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The Use of Particulate Injection Moulding for Fabrication of Sports and Leisure Equipment from Titanium Metals †

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Abstract: Advanced materials such as metal alloys, carbon fibre composites and engineered polymers have improved athlete performances in all sporting applications. Advances in manufacturing has enabled increases in design complexity and the ability to rapidly prototype bespoke products using additive manufacturing also known as 3D printing. Another recent fabrication method widely used by medical, electronics and armaments manufacturers is particulate injection moulding. This process uses exact quantities of the required material, in powder form, minimising resource and energy requirements in comparison to conventional manufacturing techniques. The process utilises injection moulding techniques and tooling methods developed and used in the plastics industry. It can produce highly complex component geometries with excellent repeatability and reduced cost where volume manufacturing is required. This is especially important when considering materials such as titanium that are not only expensive in comparison to other metals but are difficult to process by regular machining and fabrication methods. This work presents a review of titanium use in the sporting sector with a focus on sporting devices and equipment. It also proposes that the sports engineering sector could increase performance and enable improvements in safety by switching to design methods appropriate to processing via the particulate injection moulding route.

Keywords: particulate injection moulding; performance; titanium

1. Introduction

The use of titanium metals in the medical, chemical and marine industries utilise the low mass, high strength, high corrosion resistance and bio compatibility compared to carbon steels [1]. Other advanced materials such as carbon fibre composites, ceramics and engineered polymers offer many of the same material properties and have enabled improved performance in many sporting applications such as cycling, kayaking and running [2,3]. Most recently the uptake of the additive manufacturing process referred to as 3D printing has seen even more developments in these areas [4]. This has also shown increases in design complexity and the ability to rapidly prototype bespoke products using ceramics, metals and polymers [5].

Another recent processing method successfully employed in the medical, electronics and armaments manufacturing sectors is particulate injection moulding (PIM) [6–8]. This process emerged in the 1920s with its first commercial application for production of the ceramic insulators on spark plugs used in the internal combustion engine [7,9,10].

In the late 70s the process went commercial with interest in fuel cells and the semiconductor industries becoming so intense, that it became a realistic proposition [11–13]. A combination of techniques from the powder metallurgy and composite manufacturing utilises exact quantities of powders thereby minimising resource and energy requirements in comparison to conventional manufacturing techniques. The process also utilises injection moulding techniques and tooling methods developed and used in the plastics industry. As such metal injection moulding (MIM) can produce highly complex component geometries with excellent repeatability and reduced cost where volume manufacturing is required. The process can produce all of the geometries producible using polymers as well as many that can be produced by no other means [14].

One of the barriers to using titanium in many applications is the cost of the raw material when compared to metals such as readily available ferrous metal alloys and aluminum despite the better materials properties. This barrier is similar to that seen for carbon fibre composites in the 1990s with interest shown by aero giant Boeing [15,16]. Therefore, increases in demand for titanium will provide a reallocation of the metal from aerospace only use to general market use. It is already showing with growth in the additive manufacturing sector encouraging global investment in raw material production especially for metals such as titanium.

Another challenge seen with many powder metallurgy processes is that material density and fatigue properties are generally seen to be lower than for comparable bar stock. These issues can be eliminated by using secondary processes such as forging, isostatic compression and surface treatments. They can also be reduced by using finer powders, optimizing thermal profiles and with the addition of alloying elements such as boron and iron [17].

2. Background

Despite the cost the sport and leisure sector has been using titanium for many years [2]. Titanium is providing benefits for Paralympic athletes, wheel chair [18] and disabled sports [19]. It is showing strongly for amputees limb replacement (Figure 1a) as well as orthopedic inserts [20] where is considered to improve osseointegration and reduction/elimination of micro-motion causing damage [21]. Most prevalent is use in golfing (Figure 1b) as evidenced in the uptake for golf clubs [22], shafts [23] and balls. It is used in for sports shoes such as track sprinting and climbing spikes [24], motor sports for brackets and drive chains [25] and, skiing in both skis and bindings [26]. Titanium is also indirectly in demand for use in instrumentation and sensor devices cases [27] as well as new smart watches used for sport and leisure monitoring.

