Development of High Temperature High Current Contact Technology in slipring Assemblies for the BepiColombo MPO & MTM Spacecrafts

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Abstract

RUAG Space Nyon has been selected to design, develop and test the slipring assemblies of the Mercury Planetary Orbiter (MPO) and the Mercury Transfer Module (MTM) spacecrafts for ESA's BepiColombo Scientific mission. The exposure of the spacecrafts to the harsh thermal environment of this mission to Mercury has inhibited the use of standard high current contact technology in the design of MPO and MTM cylindrical slipring assemblies. In order to sustain the particularly high thermal requirements resulting from the combination of the thermal environment with the significant thermal dissipation of high current transfer at high temperature, new contact and electrical transfer technologies were developed and tested. Validation tests were performed on breadboard models (BBMs) with flight representative contact system at temperatures ranging from -33°C to +186°C.

This paper first presents the new developments integrated in the electric contact system design to meet the simulated thermal environment. It is then followed by a detailed presentation of the objectives and results of the validation tests. Lessons learned and the optimization of the design for the flight configuration are presented in the last sections of this article.

Introduction

Standard high current contact technologies used for space applications at RUAG consists of composite brushes soldered to a flexible copper beryllium blade. This flexible element provides a contact preload force that is designed to not only compensate the abrasive wear of the composite brush during its lifetime but also compensate for the preload loss due to the inherent creep of this material. The current is directly transferred from the composite brushes through the flexible blade. The composite brushes slide on hard gold-coated cylindrical tracks.

For the BepiColombo slipring assemblies, the high temperature environment inhibits the use of standard solder which has been replaced by a high temperature gluing compound. Consequently, current from the composite brush is not transferred through the blade, but through copper braids directly sintered into the composite brushes. This standard industrial process is for the first time used in a space application.

Additionally, composite brushes material has been adapted to the high-temperature environment while considering the need for reduced friction and low electrical resistance of the sliding contacts in vacuum conditions. Since this material differs from standard ones used by RUAG for space applications, validation tests have been performed to validate the new contact technology and the composite brush assembly for space applications.

Technology overview and main features

For the BepiColombo slipring assemblies, the high temperature environment inhibits the use of standard solder which has been replaced by a high temperature gluing compound. While providing a fixation system compliant with the local thermal environment, this new gluing system is relatively resistive, such that the electrical conduction through the flexible blade is not effective. In order to re-establish a low

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Proceedings of the 41st Aerospace Mechanisms Symposium, Jet Propulsion Laboratory, May 16-18, 2012

resistive electrical path between the composite brushes to the brush holder's electrical distribution system, ultra-flexible copper braids (two per composite brush) are directly sintered into the composite brushes. This standard industrial process is used for the first time in a space application. Sintering is directly performed by the composite brush manufacturer. This process implies very high temperatures, thus preventing the use of standard space cables with polymer insulation material. In order to minimize the parasitic stiffness of the cable assembly in the composite brush suspension system, ultra flexible copper braids are used. The reduced stiffness of these cables is obtained by using small diameter strands (Ø0.05 mm) specially woven in 3 braids of 43 strands. As for all space applications, copper braids have to be silver plated. While standard space-grade cables commonly have a silver thickness of 2 µm, it was not possible to procure ultra-flexible braids in standard space grade with a silver coating thicker than 1 µm for this special type of braid.

At the other extremity of the flexible braids, standard soldered electrical connections could not be implemented due to the high local thermal environment. This connection has therefore been replaced by a terminal lug with the pair of flexible braids crimped to it.

In order to electrically insulate the flexible braids, PTFE heat-shrinkable insulating sleeves have been used. This material has been selected for two main purposes. While PTFE is fully compatible with the local thermal environment, it also has the advantage of shrinking at higher temperatures than the maximum predicted local temperature. This permits a control of the forming of the shrink sleeves in the production process while guaranteeing no further shrinkage during the operational life of this component. The control of the dimensions of the insulating sleeves has been considered important based on the observation of the ultra-flexible braid under the microscope. This particular braid construction has a very loose braid structure to minimize strand contacts during flexion. Therefore, a too tight sleeving will augment the stiffness of the insulated braids, affecting the stiffness of the flexible blade system. The diameter and thickness of the shrunk sleeves also plays a role in the stiffness of the system. The final definition of the PTFE sleeves for the ultra-flexible braids has been based on numerous stiffness tests in order to minimize the parasitic stiffness brought on by this electrical connection to the composite brush.

A 3D CAD view of the composite brush assembly is provided in the left side of Figure 1. A picture of a completed composite brush assembly for the production of the flight units is also shown on the right side of Figure 1.

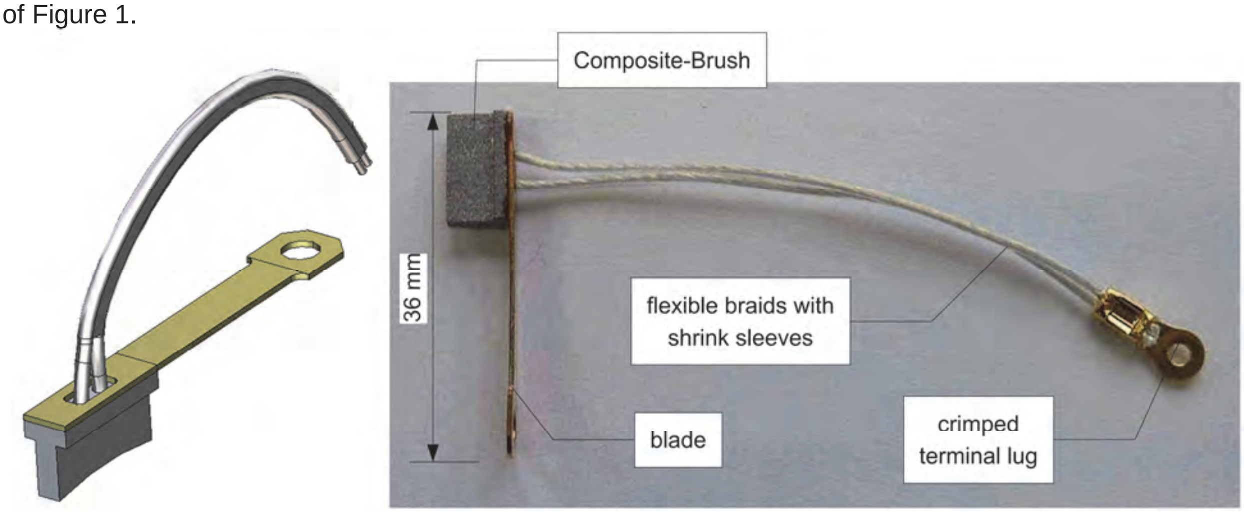

Figure 1. Composite brush assembly (CAD and final flight configuration)

Each composite brush assembly is designed to transfer 8.25 A in the worst case thermal configuration of the mission. The material of the composite brushes has been adapted to this high-temperature environment while considering the need for reduced friction of the sliding contacts in vacuum conditions.

