Product
Innovation and Development

Document scope

BMT Aerospace is best known for its capabilities for *manufacturing* of *gears and other torque transmitting components*. It is no surprise that majority of our innovations can be found in the field of *production technology* such as automation, machining simulation, innovative gear manufacturing through skiving, advanced heat treatments involving press quenching and additive manufacturing to name a few.

Less well known are BMT's *research and development projects* targeting product improvements for both technical performance and manufacturability (cost). A broad range of topics is addressed, going from tribology of metal-to-metal contact, material characterisation, surface engineering (heat treatment, roughness, coatings) to geometrical design optimisations for stress and weight, etc.

The goal of this paper is to illustrate BMT's product innovation and development progress by highlighting the outcome of the recently finished RAPIT project.

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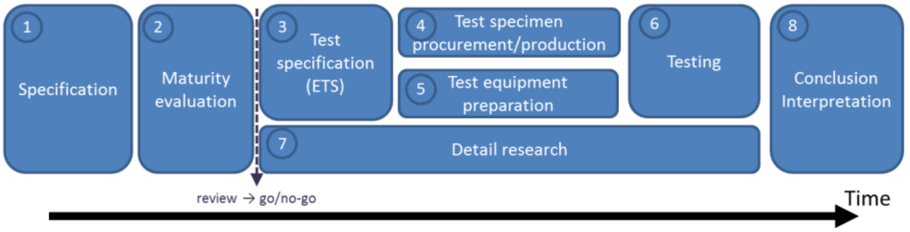
Project RAPIT

The acronym RAPIT stands for *Rack and Pinion of Tomorrow*. Rack (sector gear) and Pinion are used for the actuation of the wing leading edge slats. This actuation mechanism is proven to be very effective. Nevertheless, new challenges emerge from the desire to design lighter planes, reduce maintenance, limit environmental impact of aviation and at the same time remain competitive.

To address these challenges, BMT Aerospace teamed up with ASCO Industries for the collaborative project RAPIT. The project was carried out from mid 2018 to beginning 2021. BMT Aerospace was responsible for the project coordination and 80% of the workshare. Many design aspect are critically assessed: material, geometrical design and surface treatments. Since the challenges are not unique to this particular component, the solutions are also valuable to other products, i.e. shafts, levers, bearing housings, etc.

The project was structured in such way that there is a balance between analysis and physical prototyping and testing.



The project partner ASCO Industries main involvement was related to efficient integration of the rack with the slat track. (Project responsible for ASCO: Antoon Vervliet Antoon.Vervliet@ascoindustries.com) For individual work packages, collaboration with several leading technology companies took place (see further). RAPIT is supported by VLAIO (Flanders Innovation & Entrepreneurship) bmt aerospace

CARPENTER® TECHNOLOGY

Stainless Steel

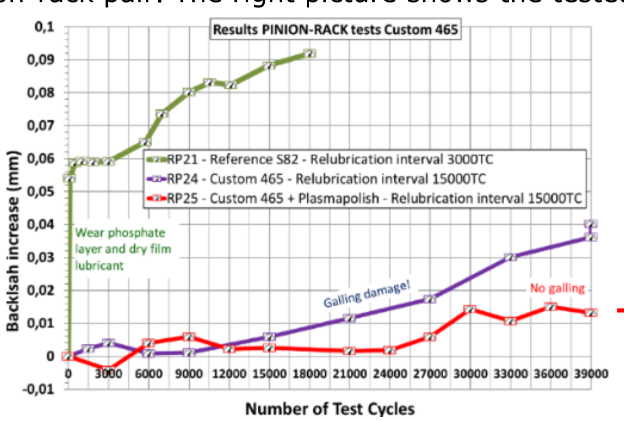
Custom 465® (AMS5936) is a *precipitation hardening stainless steel* for the most demanding applications. The material is capable of achieving very high yield strength and tensile strength, targeting for example applications that are currently using the 300M low alloy steel. Thanks to the materials inherent corrosion resistance, environmentally harmful corrosion protection solutions such as cadmium plating is avoided.

The first analysis deals with the basic material properties. Mechanical properties depend on the selected heat treatment (mainly aging temperature). The H950 (510°C aging) condition was chosen as the most suited for gear applications. The table below compares datasheet properties with actual measured values during the project. Significantly higher strength than expected from the datasheet is found and a hardness of typically 50HRC is achieved which is high in comparison with other stainless steels.