(**a**) (**b**)

Figure 1. Sports application of the PIM process, (**a**) GKN Sinter Metals Germany produced MIM parts for the Otto Bocks prosthetic knee joint. (**b**) Callaway's FT-iZ Hybrid golf club uses adjustable weights produced by MIM (Images PIM International Vol. 4 No. 3, 2010).

Cycling is also embracing titanium use [28], in 1982 the Lotus Sport bicycle, developed by Mike Burrows of England, used titanium for saddle, brackets and cranks [29]. More recently Australian bicycle manufacturer Bastion Cycles Pty Ltd (http://bastion-cycles.com) is using titanium lugs and brackets although not currently produced using PIM. Figure 2 shows other cycle componentry, the derailleur component (a) and the gear (b) produced by MIM from titanium metal.

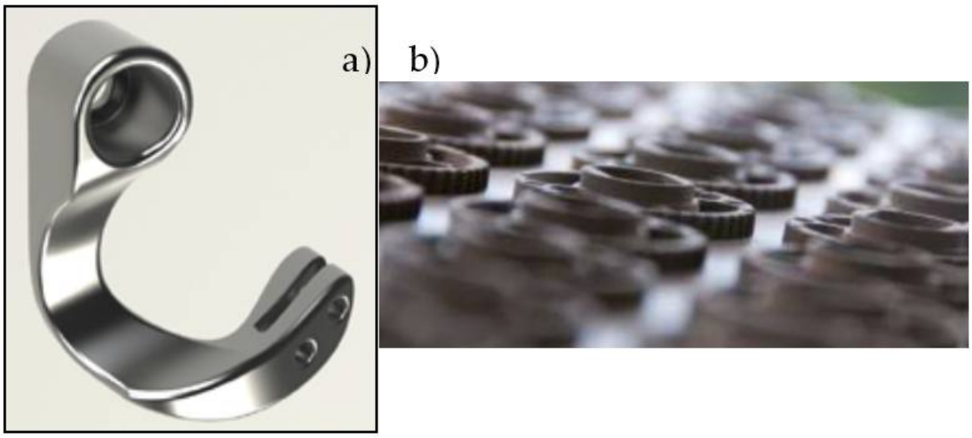

Figure 2. Titanium bicycle components produced using MIM, (**a**) derailleur component produced by Element22 GmbH. Germany (Image PIM International, Vol. 6 No. 2, 2012), (**b**) bicycle gears produced by Mimest SpA, Italy (PIM International Vol. 4 No. 3, 2010).

3. Metal Injection Moulding

In order to justify investment in new fabrication processes and the development of products using a new technology there has to be an economic and/or a performance benefit identified to outweigh the cost and the risk element. It has been shown above that there is a market demand for titanium use due to its ability to impart superior specific properties, corrosion resistance, light weight and high strength. Further cost benefits can be gained with the use of particulate processing techniques that reduce raw material usage due to net shape production the minimizes or even eliminates waste. This supports sustainability practices [27] gaining support by the new generation of industrial designers and engineering specifiers with mandates to practice social enterprise.

The global PIM market indicates the process is most viable for small components (1 to 20 g steel). The leading components are through mass production of electronic devices, such as smart phones, manufacturing with 100,000 units per day not uncommon. However, it is also shown to be a viable process for volumes of 5000 per annum [7] and even lower volumes can be seen to be profitable where the component size is large, material value is high, conventional processing is not possible and the complexity is high. Consider a very simple production tool has a useful life of 100,000 components at a cost of NZ$10,000–20,000 and this is a barrier to low product volumes or product development where the outcome is uncertain. The use of rapid tooling and mould inserts enable cost effective tooling to produce 10 s or 100 s of units and therefore enable the lower volumes and investigation with reduced risk. Current developments also enable profitable production of large (300 g titanium) components such as the marine hold-down shown in Figure 3. This component is produced in batches as small as twenty and less than 1000 annually.