The selected composite brush material basically consists of high silver content composite brushes with MoS_2 lubricant. Since this material differs from standard ones used by RUAG for space applications, validation tests have been performed to validate the new contact technology for space applications.

Validation Test Program

In order to validate the high temperature contact technology selected for the BepiColombo slipring Assemblies, the following validation test program has been established. The main objective of this validation test program was to verify that the selected composite brushes technology is adequate for the BepiColombo mission. Validation tests have been performed at component level as well as at system level on breadboard models fully representative of the newly developed contact system.

Component-level validation testing aimed specifically at the validation of the new gluing system, the validation of the sintered connection between the flexible braid and the composite brushes as well as the validation of the electrical performances of the new composite brush assembly.

Component-level validation tests specifically consisted of:

- Shear tests on the glued interface
- Microsections of the glued assembly
- Pull test of flexible braid sintered into composite brush
- Verification of electrical continuity between composite brush and blade
- Anthony-Brown test on silver coated flexible braids (red plague risk assessment)

In addition, the inability to procure ultra-flexible braids in full compliance with European Cooperation for Space Standardization (ECSS) requirements on silver coating thickness of copper wires (1 µm coating instead of 2 µm) has necessitated additional testing for the assessment on red plague contamination control.

Performance of the composite brushes in terms of electrical dynamic resistance, friction torque and wear has been characterized on breadboard models and compared to the initial design values. The validation tests have been conducted in parallel with the development of both MTM and MPO slipring assemblies for programmatic reasons. Both breadboard models have been used to validate the overall slipring assembly concepts with main focus on the new contact technology. These have been tested with respect to the various representative mission environments, which consisted of random vibrations, shocks, thermal vacuum cycling and accelerated life tests with intermediate electrical and mechanical functional tests.

Component-level validation tests

Mechanical validation tests of the new gluing system of the composite brushes mainly consisted of post thermal-cycling shear tests of composite brushes samples as well as analyzing microsections views of the composite brushes after performing the validation test campaigns. These two tests aimed specifically at the verification of the mechanical properties of the gluing system after aging. These tests are described hereafter, along with other components tests.

<u>Shear test on glue interface</u>
Shear tests were performed after 100 thermal cycles on numerous samples of the composite brush/flexible blade assembly by Aerospace & Advanced Composites GmbH - AAC. Table 1 summarizes the shear test results performed on two series of samples and reference samples (without thermal cycling). These results have demonstrated that the aging through thermal cycling has not impacted the structural integrity of the adhesive system that is fully compliant to the design requirements.

Moreover, the margin of safety with respect to shear force is significant, as in the real application, the composite brush experiences a shear force approximately 1000x smaller than the minimum ultimate shear force resistance when the slipring's motion is initiated.

Table 1. Shear test results summary

Series 1	**Shear Force**	**Std deviation**
Thermocycled Samples (8 samples)	442 N	14 N
Reference Samples (2 samples)	448 N	4 N
Series 2		
Thermocycled Samples (8 samples)	427 N	20 N
Reference Samples (2 samples)	448 N	20 N

Figure 2 provides pictures of shear test samples after shear testing to illustrate the fracture mode of the composite brush glued assembly. The same fracture mode has been observed on all test samples.

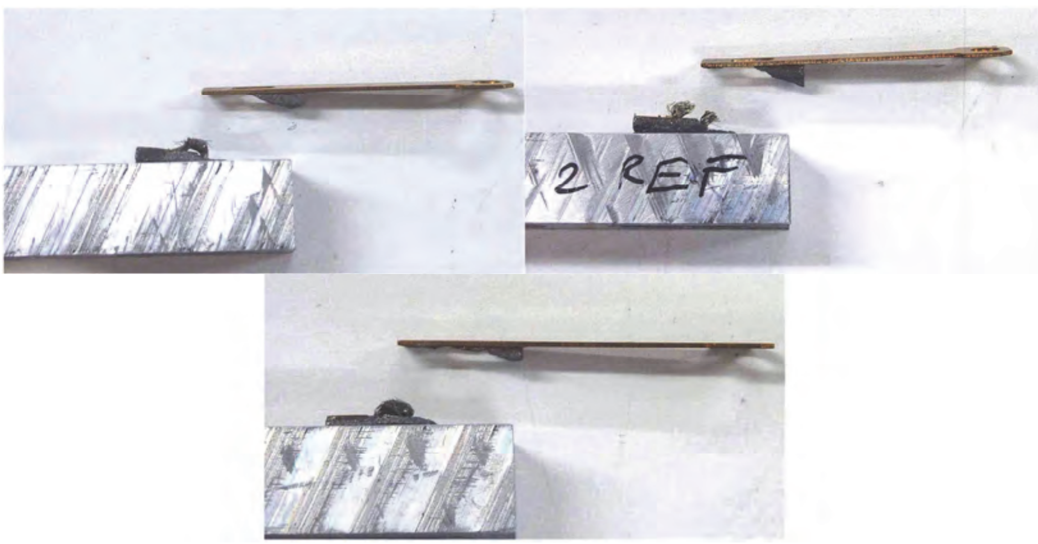

Figure 2. **Shear test samples**

Figure 3 illustrates the shear fracture propagation mode. A crack initiates on the side of the composite brush where it is held in the shear test fixture, and then propagates up to the glue interface, underneath the blade. The glue interface surface then breaks very quickly as the contact surface between the blade and composite brushes reduces rapidly. The initiation of the crack in the composite brush suggests that this component has a shear-stress limit lower than the glued interface.

<u>Glue layer microsections</u>

Examples of transverse micro-sections views of the composite-brush/flexible blade assembly made after life tests are presented in Figure 4. The Copper Beryllium blade section is shown on the top-half of the micro-section views (uniform color) and the composite brush sections on the lower half (marbled section). All micro-section views have shown that the integrity of the gluing system of the composite brushes is not compromised by both the thermal cycling and life tests performed on the breadboard models.

