Design and Manufacture of a Highly Reliable, Miniaturized and Low Mass Shutter Mechanism

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Abstract

This paper describes the development, manufacturing and testing of a lightweight shutter mechanism made of titanium for the MERTIS Instrument. MERTIS is a thermal infrared imaging spectrometer onboard ESA's future BepiColombo mission to Mercury. The mechanism is built as a parallelogram arrangement of flexible hinges, actuated by a voice coil. In a first test run, it was shown that the selected EDM processing led to the generation of titanium oxides and an oxygen-enriched surface layer on the substrate (so called α-case layer). In the revised version of the shutter, it was possible to manufacture the complex geometry by micro-milling and an adjacent pickling procedure. The adequacy of this approach was verified by lifetime and vibration testing.

Introduction and Requirements

The MERTIS instrument is a thermal infrared imaging spectrometer onboard ESA's future BepiColombo mission to Mercury. For the spectrometric data acquisition, a calibration signal that contains information about the instrument background radiation is required. This is performed by periodical acquisitions while the targets scene (i.e., planet radiation) is blocked. Therefore, a mechanical shutter is required to block the optical path from the planet view of the instrument.

The main requirements for the shutter mechanism are specified in Table 1.

Table 1: Shutter main requirements

	Requirement
Mass	25 g
Max. dimensions	20 x 40 x 5 mm^3
Max. Frequency	10 Hz
Duty cycle	1:10
Lifetime test	100 x 10^6 cycles
Fail safe position	Shutter-blade in open position
Aperture	1.5 mm x 8 mm

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Shutter Design

In an extensive study, all major shutter driving principles have been investigated for their use in MERTIS: rotary DC motors, linear piezo actuators/motors, piezo bender actuators, and linear voice coil actuators (VCA).

An important criterion was that the majority of possible failures shall lead to a defined fail safe position (i.e., shutter-blade open). Therefore, the voice coil actuator with a moving magnet and a stationary double coil (HELMHOLTZ alignment) was selected. It is simple to design a VCA mechanism where the inactive or standby shutter-blade position is open.

Figure 1 shows the assembled shutter. Flexible hinges that enable frictionless, linear guiding were selected to achieve the demanding lifetime requirements. The shutter consists of a parallelogram assembly with two flexible hinges that enables a nearly linear 1.5-mm movement of the rocker with its shutter-blade. Furthermore, the VCA with its moving magnet, the stationary double coil and a magnetic sensor (GMR) for a position feedback signal for the control electronics are shown.

A number of dramatic failures of flexible hinges systems during vibration test have been reported. For random vibration, the high Q-factors at resonance together with high mid-frequency PSD levels can lead to high loads on the flexible hinges [1]. Furthermore, a sufficient stability against transverse loads has to be guaranteed. Two measures have been taken in order to prevent damage during vibration tests or during satellite launch:

- a snubber that acts as a mechanical limiter against unwanted high displacements of the rocker,
- reduction of the moving mass to the smallest possible amount in order to limit the kinetic energy of the rocker.

It was possible to reduce the moving mass of the rocker to 0.3 gram. The design process was supported by rigorous analysis, including detailed FEM and stress analysis of the flexible hinges.

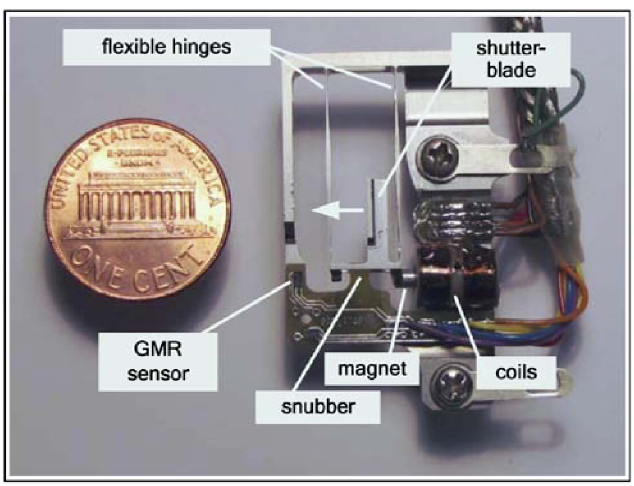


Figure 1: Complete integrated shutter mechanism with milled titanium structure (EM, Engineering Model). The arrow near the shutter-blade indicates the displacement direction for the 1.5-mm movement.

