

Recent Developments in Aerospace Gears and Gearbox Designs

Mert Vardar

AeroGDT Power Transmission Systems Inc, Ankara, Turkey
E-mail: mert.vardar@aerogdt.com

Fatih Erdogan

AeroGDT Power Transmission Systems Inc, Ankara, Turkey
E-mail: fatih.erdogan@aerogdt.com

Nihat Yildirim (Corresponding author)
Gaziantep University, Gaziantep, Turkey
E-mail: nyildir@gantep.edu.tr

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Ankara TURKEY*

Abstract

Aerospace power transmission elements and units like gears and gearboxes are critical components which need to be designed, manufactured and installed for a well performing fail-safe operation. Recent development of such components has seen rather satisfying improvements regarding different subjects like materials, design, manufacturing processes, surface treatment, etc. While cleanliness of material and special alloys help increase the strength of gear material, different design methods help reduce stresses under service loads. Similarly, different manufacturing methods help reduce surface burn like defects while material surface coatings help increase the resistance to wear and pitting like failures of both gears and bearings. Different examples of recent developments in aerospace gears and gearbox designs are provided in this paper to keep readers up to date with the aerospace power transmission technology.

Keywords: aerospace, development, design, gear, gearbox, performance

1. Introduction

All aerospace vehicles have to employ some kind of power transmission units and elements to transmit engine power to main and auxiliary power consuming units like main propellers, generators, pumps, etc. In last 20-30 years of aerospace power transmission technology many subjects have been re-studied and re-evaluated for likely valuable contributions to provide better performing components in terms of either improved power density and improved safety or service life. An overview of those recent developments will be presented here regarding the power transmission gears and gearbox designs only.

The most likely contributions and developments in transmission gearboxes have been seen on subjects like engineering materials, design methodologies, manufacturing processes and surface treatments. Such contributions have been employed for main components like gears, bearings and shafts of power transmission units.

2. Developments on Aerospace Power Transmission Materials

Gears as one of the main power transmission elements suffer both tooth surface failures and tooth fracture due to cyclic loadings. Contact stress at tooth flank and bending stress at tooth root are the main causes of those gear failures. While shafts usually fail due to bending fatigue, bearings fail due to repetitive high contact stresses between rolling elements and races.

Due to high power density requirements of aerospace vehicles power transmitting materials are usually loaded almost up to their maximum loading capacity. However, new demands for improved capacity are pushing the metallurgists to develop better performing materials for components like gears and bearings.

Regarding material developments, different aerospace materials have been introduced for improved performance of gears and bearings. Such materials have provided better durability against bending and contact stresses because of improved strength and hardening abilities/properties.

McPherson, 2002, had an extensive research program on engineering performance of gear made from high hot hardness materials. The objective of the research program was to characterize new materials like M50-NiL, CBS-600, Nitralloy-N, Pyrowear 53, and Vasco X-2M in terms of bending strength and surface durability, and compare their performance with that of 9310 VIM-VAR. Bending strength was characterized via the Single Tooth Fatigue (STF) method. Surface durability was characterized via the Rolling/Sliding Contact Fatigue (RCF) method at two different temperatures, 93°C and 204°C.

At 93°C, bending strength and surface durability of 9310 VIM-VAR was quite competitive with the other materials. As expected, exposure to 204°C tempered this material and degraded performance in both categories below useable level.

Pyrowear 53 has the highest surface durability at 204°C. It also had good bending strength at 204°C. Based on this combination of bending strength and surface durability, Pyrowear 53 appears to be the most promising candidate material of the group. The Aerospace Gear Industry has de-facto adopted Pyrowear 53 as a replacement material for 9310.

Grabowski et al 2014, have studied design and testing of new high performance Ferrium alloy steels (*Ferrium S53*[®] and *Ferrium M54*[®], *Ferrium*[®] C61[™] and *Ferrium C64*[®]) used in demanding gear and bearing applications in ground and aerospace military, commercial aerospace, high-performance racing, oil and gas and other industries. *Ferrium*[®] C61[™] and C64[®] steels are commercially available secondary hardening gear steels that provide significantly improved tensile strength, case hardness, fracture toughness, fatigue strength, corrosion resistance, and temperature resistance, resulting in performance benefits over conventional gear steels such as AISI 9310 or Pyrowear[®] Alloy 53.

