Manufacturing of high added value titanium components. 
A South African perspective

D Dimitrov1*, E Uheida1, G Oosthuizen1, D Blaine2, R Laubscher3, A Sterzing4, P Blau4, W Gerber5 and O F R A Damm1

1Department of Industrial Engineering, Faculty of Engineering, Stellenbosch University, South Africa.
2Department of Mechanical and Mechatronic Engineering, Faculty of Engineering, Stellenbosch University, South Africa.
3Department of Mechanical Engineering, University of Johannesburg, South Africa.
4Fraunhofer Institute for Machine Tools and Forming Technology, Germany.
5Aerosud Aviation, South Africa.

*Dimitrov@sun.ac.za

Abstract. South Africa has significant titanium reserves and is developing strategies to not only provide this raw material on global markets, but to manufacture complex titanium alloy products and participate fully in global supply chains. Pursuing more sustainable process chains, manufacturers are constantly striving to enhance the resource efficiency of their high added value processes. Titanium alloys are used comprehensively in aerospace and biomedical applications, due to its favourable strength-to-weight ratio, corrosion resistance and biocompatibility. These properties, however, contribute to the manufacturing challenges, classifying it as a difficult-to-machine material. Various input factors affect the efficiency of a hybrid process chain. The objectives of this multidisciplinary research group were to demonstrate the reduction of material wastage by up to 50% and machining time up to 20% for selected titanium components. The results clearly demonstrate the ability to increase the technology readiness levels of the selected components and to develop competitive hybrid titanium process chains that will enable South Africa to integrate more into global manufacturing value chains.

1. Introduction
Titanium alloys have found wide application in the aerospace and biomedical industries due to their good strength-to-weight ratio and superior corrosion resistance. However, machining of complex titanium geometry (e.g. thin walled blades) is a challenging process. As titanium is difficult to shape, normal fabrication methods such as forging and machining from billets, are expensive, wasteful of raw materials, and time consuming as titanium machining is 10 times slower than aluminium. The efficiency and life service of these titanium engine blades are strongly affected by the precision of the production method [1, 2]. In the aerospace industry, buy-to-fly ratios of forged titanium parts are often only 15% to 20%, adding to the large cost for component material and machining. Blade manufacturing requires multitasking of hybrid machines such as turn-mill, which offer many technological and economic advantages.
Nowadays, the research focus shifted to enhancing the resource efficiency of the entire process chain, and is no longer driven by only high performance operations [3]. The development of near-net-shape fabrication methods is also significant in the expansion of titanium usage in aerospace applications. The developed hybrid processes chains include and are not limited to integrating of forming and additive manufacturing technologies with advanced machining. This paper provides an overview of the current-state-of-the-art manufacturing technologies for titanium components. Outcomes from a large collaborative research project on development and evaluation of different process chains for realization of prototypes of a generic blade geometry are presented and discussed.

2. Advanced manufacturing technologies for titanium components. A critical review

Press and sintering

Powder metallurgy (PM) has been earmarked as a potential growth area for titanium manufacturing due to its near net-shape capability. Metal injection molding (MIM) is widely used to manufacturing high production volumes (>10 000 per year) of small sized (<5 cm) components with complex shapes, where good dimensional tolerance is required, while additive manufacturing (AM) is used to produce individual components of complex shapes that are difficult to produce using other manufacturing processes. Figure 1 shows the different potential design for press-and-sinter processing to produce a component – a bracket. One of the distinct advantages of the press-and-sinter PM process is that it is much more cost effective than MIM or AM. A core advantage of all PM processes is the ability to produce near net-shape parts. This conducted study showed that production volumes of more than 2000 parts are required for the net-shape process to offer a more cost-efficient solution compared to traditional machining from blanks. Low cost, high quality titanium powder, along with excellent process control, are all aspects of the technology which must be achieved to attain these outcomes.

| Target Final shape | Sintered block | Powder preforms | Net-shape |
|-------------------|---------------|-----------------|-----------|
| Material waste | 89 vol% | 74 vol% | 1.2 vol% |
| Compaction requirements | simple, single level tooling | split punches, multilevel tooling | split punches, multilevel tooling requiring CNC press control |

Figure 1. Comparison of various designs for press-and-sinter processing of the bracket part.

Forming

Forming applications realised from titanium and its alloys are critical structural parts, landing gears, ducts. A further important field of application for titanium alloys are the aircraft engine parts such as fan and compressor blades.