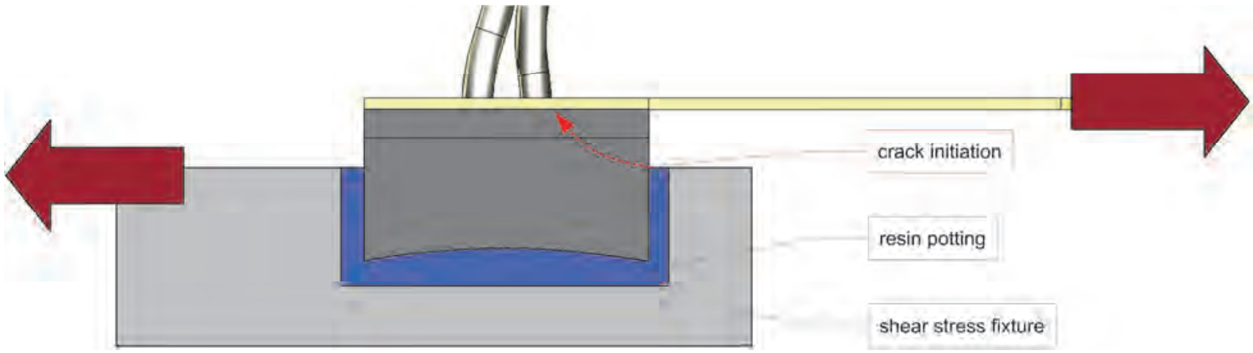

Figure 3. **Shear test setup and fracture mode description**

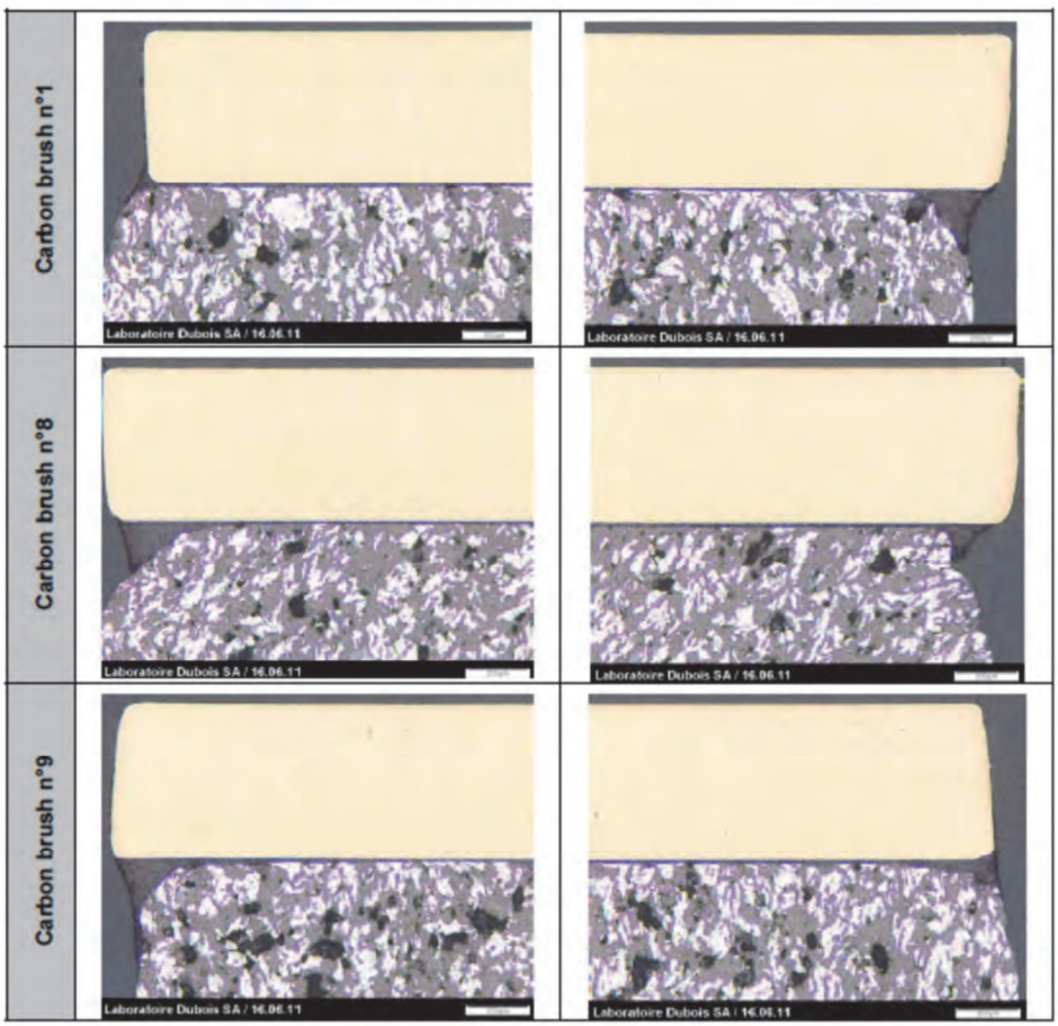

Figure 4. Example of composite brush micro-section views (**© Laboratoire Dubois SA**)

<u>Pull test on composite brushes sintered cables</u>

Flexible braids are directly sintered into the composite brush as part of the composite brush manufacturing process. In order to validate the proper mechanical fixation of the braids, pull tests have been performed by RUAG.

To assess the potential impact of thermal vacuum cycling on the mechanical fixation of the sintered braids, composite brushes from both breadboard models have been tested and the results compared with the ones obtained on the QM/FM composite brushes fabrication batch. The flexible braid pull test results are summarized in
Table **2.**

Table 2. Pull test results summary

	Pull Force	Std deviation
composite brushes from BBMs (thermal vacuum cycled)	58.3 N	4.8 N
composite brushes from QM/FM production lot (not cycled)	52.5 N	2.8 N

No major impact of the thermal cycling on the resistance of the sintered connection can be observed from the pull test results. In fact, in most cases the rupture mainly occurred on the flexible braid rather than on the sintered joint. This is illustrated in Figure 5 on a composite brush assembly that encountered both fracture modes during the flexible braid pull tests.

