CIRP Annals - Manufacturing Technology 63 (2014) 703–726

Contents lists available at ScienceDirect

CIRP Annals - Manufacturing Technology

journal homepage: http://ees.elsevier.com/cirp/default.asp

# Turbomachinery component manufacture by application of electrochemical, electro-physical and photonic processes

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ARTICLE INFO

*Keywords:*
Manufacturing
Material Removal
Turbomachinery

ABSTRACT

This paper presents an overview of the current technological and economical capabilities of electrochemical (ECM-based), electro-physical (EDM-based) and photonic (Laser-/EBM-based) additive and removal processes for turbomachinery component manufacture. Starting with the industrial demands and challenges of today, the technologies are reviewed in detail regarding achievable geometrical precision and surface integrity as well as material removal and deposition rates for conventionally difficult-to-cut Ti- and Ni-based alloys and dedicated steels. Past, existing and future areas of technology application of these advanced non-mechanical manufacturing processes are discussed. The paper focusses on the description of shaping processes therefore excludes pure welding or coating applications.

## 1. Introduction

The demand for turbomachinery systems such as aero-engines, stationary gas and steam turbines as well as turbochargers for engines is constantly growing due to the increasing worldwide requirement for energy and mobility. In contrast, conventional energy resources such as oil, gas and coal together with important raw materials are shrinking while environmental pollution due to $CO_2$ and $NO_x$ emissions is on the rise. Thus, energy and fuel prices as well as costs for environmental protection and sustainability are constantly increasing, necessitating the development and introduction of highly efficient turbomachinery systems.

Taking the aerospace sector as an example, air traffic is resiliently growing at a rate of 4–5% a year both for revenue passenger (RPK) as well as cargo traffic tonne kilometres (RTK), practically doubling within 15 years. According to the 'Global Market Forecast 2012-32', Airbus predicts a doubling of the passenger aircraft fleet ($\geq$ 100 seats: single/twin-aisle and very large) from 16,094 to 33,651 by 2032. Including replacements, some 28,355 new aircraft deliveries are anticipated. Similar numbers are presented in Boeing's 'Current Market Outlook 2013-32' showing the 20,310 aircraft (regional jets, single aisle, small/medium/large widebody) currently in service increasing to 41,240 by 2032 with new deliveries of 35,280 [29,86,123]. In terms of aeroengines, Rolls-Royce expects ~68,000 deliveries (including business jets) over the period 2012-31, with a market value of $975 billion [164]. Adding to this, the servicing of commercial engines involving maintenance, repair and overhaul (MRO) is also growing in importance. Within GE Aviation, the service market for 2011 amounted to $7.2 billion while the new engine market was $4.9 billion [100].

Besides market growth, the challenges faced by industry are also growing, because future aircraft including the engines must also be more fuel efficient, quieter and cleaner due to official regulations and agreements. The new ACARE (Advisory Council for Aviation Research and Innovation in the EU) goals for 2050, schedule a reduction of 75% in $CO_2$, 90% in $NO_x$ and 65% in noise relative to 2000 [2,86]. In summary, there is an extensive and pressing need for design – as well as advanced manufacturing and repair technologies able to handle the current and growing future demands for turbomachinery components.

## 2. Challenges of turbomachinery component manufacture

Core functional components of turbomachinery systems are characterised by the use of dedicated high temperature, high specific strength and wear-resistant materials (Fig. 1).

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http://dx.doi.org/10.1016/j.cirp.2014.05.004
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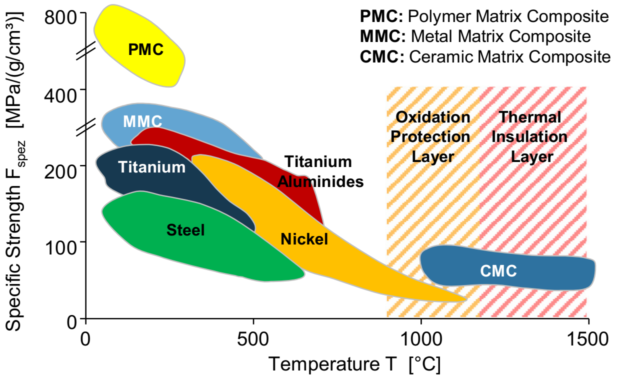

**Fig. 1.** Specific strength of materials as a function of working temperature for turbomachinery components. Based on [181].

Machining such "difficult-to-cut" materials using conventional means is very challenging, often resulting in low material removal rates (MRR), reduced precision due to high cutting forces, high tooling costs due to increased wear and consequently low process efficiency [178]. In addition, the resulting surface integrity is often characterised by thermo-mechanically altered or even damaged rim zones [97,178,196]. Thus, the utilisation of technological as well as economically suitable manufacturing technologies is of great interest.

Taking the aerospace sector again as an example, Fig. 2 shows the specific areas of application for preferred Ti and Ni-based alloys in aeroengines. The temperature capability of such materials is constantly increasing through the development of new materials with different primary manufacturing technologies [158] (Fig. 3). Due to the absence of grain boundaries, single crystal materials exhibit far better creep properties than polycrystalline materials and can therefore be utilised at higher temperatures [34]. The use of such new materials and especially the advanced gamma titanium aluminides (for compressor as well as turbine applications) [13] and polymer matrix composites – PMC (for fan blading components), (Fig. 2), require amongst others, the development of appropriate manufacturing technologies.

