SLIPRING MADE BY ADDITIVE MANUFACTURING: FROM REDESIGN TO VALIDATION TEST RESULTS

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ABSTRACT

The rotor of a cylindrical Slipring Assembly (SRA) has been re-designed based on a combination of Additive Manufacturing (AM), resin casting and machining. Whilst fulfilling all Form-Fit-Function (FFF) requirements derived from the existing SRA rotor design, the new design reduces the number of parts involved from 60 to 1 (considering a 30 channel rotor). This results in substantial reduction of the lead time and manufacturing costs.

A trade-off on the AM technologies and materials based on several breadboard models (BBMs) allowed to confirm Laser Powder Bed Fusion (LPBF) and bronze as the most suitable process and material. The BBMs and their functional testing results were used to iterate on the design which led to the manufacturing and functional testing of a set of rotor Qualification Models (QMs) as shown in Fig. 1. The QMs have been integrated with conventional SRA stators and followed the functional, performance, and environmental tests required to reach the TRL6. A set of "conventional" SRAs has been tested in parallel to confirm the potential of this new rotor generation to supersede the traditional one.

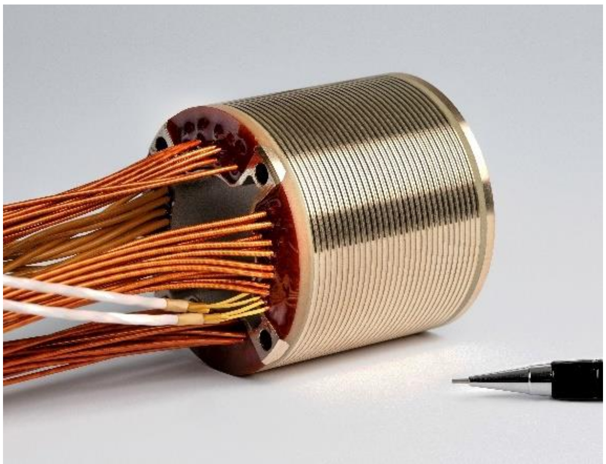

Figure 1. Additively manufactured QM slipring rotor

1 CONTEXT

1.1 SRAs and industry 4.0

Sliprings are electrical continuity devices intended to transfer multiple electrical signals from a stationary member to a rotating member. SRAs are present in many satellite sub-systems such as Solar Arrays Drive Mechanisms (SADMs), Antenna Pointing Mechanisms, Control Momentum Gyroscopes and other instruments [1]. To respond to the new paradigm of Industry 4.0, Beyond Gravity Slip Rings SA (BGSR) is developing a new generation of SRAs whose objectives are driven by customer specific requirements on LEO/MEO/GEO markets. Those objectives are to guarantee short lead times, high throughput production and cost savings whilst keeping the highest reliability level. BGSR ongoing developments also seek at proposing highly optimized modular & configurable SRAs to precisely match various customer needs. As a central part of the SRA, the re-design of the rotor was a key pre-requisite to reach those objectives.

1.2 Conventional slipring rotor architecture

The physical architecture of slipring rotors relies on a precise manufacturing and assembly sequence involving many operations. As a rule of thumb, the number of components increases with the number of electrical channels to be included in the rotor, following a multiplication factor of 2 (cables excluded). In other words, each channel to be achieved involves three components: an insulating ring, a conductive ring and an electrical wire (Fig. 2).

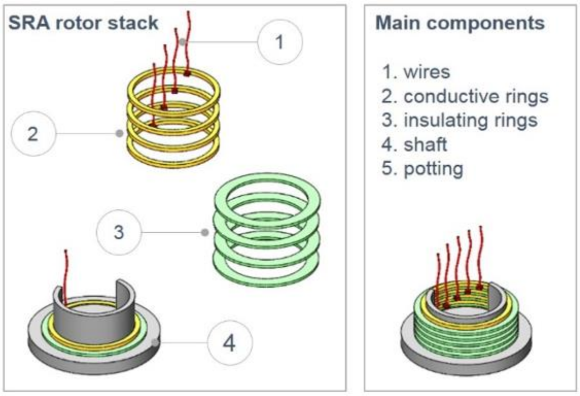

Figure 2. Traditional architecture of a cylindrical SRA

Unsurprisingly, the manufacturing and assembly efforts tend to increase accordingly, as well as the probability of reliability issues. Furthermore, stacking conductive and insulating rings implies a long tolerance chain which makes it mandatory to achieve high dimensional accuracy for each component. As an example, a 30 channel SRA rotor involves the stacking of 60 rings. Considering a ring thickness tolerance of ±10 µm, the overall track pitch deviation increases to ± 600 µm, causing obvious manufacturing and assembly challenges. To reduce the number of components, a novel design concept based on an Additive Manufacturing process has been proposed and applied to the SRA rotor.