Gears and gearboxes using C61 and C64 steels can handle higher impact loads and internal stresses than comparable designs using traditional materials. In some cases, gears and gearboxes can be reduced in size and weight due in part to C61 and C64 steels' very high fracture toughness and bending fatigue resistances. The combination of excellent gear fatigue properties and high surface hardness in C64 makes it an option for improving durability (and reducing weight) in rotorcraft component designs that incorporate toothed-gears with integral bearing races (e.g., planetary gears in epicyclic rotorcraft transmission designs).

Ferrium S53 and *Ferrium M54* are power transmission structural steels with high toughness, high-strength, excellent fatigue properties and enhanced resistance to stress corrosion cracking.

Gasparini et al 2009, have studied bending fatigue capacity of specific gear materials (VIM-VAR 9310 and VIM-VAR EX-53) with differing gear manufacturing processes for a reliable design and service life. Single tooth bending fatigue tests (see Fig.1) were performed extensively. High cycle fatigue S-N curves of those two materials were constructed to serve gear designers for reliable designs of gear.



Figure 1. Single tooth bending fatigue test rig (Gasparini et al 2009)

Gasparini et al 2014 have studied one of the most critical case in helicopter transmission service, Loss of Lubricant (LoL). In case no lubricant flow reaches gears and other contacting and rubbing surfaces, metal-to-metal contact starts happening and temperature of materials increase. Gear and bearing materials including casing material in such critical conditions have to perform satisfactorily for at least 30mins as an aerospace legal requirement.

Deteriorations of the tribological contact surfaces of gears and bearings can be prevented or at least limited/deferred by adopting proper material with higher temperature resistance with respect to conventional ones. For example:

- For gears, use of nitriding steels maintaining high hardness up to about 500°C instead of

- conventional carburizing steels which soften above 150°C.
- For gears, use special high hot hardness carburizing steels (such as EX 53 “Pyrowear” or Vascojet) maintaining high hot hardness up to about 350°C in place of conventional carburizing steel.
 - For bearings, use M50 tool steel or M50NiL carburizing steel providing high hardness up to about 350 °C in place of conventional 100Cr 6 (AISI52100) bearing steel which can be stabilized only up to 150°C.

Table 1. Alternative housing materials and thermal conductivities (Gasparini et al 2014)

Material	Thermal Conductivity [W/M/°K]
Aluminum Alloys	≈ 200 ÷ 250
Magnesium Alloys	≈ 150
Low Alloy Steels	≈ 40 ÷ 50
Stainless Steels	≈ 15
Titanium	≈ 20
Carbon Fibers Reinforced Plastics	≈ 25

Housings and casings should perform the function of heat removal as quickly as possible with maximum thermal conductivity. Table 1 is qualitative only, but it highlights that the preferred materials for housing should be aluminium alloys and secondarily magnesium alloys, whereas the titanium, stainless steel and carbon fibres and other composite materials should be avoided to prevent hot spots under LoL conditions. Therefore AW189 MGB casing is made of aluminium castings

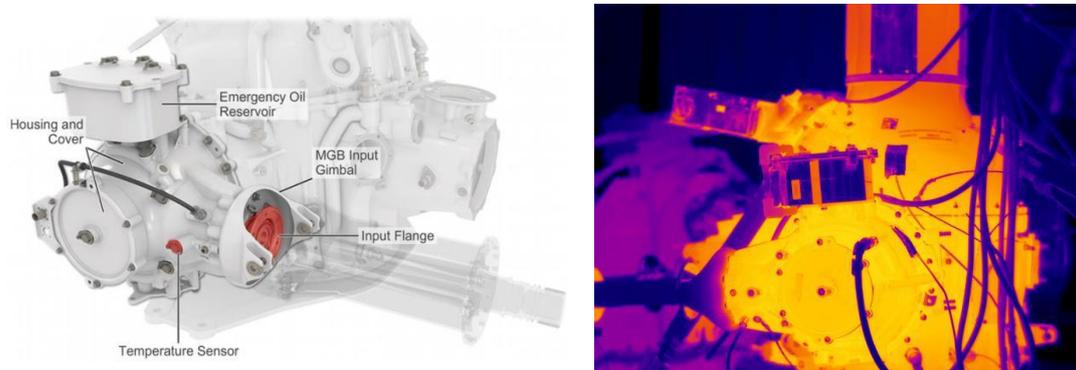


Figure 2. AW189 input module view and heat distribution on the AW189 MGB (Gasparini et al 2014)

In addition to the clever material choice, also very important is the design of thermal path inside the gearbox: allowing fast transfer of heat from sources to casing and housings (see Fig.2).