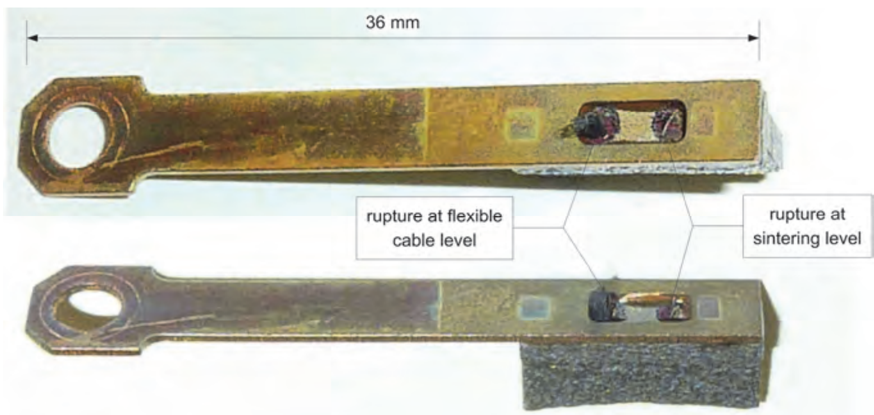

Figure 5. **Pull test results on composite brushes sintered cables with both rupture modes**

The maximum design loads on the flexible braids are generated by the vibration and shock environment and principally due to the inertial loads on the flexible braids. These loads are marginal with respect to the ultimate traction load.

These pull tests have proven the suitability of the sintered connection between the flexible braids and the composite brush for the BepiColombo slipring assembly design.

<u>Electrical grounding between composite brush and blade</u>
In this new composite brush Assembly the spring blades are not part of the electrical line anymore. Since the flexible blades are connected to the composite brush using electrically insulating glue at one end, and supported by a brush holder made of insulating material at the other end, the electrical grounding of the blades needed to be insured by tests or by the use of an additional grounding lug.

Continuity tests have been performed on the composite brushes assembly of both breadboard models after the validation tests. The tests were fully successful and proved that the electrical continuity was guaranteed between all blades and composite brushes, despite the use of electrically insulating glue.

Using a purely theoretical approach on the insulating properties of the thin layer of glue used, the spring blades should have been electrically insulated. However, the electrical grounding tests have enlightened that the assumption of a uniform barrier of glue between the composite brush and the flexible blade is not realistic. In fact, a good electrical conduction between the blade and the composite brush is ensured by discrete electrical contact points arising from the high surface roughness of the composite brush in combination with the gluing process performed under preload. In order to guarantee the electrical grounding of the flexible blades during QM/FM production, an electrical continuity check is performed on every composite brush assembly.

Anthony-Brown tests on silver plated flexible braid

The applicable requirements from the ECSS call for a 2-μm silver plating thickness on copper conductors. While standard space grade cables commonly have a silver thickness of 2 μm, it was not possible to procure ultra-flexible braids in standard Space grade with a silver coating thicker than 1 μm for this special type of braid.

“Red Plague” is a well-known phenomenon that causes corrosion of copper on silver plated copper cables. The risk of occurrence is increased in the presence of humidity, particularly in condensed form. With the selected composite brush assembly, this is typically the case considering the thermally insulating sleeving of the flexible braids in humid atmosphere and submitted to temperature variations.

Samples of the flexible braid production batch have been equipped with the PTFE shrink-sleeves and provided to ESA’s Test Center (ESTEC). Anthony-Brown tests are currently being performed for the assessment on red plague contamination control.

Breadboard Model Validation Tests

The new composite brush sliding contact system has been validated at system level on two breadboard models (MTM and MPO slipring assemblies). Figure 6 provides a picture of one of these breadboard models for illustration purposes.

Both models shared the same composite brush contact system and were fully representative of the flight hardware in terms of materials, contact configuration and dimensions, with the exception of the number of tracks that was reduced in the breadboard models. The main implication is that the breadboard models have a reduced overall length with respect to the QM/FM design.

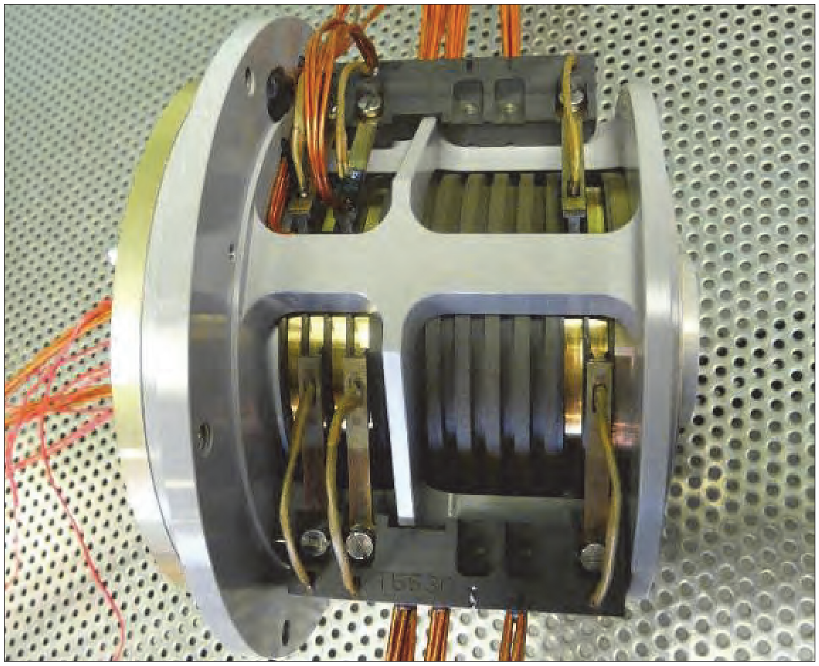

Figure 6. BepiColombo BBM 1 (configuration with contacts not fully populated)

The validation test sequence for both breadboard models is schematized in Figure 7. Breadboard model validation tests mainly consisted of mechanical vibration and shock tests, thermal cycling and life tests with numerous electrical functional tests to demonstrate the adequacy of the contact technology to this high temperature application.

Figure 7. **Breadboard models** validation sequence

In addition, the preload force drop due to the combination of the wear of the composite brushes and flexible blade material creep has been measured and assessed. These measurements were then used to compute the friction coefficient of the contact system from torque measurements performed both in air and in vacuum as well as with and without brush holders in order to remove the contribution of the bearings on the overall measured torque. The main results of these BBM validation tests program are described in the next subparagraphs.

<u>Thermal vacuum cycling, mechanical and accelerated lifetime tests</u>

BBMs have been tested under representative mechanical, thermal and accelerated lifetime (number of cycles including qualification margin) of the BepiColombo mission. During the lifetime testing, monitoring of the dynamic resistance and friction torque was performed, in order to measure the evolution of these critical parameters.

Figure 8 and Figure 9 present the static and dynamic RMS contact resistance evolution during lifetests (measured with a current of 1A). Both graphs show a slight increase with the number of revolutions, which reflects the impact of the generated wear particles on the sliding contact electrical characteristics. However, these resistance values remain very small and well within the specification.