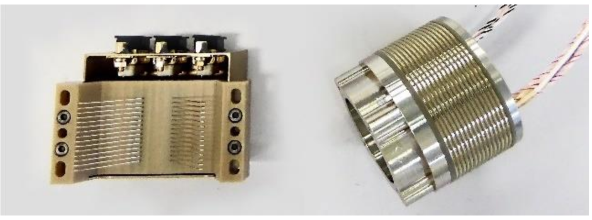

Figure 3. Picture of a traditional SRA
(stator left side, rotor right side)

2 DEVELOPMENT

2.1 Redesign of an SRA rotor for additive manufacturing

This project started with the redesign of a slipring rotor to benefit from the design freedom and the increase in complexity possible with additive manufacturing. Especially, a significant reduction in assembly time has been obtained with the AM rotor: one printed part, followed by a casting operation and machining of the complete rotor instead of several tens of parts that need to be precisely and individually machined and assembled together.

The redesign for AM integrated several new features to benefit as much as possible from this technology:

1. Integrated mold
2. All conductive rings for one rotor, i. e. 30 tracks
3. Machining references, such as orientation pin holes, crossed central axis fitting
4. Injection channels for resin, to inject from the bottom and avoid air bubbles.
5. Electrical conductors to ease wire soldering
6. Part reference and serial number

2.2 Technologies and materials trade-offs

After the preliminary design, multiple trade-offs have been performed with technologies available in 2019:

- Three different technologies based on AM:
  - Binder Jetting
  - Investment casting with AM green parts
  - Laser Powder Bed Fusion (LPBF)
- Several materials:
  - pure copper
  - aluminium alloy
  - stainless steel infiltrated with bronze
  - bronze

The binder jetting could be an interesting solution for series production, but significant distortions were found on the prototypes. The 2-3% shrinkage during sintering lead to unacceptable anisotropic deformations. Moreover, the design limitations for slender parts were problematic for the rotor geometry.

Investment casting is of particular interest with low surface roughness and good accuracy. But other process limitations forced us to implement some design adaptations which led to manufacturing issues, such as cracks in the mold, resulting in inadmissible metallic connections between electrical tracks.

Finally, Laser Powder Bed Fusion (LPBF) was chosen as the most suitable manufacturing process for this project. Several acceptable parts have been produced in aluminium AlSi12, but unfortunately, the gold plating adherence was insufficient. A denser material -pure copper- was evaluated with both conventional IR but also green laser. For the first one, porosities size and number were too important, even after HIP, while for the second one, the low hardness lead to machining issues. Ultimately, rotor parts made of bronze were 3D printed, casted with insulating resin and machined. The gold plating process is the same as for conventional rotors since they are also made of copper alloy rings.

2.3 Manufacturing process workflow

The manufacturing workflow was more complex than expected: several process steps have been added to ensure the requirements. Notably, the protection against oxidation for the bronze required to bathe the parts in a solution right after AM and depowdering. In addition, the nickel-plating process has been performed earlier to avoid corrosion and ease cable soldering wetting.

Thanks to early prototyping allowed by AM, we were able to de-risk and improve the complete manufacturing workflow. Design adaptations were also needed to ease powder removal, to add jigs for casting under vacuum and to protect the inner volume against chips during machining. More details of the project development, design and trade-offs can be found in the ESMATS 2021 paper [3].

3 NEW GENERATION OF AM ROTORS

3.1 AM build-in electrical wires concept

The generic design concept (patented) and its implementation for a slipring rotor have been described in [2] and [3]. This concept has been reused to benefit from most of the 'free' design complexity offered by AM, as shown in the next chapter.