Material Selection and Manufacturing Aspects

A large variety of materials is available for flexible hinges. Properties like material density, Young's modulus, endurance strength, thermal conductivity and manufacturability have to be considered carefully for each application. For MERTIS, different materials like copper-beryllium alloys (e.g., $CuBe_2$), martensitic steels, and titanium alloys have been traded. The combination of high fatigue strength and low density made titanium Ti6Al4V the material of choice. The maximum Von Mises stress in the shutter structure is 132 MPa, which is well below the limit of 350 MPa at 0.5×10^9 cycles for Ti6Al4V [2].

The dominant design driver for the hardware realization was the manufacturability of the 80-µm-thick titanium hinges with a reproducible quality. Basically, there are two possible ways for the implementation:

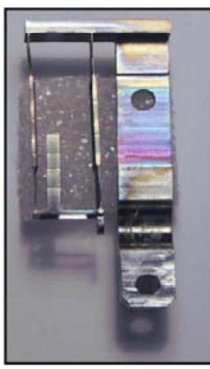
- A setup where separate components and materials like hinges, shutter-blade and support structure are assembled together.
- An integral, monolithic approach where hinges, shutter-blade and support structure are manufactured in a single process and from a single piece of raw material.

The chosen integral, monolithic design offers the important advantage that deformations due to different coefficients of thermal expansion can be avoided and that no adjustment is required after the manufacturing. However, taking into account the required flexible hinge thickness of 80 µm (result of the FEM-Simulation), the challenge for the hardware manufacture becomes apparent.

Indeed, the manufacturing of the very thin monolithic structure with the sophisticated mounting of the rocker caused most of the difficulties.

In a first run, the structure was manufactured by wire-cut EDM (Electrical Discharge Machining). The result was not satisfying due to the heat induced surface changes during the machining. One influence was visible as annealing colors on the titanium structure. Furthermore, the high affinity of titanium to oxygen in combination with high local EDM-processing temperature resulted in the formation of titanium oxides and an oxygen-enriched surface layer on the substrate (so called α-case layer, see Figure 3). The presence of such a layer promotes crack formation under loading conditions.

The resulting spring constant of the flexible hinges varied by more than factor 2 (see table in Figure 2).



	Spring const. in N/m
Nominal (Design)	91,46
Sample #1	82,96
Sample #2	33,80
Sample #3	65,00

Figure 2: EDM-processed shutter sample structure (left) and variation of the spring constants of three EDM-machined samples (right).

Due to the strong variation of the spring constants, the EDM-process has to be judged as being not practical for the MERTIS shutter. The negative (thermal) influence of EDM machining on the fatigue behavior of Ti-alloys has been observed by several other authors. An antiquated, but still excellent overview is given in MIL-HDBK-697A [3].

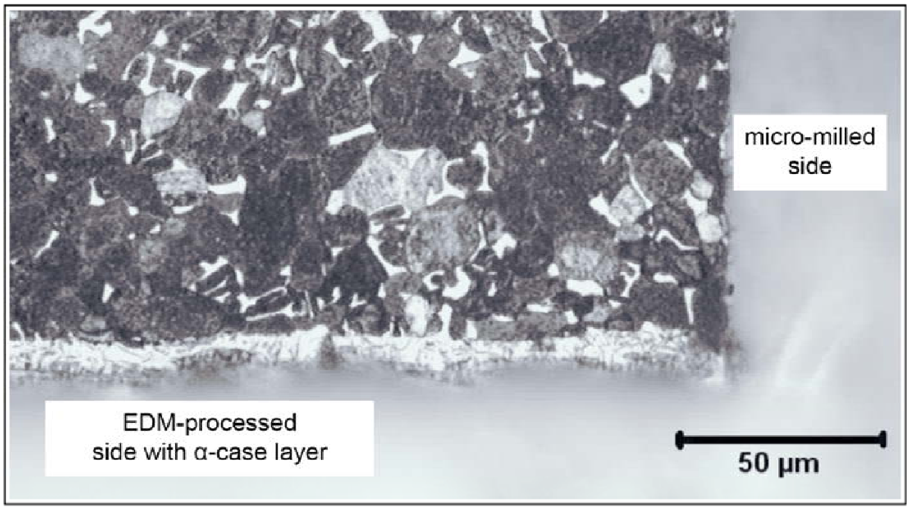


Figure 3: Micrograph of the Micro-milled (right) and EDM-processed (below) shutter structure.