Forging. Forging can be classified into die forging and closed die forging. Advantages are low material loss in comparison with machining and the targeted change of the structure and increasing strength. A disadvantage is the lower geometric precision compared to machining processes. An example is the production of structural components where up to 95% of the material is machined. Forging is also used for manufacturing of appropriate preforms (Figure 2) for subsequent finishing...
operations or finished components, respectively. It reflects the forging process as a part of an entire process route for the realization of preforms in blade manufacturing.

![Figure 2](image)

**Figure 2.** Process routes for preform in blade manufacturing based on forging.

**Incremental sheet forming.** Single point incremental forming (SPIF) application areas include rapid prototyping in aerospace and automotive industries, patient specific biomedical products, as well as components in architectural engineering. There are, however, several process issues such as poor geometric precision, high residual stresses and constrained forming limits that still need to be improved before the SPIF industrialization can take place.

A framework for understanding and analysis of the SPIF formability, forming forces and temperature limits can be found in [4]. The assembling of the three process limits enabled construction of the diagram shown in Figure 3, which can be considered as a process map for SPIF of CP grade 2 sheets. Integrating the thermal limits into the map is a novel contribution to the process knowledge; this may prove to be an expedient tool for the process analyst, to individuate design of a more efficient process when working with titanium alloy sheets [5].

**Machining**
The machining process is characterized by different cost factors that vary depending on the type of setup or process. The main costs, however, can be categorized into three groups, namely: machining cost, cutting tool cost and non-productive costs (Figure 4). The aim is to reduce each of the respective cost elements so that the overall costs can be minimized.

![Figure 3](image)

**Figure 3.** Schematic plot of the SPIF process map, showing the working window for the CP grade 2.

Research was focused on developing cost modelling approach and user interface that will allow manufacturers to improve the process production rate and cost and tool wear mapping [6]. Several demonstrators were selected from the production line of an aerospace manufacturer with the purpose...
of enhancing the resource efficiency of the milling process chains by utilizing the developed models. Validation has shown enhanced part accuracy, shorter machining time, and cost reductions close to 40% for producing the titanium aerospace components [7].

Additive manufacturing / SLM
Selective Laser Melting (SLM) is a powder bed additive manufacturing (AM) process whereby fine metallic powder is melted by means of a laser energy source, layer-by-layer, in order to create a 3-dimensional object. Due to the current limited capacity of metal AM machines in the country, the technology has not yet been fully adopted by industry for production purposes.

Applications in the medical industry include but are not limited to patient specific dental implants, knee and hip implants [9, 10]. Applications for the technology found in the aerospace industry are predominantly for weight reduction of low volume parts (Figure 5). For that purpose, topology optimisation can be efficiently used.

Inspection
Inspection and testing of manufactured parts typically encompass an assessment of the accuracy relative to the design and an assessment of the surface integrity. Various contact and non-contact techniques are used to assess the geometric accuracy of the part and if it is suitable for use. These must be conducted on a regular basis to maintain consistency. Surface integrity is an encompassing expression that describes the surface and near subsurface properties and state of a manufactured product. It is usually imperative that the surface integrity of high value parts be consciously engineered and quantified to ensure design performance. The two most often assessed surface integrity descriptors are topography and residual stress state.

The effect of a different cutting strategy on a typical surface integrity descriptor (residual stress) is illustrated in Figure 6 [11]. Two similar Ti6Al4V parts were manufactured at two different facilities using slightly different cutting strategies.

Finish milling for Process II was conducted at a higher cutting speed than Process I (100 m/min compared to 50 m/min). The near surface residual stress state was measured by XRD at different positions and presented (Figure 6). This clearly shows that the process utilizing the higher finishing cutting produced a higher compressive residual stress state that may be beneficial for fatigue purposes.

3. Manufacturing of high added value components. A case study
The objective of the case study is the realization of prototypes of a generic blade geometry based on the selected manufacturing routes:
- Machining from a whole, i.e. billet
- Forming (for preform realization) + machining
- Additive manufacturing (for preform realization) + machining

The reference basis was the conventional machining process. Within this project, the complete process routes were developed in detail, including single process steps. Another aspect which played an important role was the achievement of a high Technology Readiness Level (TRL) for the manufacturing route.