3.2 AM slipring rotor design

The detailed design illustrated in Fig. 4 comprises a total of 30 annular rings with an equal number of built-in wires spread all around the periphery of the rotor. Two designs were established to address two rotor sizes. The requirement of being fully compatible with conventionally assembled rotors was a key driver so that the external dimensions are identical (diameter, length, track numbers, pitch, etc.). The AM rotor can be integrated in a conventional SRA stator. For the product reference “404”, the external diameter of the rotor after final machining is a cylinder of 53 mm diameter and 50 mm height. This reference is the most challenging for manufacturing since it involves the narrowest resin gap between the tracks. A second design was established for the product reference “507” (66 mm diameter and 85 mm height). Its larger size shall allow to assess the adaptability of the AM technologies tested.

For both designs, the notable characteristics are:

- “Pierced terminals” designed in accordance with [2], each one allowing to solder up to two AWG20 wires
- Conical cross-shape inner shell to reduce the amount of resin and allow the interfacing of the SRA shaft
- Built-in channels to inject the resin from the bottom and thus avoid projections and bubbles
- Machining interfaces and positioning references

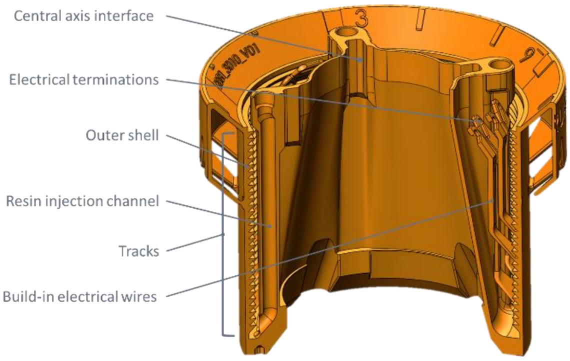

Figure 4. Printed rotor structure (cross-section view)

3.3 SRA rotor production workflow

Fig. 5 shows the simplified rotor production workflow which starts with the additive manufacturing of the one-piece structure. After cleaning, the electrical cables are soldered on the terminations and the resin is casted through the dedicated injection channels. After the curing of the resin, the rotor is machined to remove the outer shell and reveal the cylindrical conductive tracks separated by barriers. To ensure an optimal electrical contact with the stator brushes, the tracks are machined with a V-shaped groove and plated with a precious metal alloy.

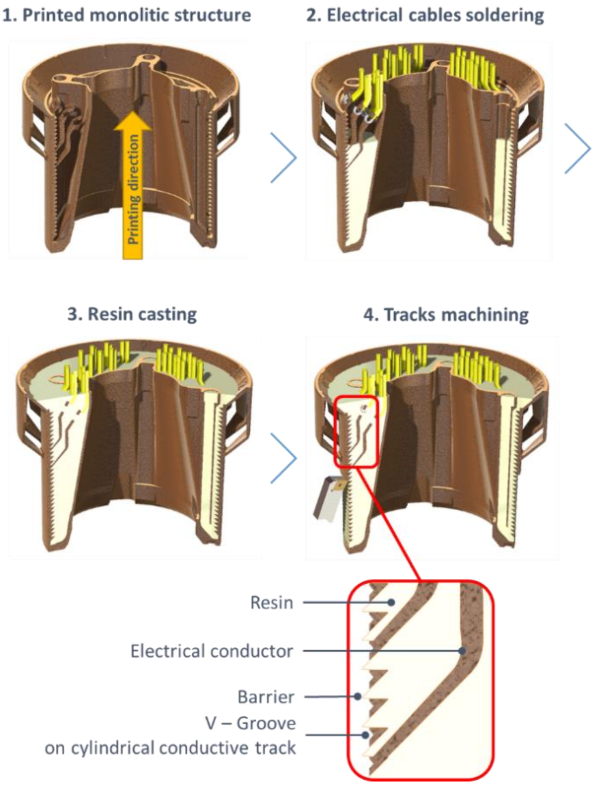

Figure 5. AM rotor workflow

The complete manufacturing workflow was more complex than expected since several steps had to be added to protect the bronze part from corrosion, to limit particles inside the shell and to ensure a reliable soldering of the electrical wires.

4 PRODUCTION OF QM ROTORS

4.1 QM rotors manufacturing

The manufacturing of the QM rotors had been de-risked with the production of several critical features and breadboard models.

