so-called 'weak stability boundary capture technique' to enter into polar orbit around Mercury. After reaching MMO's orbit also the MPO will be separated and lowered in altitude to its operational orbit by chemical propulsion [3].
In Figure 2 the fully separated spacecraft is drawn.

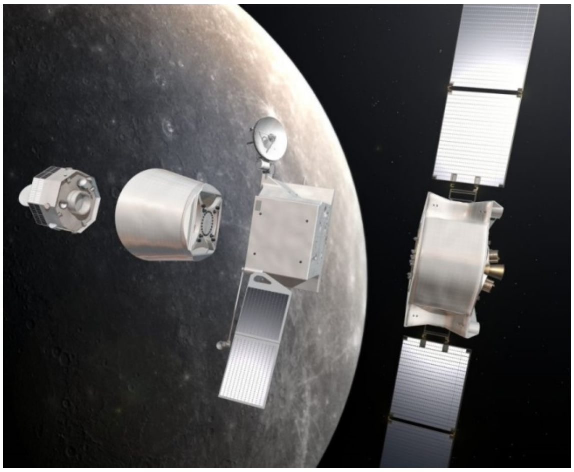


Figure 2: BepiColombo's cruise components separate at Mercury [3]

1.2 Mission objectives

Being the second spacecraft to orbit Mercury, BepiColombo will study intensively the composition, geophysics, atmosphere, magnetosphere and history of the planet. A lot of experiments will help exploring the least explored planet of the inner Solar System. A lot of questions shall be answered such as is Mercury's core liquid or solid, why is there in intrinsic magnetic field or if there is sulphur or water in the permanently shadowed craters. Further details on the mission objectives are documented in the source [1].

1.3 Challenges

Reaching Mercury is the challenge when designing the MTO. Using the available energy soaring such a far way is only possible by gravity-assistance manoeuvers. Once reached Mercury's orbit the orbiters face a harsh environment. Due to the proximity of the sun the solar radiation is ten times higher than in Earth's proximity. Besides that Mercury's surface reaches temperatures up to 470°C and does not reflect only the solar radiation but also the thermal infrared radiation [1].

The expected temperatures for parts of the MPO will vary between -10°C and +400°C, while a temperature raise of 400°C in 10 minutes is expected. Design criteria for some parts including the antenna reflector assembly defines a temperature range from -196°C up to +550°C as worst case scenarios.

3. High Gain Antenna

ESA's MPO will carry a lot of on board equipment for tests and measurements. For communication a high gain antenna is installed allowing communication and data link with earth. The antenna will also be used for the so called Radio Science Experiment (RSE), which requires a very high accuracy of the reflector position. As a typical accuracy of the sub-reflector position opposite the reflector one (1) mm is required. In an ambient temperature this accuracy is easy to reach, but keeping in mind the wide temperature range in Mercury's orbit thermo-stable design and materials are required.
In Figure 3 a CAD illustration of MPO with view on the High Gain Antenna is shown. The antenna is mounted on a movable arm allowing accurate positioning.

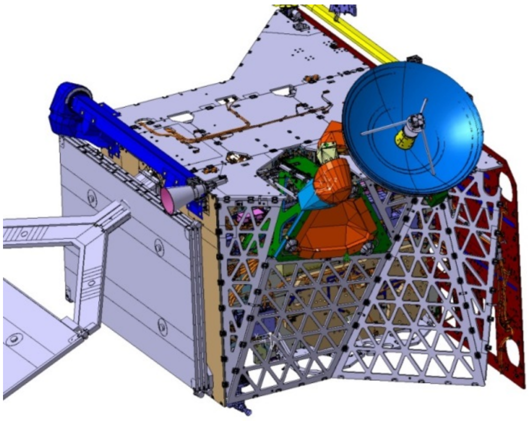


Figure 3: CAD illustration of MPO with view on the High Gain Antenna

3.1 Antenna structure

The antenna basically consists of the main reflector and sub-reflector, a support structure, all three made from Titanium, and six thermo-stable struts forming a tetrahedron and connecting the sub-reflector with the support structure.
In Figure 4 a CAD illustration of the High Gain antenna is published showing the reflectors and support structures.