Process route “Machining”

Machining of high-added value titanium blades is a challenging process. The main reason for this is not only the exotic material, but largely the complex geometry and tight tolerances required. The blades are usually very thin and high in length, making the clamping and machining especially difficult. Introducing multitasking machining that comprises several machining operations in a single platform, such as turn-mill, can respond to the complexity and energy saving growing demands [13].

The turn-mill technology was used to produce rotor blades from Ti6Al4V rod-type workpiece. The blade design obtained from a reputable manufacturer of power generation was used as a capability demonstrator. The blade thin and varying thicknesses over its specified height add to the machining and clamping complexity. Figure 7 depicts the turbine blade on the turn-mill machine, showing the workpiece, the clamping system and the volume ratio of material used. Three fan blades were machined of Ti6Al4V pellets (Ø110, 350 mm). Figure 7(c) highlights the large waste of material by volume ratio. This also can be improved by using more efficient start-up workpieces geometry as well as better clamping strategy.

**Figure 7.** Machining of turbine fan blade out of mill product showing the clamping on both main and sub-spindle: (a) the starting billet; (b) the machined blade before the offcut; (c) material usage.

**Figure 8.** Optimisation of the machining operation: (a) reduced cycle time; (b) reduced costs.

The iterative-like approach followed, that is stimulus, or adapting of the process over the course of machining enabled learning and optimise the process over the three samples. Reduction of machining time and cost was obtained using various milling strategies, and different tool types. Figure 8(a)
illustrates a comparison of the actual machining time between the three iterations (blades) from both the roughing and the finishing operations. The assembled costs of the machining hours, tools and material are shown in Figure 8(b). Comparatively, significant reductions of the total costs have been realised between the first and last samples.

Process route “Forming + machining”

Based on an analysis of the generic blade geometry, the rough process route that was identified as a promising variant for the realization of the preform comprises cross wedging, upsetting and forging as shown in Figure 9(a).

Concerning the subsequent finishing process, the blade geometry was slightly changed to optimize the clamping strategy. Based on successfully performed feasibility studies using FE simulations, required tools, jigs, etc. were realized and the prototyping process was started. Finally, it was possible to realize preforms based on the selected forming route. Figure 9(b) illustrates the final forging step for the realization of the preforms.

The next process step was the machining of the blade root which is the basis for workpiece clamping and referencing. The machining of airfoil geometry was realized using a 5-axis turn-mill-centre. The root part was mounted on the main spindle. Therefore, a special clamping adapter was developed for adapting the prismatic root on the three-jaw chuck. With the opposite spindle the counter holder was gripped. Chucking from both sides gave high stiffness to the part clamping and provided the ability to machine the entire blade surfaces in a single clamping setup. Finally, the airfoil area was finished based on two step strategy consisting of pre-finish milling and finish milling.

Figure 9. Process route for preform realization: (a) based on intermediate part geometries; (b) proof of feasibility for modified preform geometry.

Process route “Additive manufacturing + Machining”

Additive Manufacturing is another promising process route for realization of blade preforms. An advantage is not only the realization of (near) net-shape contours. It is also possible to realize internal structures, i.e. cooling channels can be integrated. To realize an appropriate preform for subsequent machining processes, the working steps performed included: development of adequate pre-part, development of additive manufacturing strategy, development of finish machining strategy and prototyping.

Similar to the process chain described above, the preform geometry was also modified in this case in order to ensure an optimal clamping condition in the machining process. Only the airfoil area was realized by additive manufacturing to increase the efficiency. The blade root was realized by machining from a solid titanium bar. This approach enabled significant reduction of part volume to be built and a precision root as reference base for subsequent machining. Selective Laser Melting was used as a suitable process for the realization of the airfoil area. The parts are generated directly from

\[ \text{in case of series production} \rightarrow \text{double parts will be realized} \rightarrow \text{avoidance of scrap} \]
titanium powder. The structure is built up in layers. For an increased efficiency three blades were built up simultaneously in one additive job (Figure 10).

![Figure 10](image)

**Figure 10.** The AM route: (a) pre-machined root parts mounted on SLM-table; (b) middle-additive building process; (c) SLM-table with AM pre-parts.

| Table 1. Optimizing AM process time with batch size. |
|-----------------------------------------------------|
| Part number per job | 3 | 6 | 10 | 20 |
| Light exposure per part, hr | 7,9 |
| Light exposure total, hr | 23,8 47,6 79,3 158,7 |
| Layer lamination, hr | 16,5 |
| Time per part hr | 13,4 10,7 9,6 8,8 |

Measurements of the first preforms showed a torsional distortion of the air foil geometry. This geometric error can be mainly attributed to residual stresses because of the thin walled geometry and the local heating during the additive manufacturing process. A beneficial tool to solve this problem is a new simulation code, which is still under development. The process can be simulated regarding the thermal and residual stresses. Consequently, these stresses can be minimized and the SLM process optimized.