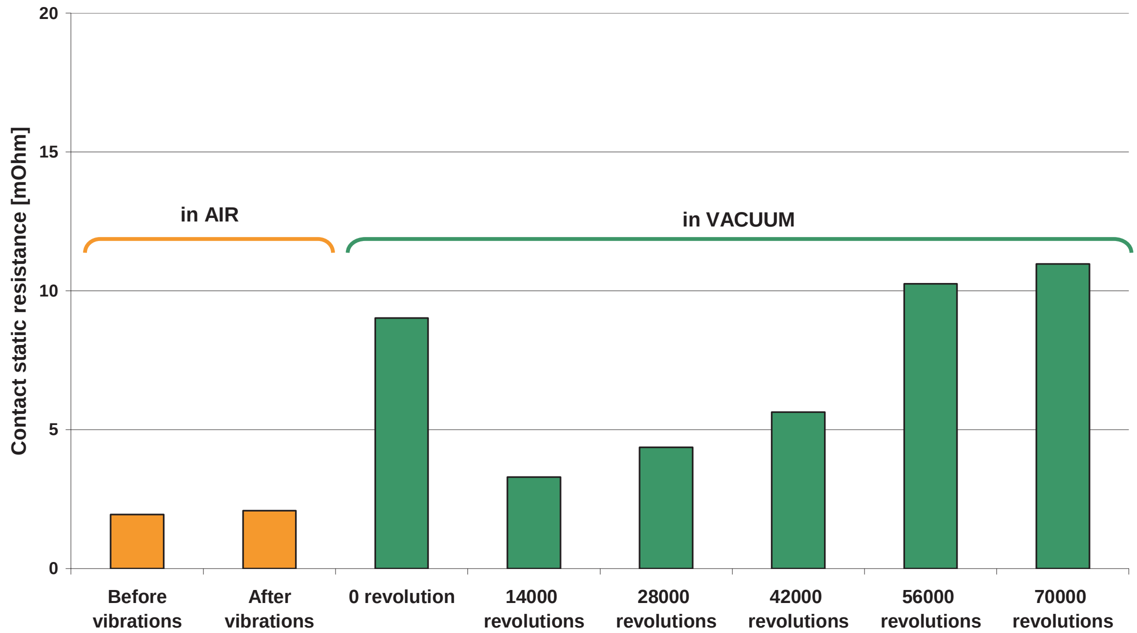

Figure 8. Static contact resistance evolution – RMS value

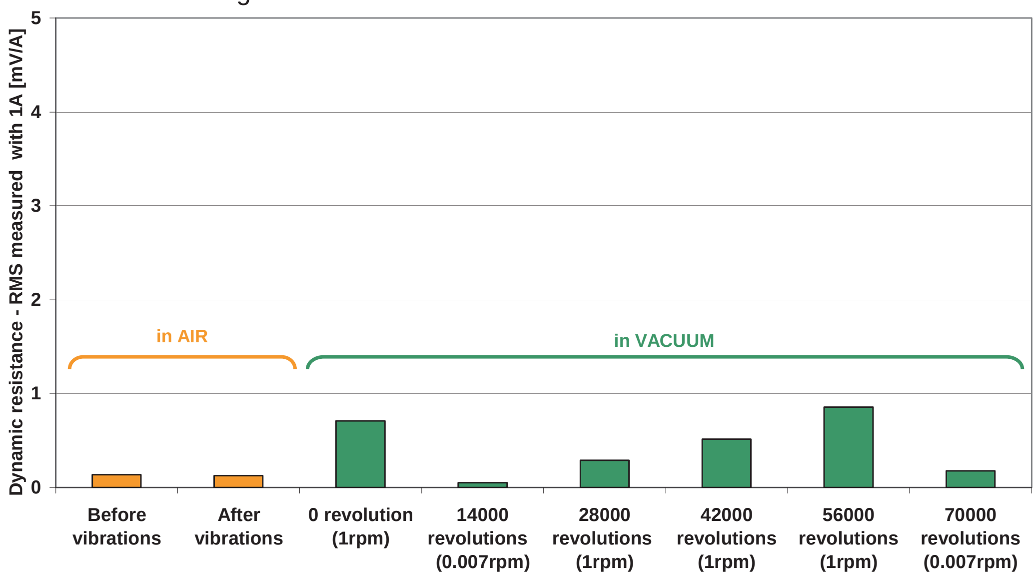

Figure 9. Dynamic resistance – RMS value

The design of the composite brush preloading system is inherently critical with respect to the mechanical environment, mainly due to the configuration of this system that has a concentrated mass at the end of a spring blade. The weight of the composite brush design has been minimized and the preloading system designed to avoid eigenfrequencies in the vibration frequency spectrum. Moreover, the mechanical dimensioning of the preloading system is such that lift-off of the composite brush is prevented as well. Vibration and shock tests have been performed on both breadboard models to validate the design of the composite brush suspension system and demonstrate that the composite brushes and tracks were not affected by these mechanical environments.

An illustration of the contact system after vibration and shock tests on a breadboard model is shown in Figure 10. Slight traces were visible on all tracks near the composite brushes. After close inspection, it turns out that these marks were coming entirely from the local composite brush wear during vibration and shock tests. As a matter of fact, the rotation of the rotor was not rigidly blocked such that a reduced back and forth sliding movement was enabled. This local sliding created deposition of the composite brush wear particles on the tracks. These residues could easily be wiped off and a visual inspection of the gold-coated tracks under magnification did not reveal any damages or wear of the track surface. It should be noted that the dimensioning of the composite brush preloading system is such to avoid any lifting of the contacts under the applicable vibration and shock environment. The observed agglomerates of wear particles are typical of composite brush contact slipring designs and have already been previously observed by RUAG. These traces do not affect the performances of the contact system.

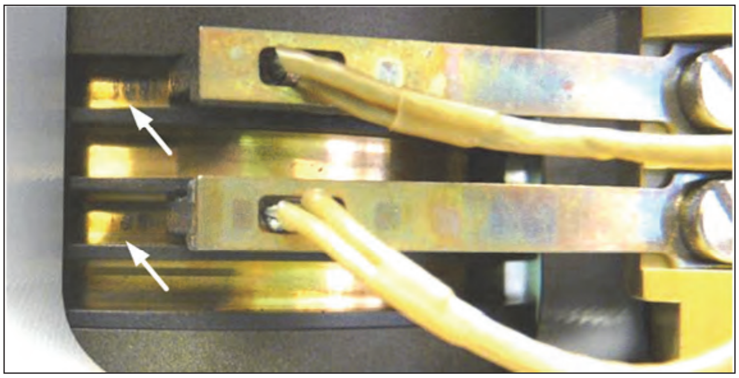

Figure 10. **Wear traces due to composite brush sliding effect during vibration**

In terms of accelerated lifetime testing, one of the breadboard models was subjected to more than 70'000 revolutions, which corresponds to more than seven times the specified number of revolutions for the BepiColombo mission. Thorough visual inspections of the tracks and composite brushes after life test and under magnification have shown that the overall conditions of the tracks and composite brushes were fully satisfactory. As a matter of fact, very limited amount of wear particles were found, and slight wear traces were visible on the tracks. The analysis of the total wear of the composite brushes demonstrated that the wear of the composite brushes was extremely limited, despite the number of revolutions experienced on top of the design life of the contact system. Moreover, the wear was observed to be uniform on all the composite brushes. It should be noted that the design life of composite brushes in industrial applications is at least more than one order of magnitude higher than the one tested in this application. Finally, the complete visual inspection of the breadboard model slipring assembly showed that it was still in a very good condition.