Figure 6. QM rotor parts

Thanks to the ability of having representative prototypes very early offered by AM, the design was updated to improve the printing, resin casting and machining. Nevertheless, each AM batch should be checked to ensure that it is defect free. At least tensile, unfused powder cube and rods for metallography are added on the build plate for each batch. At the start of the project in 2019, the ECSS standard about LPBF parts processing [4] was not released and therefore the quality assurance was based on best practices. For example, X-ray Computed Tomography scan was performed only on one rotor. Due to the high density of the copper alloy, the resolution of this method is barely sufficient to detect small defects.

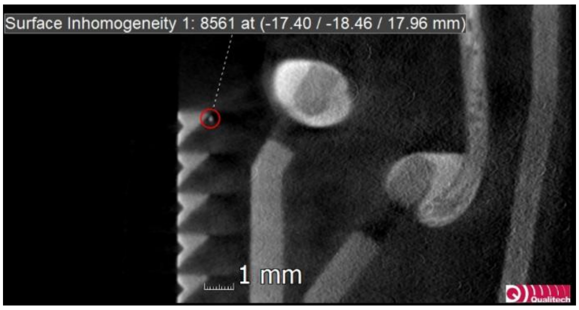

Figure 7. X-ray CT-scan image with tracks, terminations and solders in cross-section

4.2 Rotor post-processing

After being 3D printed, the rotors were de-powdered carefully. The removal of all powder particles (size 10-45 µm) inside the rotor was a challenge and the cleaning method has been improved to avoid agglomerations as experienced during some preliminary tests. As soon as the rotor is free of powder, a temporary corrosion protection coating was applied. The casting of the insulation resin is performed under vacuum and with injection channels starting at the bottom of the rotor to avoid the formation of bubbles. As shown in Fig. 8, Some jigs were also designed and 3D printed in polymer to ease the casting.

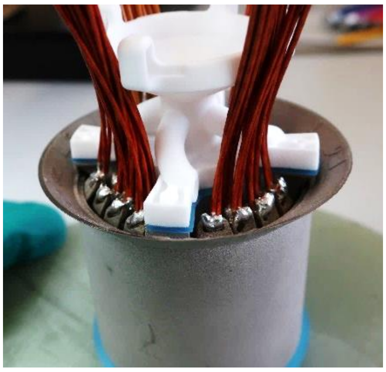

Figure 8. Casting jigs

After a first resin casting, the cables were soldered on the dedicated features. Two or three cables could be connected to each AM electrical termination. A second resin casting ensured a complete electrical insulation of the termination and a mechanical fixation of the cables.

The machining of the rotor to remove the shell and reveal the cylindrical tracks was performed according to the conventional BGSR procedure. Unfortunately, on the smallest rotor size 404, it was not possible to leave insulating resin barriers at a higher diameter between the tracks because of the significant roughness leading to less space than expected. This feature – used in classical rotors – is an important aspect to improve electrical insulation between tracks. Identification of possible improvements such as surface roughness reduction indicates that it should be possible to ensure physical insulating barriers in the near future.

The machining was followed by the same gold plating as the conventional rotors. The visual aspect of the surfaces where brushes occur is fully comparable. To avoid additional process and material validation, the same resin and gold plating as the classical rotors were chosen.

5 TESTING

The QM rotors made by AM - integrated with conventional stators - followed the same qualification test campaign as conventional SRAs as detailed in Fig. 9.

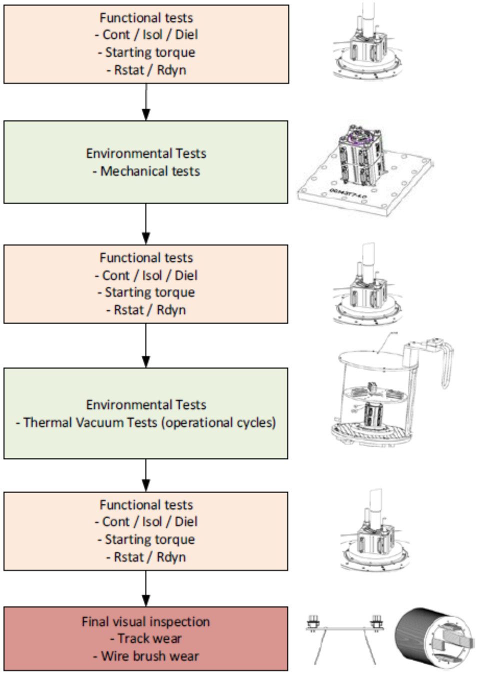

Figure 9. QMs qualification test sequence

5.1 Functional results before environmental tests

Some electrical insulation issues were detected between tracks: one short-circuit was present on each of the two QM rotors. Each time, two tracks were in short-circuit over the 30 channels per rotor. After non-destructive investigations, such as thermal camera inspection to detect local heating under power, the location of each bypass was determined, as shown in Fig. 10. Based on this, the root cause was identified as some residual bronze powder (on one rotor only) and drops of weld solder due to lack of cleaning prior to potting.