Other than the type and alloy composition of steels, the cleanliness of steels used for gears is of great importance if you need to improve their fatigue service life or load capacity. Fagerlund, J and Kamjou, L 2017, have conducted an investigation. The objective of the investigation was to evaluate the cleanliness and how it is related to the fatigue performance of carburizing steels with similar basic chemistry but with a varying degree of cleanliness, seeing as this type of steel is commonly used for different types of gear applications.

As the investigation shows, steels with a higher cleanliness level — that is, less detrimental defects in the loaded volume — give a higher performance level. These results correspond well to component testing done on gears and can therefore be considered a relevant method of testing for expected material performance.

3. Developments on Aerospace Material Surface Treatments

Surface treatments are the processes which help components of power transmission units for improved durability and efficiency. Materials of gears, shafts and bearings exposed to high bending and contact stresses (also shear stresses) are usually exposed to surface treatment processes like hardening, shoot peening, hard coating, superfinishing etc. However, these treatments are not material free and proper treatment process depends on the type & composition of material.

Case hardening processes like case carburising and nitriding are the common processes applied to both industrial (Otto F J & Herring D H, 2002) and aerospace gears, shafts and bearings (Gorla. et al 2017). Loss of lubricant is one of the most critical condition for aerospace power transmission elements. It is suggested by Gasparini et al 2014 to reduce the power losses and the generated heat by reducing the coefficient of friction. The coefficient of friction can be reduced by working on surface finish improvements of gears, bearings and seals by fine grinding or even super-finishing. Special coatings, such as dry lubricant or DLC (*Diamond Like Carbon*) on bearings and introduction of ceramic rolling elements in the most critical locations added benefits of both an appreciable weight reduction and reduced friction(see Fig.3).



Figure 3. DLC coated inner bearing raceway and ceramic rolling element bearings used on AW gearboxes (Gasparini et al 2014)

Joachim, et al, 2004, have studied the effects of hard coating and superfinish surface on the service lifetime of gears. Two types of coatings, tungsten carbon carbide (WC/C) and amorphous boron carbide (B4C) were the main focus of study. The tungsten carbon carbide layer WC/C is a metallic-hydrocarbon layer (Me-C:H), which is increasingly used in power transmission units and other engineering applications to reduce wear. These layers are applied using a PVD process which permits coating and material temperatures less than 200°C and therefore makes the coating of case hardened components possible. Boron carbide (B4C) is applied using a PVD process similar to that used for WC/C. This layer has a substantially higher hardness level than WC/C.

Superfinishing of contacting surfaces like tooth flanks are performed by two methods; standart superfinishing by grinding particles to abrasively remove peaks of roughness and chemically accelerated superfinishing by fluid compounds. Both methods create much lower surface roughnesses than conventional grinding hence reduce the effect of wearing action of touching and sliding flanks of gear teeth.

PVD hard coating and superfinishing processes can provide significant increases in scuffingresistance, wear resistance, macropitting resistance, and micropitting resistance hence service life for heavily loaded aerospace gears. Furthermore, the coefficient of friction can be reduced with increased efficiency of the system.

Another research about coating of aerospace gear teeth surface was conducted by Krantz et al 2003. Here too, a hard coating, W(tungsten)-DLC, were deposited onto carburized spur gears (made of AISI 9310) after final grinding, by using a sputter deposition process, at a deposition temperature of approximately 200°C. Coated and uncoated gears were tested using a four-square type gear fatigue rig. Tests were run until either of surface fatigue failure of any one gear tooth or until a predetermined number of cycles had occurred with no failure (see Fig.4).

For the uncoated gears, all tests resulted in failure with test durations ranging from 25—272 million revolutions. For the coated gears, three of the tests resulted in failure while eleven tests were suspended without failure. The testing durations ranged from 63—311million revolutions.

Effect of shot peening the gear teeth were studied by Gorla et al 2017 for case hardened gears made of different versions of 9310 and EX-53 steel, the most commonly used materials for aerospace gears,.The use of a shot peening process to enhance the bending fatigue performances can lead to an improvement significantly higher than that assumed by gear standards. For case hardened steels, the improvement achieved in the present research by shotpeeningwas about the 14%, i.e. significantly larger than the maximum prescribed by the ISO standard, equal to 5%. For a specific family of nitrided steels, the enhancement of the properties with shot peening, which is not considered by gear standards, was also tested, obtaining an increase of the fatigue limit of about 18%.

