Recent developments in turbomachinery component materials and manufacturing challenges for aero engine applications

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Abstract. In the recent years the development of turbomachinery materials performance enhancement plays a vital role especially in aircraft air breathing engines like turbojet engine, turboprop engine, turboshaft engine and turbofan engines. Especially the transonic flow engines required highly sophisticated materials where it can sustain the entire thrust which can create by the engine. The main objective of this paper is to give an overview of the present cost-effective and technological capabilities process for turbomachinery component materials. Especially the main focus is given to study the Electro physical, Photonic additive removal process and Electro chemical process for turbomachinery parts manufacture. The aeronautical propulsion based technologies are reviewed thoroughly where in surface reliability, geometrical precession, and material removal and highly strengthened composite material deposition rates usually difficult to cut dedicated steels, Titanium and Nickel based alloys. In this paper the past aeronautical and propulsion mechanical based manufacturing technologies, current sophisticated technologies and also future challenging material processing techniques are covered. The paper also focuses on the brief description of turbomachinery components of shaping process and coating in aeromechanical applications.

1. Introduction

In the present trend the aeromechanical propulsion industry response for turbomachinery sector like steam turbines, gas turbines engines and stationary turbines and all air breathing engines, aircraft engine starting device turbochargers are also consistently developing due to increasing global necessity for vitality and flexibility. These turbomachinery components need to develop keeping environmental safely constrain in usage of oil, gas and coal together in producing the levels of carbon dioxide, nitrogen oxide levels to be maintained according to the international air standard environmental defined safety marginal levels. Thus, it is required to produce the environmental free highly sophisticated effective turbomachinery structures.

Especially in aeronautical engineering sector day to day according to IATA (International Air Transport Association) 2016 year calculation the growing rate drastically changed to 7.25 % in both
passenger aircrafts and cargo aircrafts. This value virtually almost twice within a decade according to International global market forecast 2016. Adding to this the maintenance, repair and Overhaul are also playing a vital role increasing demand. Further the market growth, future challenges faced by aircraft turbomachinery components manufacturing organizations are also increasing, as upcoming aircraft engine turbomachinery components need also be cleaner due to official rules and regulations, quitter and most importantly more fuel efficient. According to the survey conducted by the Airbus engines council for aviation goals for 2020, plan to reduce carbon monoxide levels 55%, and 75% Nitrogen oxide and also noise levels reduction by 30%. Finally in precipitously understood that there is huge research gap need for selecting good design in the process selecting materials, extensive manufacturing methods, repair technologies able to phase present challenging impending difficulties for turbomachinery structures.

2. Turbomachinery components challenges and manufacturing capabilities

Especially in aeronautical propulsion industry, the turbomachinery components like fan, axial flow compressor, centrifugal compressor and turbines required to handle large amount of mass flow of air and hot gas at higher velocities. Therefore the turbomachinery components required to have characteristics like to hold maximum temperature, maximum clear-cut strength and uniform resilient resources. Machining of these component edges really too difficult to cut by method of conventional methods. Conventional methods has drawback that it takes more metal removal rate, low precession due to great cutting forces leads to more tool cost due to more wear subsequently low process efficiency[1]. Therefore, use of economical and highly sophisticated technologies is of more interest.

The aircraft engines preferred more Titanium and Nickel based alloys (see figure 1). The temperature capability of these composite materials improved continuously through different manufacturing techniques and new alloy composition [2]. Single crystal materials gives much better properties compare to polycrystalline materials as it gives superior creep properties and also best suitable for high temperature applications like aero engines [3]. The use of such advanced titanium and Nickel based composites (used in aero engine turbines and compressors), matrix composites (especially polymer matrix composites [4] used in aircraft turbofan engines) required the more sophisticated advanced manufacturing strategies.