Friction coefficient

The friction coefficient of the electrical contact system plays an important role in the friction torque of a slipring assembly, mainly due the high number of contacts, and is, of course, an important parameter for the design of the drive assembly. In order to validate the friction coefficient used for the design of the BepiColombo slipring assemblies, torque measurements were performed in air and in vacuum as well as with and without brush holders in order to reject the torque contribution from the bearings. Measurements of the preload force of the composite brushes allowed the actual friction coefficient of the electrical contacts in air and vacuum to be calculated.

Figure 11 summarizes the friction coefficient measurement results. These data, besides enabling the validation of the total torque calculations for the slipring assemblies, have also shown that measuring the torque in air can be considered as worst case conditions for the definition of the qualification and acceptance test programs. These results furthermore confirm the adequacy of the selected composite brushes technology with respect to space applications.

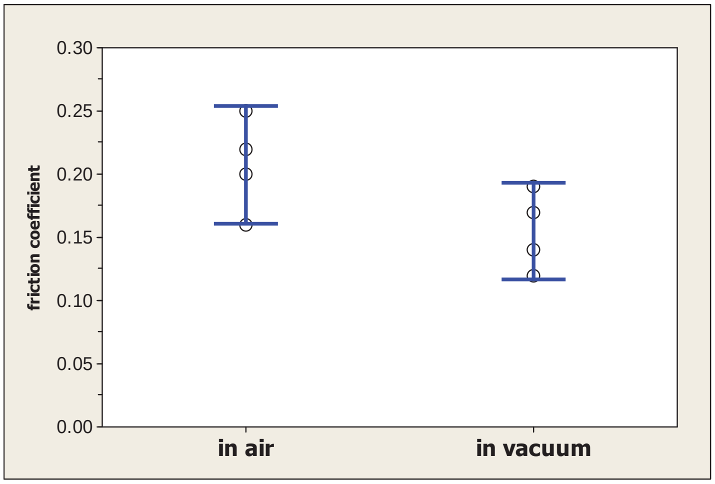

Figure 11. Friction coefficient measurement results

Dynamic contact resistance

Examples of the dynamic electrical contact resistances measured over a full revolution and after run-in of the composite brushes are presented in Figure 12. These measurements were performed at the nominal current of 12.5 A per track on four different tracks in air and vacuum. All results have shown a low electrical contact resistance in both vacuum and air conditions with great consistency between the different measured tracks. Moreover, the performances of the composite brushes are significantly better in vacuum environment, which, again, confirms the adequate selection of the composite brush material for space applications.

The RMS values of the dynamic electrical contact resistances are of particular interest, as contact resistance is a key driver for the thermal dissipation at the contact interfaces due to the electrical power transfer. This is particularly critical considering the thermal environment of the BepiColombo mission.

Figure 13 summarizes the RMS values of the dynamic contact resistance curves presented in Figure 12, with the addition of measurements performed before run-in of the composite brushes. These results show that with the selected composite brushes technology, RMS values of the contact resistance are very low, especially under vacuum. Composite brushes run-in also shows its benefits, with an overall reduction of the dynamic contact resistances. These results show that composite brush technology becomes optimal under vacuum and is furthermore improved by the effect of the run-in, which correspond to the flight configuration.

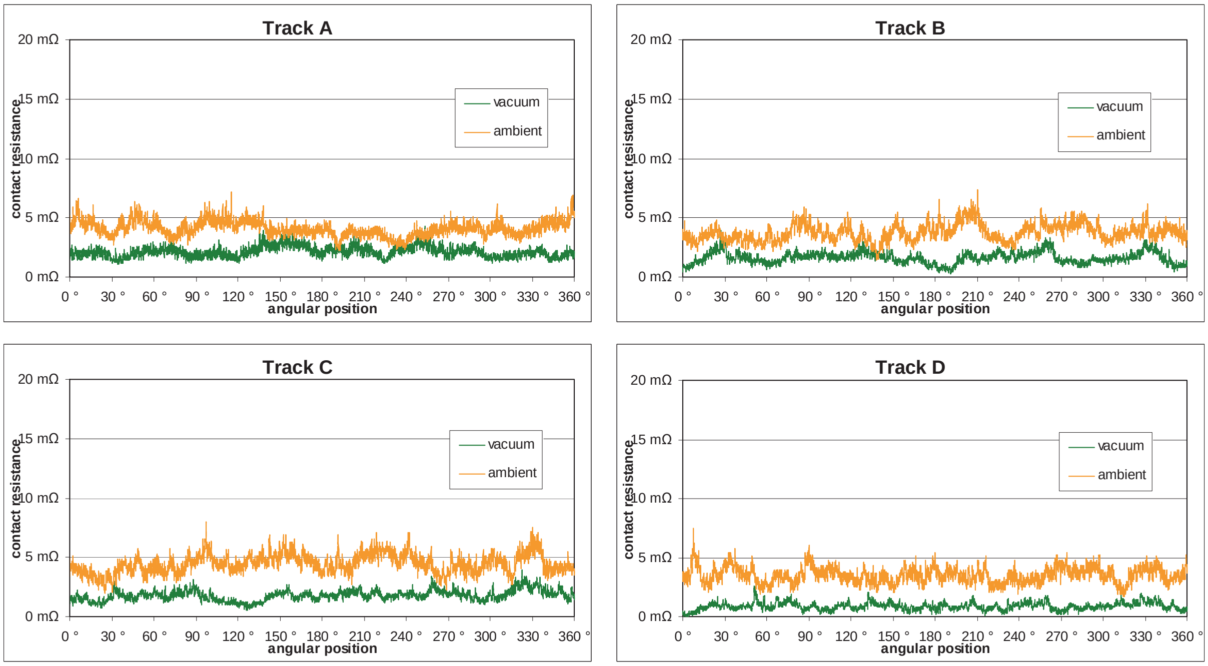

Figure 12. Dynamic contact resistance curves over 360°– VACUUM & AMBIENT (after run-in)