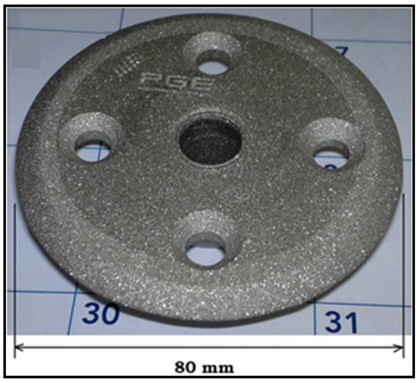

Figure 3. Both small and large components are produced using PIM. The marine hold-down produced from titanium for Earthrace Conservation for the Earthrace 2 vessel, is >300 g [Image by permission AME Powder Technology Ltd. Hamilton New Zealand].

Globally the leading sector for PIM markets varies geographically depending on the consumer base. Asia leads the electronics sector; North America leads the medical sector and Europe leads the consumer sector [8]. The process is also proving viable for thin wall (<1.0 mm) sections as well as reduce the need for assembly of parts when combined with complex tooling. It is a proven method of maintaining tight tolerances and is a cost-effective process for volume manufacturing [6,8].

3.1. An Overview of the Fabrication Process

The MIM process utilises the high surface energies of finely divided powders (<100 μm) that enables consolidation at temperatures of 70% those required for conventional melt processing of ingot and bar stock. Another benefit of the MIM process is that the majority of the processing is done at temperatures similar to those used to process thermoplastic polymers. The PIM process is a combination of the four processing steps as depicted in Figure 4 and narrated in the subsequent PIM process outline below.

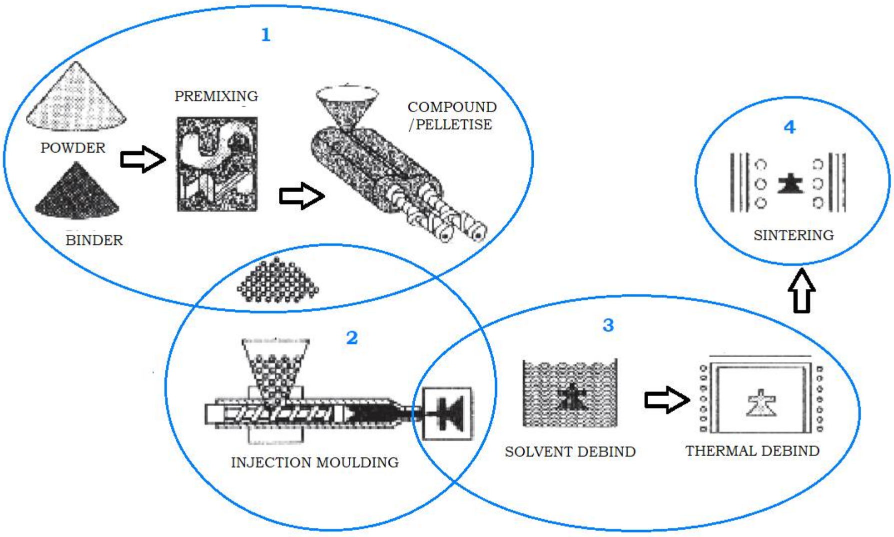

Figure 4. The PIM processing steps combine to produce the desired component [30].

The following is an outline of the PIM process.

1. Feedstock formulation

A thermoplastic carrier system is formulated and compounded with the titanium particles at powder loadings of 50 to 70% by volume. This allows the powders to flow during the moulding process and bind them together at ambient temperatures.

2. Greenpart formation

The feedstock is loaded into the injection moulding machine and heated. The binders encapsulating the powders melts enabling the powders to flow into the mould cavity. The mould is produced similarly to those used in polymer moulding. The moulded feedstock is allowed to cool and once removed from the mould is referred to as a green part.