![Figure 1: Representation of material requirement between strength and temperature for aero engines.](image)

All the aircraft turbofan engines have additional features like after burner with bypass provision to increase propulsive efficiency [5-7]. These additional features enhance the thermal effectiveness, the enhancement further can improved by incorporating blade cooling materials, maximum temperature resilient and low weight carrying materials like single crystal, smart graded materials, ceramic materials and ceramic matrix metal materials [8-12]. Further it is from the literature that Nickel based
alloys gives more predominant outcomes in improvising thermal efficiency and propulsive efficiency in turbofan engines [13]. Additionally light weight material engine structures, aerodynamic shaped smart trailing edge structures require more sophisticated techniques which also improves the thrust development and high efficiency enhancement [97].

In order to overcome the difficulties currently phasing in aircraft engine component manufacturing design for manufacturing (DM) and single process tools as well as innovative primary manufacturing and process chains for repairs necessary [14]. For example considering the milling process in compressor blade electro chemical based manufacturing the metal removal rate reduced the risk of blisk gap so that saved the manufacturing time as well as maintained high precision [15]. Economic capabilities have to be assessed especially in aero engines components to produce in large volumes through electro chemical manufacturing techniques [16].

**Table 1:** Materials used in turbomachinery components [90-91].

| Material                           | Turbomachinery component |
|-----------------------------------|--------------------------|
| Titanium Based alloy (HK40)       | Housing                  |
| Titanium Based alloy HK50         | Housing                  |
| CAFA7                             | Housing                  |
| Alloy 282 (cast)                  | Housing                  |
| Waspaloy                          | Disk                     |
| Udimet 720                        | Disk                     |
| Alloy 718                         | Disk                     |
| A-218                             | Disk                     |
| Rene 41                           | Disk                     |
| CMSX-8                            | Turbine Blade            |
| PWA 1483                          | Turbine Blade            |
| Rene N4                           | Turbine Blade            |
| CMSX-4                            | Turbine Blade            |
| Nickel Based alloys (316-SS)      | Compressor blades        |
| Nickel Based alloys (Heyness 230) | Compressor blades        |
| Nickel Based alloys (Alloy 625)   | Compressor blades        |
| Nickel Based alloys (PE16)        | Compressor blades        |
| Chromium based alloys (316ss)     | Fan, rings               |
| Chromium based alloys (310ss)     | Fan inlet guide vanes    |
| Chromium based alloys (800H)      | Turbine outlet guide vanes |

Various materials used in turbomachinery components listed in table 1. The compressor hub housing made with HK 50/40 due to its high strength to weight ratio. The CAFA7 also used for high temperature resistant engine housing casting. For the industrial gas turbine housing purpose Alloy 282 (Cast) used. The stator blade disk made with Alloy 718, Rene 41 due to its high stiffness and high temperature resistance capacity in aero engines. Similarly the nickel based alloys like 316-SS, Heyness 230, Alloy 625 and PE 16 are used for axial flow compressor stages at higher Mach number ranges. Chromium based alloy grades like 316ss/310ss uses axial flow fan in turbofan engines. In the recent years especially turbine outlet guide vanes chromium based alloy grade 800H using.
The main objective of this paper is to give holistic view of more sophisticated manufacturing technologies and economically more compatible in producing large volumes. Especially concentrating earlier, current and future modern techniques like electro discharge machining, electro chemical machining and laser beam process for turbomachinery structures. More focuses on the explanation of shaping process not including the coating and welding process applications. All the aero engine turbomachinery components manufactured and designed by titanium and nickel based alloys, therefore this paper more described about the analysis of titanium and Nickel based alloys.

3. Advanced processes in turbomachinery components

3.1 Turbomachinery components manufacturing process through electrochemical machining

The major advantage with electrochemical machining features are maximum material cut rate with virtually less instrument wear. The tool used for electrochemical machining generally high cost intensive one, therefore during the production process the wearing rate very much minimum also this process is best suitable for massive production of turbomachinery components like centrifugal compressor, small scale axial flow compressors and turbines etc [92]. This electrochemical machining technology is an alternative manufacturing technology for turbomachinery components. Through this type of manufacturing process can achieve excellent workpiece surface quality at high metal removal rate without any heat exaggerated zones / strain hardening regions and white layers [17-19].

