DESIGN AND MANUFACTURING CHALLENGES OF A MICROTURBINE WHEEL

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ABSTRACT

Micro gas turbine (MGT) is a core technology in many hybrid and integrated power systems to address the low-emission future aviation and decentralisation of energy generation. To achieve a high power-to-weight ratio as well as lowering the required maintenance, a new compact configuration with an air-bearing compartment was developed to build a 2 kW micro gas turbine. Designing a turbine wheel faced a multidisciplinary problem with many inputs and constraints in aerodynamic, heat transfer, strength, and manifesting aspects. To meet all requirements of these aspects, a design procedure is proposed in this paper. Since the manufacturing process affects the performance and life of the system, several processes, including casting, additive manufacturing (AM) and machining of the turbine wheel with different materials, were carried out, and the structural strength and performance of the components were investigated in this study. The prototype was tested experimentally to prove its performance and validate the concept. The cast wheel demonstrated both the required performance of 2 kW power output of the MGT in turbine inlet temperature of 1200 K and rotational speed of 170 krpm. However, the machined and additive manufactured samples for low-temperature/low-speed off-design conditions did not withstand structurally and called for a re-design or change in conditions.

KEYWORDS: MICRO GAS TURBINE, PROTOTYPE, TURBINE WHEEL, ADDITIVE MANUFACTURING, CASTING, MACHINING

INTRODUCTION

The micro gas turbine is considered one of the main solutions to generate power on land, sea and air as the main system or extender in developing applications and smart grids (Global 2018). High flexibility and availability of MGT regarding fuel type and short start-up time, respectively, have made it capable of combining with other energy sources including renewable ones to compensate for their inherent intermittencies (Hosseini, Izadi and Boloorchi, et al. 2021). Hybrid systems with solar dish concentrators (Arifin, Schatz and Vogt 2020), wind turbines (Hosseini, Izadi and Madani, et al. 2021) and fuel cells (Ferrari, et al. 2010) are some interesting examples. Furthermore, MGT can be integrated with a heat exchanger to harvest the energy waste of its exhaust gas, so a combined heat and power generation system can be created in a micro size. This cogeneration can be inherently more efficient than conventional power generation technologies since the residual heat of the main power generation operation is also utilised, which can reach more than 90% of overall fuel efficiency in micro-scaled units that bring the point of generation closer to the consumers (Kari Alanne, Arto Saari 2004). This paper is a part of project TwinGen (TwinGen - the world's most compact heat and power boiler 2019), which aimed to integrate an MGT into a compact and high-performance combined heat and power (CHP) system suitable for domestic use. The TwinGen unit was designed to produce 2 kW of electrical power and 18 kW of heat with an overall system efficiency of up to 93%.

While there are some similarities between large and small-scale turbines, the micro-scale turbines need specific theoretical concerns on high viscous turbomachinery losses, high tip clearance to main path ratio, high heat dissipation, and high heat transfer from the turbine to the compressor (Visser, Shakariyants and Oostveen 2010). These characteristics caused the lower efficiency of both the component and the cycle in comparison with the large-scale ones. Although a combination of various advanced cooling methods (Izadi, et al. 2020), super alloys, and thermal barrier coatings (TBCs) have been developed and commercially applied on various aero and industrial gas turbines to increase efficiency, the MGT industry lacks deployments of these achievements which has not allowed the turbine inlet temperature (TIT) in the microturbine to go far beyond 1200 K. Product cost is another barrier to the development of MGTs, while most manufacturers prefer to utilise high-performance off-the-shelf turbocharger components to assemble a micro gas turbine (Visser, Shakariyants and Oostveen 2010) This has prevented the achievement of more than 10% efficiency since turbochargers are designed for slightly different operating conditions (Rodgers 2011). The recent changes in the MGT applications, however, require the detailed design of compressor and turbine to reach high cycle efficiency (Visser, WPJ, Shakariyants, S, de Later, MTL, Haj Ayed, A, & Kusterer, K. 2012). The design of the turbomachinery components generally needs multidisciplinary design procedures to integrate aerothermal and structural aspects (Global 2018). Especially in microturbines, multidisciplinary approaches are essential to reduce the cost of R&D for high-quality products in a competitive market. Manufacturing limitations also prevent the utilisation of advanced technologies in microturbines (Badum, L., Leizeronok, B., and Cukurel, B. 2021), and design procedures that consider small-scale manufacturing characteristics have not yet been fully addressed in the open literature. This paper aims to describe the design and prototyping procedure of a turbine wheel for a micro gas turbine and review the technical issues in various aspects of its manufacturing process. This procedure integrates the design and analysis of aerodynamic, heat transfer and structural strength aspects of the microturbine wheel.