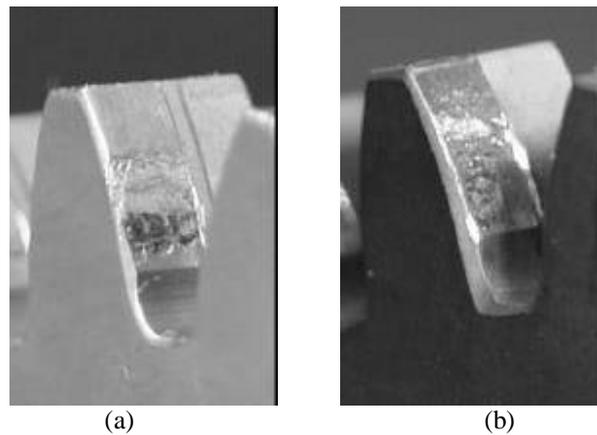


Figure 4. Typical appearance of failed gear tooth surfaces. (a) Uncoated gear. (b) Coated gear. (Krantz et al 2003)

4. Developments on Aerospace Power Transmission Designs

4.1 High Contact Ratio Gears

Compared with standard spur gears having a contact ratio between 1&2 and sharing the tooth load by two pairs at the maximum, High contact ratio (HCR) gears will have a contact ratio between 2&3 and share the tooth load by two pairs at the minimum and carry less contact force with reduced bending and contact stresses (if designed and manufactured properly). This is what some aerospace gearboxes are designed for recently. Examples of HCR gears employed in a helicopter combining gearbox (Yıldırım et al 2008) has performed quite well with not only reduced bending and contact stresses but also improved vibration, noise and lifetime performances (based on proper design and manufacturing).

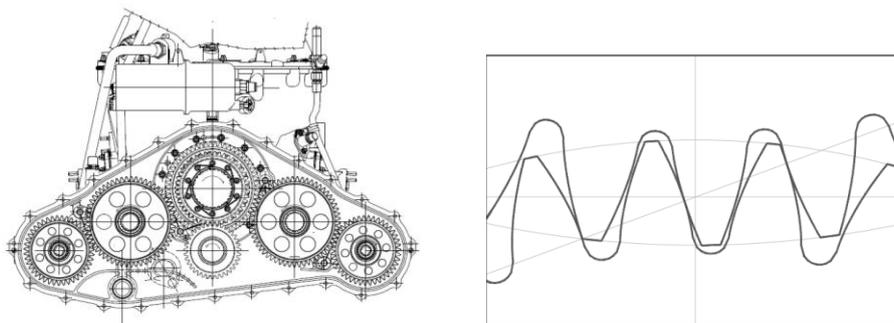


Figure 5. Main transmission combining gearbox section view and HCR gear teeth (Yıldırım et al 2008)

For the HCR gears seen in Figure 5, the achieved results, after the installation of these components on real production helicopters, were:

- transmitted power increase of 10%;
- overall weight reduction equal to 8% (teeth face width reduction of 20%);
- reduce by 2/3 of the vibrations field at the test bench;
- mean reduction of 9 dB at the test rig, in correspondence of the meshing frequency;
- acoustic emission stabilization in correspondence of the same tone, varying the flight conditions on the helicopter (maximum noise reduction of 13 dBA).

4.2 Asymmetric Tooth Gears

Asymmetric tooth gears were one of the recent gear designs aiming at reducing both bending stress and contact stress due to increased tooth root thickness and increased radius of curvature of the tooth profile compared with that of the symmetric tooth gear (see Fig.6). Usually the driving flank pressure angle is increased while coast flank pressure angle either decreased or kept constant. Brown et al 2010 is one of the important study on application of asymmetric tooth gears in an aerospace gearbox.