The minimization of the process time is another challenge. In comparison to the laser time which increases linear with the number of parts, the time for powder layer lamination is not dependent on the part numbers. Therefore, an increasing number of parts to be realized per job leads to a decrease of process time per part in general (Table 1). The machining and clamping strategies of the preform realized by SLM were similar to those used for the forged preform.

**Evaluation of process routes**

For the planned benchmark of the different routes, issues such as material use, lead time, tooling equipment, and finally manufacturing costs were considered. A first interesting aspect is the amount of titanium which is needed for the realization of the parts (see Figure 11). Furthermore, the manufacturing costs were determined. Beside of the material, criteria such as required tools, machine-hour rates and process times (including auxiliary times) were considered.

![Figure 11](image)

**Figure 11.** Comparison of material usage for realization of blade geometry between the process routes.

![Figure 12](image)

**Figure 12.** Relative cost for a titanium turbine blade demonstrator part for different manufacturing process chains and part volumes.

The diagram in Figure 12 shows the development of part costs dependent on the part quantity. Based on these calculations, it is possible to see that the complete machining of a blade is suitable for
small part numbers. Above a part number of about 65, the alternative process route “forming + machining” is gaining importance. Due to the cost of titanium powder, the parts realized using the process route “additive manufacturing + machining” are characterized by the highest costs.

Therefore, in summarizing the advantages and disadvantages of the process routes considered, machining provides high flexibility, low material utilization ratio, and is therefore suitable for low demand. In the process route “forming + machining”, part costs are considerably reduced with increasing production volume. However, it has low flexibility with an expected tool life of 1500 (tool reworking expected) parts which renders this process route suitable for medium to high demand. For “additive manufacturing + machining” the high flexibility and material utilization with additional function integration in tooling is advantageous, but the feasibility of this route is challenged by high residual stresses in as-built parts and elevated powder costs.

Regarding the achieved results, the used processes, the used machine equipment and the state-of-the-art in blade manufacturing it can be summarized that TRL 9 was achieved/proven for the process route “forming + machining”. In the case of the route “additive manufacturing + machining” further optimization loops regarding the guarantee of dimensional and geometrical accuracy are required. However, the principal feasibility was proven and TRL 7 was achieved.

4. Resource efficient production of high-added value components. A South African perspective

The research outlined in this paper forms an integral part of the broader DST R&D led industrialization strategy, which aims at the growth of local industrial capacity and activity, as well as value addition to South African minerals. The work to date has been successful in developing core competencies in downstream manufacturing technology building blocks, such as high efficiency machining of titanium (and aluminium), additive manufacturing, powder metallurgy, forging, and materials/component characterization. More importantly, these building blocks have been combined in different manufacturing process chains to investigate the optimum configurations for particular component types. This is a differentiating competence that can provide a competitive advantage to local manufacturers of high value titanium products for the fast-growing aerospace as well as the more established biomedical markets in particular.

The importance of this ability to design and implement different process chains is illustrated in Figure 12 above. This graph is significant in that it is based on validated data that was derived from manufacturing processes that are within the locally developed competence base.

Evidently, different process chains and production volumes yield very different cost curves and part costs. If local manufacturers were not able to have access to such data and competence, then clearly they would not be able to compete in the global marketplace; and local value addition to titanium minerals would be limited to raw materials such as powder, or semi-finished products like plate and sheet.

In this context it is important to note that for the current powder bed additive manufacturing technologies, the titanium powder accounts for less than 10% of the actual AM component cost. Hence, the cost of the titanium powder is not a significant cost driver in the hybrid additive manufacturing chain. Powder cost nevertheless becomes more significant for AM processes with much higher material deposition rates. Such processes/machines are currently under development, e.g. the local Aeroswift programme). Moreover, there is a global oversupply of titanium metal sponge, which has seen sponge prices fall to historical lows [14].Titanium and titanium powder are thus commodities, albeit with a relatively high value, and the local manufacture of high value parts and products must form a key part in a sustainable titanium industrialization process.