	Expected minimal preperties from datasheets							Typical values experienced by BMT (RAPIT)			
Material	Rp0.2 [MPa]	Rm [MPa]	Elongation (%)	Impact (J)	Hardness Annealed	Temper T (°C)	Hardened Core (HRC)	Rp0.2 (MPa)	Rm (MPa)	Elongation (%)	Izod Impact (J)
300M	1586	1931	7	Typ CVN>30 Typ IZOD>10	<311HB	302	52-55	1630	1965	11	13,5
Custom 465	1515	1655	10	Typ CVN>27 Typ IZOD>?	<331HB	510	≥ 47	1675	1780	11	19

The next analysis focusses on the manufacturability. In comparison with carburizing steels, the heat treatment of Custom 465 turned out as a remarkable simplification. There are less and shorter process steps. For example no masking operations are needed and deformations have a limited impact due to the uniform composition. Because high performance creep feed grinding is used, the gear teeth are made in hard condition without gear milling or pre-grinding prior to hardening. Although racks have been successfully produced, avoiding onset of grinding burn is extra challenging with this material. Another apparent drawback is a reduced efficiency of the rough milling. Optimization of the milling strategy and the cutting tools is of great importance.

The third analysis deals with gear performance. Functional tests are carried out on a modified FZG back-to-back test rig and a custom build pinion-rack endurance test rig. A surprising result is that Custom 465 showed the potential of lower wear rates than carburized steel gears, even with extended lubrication intervals (15000FC instead of 3000FC). However, to achieve this low wear rate, the surface preparation (roughness) and lubrication type should be optimal to avoid galling. The figure below shows the wear for a pinion-rack pair. The right picture shows the tested pinion after 39000 test cycles.



* *Custom 465® is a registered trademark of CRS Holdings, inc., a subsidiary of Carpenter Technology Corporation*

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Additively Manufactured CRES

Next to the conventionally manufactured components (see previous section), the additively manufactured alternative is developed. Thereto, BMT and Carpenter Additive had a close collaborated to design, manufacture, heat treat and test pinions using Carpenter Technology's Custom 465 stainless steel powder for AM. AM enables a lightweight design (-35%) while maintaining a high load capacity.

Pinions were subjected to an endurance test with 96000 simulated flight cycles (2-3x more than typical aircraft lifetime). The performance was directly compared with pinions from conventionally machined Custom 465 stainless steel. The AM stainless steel pinions showed similar wear rate. Post-test inspection by stiffness measurement and MPI did not reveal damage of the lightweight structure.

New generation carburizing steel

New generation steels that have higher mechanical strength and useable temperature than the current common choices (e.g. AISI9310, BS S82) are under development. This opens the potential for lighter designs, operation at high temperatures and also enables the use of production processes during which high temperatures are experienced (e.g. coating processes, see later). Pyrowear® 225 was selected as such new material worth investigating. This material was initially introduced by Carpenter Technology under the name PremoMax® as a through hardening steel. With engineering support from Carpenter, BMT pioneered on the use of this material as a carburizing steel.

A study, similar to the one for Custom 465 steel, is conducted. The coupon tests showed that expectations from the datasheet are easily met. Great hardenability (even at modest cooling rates) is observed. The tempering temperature of 288°C, which is 100°C higher than many other common carburizing steels, comes without penalty on the surface hardness (>58HRC).

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BS S82	1030	1320	8	Min Izod >34	<277HB	160-190	41-47	1070	1397	16,8	98
PremoMax Pyrowear 225	1241	1448	12	Min CVN>61	<285HB	233-288	≥ 45	1260	1530	13	85

Prototype gears are produced. The prototypes are finished with different surface treatments to learn about the manufacturability and corrosion performance.

Wear tests showed equivalent tribological performance for a rack and pinion application in comparison with the current baseline (S82). This remains true when the gears are exposed to contaminants: salt water, de-icing fluid, jet fuel, hydraulic oil and a mixture of sand and dust. Wear tests with different type of greases are carried out. With the best grease, the wear rate is reduced to nearly non existing.

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Plasmapolishing for surface enhancement

Electrolytic plasmapolishing is a process for smoothing and cleaning the metallic surface. It is suited for stainless steels and several non-ferrous materials (Titanium, Magnesium, Chromium-Cobalt). The process setup is related to electropolishing but different voltages and electrolytes are used. Despite its great potential, it is still relatively new to the industry.