The final product specifications after completion of electro chemical manufacturing depends on the particular configuration of the bulk composite material. The limitation with this type of manufacturing process is to ensure that material must not be mechanically damages or no thermally damaged otherwise during the machining process rim zones may form over the surface of the material which leads to internal flaws inside the material. The study of internal flaws in alloys through electrochemical process can achieve by crystallographic orientations method [20]. The study of the waviness on the titanium and nickel based alloys studied in detail after specific electrochemical treatments [19, 21].

Figure 2: Image of the experimental setup for blade EDM slicing [21].

Figure 3: Simplified gap geometry from 3rd LPC stage of EJ 200 [18, 24]

The figure 2 [21, 32] shows for Ti-6Al-4V higher wavelength observed at 5µm due to quicker dissolution in the material. These electrochemical techniques have more significance because it depends purely on iterative cathode designing process and knowledge based approach. Before starting the electrochemical process the model will verify with the theoretical and numerical error based on the
consistency then the workpiece further contrived to the actual size, the same flow model is well described in the figure 3 [18, 24]. The process of involving different engineering stream applications called Multiphysics approach, where it involves different physical aspects is well known [22-23]. All aeronautical problems related to aircraft components manufacturing much complicated especially related to engine components. Materials which is used for these components highly classy therefore require too many design factors. To solve all the design factors require Multiphysics with advanced computing facilities [93]. The electrochemical machining process also connects with high computational facilities so that simulations can possible to complete in few hours even any critical geometrical features of turbomachinery components [25].

Figure 4: representation of electrochemical machining process various physics coupling modelling [33, 34].

Figure 5: Representation workpiece Figure modelling dependency [25].

Figure 6. Material removal rates for aero engine alloys [30]
The figure 4 [23] shows complicated blade geometry being solved by Multiphysics approach using high computation facility with better accuracy with minimum time. Based on the geometrical features the profile further modified using inverse simulation method to reduce the computational time for finishing the machining process [27]. The figure 5 [25] shows the three dimensional compressor blade cutting edge by implementing electrochemical process through multiphysics approach. Further the multiphysics simulation results are also well matching at rounded cuboid region of the blade with the experimental data, the error was very minimum 10^-08 and gap was 300 µm [27]. The multiphysics flow simulation also solve many problems like thermal coated metal barrio problems and fluid flow heat transfer using the computer aided cathode design [94].

In the electro chemical machining one more advanced technology is called “pulsed electro chemical turbomachinery component machining”. The word ‘pulsed’ means ‘precision’ which is most important all the components of aircraft engine [30]. Between the electrodes to workpiece minimum gap maintained to vibrate with designed frequency so as the tool touches the workpiece at desired level so that it goes on remove the material from the work surface [28-29] as shown in figure 6 [30]. The recent pulsed electrochemical machining device tools permits polishing, roughing, and finishing on one single stage [31].

Figure 7: Representation of 2 vibrating cathode tool electrodes of blisk geometries [39,40].

Figure 7 shows the modern electrochemical pulsed machine having total 8 axis degrees of freedom, in which four axis given to tool axis and remaining four axis given to workpiece operating by two fluctuating cathode[32]. This type of machine tool is locked system generally operates by through self-directed electrolyte management. The more advantage with this type of machine for absolutely titanium based alloys. The cathode guns operating at different temperatures ranges according the geometrical profile of the blade so as to reach good smooth workpiece [33-35].

Figure 8: Representation of electro chemical machining process applications[35,87].
Figure 9: Representation of jet engine casing and disk machining process using electrochemical machining [40].