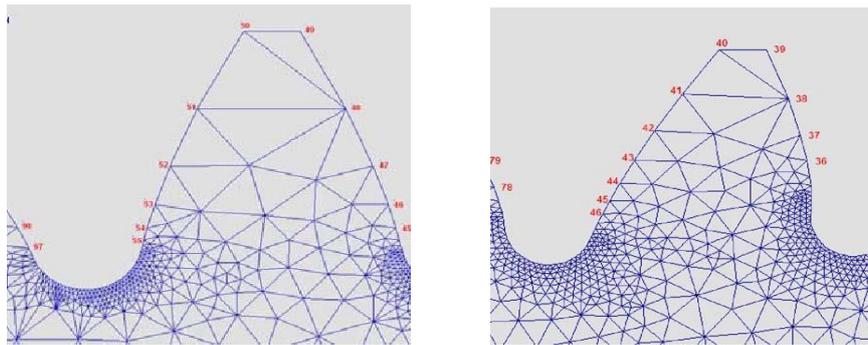


Figure 6. Symmetric and asymmetric tooth forms (Brown et al 2010)

Asymmetric and baseline (symmetric) toothed gear test specimens were designed, fabricated and tested to experimentally determine their single-tooth bending fatigue strength and scuffing resistance. Test results demonstrated higher bending fatigue strength for the asymmetric tooth form compared to baseline designs. Scuffing resistance was significantly increased for the asymmetric tooth form compared to a conventional symmetric involute tooth design.

Asymmetric STBF gears demonstrated a 16% improvement in mean single tooth bending fatigue load capacity compared to baseline symmetric tooth STBF gears. The asymmetric gear tooth form demonstrated superior scoring performance when compared to conventional symmetric gears. The mean value for a limited data set showed an improvement of approximately 25%

4.3 Asymmetric Root Gears

Similar to asymmetric tooth gears, another design method, named "asymmetric root gears" was suggested to improve the bending stress capacity of aerospace gears by employing different/asymmetric cutter tip radii on two sides of rack or hob cutter (see Fig.7). The cutter design and the analysis of bending stress reduction with asymmetric root gears are given in Akpolat et al 2017. In reference to symmetric root gears, nearly 10% bending stress reduction is obtained by employing asymmetric root gears.

Combination of both asymmetric tooth and asymmetric root on the same gear is studied in Şahin et al 2018. Depending on the level of asymmetry both in pressure angle and root (of the drive and coast flanks), 10-15% reduction in bending stress and 8-14% reduction in contact stress are predicted by numerical analysis (see Fig.8).

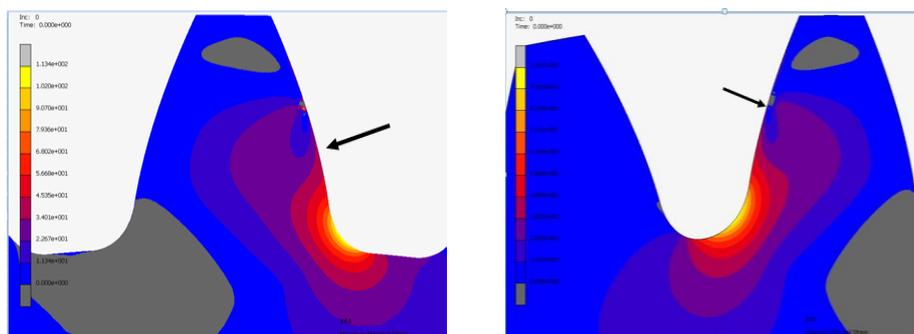


Figure 7. Symmetric and asymmetric root forms (Akpolat et al 2017)

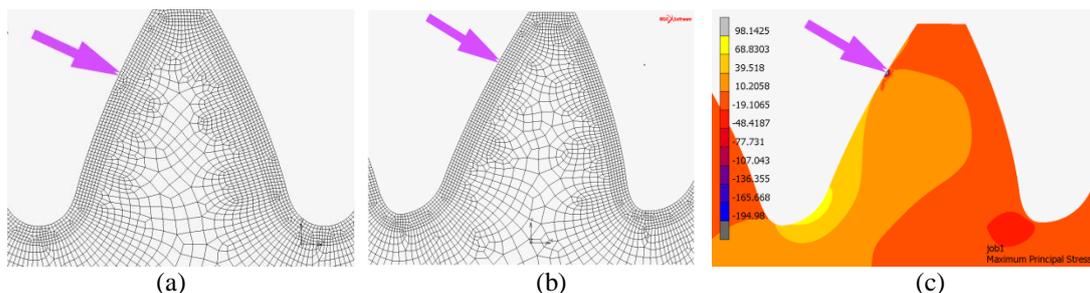


Figure 8. Symmetric tooth symmetric root (a), Asymmetric tooth asymmetric root (b,c) (Şahin et al 2018)

4.3 Face Gears

Spiral bevel gears are used in helicopter main gearboxes due to relative positions of engine and propellers. Face gears, in Fig.9, can be used in aerospace applications similar to those of spiral bevel gears, when reduction ratios are greater than approximately 3.5 to 1. The geometry of face gears provides an inherent capability to handle larger reduction ratios than bevel gears.