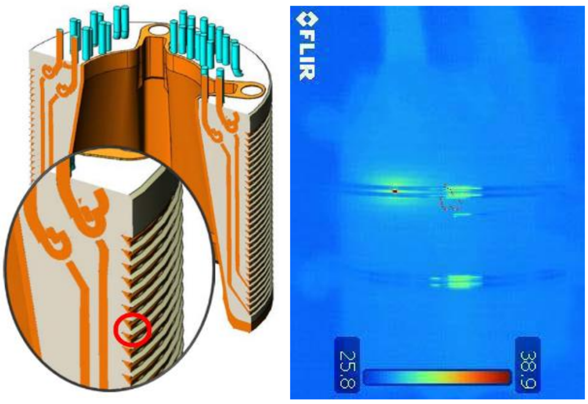

Figure 10. Determination of short-circuit location with thermal camera

5.2 Vibration and shock testing

The two AM rotors integrated in two SRA modules stacked together successfully passed the vibration and shock tests with the criteria of frequency shift <10% and no visual degradation. The X, Y & Z vibration levels were the following:

- high-level sine 25 g
- random 30.7 g_{RMS}

The X, Y & Z shocks : 3 per axis, 2000g

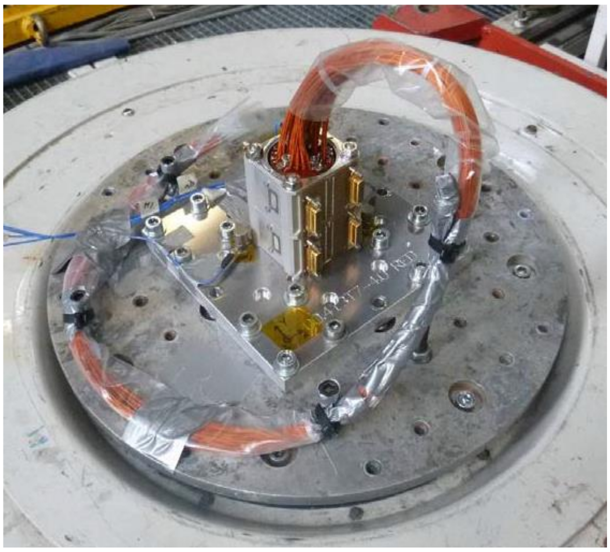

Figure 11. Two adjacent SRA modules with AM rotors on the vibration shaker with careful bundle routing

5.3 Thermal vacuum cycling

The TVAC testing comprised one non-operational cycle followed by 8 operational cycles from -50°C to +95°. More than 9000 revolutions at 1rpm were attained by two powered sliprings with AM rotors (up to 4A / line). Globally, the electrical performances were similar to traditional SRA rotors.

5.4 Functional results after environmental tests

Apart for the few tracks in short-circuit, the insulation performances before and after environmental tests are fulfilling the requirements:

- Insulation >100 MΩ under 500 VDC
- Dielectric strength <1 mA under 500 VAC

The electrical performances are considered as good, in compliance with success criteria.
Resistance values, :

- Mean 40-50 mΩ, spec. <67 mΩ
- STD 0.5-1.5 mΩ, spec. <5 mΩ
- Peak-to-peak 2-11 mΩ, spec <20 mΩ

5.5 Final visual inspection, stripdown

The AM rotors present the following characteristics after the qualification campaign:

- Few wear particles
- No visual degradation of the gold plating
- Normal wear on wire brushes
- No delamination / crack / flaking of the resin in between tracks

Some particles and wear tracks can be seen in Fig. 12. It shows the absence of higher barriers between tracks and the significant roughness of the raw AM part leading to irregular track borders.