Figure 8 [35,36, 87] is the best example of electro chemical machining process for aero engine compressor blade and gas turbine blade. The machining completed according to the geometrical and aerodynamics features defined in the simulations. In this paper the materials type used for blade is X12CrNiWTiB16-13 at the rate of 2.5 cm³/min. Few papers also described about nickel based alloys (material type: Inconel 718, at the rate of 2.1 cm³/min) and titanium based alloys (material type: Ti6242, at the rate 3.9 cm³/min) [35-36]. The metal removal rate is very much minimized also maintained high accuracy of surface roughness (Ra=0.8 µm), good accuracy (0.1mm) and estimated the total savings through the manufacturing 30% in comparisons to traditional methods of cutting procedures [37, 95]. Tooling costs mainly reduced because of continuous production operation. The blade shroud and hub surfaces smoothening also much free through this electrochemical process [38].

Figure 10: Representation of subsonic low pressure turbachinery blisk using electro chemical machining. [40, 43].

Figure 11: presentation of Electro chemical machining on aero engine gas turbine blades [39].

Figure 9 describes the steam gas turbines machining process representation using direct current electrochemical process. The material used titanium and nickel based alloys (X22CrMoV211), the feed rate maintained in this process from 3mm /min [39].

Figure 12: Representation of polished technique on turbomachinery components using electro chemical machining [44, 32].

Figure 10 represents the aircraft engine casing machining process (size 350x350 mm) operated at the voltage of 20 V and current 12 KA [40]. New attempts also made providing currents of 12-15 KA,
feed rate takes from 1 mm per minute and the voltage range from 13 V to 18 V the component finishes within 5 minutes of time per blade [40-42]. Especially like low speed axial flow compressor two electrodes used to perform the machining process where the gap maintained minimum 100 mm per cycle so that, blade grooves well maintained with high precession shown in figure 11 [40, 43].

Figure 13: Representation of centrifugal compressor drilling the cooling holes through electro chemical machining [40, 45].

In order to have better look with shining the blades undergo removal of oxide particles through oscillating polishing shown in figure 12 [32,44]. Further the complex geometries like aircraft gas turbine blades, applications of turbo charger disk machined successfully through electrochemical process [36]. In order to sustain the high temperature releasing from the aircraft combustion chamber, the turbine blade cooling system plays vital role to increase the performance of the turbine. The electrochemical process also make small holes in the blade to pass the coolant in it. Figure 13 represents the blade cooling system arranged through electrochemical drilling (0.3 to 5 mm) operation principle [45]. In the blade spherical holes can be created by incorporating the feed rate reduction and tool higher degree of freedom swirl within the air flow. Much more clear information regarding blade swirl creation process, modelling and performance parameters can be found several journal publication papers [46-49, 96].
There are many more innovations need to invent in electrochemical machining process especially drilling maintaining the high aspect ratio number that too with mixed approach adapting with cathodes is inevitable. To know more about these parameters one can review article by Sen and Shan detailed study on micro and macro electrochemical drilling process [50-52]. This process has a high significance with lower metal removal rate, especially new innovative metal composite difficult to cut titanium alloys in industrial aeromechanical applications.

3.2 Turbomachinery components manufacturing process through electro discharge machining

This type of machining process quite new especially in aeronautical applications in 1955’s. The electro discharge machining either wire based or die-sink based device, however recently several new innovations brought into the aeromechanical industrial applications [53-55]. For aerospace applications there are other numerous innovations brought like drilling the holes in turbine blades and radial compressors through electro discharge machining [56]. Through this electro discharge machining process it is possible to polishing (swirl grinding) the engine casings (material: Ti–6Al–4V) surface [57-59]. Recent year’s transistor based ultra-fast recovery electro discharge machines introduced in which very low level inductances incorporated up to 0.5 μH, current slopes up to 600 A/μsec (see in figure 14) and metal removal rate of 600 mm² / minute. This type of facility more useful in machining the groove surface of the blade in axial flow compressor and turbines, see [60-62].