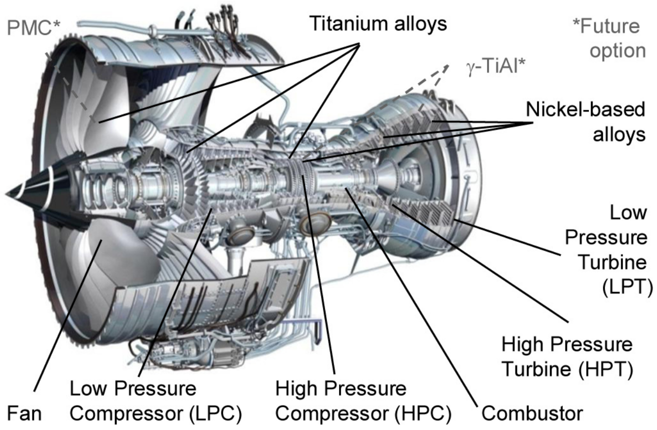

**Fig. 2.** Current and future temperature specific application of materials in aero engines (example: Rolls Royce Trend 800 engine).

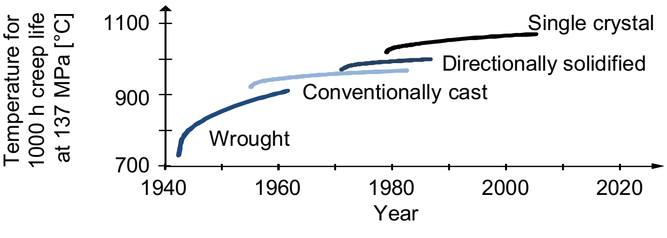

**Fig. 3.** Evolution of high-temperature strength capability of turbine blading nickel-based super alloys. Based on [158].

The most important turbomachinery steel, Ti- and Ni-based materials discussed in this paper are:

- *Steel alloys*: X22CrMoV211; X12CrNiWTiB16-13
- *Ti-based alloys*: Ti–6Al–4V (Ti64/Ti6Al4V); Ti–6Al–2Sn–4Zr–2Mo–0.1Si (Ti6242); Ti6246; Ti–5Al–2Sn–2Zr–4Mo–4Cr (Ti17)
- Gamma titanium aluminides (γ-TiAl): TNM; GE 48-2-2; 45 XD
- *Ni-based superalloys*: Inconel 718$^{**}$ (In718); In718 DA$^{***}$; IN100$^{**}$; Inconel 738$^{**}$; Inconel 939$^{**}$; MAR-M002$^{\circ}$; MAR-M247$^{\circ}$; Waspalloy$^{*}$; Udimet 720$^{*}$; Nimonic 105$^{*}$; Nimonic 713$^{*}$; Rene88$^{**}$; RR1000$^{\circ *}$; CMSX4$^{\circ\circ}$; LEK94$^{\circ\circ}$

Legend: $^{*}$wrought, $^{**}$cast, $^{\circ}$directionally solidified,$^{\circ\circ}$single crystal,$^{\circ *}$ powder metallurgical, $^{***}$direct aged

In order to increase aeroengine economic and ecological efficiency, current focus centres on the enhancement of propulsive as well as thermal effectiveness [31,98,198]. Propulsive efficiency can mainly be improved by realisation of higher by-pass ratios such as via the concept of Geared Turbo Fans [81]. Due to limited ground clearance of aircraft (classical design) and therefore limited fan diameters, the core engine has subsequently also to be reduced in size. The thermal efficiency can be further increased through higher temperature combustion requiring new high temperature resistant and lightweight materials (e.g. graded materials, single crystal, metal matrix composites – MMC and ceramic metal composites – CMC) and better cooling concepts (new cooling hole geometries, double walled bladings) as well as thermal barrier coatings (TBC) [32,64,175,180,181]. As a consequence, the need for more Ni-based compressor/turbine stages can be expected. Additionally, improved aero-dynamic and lightweight construction designs involving "hyper-polished" airfoils, elliptical leading/trailing edges or blisk manufacture, (Fig. 4), can further increase stage pressure ratios and thus efficiency [36,38].

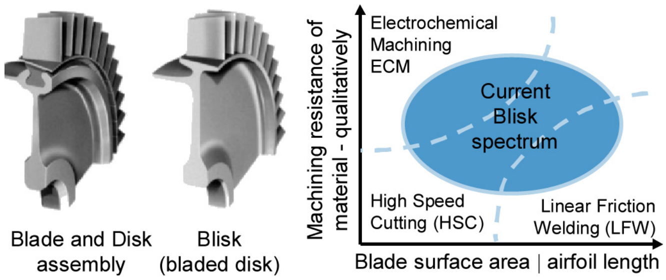

**Fig. 4.** Blisk principle design [163] and exemplarily, qualitative classification of currently used machining technologies as a function of blade surface are size (and airfoil length) and material machinability, [36].

In order to overcome current manufacturing limitations of conventional machining and to extend the potential of Design For Manufacture (DFM), an evaluation of the capabilities of advanced, non-mechanical, single process technologies, as well as new process chains both for initial manufacture and repair is necessary [37]. Comparing e.g. milling and ECM (Fig. 5), the MRR is reduced hyperbolical with the cutting tool overhang while constantly increasing with the ECM working area for comparable axis scales during blisk slot roughing. Besides productivity, the criticality of aeroengine failures necessitates appropriate workpiece surface integrities [196]. Also, economic capabilities have to be evaluated against the background of constantly growing volumes in turbomachinery serial production [22].

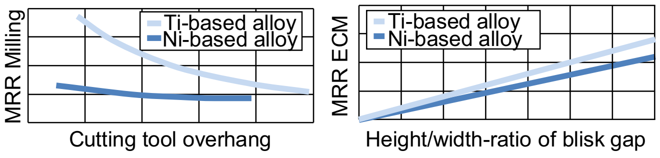

**Fig. 5.** Conceptual qualitative comparison of technological potential of conventional milling and ECM for machining of blisk blading gaps.