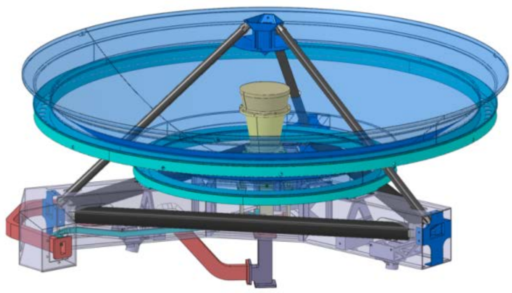


Figure 4: CAD illustration of the High Gain Antenna

3.2 Struts

Being connected with the sub-reflector the struts influence directly the accuracy of positioning the sub-reflector. The key factors for keeping the accuracy within the requirements are the ability of the material to withstand the high thermal loads and having a very low Coefficient of Thermal Expansion (CTE). Additionally for launch a high stiffness is necessary to withstand the vibration load. As for all space structures weight is always an issue, so the struts shall be as light weight as possible.

These requirements lead to the selection of ASTRIUM's carbon endless fiber reinforced silicon carbide material (C/SiC - SICARBON) supported by the TRL / MRL reached over the last years developing such thermo-stable structures using ceramic matrix composites (CMC).
In Figure 5 a detailed view of the C/SiC tetrahedron structure is shown. The three struts building the support structure measure 40mm in diameter while the struts keeping the sub-reflector in position are 20mm in diameter.

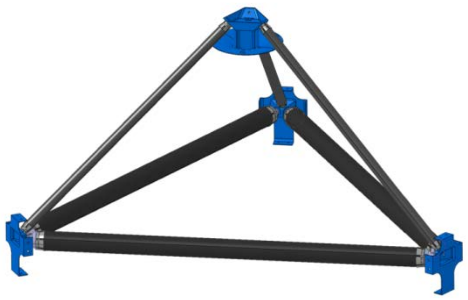


Figure 5: Tetrahedron structure of high gain antenna with six C/SiC struts and connectors (CAD illustration)

4. C/SiC struts

CMC are advanced materials developed for applications like aerospace, energy, automotive industry and others because of their mechanical strength, chemical resistance against a lot of materials and mainly because of their heat resistance.
In comparison to monolithic ceramics CMCs show a damage tolerant behavior which can be called also "quasi-ductile". This fracture mechanism is realized by the endless fiber reinforcements, which re-direct the fracture energy coming across the matrix, along the fiber direction until rupture of the fiber and the pull-out out of the matrix.
CMC can be manufactured via various processes, for manufacturing the C/SiC struts ASTRIUM is using the Polymer Infiltration Pyrolysis (PIP) process [4].

4.1 Manufacturing process

The PIP process for strut manufacturing consists of five main steps, which are also illustrated in Figure 6:

- Step 1: The carbon fibers are coated to create a weak interface. This is necessary to ductilize the fiber-matrix bonding and to allow the quasi ductile behavior created by fiber pull out.
- Step 2: Infiltration of coated fibers (roving) with a polymer system or a powder filled slurry and in-situ filament winding of strut on mandrel tool.
- Step 3: After filament winding the struts are cured under temperature and pressure in an autoclave.
- Step 4: Curing is followed by ceramization of cured struts via pyrolysis. Pyrolysis is a high temperature process under vacuum or inert atmosphere.
- Step 5: Several re-infiltration with a pre-ceramic polymer followed by pyrolysis in order to reduce porosity [4].