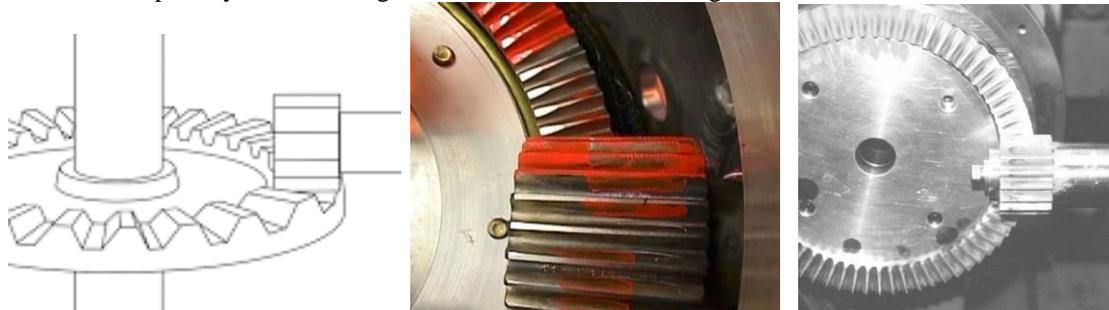


Figure 9. Face gears (Heath et al. 2002)

The proof-of-concept split torque tests of Heath et al. 2002 in helicopters have determined that, with some improvements, face gears can be applied effectively in a split torque configuration which yields significant weight, cost and reliability improvements over conventional designs.

5. Developments on Aerospace Gear Manufacture

Aerospace gears need to be more accurate and more reliable than any other gears used in most power transmission applications. Therefore, manufacturing and measurement, based on what was targeted at design stage, are the two important stages of realization of the gears. Aerospace gears are also rough cut, hardened, finish cut and measured as all other gears. However, for the near perfect performance of those aerospace gears both the manufacturing machine and the manufacturing process have to be better than the conventional ones to minimize the likely errors and defects. Especially the finishing operations have to be under close control with some special inspection and measurement methods.

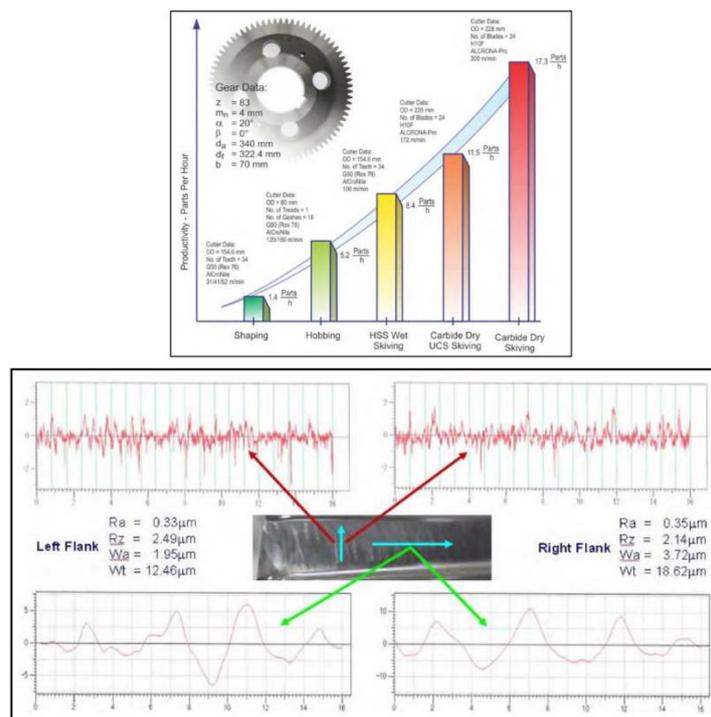


Figure 10 Gear Skiving advantages: productivity comparison and surface roughness & waviness (Stadtfeld H.J. 2014)

Based on the improved machine structural rigidity and the high speed synchroization of machine axes Skiving process (Stadtfeld H J 2014) have been developed with increased production capacity and improved cutting accuracy (see Fig.10). While skiving gears may be satisfactory for some industrial applications with reasonable surface quality and dimensional accuracy, final finishing operations will still be needed for aerospace gears.