Within the RAPIT project, Custom 465 gears and test coupons are treated by Plasotec GmbH. Treated parts have an almost mirror-like shiny surface. Upon measurement it is seen that the waviness (e.g. milling pattern) is still present but the micro-roughness disappears. Dimensional impact is limited and uniformly distributed. More important for the gear application is that the plasmapolished Custom 465 gears showed improved performance during wear tests: the onset of galling is postponed or avoided. Also in corrosion tests, the plasmapolished samples had a great advantage compared to chemical HNO_3 passivation. This is caused by the combination of the surface smoothening, passivation and cleaning action, effectively removing surface contaminants from the heat treatment.

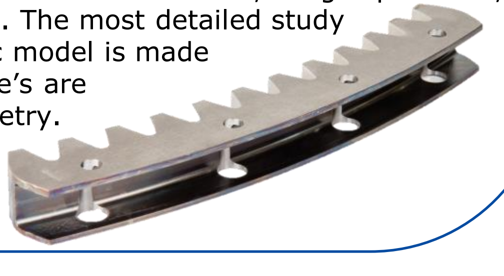
Geometrical optimization

Together with the material properties, the geometrical design is the key parameter that defines the function, performance capability ánd cost of the component.

Brainstorm sessions with participants from various backgrounds (Design, CNC, Quality Inspection, M&P,…) are the first step to identify potential improvements. On the one hand straightforward ideas are formulated such as geometrical optimization to use standardized CNC tools or avoiding difficult to inspect features. On the other hand, more radical changes are proposed that enhance the function or performance of the part. The challenging ideas still have many uncertainties and thus theoretical analysis, finite element stress analysis and test is needed to verify their potential.

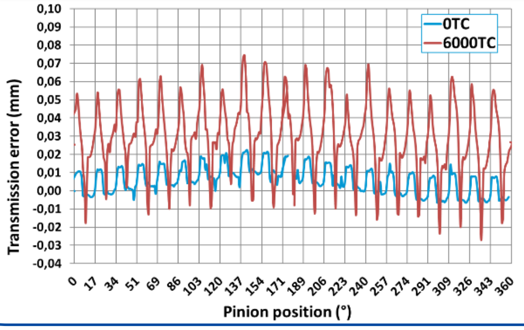
One of those challenging concepts is the so-called pinion-roller that combines the gear actuation function with a main track roller function. What is new in comparison with existing designs is that the two functions are combined in a single part rather than an assembly. The benefits of less components are the leaner assembly and shorter tolerance stack. It also has a big disadvantage: instead of a pure rolling contact, a *roll-slip* contact exists between the roller and the track surface. Therefore, wear tests are conducted to characterize the durability of it. Unfortunately, results indicated that more optimizations are still needed to improve the contact conditions.

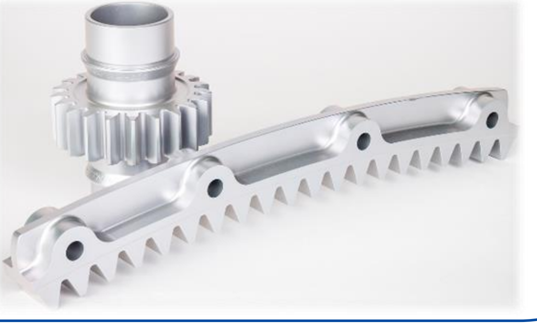
Another design study concerns the cross section shape of the rack. Typical sector gears have a T or I-shaped cross-section. However, other cross-sections can be thought of: π, Ω and U-shape. The cross-section has impact on the stiffness distribution, weight potential, integration options with the track, water drainage, etc. The most detailed study was conducted for the U-shaped section. A parametric model is made for strength and weight optimization by FEA. Prototype’s are manufactured to study manufacturability of this geometry. Finally, the prototype is installed in a representative dummy track to evaluate its impact at assembly.