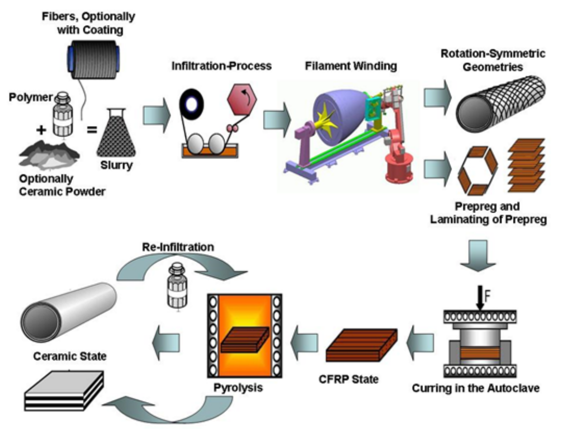
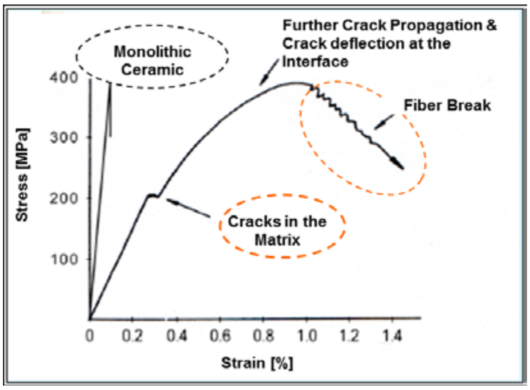


Figure 6: PIP process for strut manufacturing

4.2 Damage tolerant behavior

Often CMC are classified as technical ceramics, e.g. silicon carbide (SiC) or silicon nitride (SiN). From the terminology the close relation is obvious but the fracture behavior is totally different. Also most technical ceramics are monolithic ceramics. For qualification of technical ceramics often a high amount of specimen has to be tested to obtain a wide range of values to calculate the probability of failure. While test results of CMC, for example tensile tests, do not scatter in such a wide range, a smaller amount of specimens is required to keep the qualification costs lower. To provide evidence of the damage tolerant fracture behavior, ASTRIUM is working on the development of stress calculation methods for CMC.
In Figure 7 (a) typical stress-strain curves of monolithic ceramics and CMC are plotted. While the ceramic is cracking brittle, the CMC is showing a so called quasi - ductile behavior. This can be explained with help of Figure 7 (b) showing the principles of crack propagation in CMC. If the load is too high the matrix will crack. The crack will propagate up to the next fiber where it will be deflected along the fiber. The fibers itself can transfer much higher loads. If these loads are too high the fiber will crack also. Due to a weak interface to the matrix the fiber will be pulled out now. This fracture mechanism is the reason for the quasi - ductile behavior [4].



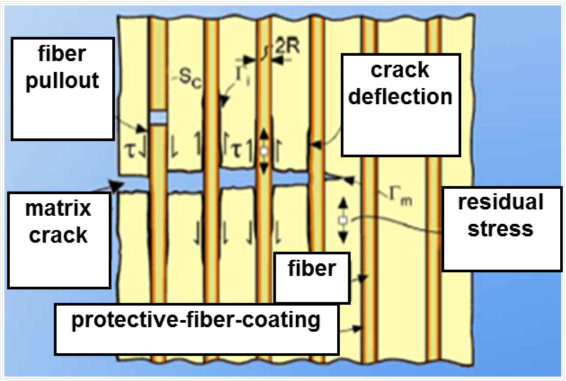


Figure 7: (a) Stress - Strain diagram of monolithic ceramic and CMC; (b) Schematic view on crack propagation in CMC [4]

A fatal fracture caused by overload during launch, hit by debris or micro meteorites would mean the loss of the strut and loss of mission. By testing the strength of struts in tensile and compression direction the quasi-ductile behavior, the acceptance for flight could be realized. To demonstrate the fracture behavior a strut was penetrated by hammering nails into it as impressively shown in Figure 8. A monolithic ceramic would have been broken, but due to the fiber reinforcements the strut is still intact.

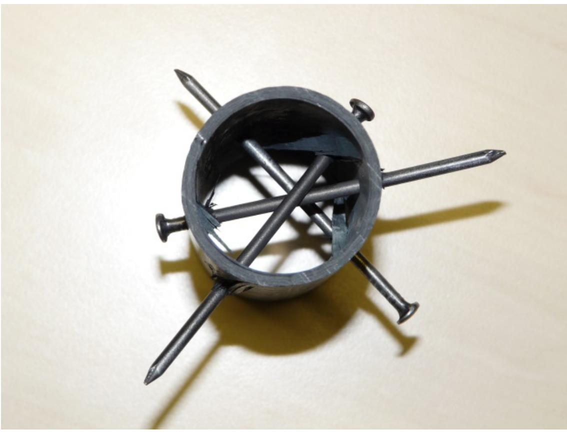


Figure 8: C/SiC strut penetrated with nails

4.3 Design of C/SiC struts

The C/SiC struts are designed to withstand the expected temperatures (see §1.3), showing a very low CTE (see §3) but providing at the same time a high stiffness required for the high acoustic and mechanical loads during launch. With the given strength requirements the fiber orientation and stacking is designed.