Developments in grinding and superfinishing type of manufacturing processes help improve the quality of gears for aerospace applications. Grinding developments has resulted in a process called molecular decomposition process (MDP). MDP, as explained in DeAngelo, J A. 2017, is an anodic dissolution process (electrochemical) whereby the work piece is the anode and the grinding wheel is the cathode. MDP process produces a superfinished gear tooth surface with Ra less than 0.025micrometer as compared to conventional "as ground" surface with less than 0.45micrometer (see Fig.11)



Figure 11. MDP ground gear (left) and conventionally ground gear (right) (DeAngelo, J A. 2017)

The risk of grinding burn in conventional grinding process is relatively higher and cause early failure of aerospace gears due to metallurgical changes hence mechanical weakness usually at tooth root and flank. Such defects have to be inspected, detected and if possible removed prior to service installation. The method of magnetic Barkhausen noise is explained in Thomas J, and Kendrish S, 2017, as an alternative to nital etch for the detection of grind temper on gears in laboratory conditions.

A shop-floor inspection method being developed (Ophey, M and Reimann, Dr. J, 2014) based on the grinding process cutting force measurement & heat flow density evaluation help determine/predict likely detrimental surface zones on gear tooth during manufacture (see Fig.12).

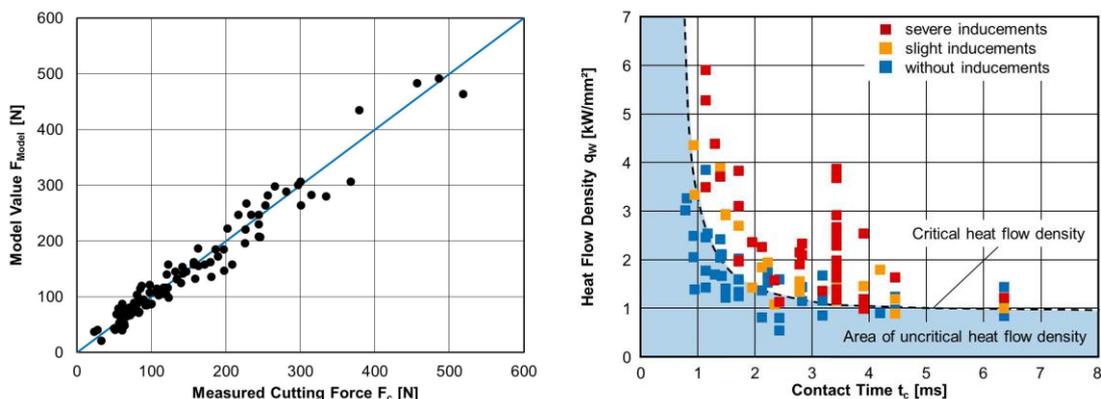


Figure 12. Grinding cutting force measurements and surface zone inducements depending on heat flow density (Ophey, M and Reimann, Dr. J, 2014)

Double flank gear tester, used in quality control of gears, is a laboratory test unit allowing different gear inspection details of a manufactured gear against a master gear usually (see Fig.13). It requires gear to be mounted on test unit in the laboratory with special tooling like expanding arbor and others.

A specially developed, sensor supported, mechanical gage unit explained in Baruchello, R and Sicheneder, G, 2009 (see Fig 14) allows the real time measurement to be performed in shop-floor at different stages of manufacturing with better accuracy and acceptable repeatability. The unit helps increasing productivity and closely controlling the quality of gears for aerospace like critical applications.

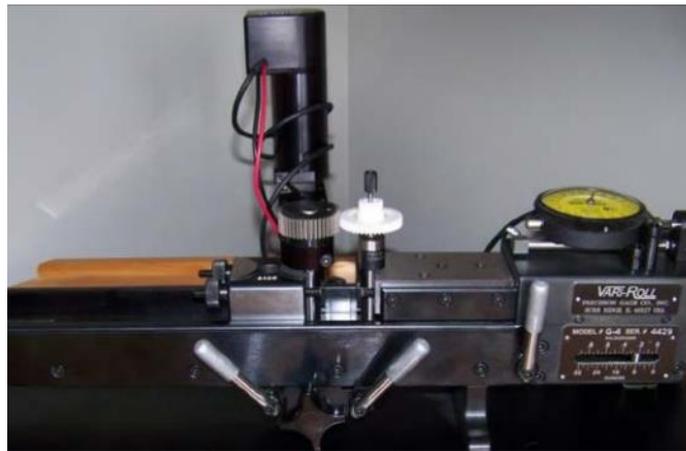


Figure 13. A double-flank composite tester in tight mesh



Figure 14. A specially developed, sensor supported, mechanical gage unit for shop-floor inspection of gears (Baruchello, R and Sicheneder, G, 2009)