Competencies and technologies are of little value, however, unless they can be transferred and implemented in industry. The work described in this paper has been successfully demonstrated at a TRL level of 5 – product related, which is still some way away from commercial implementation.

For any new technology or process, the key requirement for successful industrialization is a motivated user (MU), who is able to develop the technology to TRL level 9 in collaboration with the technology partner. Ideally, the MU should be involved in the technology development process to
ensure a seamless progression. Once the technology has been successfully demonstrated and adopted by the MU, it can then be industrialized further by the MU and/or diffused into broader industry. From an industrialization perspective, it is thus important to progress the hybrid process chain technologies described in this work from TRL 5 to TRL 9, in collaboration with a MU.

5. Conclusions
The most important outcomes and conclusions from the presented research can be summarised as follows:

1. The initial target to demonstrate reduction of material wastage by up to 50% through implementation of preforms and near-net shape manufacturing technologies (thereby reducing the required amount of machining to achieve the final component geometries) has been clearly proven, in fact substantially exceeded.
2. The second target—reduction in machining time up to 20% has been clearly proven too. This becomes possible through implementing of more efficient cutting and clamping strategies. The using of preforms brings additional advantages in this regard.
3. The TRL challenge:
   - The lack of an end user partner forced the project to differentiate between component readiness levels and process readiness levels.
   - Component readiness levels cannot exceed TRL 5 in the absence of a “real” component.
   - Process readiness levels can be proven all the way to TRL 9.
4. The importance of the results represented by the graph (Figure 12) is far reaching, in the sense that, it is validated data which was derived from processes within our reach. The data contained in the source document shows that the material price of the additive powder is not a cost driver in the hybrid additive chain. (This means further that the availability of SA powder is not a risk to this method). Moreover, this data can be used to make design and manufacturing decisions in an industrial environment.

Finally, this project clearly illustrated the value of a multidisciplinary research group. The ability to develop and demonstrate in parallel stimulates and enables cross cutting problem solving. Of a particular importance hereby is also the fact that industry have direct access to R&D institutions.

Acknowledgement
The presented results reflect to a large extent work carried out within the project “Resource Efficient Project Chains for Titanium Components in Aerospace, Automotive and Medical Applications”, which forms part of the research platform of the TiCoC. The authors express their sincere gratitude to the DST for funding and supporting the research over several years.

References
[1] Tung C and Tso P 2011 Int. J. Ind. Manuf. Eng. 1 172–7
[2] Lu D, Liu J, Zhao W, Lu B, Wu D, Song D, Xue F and Cheng B 2017 J. Manuf. Sci. Eng. 139 111015
[3] Mose C and Weinert N 2015 Robot. Comput. Integr. Manuf. 34 44–51
[4] Uheida E H 2016 Development and optimisation of incremental sheet forming of titanium grade 2—Process mapping (Dissertation, Stellenbosch University)
[5] Grün P A, Uheida E H, Lachmann L, Dimitrov D and Oosthuizen G A 2018 Int. J. Adv. Manuf. Technol. 5–7
[6] Oosthuizen G A 2010 Wear characterisation in milling of Ti6Al4V – A wear map approach (Dissertation, Stellenbosch University)
[7] Conradie P, Dimitrov D and Oosthuizen G 2016 Procedia CIRP 46 412–5
[8] Neugebauer R, Drossel W, Wertheim R, Hochmuth C and Dix M 2012 Procedia CIRP 1 3–16
[9] Santos E C, Shiomi M, Osakada K and Laoui T 2006 Int. J. Mach. Tools Manuf. 46 1459–68
[10] Murr L E, Quinones S A, Gaytan S M, Lopez M I, Rodela A, Martinez E Y, Hernandez D H, Martinez E, Medina F and Wicker R B 2009 J. Mech. Behav. Biomed. Mater. 2 20–32
[11] Dimitrov D M, Laubscher R F, Sterzing A, Conradie P J T, Oosthuizen G A, Blau P, Schmidt G, Hochmuth C, Styger G and Zachäus R 2016 Procedia CIRP 45 155–8
[12] GmbH C L 2017 Voraus! Topologisch optimierte Bauteile in der Luftfahrt - Ahead!
Topologically optimised components in aviation
[13] Calleja A, Fernández A, Rodríguez A, De Lacalle L N L and Lamikiz A 2015 Proc. Inst. Mech. Eng. Part B J. Eng. Manuf. 229 1324–36
[14] TBGA The Barnes Group Advisors, Personal communication