A new manufacturing approach was selected and the shutter mechanical part was optimized for micro-milling instead of EDM machining. Through the application of dedicated cutting parameters, the generation of heat in the device was effectively reduced. Due to a lower the power consumption the spring constant was designed to 39 N/m.

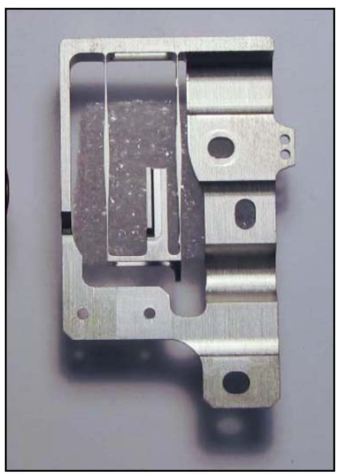


Figure 4: Micro-milled and passivated shutter structure.

Despite the demanding and sensitive manufacturing tolerances, the spring characteristics of the micro-machined shutters had a variance below ±1 N/m, which indicates a good reproducibility.

An unwanted result of the micro-milling process is the generation of burrs that are formed on the material edges. These burrs have shall be removed for fracture prevention, fatigue resistance, or the danger of flaking particulates. The burrs were eliminated by chemical deburring, i.e., an acid pickling procedure. Besides deburring, the pickling process was also used to tune the spring constants to their nominal values. The final step was a metallographic analysis and microscopic inspection of the structure and especially the surface.

The chemicals which have been used for pickling are free of nitrate, produce no hydrogen when applied (prevents hydrogen embrittlement), and the material removal is about several µm/min. The process works at ambient temperature and leaves a smooth silvery, passivated surface finish on the shutter structure (see Figure 2).

Table 2: Variation of the spring constants of four, micro-milled and chemical processed shutter samples. The final, nominal values is 39 N/m ± 8 N/m.

	Initial spring const. after micro-mach.	After pickling process
Sample #4	76.8 N/m	36.1 N/m
Sample #5	76.0 N/m	37.6 N/m
Sample #6	77.04 N/m	37.97 N/m
Sample #7	75.95 N/m	36.24 N/m

The assembled mechanism (as shown in Figure 1) is currently in life testing and further environmental tests. Tale 3 summarizes the actual performance of the shutter engineering model.

Table 3: Intermediate results of the shutter development.

	Requirement	Result for the EM
Mass	25 g	13 g
Max. dimensions	20 x 40 x 5 mm^3	20 x 38 x 4 mm^3
Max. Frequency	10 Hz	130 Hz
Duty cycle	1:10	compliant
Lifetime test	100 x 10^6 cycles	in progress
Fail safe position	Shutter-blade in open position	compliant
Aperture	1.5 mm x 8 mm	compliant

Vibration and Lifetime Testing

Extensive mechanical load tests have been performed. The selected maximum load level of 53 g RMS was about 150% above the nominal load.

The test criteria were:

- no deformation on the flexible hinges or structure,
- no performance degradation and
- no failures in microscopic inspection.

The shutter EM showed neither degradation nor any other failure after the mechanical load test.

After the vibration test, accelerated life testing is currently in work to verify the lifetime performance of the shutter. Currently over 90 million cycles have been processed without any change of the initial shutter parameters.

Summary and Lessons Learned

The initially used procedure of EDM machining of the thin flexible shutter hinges was not the appropriate technology. It was shown that the unfavorable oxidation affinity of titanium, which is accompanied by a variation of the structural properties, lead to arbitrary results and a low surface quality.

With a revised version of the shutter, it was possible to manufacture the complex geometry by micro-machining and an adjacent pickling procedure. The variation of the spring constant was below ±1 N/m. The realization as a monolithic structure offers further potential for miniaturization. In general, the usage of titanium offers advantages due to the low mass, high specific stiffness (ratio of the specific strength and the Young's Modulus) and high fatigue strength.

Acknowledgements

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