The figure 15 represents the high ultra-speed electro discharge machine set up for blade electrodes to finish the groove vane. The figure 16 represents the industrial based gas turbine engine different components machined by electro discharge machining process. Some articles are also discussed in detail mathematical model for electro discharge machining process for calculating the performance parameters like improving workpiece surface roughness, metal removal rate etc. [63-65]. Later the electro discharge machines with the multi degrees of freedom facility introduced for die-sink based titanium alloys applications [66-70]. Later the wire based electro discharge machines introduced, in this machining process instead of solid tool the continuously travelling wire used to cut the material. Despite from few decades the research and development conducting turbomachinery arc manufacturing extremely limited. The main reason for this type of machining require electro erosion need to maintain at lower metal removal rate, at lower cost for high usage of titanium and nickel based alloys. An example. In this example we can see that there are footnotes after each author name and only 5 addresses; the 6th footnote might say, for example, ‘Author to whom any correspondence should be addressed.’ In addition, acknowledgment of grants or funding, temporary addresses etc might also be indicated by footnotes.

3.3 Turbomachinery components manufacturing process through Additive manufacturing

This method is absolutely suitable for mass production at higher precession, lower metal removal and shorter time processing technique. Additive manufacturing technique employed in small scale
prototype like rapid prototype, rapid manufacturing and rapid tooling so that scaling can maintain at any small value at higher accuracy. This additive manufacturing technology also much useful efficiently in repair applications, powder metal based applications. The power metal based small scale components machined based the principle of electron beam melting or selective laser melting. This technology basically requires advanced process knowledge and also supplementary post treatment phases [71]. All the aeronautical aero engines small components and turbomachinery devices started working from 1990’s effectively. Apart from the prototyping the small scale production increased by incorporating the increased deposition rates on the workpiece at the rate 10 cm$^3$/min [72-73]. After the machining all the components required to undergo according the standards defined by the international civil aviation organisation air certification, therefore the components should undergo the quality certification through different levels.

The certifications levels are prescribed indetail especially for this additive manufacturing for all titanium based alloys [74-75]. In aero engine component machining, wherever the complicated geometrical features encounters like vane segment, impeller swirl angle, combustor swirler (see in figure 17) there new possibilities of additive manufacturing plays a vital role to keep the significant cost and weight reduction [76-80]. According to the 2016 year National Science Report of NÁSA, the organisation also using additive manufacture technique to build various small scale products in large amount for space launch systems. Especially more focus giving to selective laser melting technique and electron beam melting techniques because of its high precession and low cost process [81]. Very Recently the General Electric (GE) Company announced that by the time 2020 year the additive manufacturing process going to give more than one lakh small and medium type of aircraft engine components. Especially focusing more on engine twisted blades, fuel nozzles edges and fuel injector members as their geometrical features so critical in size and difficult to machining at high accuracy [82]. Through the additive manufacturing process, the GE company going to save approximately 24 percent of the amount saving according their initial estimation [83]. To improve the high accuracy machining in different applications like casings, tubes, brackets, vanes, tubes, nozzles, shrouds, liners the research going on through adaptive manufacturing technique [84-85].

4. Conclusions

Through this paper the applications and technical capabilities of different turbomachinery components manufacturing techniques like electro chemical, electro discharge and additive manufacturing process have been studied. Through this study the technical capabilities of aero engine suitable applications and benefits have been investigated of its procedure. Especially in the case of problems in cutting, high advanced metal elimination rate, coolant admission rate, acceptable surface integrity and greater geometrical precision is addressed. All together clear research gap is also identified for every technique with suitable example of aero engine turbomachinery components. This paper also gives a broad description how to use all the techniques effectively for titanium and nickel based alloys with lower cost and further guides to researchers to move into a better way in all aeromechanical applications.
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