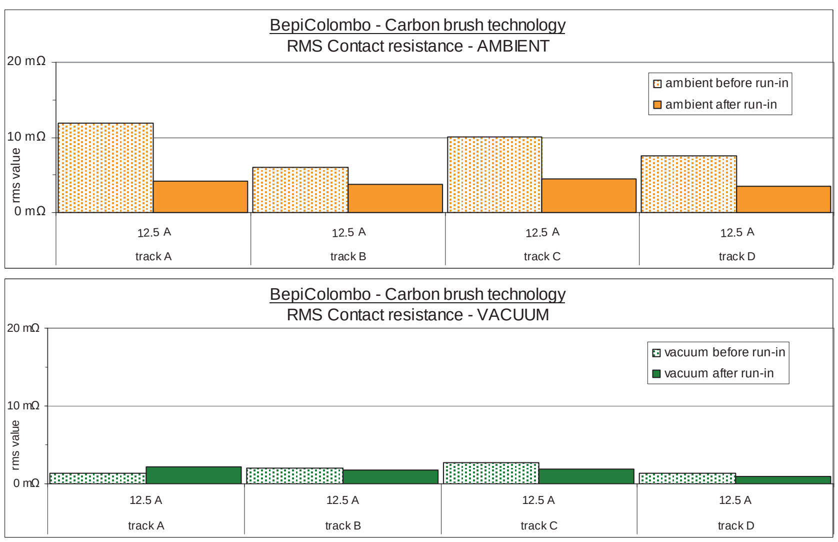

Figure 13. RMS dynamic contact resistance – VACUUM & AMBIENT (after run-in)

Lessons learned and improvements

Validation test programs performed at component and breadboard model levels have shown that the selected composite brushes contact technology is fully compliant with the BepiColombo requirements. In view of QM and FM slipring assembly production, some improvements are being carried out, namely:

- For the breadboard models, the composite brushes were manufactured as closely as possible to the cylindrical shape of the track, with the objective of performing a run-in directly on the assembled slipring assemblies. However, breadboard models tests have showed that wear is extremely low, and that a significant number of revolutions were required to obtain a perfect fit of the composite brushes to the tracks. Figure 14 illustrates the composite brushes contact surface before and after run-in tests performed on the breadboard models.

In order to accelerate the run-in process for the QM and FM production lines, the brush holder assemblies are run-in on a dedicated abrasive tooling representative of the final track dimension. In order to further accelerate the run-in process, wear particles are removed by a continuous flow of demineralized water during the run-in procedure.

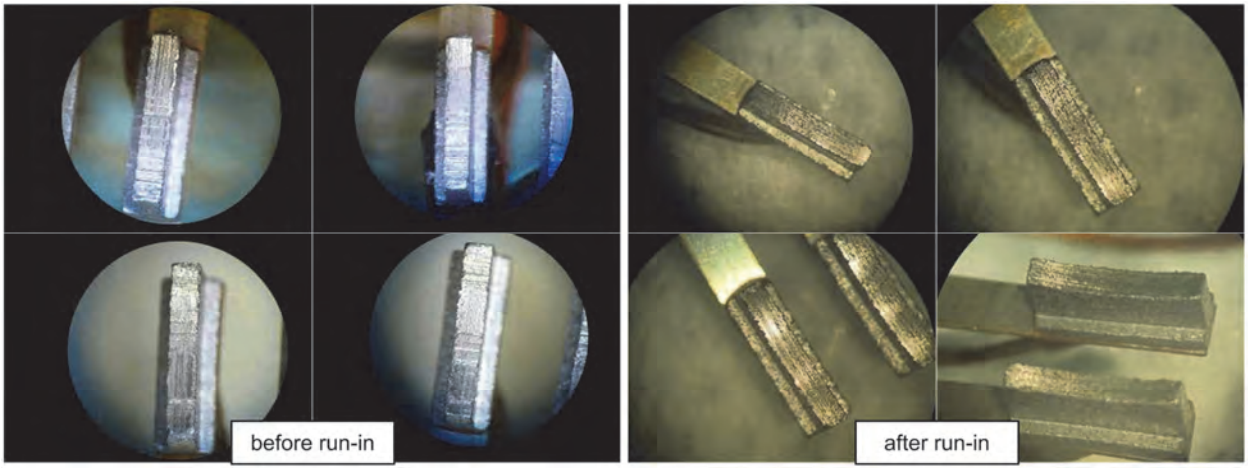

Figure 14 – Overview of composite brushes before and after run-in

- After thermal tests, a slight brownish coloration has been observed on the Kynar sleeves covering the ultra-flexible braids of the composite brushes. Initially translucent, with a pale yellowish coloration, they have slightly darken most probably due to the harsh thermal environment of the experienced thermal test (see images on the left of Figure 15), which were close to the Kynar temperature limits. Additional tests performed on the Kynar sleeves of the breadboard models did not reveal any degradation of the mechanical and electrical insulation properties.

  However, for the QM/FM design, it has been decided to switch to a PTFE-type heat shrink sleeve, which could sustain higher temperatures and avoid further shrinkage during the operational life of the slipring assemblies. Additional thermal tests have shown that this shrink sleeve was not affected by the exposition to the thermal environment defined for the BepiColombo mission (see images on the right of Figure 15).

- In the initial design of the QM/FM slipring assemblies, the flexible blades were grounded using an additional cable fixed to the opposite end of the composite brush using a terminal lug. However, continuity tests performed between the composite brushes and the flexible blades have all shown that the grounding of the flexible blades is ensured through the glued interface between the composite brushes and the suspension blades. The grounding cables have been removed in the QM/FM contact system design and replaced by a continuity test performed on each composite brush assembly during their production.