IVD Aluminium

The use of Cadmium based corrosion protection is phasing out because of its toxic nature. A drop in replacement does not yet exist but several alternatives are on the market that need to be validated on a case-by-case basis. These are often based on zinc-nickel and aluminium systems. Both alternatives are able to offer corrosion protection on par with cadmium but are lacking the lubricity of cadmium. Therefore, the impact of IVD-Al coating for use on gears is studied. Prototype rack and pinions with IVD-Al coating are manufactured. Parts are subjected to corrosion tests and wear tests. This functional test shows a rather quick increase of the transmission error, meaning less smooth operation. After removal of the coating wear debris, the normal transmission error level is recovered. This indicating that the coating does not induce permanent damage on the tooth flanks but needs to be considered during running-in.



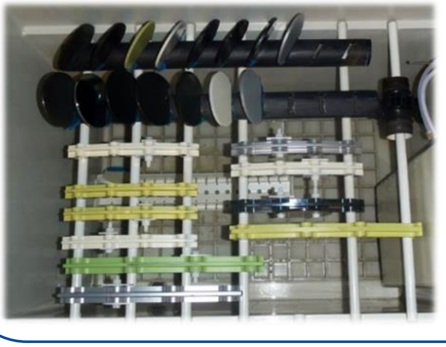


CrVI-free primer

Use of compounds containing Chromium VI is restricted by REACH. Two CrVI-free primers are selected and studied for their applicability on pinion and rack components: *02GN084* (PPG) and Aerodur *HS2121* (AkzoNobel).

The primers are applied on test coupons for corrosion tests and full-scale prototypes. Also wear tests are accomplished to study the impact of the primer on the running-in behaviour. Throughout the study it is found that these recently developed primers' performances are equivalent or better than the CrVI containing baseline. A small but not unimportant detail is that paint shop employees noticed an improved scent.

Corrosion Inhibiting Compound



Corrosion inhibiting compounds (CIC) Ardrox AV15 and waxy Ardrox AV25 (Chemetall – BASF) are studied. These products are not intended as the main corrosion protection on blank steels but are offering additional protection to improve corrosion resistance even further or to protect local defects. Although they are a secondary protection, salt spray performance is found to be even higher than the baseline primer and much higher than surfaces that are only protected by phosphating and oiling.

Maintenance reduction by thin film coating

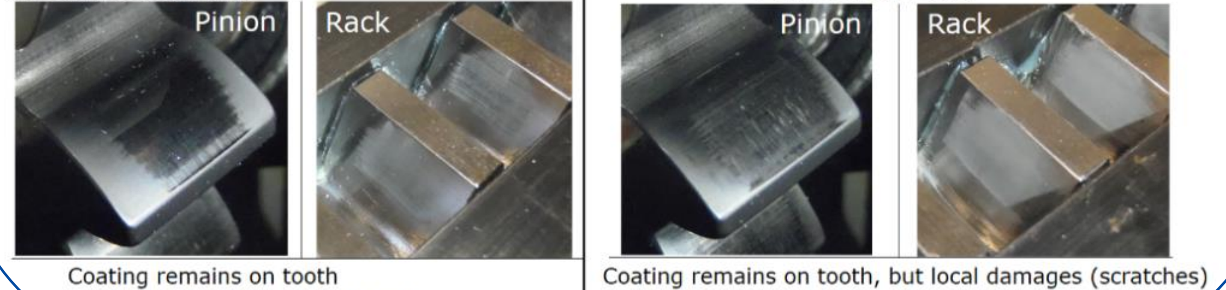
In low speed sliding contacts, a metal-to-metal contact exists. Such contact regime is called "boundary lubrication". As this name suggests, a lubricant is highly necessary to avoid bonding of the contacting surfaces, leading to adhesive wear (scuffing) and tribo-corrosion. There are several ways to reduce this scuffing regime: use better lubricants, optimize the contact conditions, optimize the roughness, select dissimilar material combination, etc. In this research, deposition of a thin film coating on the gears' tooth flanks is used to separate the surfaces and as such reduce the need for lubrication. The ultimate goal is to extend the maintenance interval from a C-check to a D-check.

Coating of gears is very challenging. Not only because of the high Hertzian contact loads but also because of the gear geometry itself. The tooth spaces and flank angle reduces uniformity and adhesion of the coating. Successful coating application is only possible when optimal substrate material, surface preparation (roughness), tooth profile modification and coating process are combined. Optimal coating procedure tailored to gears was developed together with Oerlikon Balzers. This is done based on "adjustment tests" and lab inspections at Oerlikon Balzers. The result is a process specification (confidential) and dedicated "recipes" for two coating types.