1. METHODOLOGY

The multidisciplinary design approach of this paper considers aerodynamic, thermal, material and structural aspects of the design of the first rotary blade of the turbine. The flowchart of this approach is shown in Fig. 2. This procedure starts with defining the required characteristics of the turbine. The total length of the MGT (without a combustion chamber) is less than 200 mm. The design constraint for the diameter of the turbine wheel was between 40 to 45 mm. The performance requirements are the overall parameters of the turbine modules dedicated to gas turbine cycle performance design that are listed in Table 2.

To achieve these performance targets, the aerodynamic design of the turbine was carried out to find the optimised profile design regarding structural and manufacturing constraints. The 2D profiles stack on their centre of gravity to construct the 3D model of the turbine, which is used to investigate the thermal distribution and stress domain of the solid parts, which leads to an update of material and geometrical constraints. This procedure was continued to find the design which satisfied the requirement of all the disciplines. In continuation, the main analysis of this procedure is explained, and the results are presented.

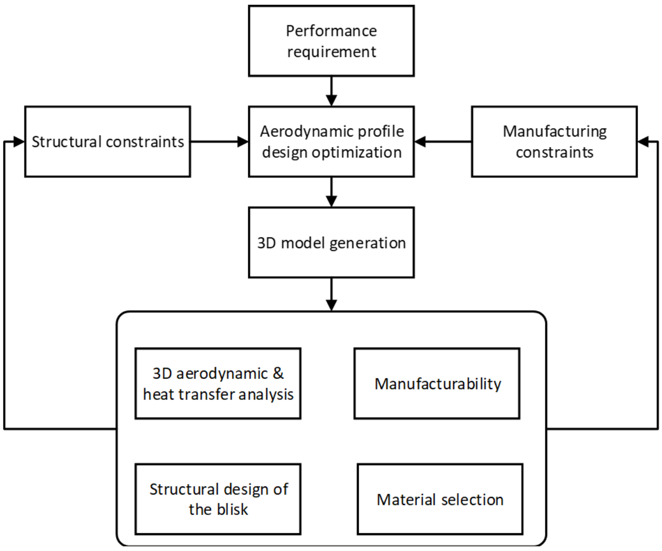


Fig. 2. Multidisciplinary design approach

Table 2. Design requirement of the turbine (performance parameters)

Parameters	Value	Unit
Turbine expansion ratio	2.6	-
Turbine inlet total temperature	1200	K
Turbine inlet total pressure	273	kPa
Isentropic efficiency	81	%
Mass flow rate	0.026	kg/s
Shaft speed	170	kRPM

2. DESIGN ANALYSIS

One of the preliminary decisions for the design of the turbine wheel from scratch is to choose between axial and radial turbines. Considering the size of the MGT, radial flow turbines are supposed to be more efficient but are rarely used in multi-stage configurations (Cohen, Rogers and Saravanamutto 1996). Since the axial flow turbines benefit from less hub mass that helps with transient thermal behaviour, thermal-induced stresses and rotor dynamics, this configuration was selected to provide compactness of the product (short-length), multi-staging capability for future development and capability to operate at a wider range of work coefficients.