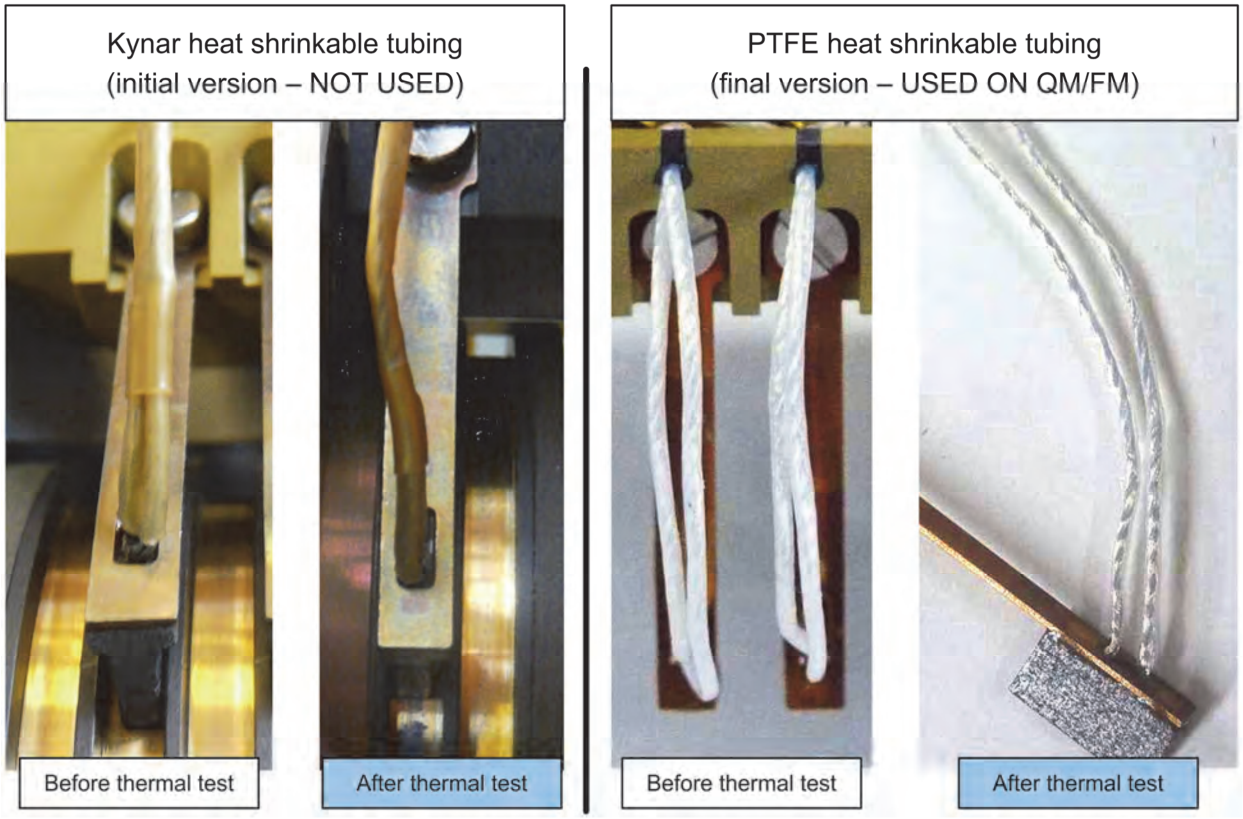

Figure 15. Change of heat shrink sleeve type (left: old, right: new)

- The gluing process carried out on the composite brushes flexible blade assembly during breadboard model production has shown that it requires careful attention. In order to enhance the QM/FM gluing process, the amount of glue and the location of its application have been defined and documented. Additionally, acceptance criteria have also been defined to guarantee a proper distribution of the glue, a precise alignment of the composite brush and in general a full repeatability of this process. Figure 16 illustrates the final configuration of the QM/FM composite brush as part of the acceptance criteria.

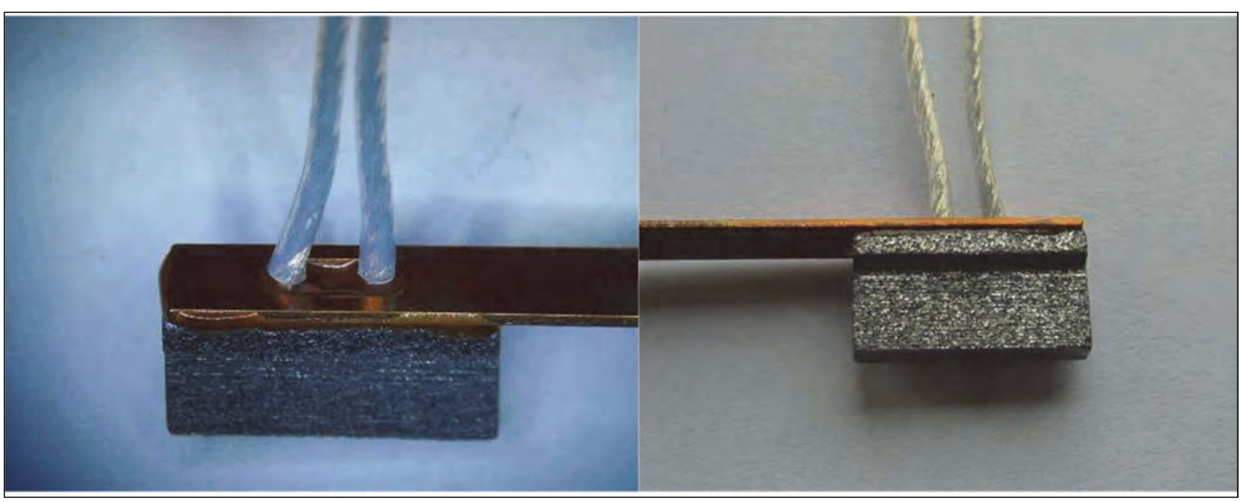

Figure 16. Close-up view of glued interfaces

Conclusions

Validation tests results have demonstrated the full adequacy of the high temperature high current contact technology implemented in the BepiColombo slipring assemblies. Moreover, the electrical dynamic resistance which has an important impact on the local thermal dissipation and consequently on the temperature distribution, appeared to be much lower than anticipated, validating the thermal simulation results with a comfortable margin.

Additionally, the demonstrated low friction and low wear properties of the composite brush technology are well above the required lifetime for the mission. Moreover, the selected material for the composite brush is well-adapted to space applications, as it behaves better in vacuum than in air.

Both validation campaigns (at component and at breadboard model levels), have helped in identifying important improvement points and lessons-learned. The production processes for the QM and FM manufacturing have been consequently enhanced. More specifically, the gluing and run-in processes, which are specific processes to the current application, have been updated and thoroughly detailed following these validation test campaigns.

Finally, it has been demonstrated that the selected composite brush assembly, including blade gluing, sintered flexible braids and heat shrink sleeves fulfills all mechanical, electrical and lifetime requirements of the BepiColombo mission.

References

1. Heinrich B, Zemann J, Rottmeier F. "Development of the BepiColombo MPO Solar Array Drive Assembly." Proceedings of the 14th European Space Mechanisms & Tribology Symposium, September 2011.