After these initial developments, test parts from various materials are send to Oerlikon for coating: tensile and impact test bars, corrosion discs and full-scale pinions (2 types). Example of coated pinions are shown in the picture on the right. The internal diameter and bearing seats remain uncoated.

Test parts are subjected to corrosion and wear tests. Some test combinations fail shortly after the start of the test due to an adhesion problem. Others combinations have comparable performance as the baseline. One tested combination showed significant improvement on the baseline. Halfway and almost at the end of the endurance test (15000TC and 27000TC), sand and dust contamination is added to simulate the most severe operational condition. Even in this harsh condition, the coating managed to avoid scuffing of the tooth flanks. By the end of the test (33000TC), the coating is clearly scratched but still largely present on the tooth flanks and free from tribo-corrosion.

The hereby tested coatings offer limited corrosion protection on their own (few µm thickness and porosities). But acceptable corrosion resistance is obtained when they are combined with CIC (Ardrox AV25 see previous section) at delivery and regreasing at installation and D-check.



Coating remains on tooth
Polished appearance of rack face

Coating remains on tooth, but local damages (scratches)
Dull appearance of rack face

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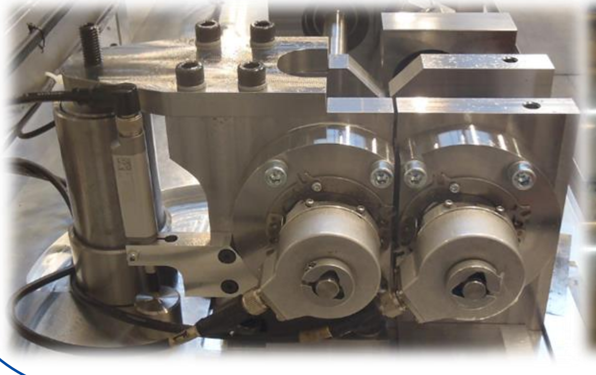
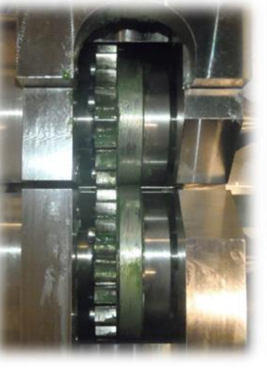
Tribology testing

A modified back-to-back endurance test rig is constructed. Besides wear tests on full-scale pinions, rolling or roll-slip tests (up to 30% slip ratio) on ring shaped samples can be accommodated. Tribological pairs can be characterised faster and without the time consuming and expensive manufacturing of test gears. Stepless adjustment of the radial load up to 25kN is possible (10kN for endurance testing). The rotation speed can vary from 1rpm to 30rpm and in one or alternating direction. Angular and linear displacement sensors continuously monitor the condition of the test rings for a detailed characterisation of the wear and surface degradation over time. Torque sensors on the drive and loading shaft provide information about the friction.

The test is used to validate the tribological aspects of the pinion-roller concept for different steels (stainless, carburizing steel and maraging steel).





Life Cycle Analysis

Controlling the environmental footprint associated with aviation has become more important than ever before. Every component and every operation step contributes to this aspect. Reducing the environmental impact is one of the main drivers of the whole RAPIT project. This is illustrated by the studies on cadmium alternatives, CrVI-free primer, weight reduction by introducing higher strength steels and geometrical design optimization.

Besides the main research topics, a side study is conducted to determine the best approach for a Life Cycle Analysis (LCA). Many methods exists and they can become very complex if one wants to take into account all influence factors. Therefore, defining the scope of an LCA is the first task: selection of process steps to include, decide about data sources for estimating eco-impact, assumptions to take, etc. Eventually an approach based on the fast track LCA method from TUDelft is proposed. Three impact indicators are used: total eco-cost, ReCiPe indicator points and Carbon CO_2 equivalent.

To our experience, the numerical values resulting from an LCA's are not to be interpreted as the exact truth and are riskful to be used outside the LCA. Nevertheless, within the LCA it is useful to get insight into the main contributors to environmental impact and to make substantiated decisions about process variants. For example, the impact of 1kg aircraft weight (A350) was estimated to be equivalent to 2600kg fuel saving during the aircraft life. The additional electricity consumption for a milling centre to machine a weight optimized component would be typically much lower than this amount of fuel.

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