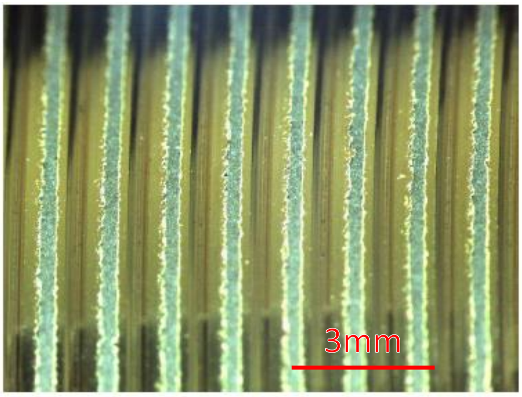

Figure 12. Close-up picture of the rotor tracks after qualification campaign

6 LESSONS LEARNED

Goal achievements

From a design point of view, there are very few differences between the AM and traditional rotors, as the new rotor was designed to be a Form-Fit-Function replica. However, the few following points should be highlighted:

- Mass: the AM 404 rotor is slightly heavier than the standard rotor : 424g versus 402g. This is not considered as an issue and could be optimized to further reduce the mass.
- The heat dissipation from track to rotor axis found more efficient for the 404 AM rotor during TVAC (temperature is 40% lower at track level based on FEM).
- The electrical resistance of conductors is lower for the AM rotor due to larger conductive cross-section.

AM advantages

This project has shown several advantages of AM SRA rotors compared to traditional ones:

- Ability of a scalable design (size, number of channels, interfaces, etc.) to answer persistent market needs for custom and optimized solutions,
- Potential of reduction of production time compared to standard technology (approx. -50%),
- Reduction of waste compared to parts machining (estimated > 50% metal, > 70% polymer),
- Reduction of costs initially estimated at 40%, but probably lower since final manufacturing workflow is more complex than planned. It is also difficult to compare an optimized traditional production of hundreds of units with only few prototypes and QMs made in AM.
- Additional functions could be envisioned on future products such as integrated thermal sensors, thermal dissipation optimized features, etc.

Insulation issue and detection limitation

A troublesome point is the inability to check the electrical insulation before the machining operation. The introduction of process monitoring during LPBF will allow detecting defects during the AM process. Post-AM defects shall be addressed by process consolidation. If a non-conformance is still detected after machining, the disassembly for repair is not possible compared to traditional rotors. Nevertheless, the significant reduction in lead time is decreasing the criticality of this aspect.

To ensure defect-free AM rotors, the preparation prior to casting and the inspection shall be improved. Lowering the surface roughness and ensuring a better cleaning of the AM part will ease to guarantee the absence of short-circuits and help to have higher barriers between the tracks. Some finishing processes have been investigated in the meantime with promising results.

LPBF process limitations

The selected use case (FFF with 404 module SRA) was critical with regards to LPBF process limitation at that time. Encountered insulation issues might have been avoided by slightly increasing the distance between adjacent tracks.

The need to support overhanging areas during LPBF process and the significant surface roughness are the main limiting factors to produce rotor with a smaller size. Currently the LPBF is the most suitable process for the manufacturing of such complex parts. As general considerations, it should be emphasized that the AM processes are evolving very quickly and what was a limiting factor two years ago could be solved with today available AM and post-process technologies.

Inspection methods

The NDI method of X-ray CT scan is expensive and has a barely enough resolution to detect small defects in such high-density parts.

Technical aspects to be addressed further

- Optimize the manufacturing workflow (cleaning, corrosion, soldering) to reduce manufacturing costs and increase reliability.
- Refine the in-process inspections & verifications
- Consolidate the approach to achieve qualification status according to ECSS-Q-ST-70-80C [4] which was not released at the beginning of the project
- Address industrialization aspects (demonstrate production stability for series production)

7 CONCLUSION

This project has been carried out under an ARTES C&G programme funded by the European Space Agency.

The successful completion of this project has been possible thanks to the addition of Beyond Gravity Slip Ring team competencies on slipring technologies, CSEM knowledge on additive manufacturing design and processes and the technical and financial support of ESA. According to ESA applicable TRL scale [5], TRL 6 is considered achieved, whilst considering electrical insulation limitations which are yet to be solved. This will be achieved through process optimization and/or an increase of the insulation gap to ensure the presence of resin barriers between tracks, and an optimum match with the maximum defect size expected.

8 REFERENCES

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