2.1 Aerodynamic design

The aerodynamic design of the axial turbine was carried out by calculating the 2-dimensional (2D) and 3-dimensional (3D) gas dynamic parameters and then constructing the computer-aided design (CAD) geometry of the turbine blades. The two-dimensional gas dynamic calculations were done using analytical formulas to calculate the 2D performance of the turbine cascade. The performance was calculated considering different profiles and secondary losses inside the flow domain. The profile losses were estimated by considering the friction effects (with Mach, Reynolds numbers and blade roughness correction factors) and trailing edge losses. While the secondary losses were calculated considering the end wall and boundary layers flow losses. The overall turbine efficiency was determined using total turbine flow losses and other corrections related to the angle of attack and the effects of axial and radial gaps. The 2D calculations provide velocity, pressures, temperatures magnitudes of the stage at the inlet and the outlet of the Nozzle Guide Vane (NGV) and the exit of the turbine rotor in addition to the overall power and efficiency.

The 2D gas dynamics parameters were used in the 3D calculations of the turbine blade. In 3D calculations, the velocity magnitudes, flow angles, and other performance parameters of the 2D calculations were projected in 11 sections along the blade span using radial equilibrium equations. 3D calculations were performed by assuming the linear distribution of maximum rotor blade thickness. In addition, constant rotor blade sections along the span and constant work along the span at the rotor blade inlet were assumed. The velocity magnitudes and flow parameters of different blade sections were used to construct the spanwise blade profiles.

Fig. 3 shows the steps from the generation of 2D profiles to the 3D numerical domain. In the numerical simulation, the Shear Stress Transport (SST) turbulence model was selected, and no wall function was implemented, in line with previous publications of the authors (Gamil, AAA, Nikolaidis, T, Teixeira, JA, Madani, SH, & Izadi, A. 2020). By construction of the fluid/solid numerical domain, the conjugate heat transfer analysis was then employed to find the temperature distribution of the blades.

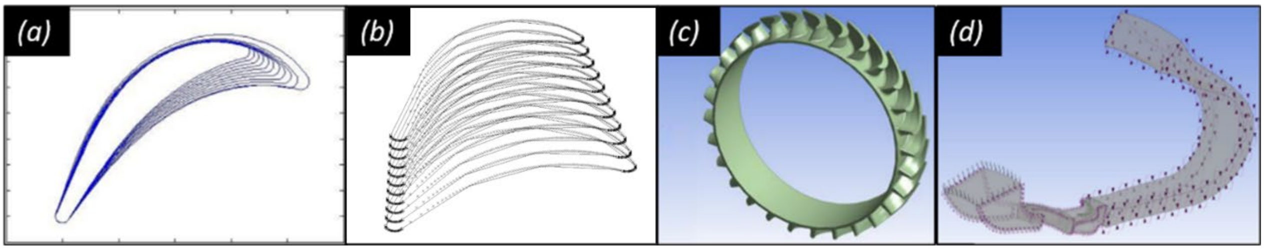


Fig. 3. Generation of the turbine blades geometry in aerodynamic analysis: (a) the 11 optimised profile sections, (b) sections of blade aligned in the 3D domain (c) 3D design of the turbine (d) turbine fluid/solid domain for numerical simulation

2.2 Structural design

Following the design procedure which is shown in Fig. 2, a finite element structural analysis is carried out for each geometry using the temperature distribution obtained from heat transfer simulation. The scope of this analysis, in conjunction with material selection, in each iteration was to obtain the stress domain of the blades (that modifies the structural constraints for the next design if required) as long as modification of the turbine disk to fulfil the strength requirements. The gradual modification was implemented in this stage to improve the stress distribution in the bladed disk (blisk) configuration. Fig. 4 shows three steps of gradual improvements for one of the design iterations.