Industry 4.0 is a fast developing future production technology and is likely to be employed by gear manufacturing sector in near future. In respect of improved productivity and high quality gears, gear manufacturers and gear manufacturing machinery designers need to get ready for an Industry 4.0 type gear manufacturing platform including stages of design, manufacturing and quality inspection.

A software based gear production conceptual system of *Gear Engine* is suggested by Brumm M and Müller, H., 2018 (see Fig 15). The system of *Gear Engine* have different modules (of design + manufacturing + inspection) with a closed loop data communication among each other. No more print out are expected to be evaluated by operators except specific cases. Modules will exchange data in the standardized *Gear Data Exchange (GDE)* format.

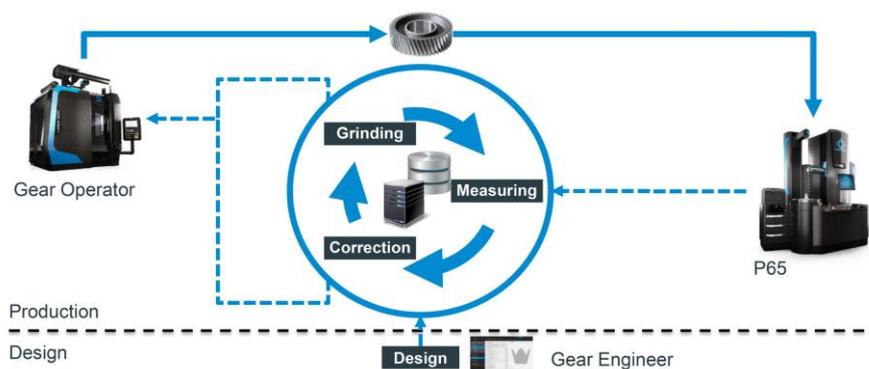


Figure 15. Closed Loop production system, Gear Engine (Brumm M and Müller, H., 2018)

The heart of *GearEngine* is a database for gear data, tool data and production data. The platform has interfaces to design software for gear and process design (e.g., *Gear Designer*). Every machine in the production network is connected to *GearEngine* and is reading and writing data. This means that data is not stored locally on machining centers — it is *centrally* stored in *GearEngine*.

CONCLUSIONS

This presentation is an up-to-date summary of the recent developments in field of aerospace gears and gearbox design, manufacturing and inspection regarding materials, surface treatments, manufacturing processes, inspections and quality measurements employed.

New ferrous steels have been developed for increasing the strength and durability of gears and bearings under heavy loads. M50-NiL, CBS-600, Nitralloy-N, Pyrowear 53, Vasco X-2M, *Ferrium S53*[®] and *FerriumM54*[®], *Ferrium*[®] C61[™] and *Ferrium C64*[®] are some of those new steels.

Regarding surface durability, hard coating and superfinish are the two treatments for aerospace gears. Two types of coatings, tungsten carbon carbide (WC/C) and amorphous boron carbide (B4C) were useful developments. Shot peening the gear teeth is another surface treatment method for improving the performance.

Regarding design developments,

- split torque configuration sharing the torque between twin power paths,
- high contact ratio gears sharing the tooth load between more teeth in contact,
- asymmetric tooth gears enduring more bending load due to increased tooth root inertia and more contact load due to increased radius of curvature at contact point,
- asymmetric root gears enduring more tooth bending load due to increased tooth root inertia and reduced stress concentration at tooth root due to increased radius of fillet curvature

are the recent design methodologies.

Face gears were applied effectively in a split torque configuration of helicopter transmissions with significant weight, cost and reliability improvements over conventional designs.

Grinding developments has resulted in a process called molecular decomposition process (MDP) producing superfinish surfaces for aerospace gears.

New inspection methods, magnetic Barkhausen noise, and new control mechanisms (cutting force measurement & heat flow density evaluation) were developed for detection of grinding burn defects.

Based on Industry 4.0 technology, new gear production systems and platforms, including design, manufacturing and inspection processes, are being developed for improved productivity and higher quality aerospace gears.

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