4.4 Interface design

CMC components often need to be connected to other structural components. For combustion chambers or nozzle extensions interfaces to the metallic engine components have to be realized. While manufacturing via the PIP process, winding does not allow in most cases the realization of an integrated interface. This has to be manufactured separately and joined or assembled in later status. Also for the struts this constraint is given. Here the interface to the sub-reflector and the main structure has to be realized.
ASTRIUM has developed two interface designs appropriate covering all requirements. First joining technique of metallic parts with C/SiC is based on a brazing process called SICBRAZE® [5].This interface is proven in several hot tests of thrusters and also tested for struts during development. The second available joining technique is based on clamping. This technique was especially designed for the BepiColombo struts and verified during the lot acceptance process.
The brazing technology of joining C/SiC with Niobium was developed for thruster application assembling the C/SiC combustion chamber with the injector head. It is also suitable for structural assembly with lower strength requirements compared to component strength caused by the low Interlaminar Shear Strength (ILS) of the 2D C/SiC laminate which is the baseline for the brazing interface. A brazed interface requires an accurate pre - machining and preparation of the surface, an activation brazing step and the brazing with fitting. A solid and light weight interface can be designed this way [5].
To overcome the lower strength of a brazed interface and to safely transfer all loads up to rupture of the CMC struts, so being able to use the ultimate tensile strength of the CMC component, another interface design is required. ASTRIUM developed a clamping fitting, manufactured out of Titanium (same material as the reflector), which is able to transfer all loads until rupture of the strut. In comparison to the brazed fitting, the amount of parts and the total weight increased, but the machining of the C/SiC part is easier. Verification of the design and acceptance for flight were realized by mechanical rupture tests, such as tensile testing, non-destructive inspections by computer tomography and measurements. In Figure 9 the clamped fitting assembled with a strut is shown.

Figure 9: Clamped fitting on C/SiC strut

5. Verification of design

5.1 Strength and stiffness

For the design of the struts and the reflector assembly, tensile and compression strength and Young's Modulus requirements had to be fulfilled. Strength of the components was investigated by samples.
In Figure 10 some results of the tensile strength measurements on diameter 20mm and 40mm C/SiC struts are plotted. It can be seen that all struts met the required 100% requirement including the safety factor. The 40mm struts show a slightly higher strength caused by the geometry.
Much more important is the Young's Modulus requirement needed to survive the acoustic and mechanical loads during launch. Also here the requirement is met. In Figure 11 the Young's Modulus of two C/SiC strut samples each diameter are plotted. Here the test was conducted in compression to verify also the strength and Young's Modulus in comparison to tensile loads.

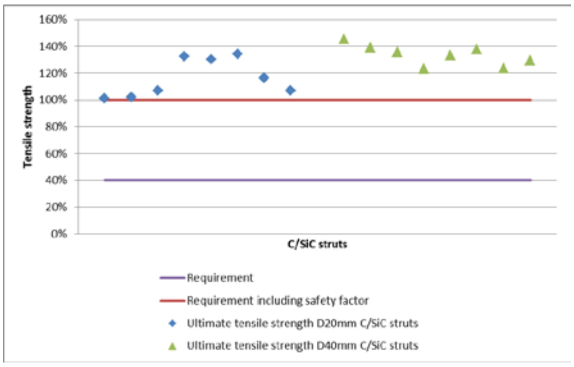


Figure 10: Tensile strength of C/SiC struts

Figure 11: Young's Modulus of C/SiC strut tested in compression

5.2 CTE measurements

CTE measurement was conducted by KRP-Mechatec Engineering, who developed a high resolution thermal deformation measurement system. This system, measuring with a laser interferometer in a thermal vacuum chamber, is able to measure the C/SiC struts diameter 20 with a length of 140mm. At the same time it is capable of measuring even smallest expansions in comparison to standard equipment capable of testing only small samples. In Figure 12 the test setup is exemplarily shown. More information is available in reference [6].