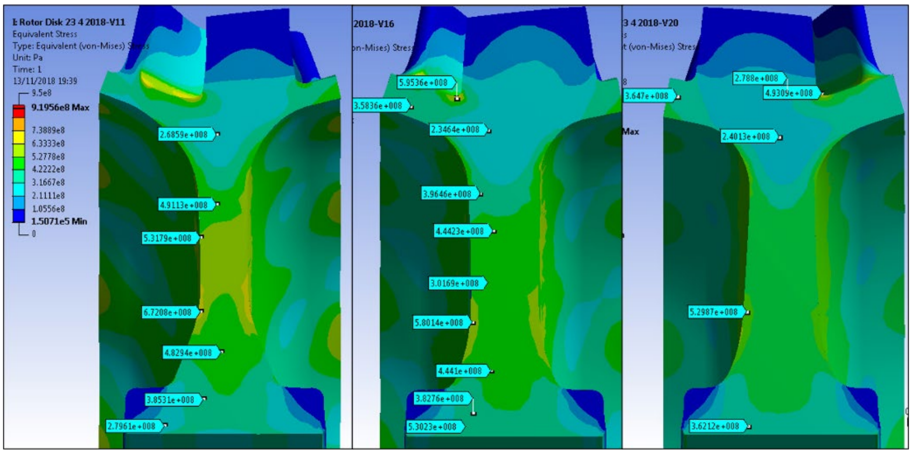


Fig. 4. Gradual improvement of the structural design in one of the design versions

2.3 Materials

The reduced specific strength of materials which is the square root of the tensile strength over the density, can generally indicate the maximum technical work of the turbomachine (Badum, L., Leizeronok, B., and Cukurel, B. 2021). So, high tensile strength and low density to have less centrifugal stress are desirable. Normally both parameters are either high or low for the super alloys and ceramics, respectively. As shown in Fig. 5, values of the specific strength of assumed materials are in the same range for the operating temperature of 1000 to 1100 K.

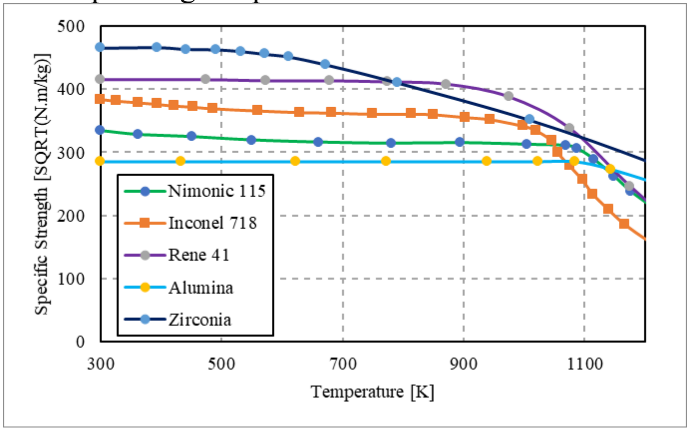


Fig. 5. Reduced specific strength of possible material for turbine wheel (Badum, L., Leizeronok, B., and Cukurel, B. 2021)

2.4 Manufacturing aspects

In the current study, four different manufacturing processes were investigated to make the turbine wheel. The initial assessment of each method is summarised in the following.

Casting

Production of the turbine wheel components would suit an investment casting process. Investment casting has a low tooling cost and relatively short lead times. With available procedures, the manufacturer believed that a surface texture value of 3.2 µm of roughness average (Ra) could be achieved on cast components.

Fully Machined

The initial assessment shows that the geometry of the turbine wheel was suitable for production using a 5-axis machining centre. A 'blank' component would need to be turned prior to machining the blade profiles. The feasibility of machining components using the low-cost Fanuc Robodrill with Nikken Rotary Table modification which was used to mass produce impeller-type components for a UK manufacturer, had been investigated. It was concluded that this machine would be the most suitable for the mass production of components should a machining process be determined to be the preferred mass production method. At the time of the project, it was believed that a surface texture value of 0.8 µm Ra could be achieved on fully machined components.

Additive Manufacture

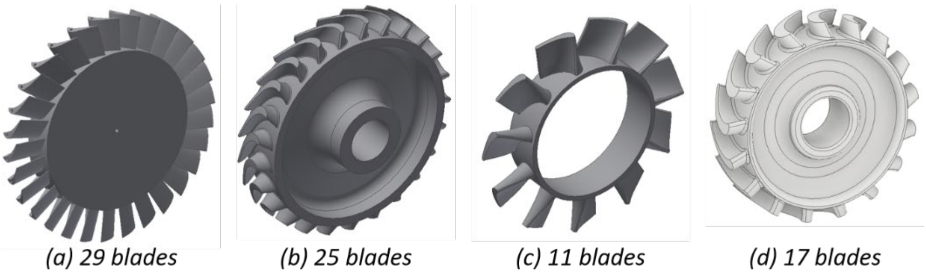
Turbine wheel components could be produced using the Additive Manufacture (AM) process, Selective Laser Melting (SLM). Part price for components produced in this way is likely to be high; as such, this process is thought suitable for prototyping only and not mass production. At the time of this project, it was believed that a surface texture value the same as investment casting (3.2 µm Ra) could be achieved using the SLM manufacturing process.

Metal Injection Moulding.

The metal injection moulding process utilises a combination of injection moulding and sintering techniques. It is well suited to the mass production of complex parts as the cost of manufacture is scalable with larger quantities. The hard tooling required for the process represents a significant cost (over £10,000 per component), however, so this process is thought to be suitable for mass production only and not prototyping.

3. RESULTS AND DISCUSSION

The method explained in this study was used to find the appropriate design for the axial turbine of the MGT. In this process, more than 10 different versions have been examined with several subversions. Fig. 6 shows the first and last versions with two middle versions. The design and manufacturing of the turbine wheel encountered several challenges, which are reviewed in this section, and the results are presented.



(a) 29 blades *(b) 25 blades* *(c) 11 blades* *(d) 17 blades*

Fig. 6. Design improvement of the turbine wheel; a) initial design with 29 blades; b) 25 blades; c) 11 blades and smaller hub radios; d) improved design with 17 blades

3.1 Material selection challenges

Due to the limitation of the manufacturing and the high probability of a ceramic material defect in the blisk configuration, their deployment was omitted through this project. In addition, the SLM process was only reliable in producing components in Inconel 625 or 718 grade, which limits the capable materials to produce components using this method. Moreover, there are some differences in the casting of different materials. For example, Inconel grade 718 is required to be cast under vacuum to control oxidation effects, meaning a dual chamber vacuum induction furnace is required. On the other side, Inconel grade 625 can be cast without vacuum, without any adverse oxidisation effects. This means that modifying the design to use Inconel 625 would mean that the turbine wheel could be cast at a reduced cost, but it needs a cooling supply since Inconel 625 cannot survive in more than 1000 K with 170 kRPM. Based on the cycle design consideration, turbine cooling was out of interest in this project, and Inconel 718 was selected as the default material for the turbine wheel structural design.

3.2 Manufacturing challenges

Following the design shown in Fig. 6, in design (a), the spacing between the turbine blades was very small in the first design. Initial analysis indicated that small diameter tooling (~ 1 mm) would be required to produce components using machining. Tooling of the required size was available; however, the small diameter and the required length of the tool would likely lead to frequent tool breakage. Due to the small spacing, the blades were relatively thin compared to the overall size of the turbine; this may present a challenge for the casting of the component. Although casting was thought feasible, a thicker blade and wider spacing were concluded to be the solution which was followed in the following iterations.

In design (b), the turbine contained blades around 3.5 mm tall, with the space between blades reduced to around 0.5 mm at the blade root. To machine the blade gap, a tool at least 7 times as long as its diameter (7xD) would be required; this would be classed as micro-tooling. At this size, tool runout and machining forces would become significant issues, while the spindle speed would also need to be very high to achieve the necessary tool surface speed. The tool length would also mean it had very little rigidity, and the large machining forces encountered whilst cutting superalloys would result in frequent tool breakage. It was concluded in the manufacturing constraint that a tool no longer than twice its diameter (2xD) be used for a machining operation of this nature.