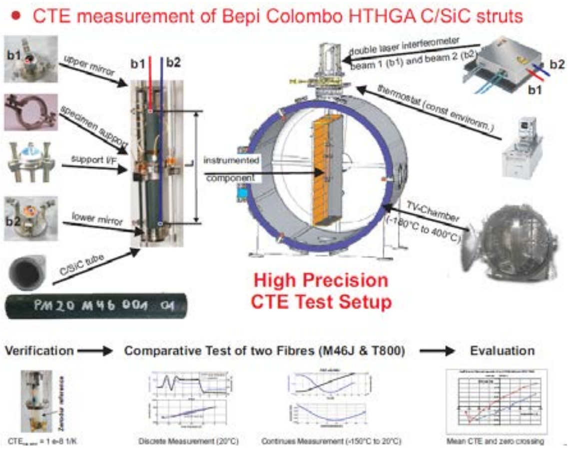


Figure 12: CTE measurement of BepiColombo C/SiC struts [6]

In Figure 13 the measurements are plotted for a comparison in between the different fibers, fiber orientations and Titanium. It is clearly visible why C/SiC was selected for the struts. Titanium has a more than ten times higher CTE than C/SiC with the high modulus fiber and orientated fibers. Showing measurements in between -150°C and +180°C the CTE especially of higher temperatures have not been measured yet on struts due to limitations of the measuring equipment. Comparing results of quasi - isotropic flat specimens a nearly linear behavior at high temperatures can be expected.

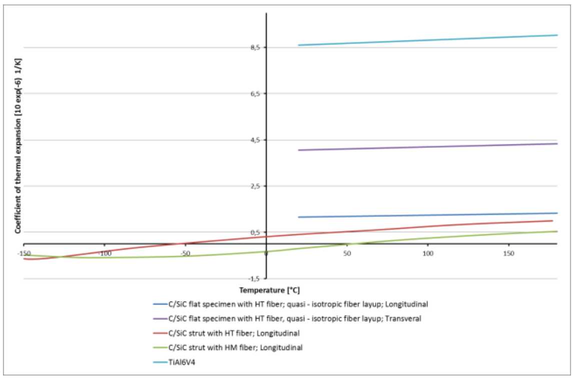


Figure 13: Measurement of coefficient of thermal expansion in between -150°C and 180°C [7]

6. Qualification approach

ASTRIUM's C/SiC material has a long history including testing and also flight heritage. Structures for Thermal Protection Systems (TPS) and rocket engines were developed and manufactured. Most famous parts are TPS for the X38, AESTUS nozzle extension or a 400N engine [4]. All parts were qualified for their application or for testing. For struts there has been no qualification until today, especially as the material cannot be standardized due to variation of fiber orientation and the resulting different mechanical behavior.
Therefore ASTRIUM, TAS-I and ESA agreed on a so called lot acceptance approach. All struts are manufactured as one batch. With an extra length on each strut witness samples could be generated which then were tested. But also the flight model struts underwent some inspections steps such as Non Destructive Inspections (NDI) by Computer Tomography (CT), thermal cycling, vibration testing on a shaker system and limit load testing. To allow conformity in between the batch all process steps were conducted at the same time wherever possible.

7. Conclusion

ASTRIUM developed, on basis of the wide experience on C/SiC, struts able to withstand the mechanical and thermal loads in the harsh environment during the journey and orbit of BepiColombo on its Mercury mission. C/SiC, specially tailored for the mission requirements, proved to be not only a material usable for hot gas environments but also for structural parts requiring a very low CTE and high stiffness. With the acceptance tests for flight ASTRIUM made a huge step forward pushing C/SiC as reliable structural material into aerospace applications.

Acknowledgements

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