Design (c) contained some other assembly and integration problems but provided the insight to proceed with a smaller number of blades which was finalised in design (4). This design provides not only the required performance and stress criteria but required spacing and straightened blades to ease the machining and surface treatments. The prototype samples of this design by three different manufacturing methods are shown in Fig. 7.

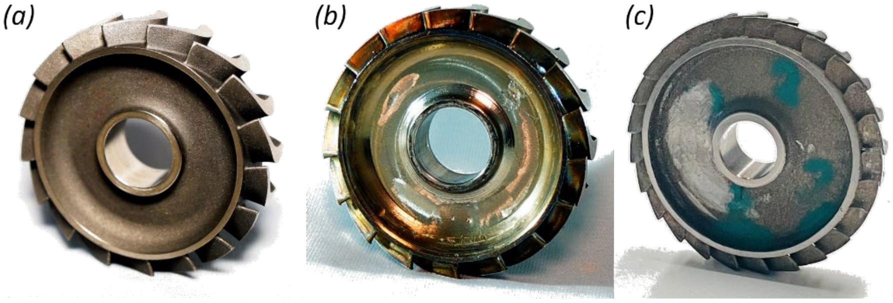


Fig. 7. Prototype samples of the turbine wheel made by: (a) casting, (b) machining, (c) additive manufacturing (AM makes it possible to manufacture the design with 25 blades)

3.3 Performance and durability

All manufactured prototypes were assembled on a prototype engine and tested on the Combined Heat and Power (CHP) test cell, which is shown in Fig. 8a and Fig. 8b. The test rig is equipped with appropriate sensors and techniques to provide the following measurements of cycle parameters:

- Ambient temperature and pressure
- Compressor outlet temperature and pressure
- Turbine inlet temperature and pressure
- Turbine outlet temperature
- Compressor inlet mass flow
- Fuel mass flow
- Shaft output power

A high-speed alternator was powered with a tie grid drive/inverter to enable a bi-directional connection of CHP to the network.

The turbine performance map of the cast turbine wheel is used to validate the design values in comparison with the experimental results, as shown in Fig. 9. The performance map can be generated by plotting the corrected mass flow rate ($\dot{m}_{corr}$) over different turbine pressure ratios (TPR), which can be defined as equations (1) and (2), respectively.

$$\dot{m}_{corr} = \dot{m}\sqrt{T_i}/P_i \tag{1}$$

$$TPR = P_i/P_o \tag{2}$$

In which $\dot{m}$ is the actual mass flow, T_i and P_i are the temperature and pressure at the turbine inlet, and P_o is the turbine outlet temperature. The performance curve of the numerical results showed a similar trend when compared to the experimental data. However, differences between the results increase for pressure ratios higher than 1.5. Since shaft speed and turbine inlet temperature for the experimental points are different (higher values for higher TPRs), the turbine experienced different tip clearances during the experiments. The value of the gap was not under control or measurement during the test, but it can be concluded that the tip leakage decreased and provided higher pressure ratios in a similar range of mass flow. Totally the CFD results agreed well with the experimental data, which indicates that the numerical model can accurately predict the performance of the axial turbine for different operating conditions.

Due to the smaller value of the surface roughness of the machined wheel, the engine results in a better match with the targeted design values for performance and power outage, as shown in Fig 10. However, the machined and additive-manufactured wheel faced rupture due to the creep after one-hour hot tests of the engine running working at a turbine inlet temperature beyond 1100 K, which shows the requirement for further investigation. The crack of the additive-manufacturing wheel is shown in Fig. 11.

(a) (b)

Fig. 8. Experimental test of the turbine wheel: (a) MGT assembly (b) MGT assembly installation on CHP test cell

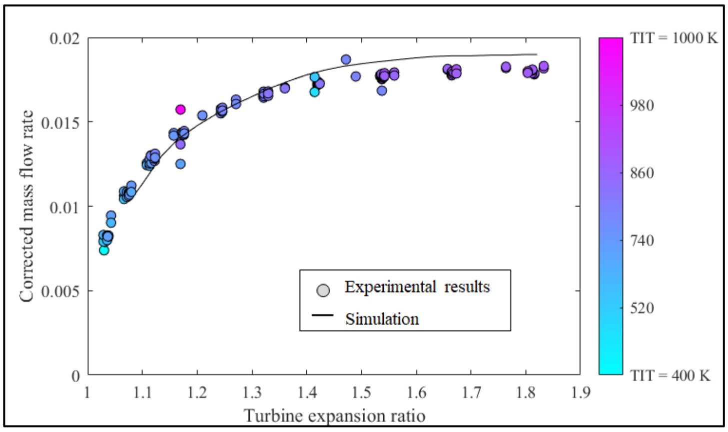


Fig. 9. Comparison between estimated and experimental results for the cast turbine wheel

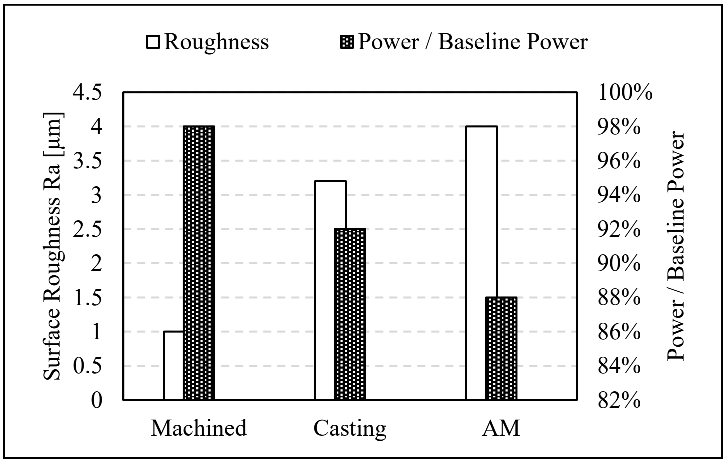


Fig. 10. Effect of manufacturing method on performance of the turbine wheel

Fig. 11. Additive manufactured turbine wheel failed after hot test

4. CONCLUSION

In the current study, to establish a procedure to manufacture a turbine wheel for a 2 kW compact micro gas turbine, different designs and manufacturing methods were investigated, and several prototypes were manufactured using casting, machining and additive manufacturing processes. A multidisciplinary approach was utilised to consider the manufacturing aspects connected with the aerodynamics, heat transfer, material and mechanical strength of the turbine wheel. Inconel 718 was selected for prototyping, and more than 10 different versions were designed, and their variations developed through gradual modifications in structural design. The results showed that machined parts provide better surface roughness which was reflected in the performance of the prototype engine, but the cast wheel is the one that can survive in hot TIT values. The authors believe that with current advancements in additive manufacturing of ceramic material, they could substitute the Inconel due to the same specific strength but higher creep resistance in high temperatures if their manufacturing constraints be considered in the design stage.

ACKNOWLEDGEMENTS

This project has been supported by the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 801604 and the UK Department of Business, Energy, and Industrial Strategy (BEIS) under the scheme of Energy Entrepreneurs Fund phase 3. The authors would like to acknowledge the support and express their appreciation to all partners of these projects.

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2023-04-28

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European Conference on Turbomachinery (ETC)

Hosseini S, Gamil A, Soodani A, et al., (2023) Design and manufacturing challenges of a microturbine wheel. In: 15th European Turbomachinery Conference: Turbomachinery Fluid Dynamics and Thermodynamics, 24-28 April 2023, Budapest, Hungary

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