3. Brownpart formation

The greenpart is then debound a process where the binder is slowly removed. The debinding is typically a solution process, a thermal process or a combination of the two. It must be done in such a fashion as to retain the desired shape and once completed is referred to as a brown part.

4. Consolidation

The final consolidation is a thermal process referred to as sintering where the particles coalesce and the brownpart shrinks by the volume vacated by the binder system during debinding.

Where the reader is interested in processing parameters the following publications by the author et.al. are suggested [14,21,31,32].

3.2. Component Design

The use of relatively unknown technologies such as PIM presents challengers that designers and manufacturers must address to move ahead in their approach to product development. In the traditional approach to design the use of practiced and proven geometries and conventional machining processes is safe but may hinder innovation. It is important to understand that although the design and mechanical properties of a component are dependent on material properties, designs can be modified to overcome material deficiencies and ensure products are fit for purpose. This in combination with repeatability, cost savings and waste reduction can be more attractive than matching a global standard that has been created to meet aerospace or medical requirements and that for sports equipment is likely adding further cost without enabling performance improvements.

4. Conclusions

In order to justify investment in a new fabrication process the development of products must enable economic benefits for volume manufacturing or performance benefits for athletes that outweigh the cost and the risk element. Fabrication using the PIM process enables production of complex geometries using titanium metals that would otherwise be extremely expensive, difficult to produce using conventional machining processes or both. The process does come with challenges similar to those seen for traditional powder metallurgy such as lower fatigue strengths and densities than when using conventional bar stock. However as with many powder processes it enables custom alloys and waste minimisation not otherwise seen. In conjunction with this design for process, production and performance is essential.

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Conflicts of Interest: The author is one of the founders of the AME Powder Technology Group.

References

1. Boyer, R. Attributes, characteristics and applications of titanium and its alloys. *J. Mater.* **2010**, *62*, 21–24.
2. Easterling, K.E. Fundamentals of advanced materials. In *Advanced Materials in Sports Equipment*; Easterling, K.E., Ed.; Springer: Dordrecht, The Netherlands, 1993.
3. Ewart, P. Micro-mechanical predictive modelling as an aid to CAD based analysis of composite sporting equipment. MSc(Tech) Thesis, The University of Waikato, Hamilton, New Zealand, 2008.
4. Franz, P.; Mukthar, A.; Downing, W.; Smith, G.; Jackson, B. Mechanical behaviour of gas nitrided Ti6Al4V bars produced by selective laser melting. In *Powder Metallurgy of Titanium II*; Ebel, T., Pyczak, F., Eds.;Trans Tech Publications Ltd: Pfaffikon, Switzerland, 2016.
5. Caine, M.; Hopkinson, N.; Joku, U.; Lever, G. The feasibility of producing bespoke football boots comprising selective laser sintered outsoles. In *The Impact of Technology on Sport*; Subic, A., Ujihashi, S., Eds.; Australasian Sports Technology Alliance ty. Ltd: Melbourne, Australia, 2005.
6. German, R. *Metal Injection Molding A Comprehensive MIM Design Guide*; Metal Powder Indusrries Federation: Princeton, NJ, USA, 2011.
7. German, R.; Bose, A. *Injection Molding of Metals and Ceramics*; Metal Powder Industries Federation: Princeton, NJ, USA, 1997.
8. Heaney, D. *Handbook of Metal Injection Molding*, 1st ed.; Woodhead Publishing: Cambridge, UK, 2012.
9. Schwartzwalder, K. Refractory Body and Method of Making the Same. U.S. Patent 2122960, 5 July 1938.
10. German, R. *Final Report on the Workshop on Scientific Issues for Medical and Dental Applications of Micro/Nano Powder Injection Molding—Molding, Sintering, Modeling, and Commercial Applications*; Metal Powder Industries Federation: Princeton, NJ, USA, 2009.
11. ATW Companies. Profile. Available online: http://www.parmatech.com/parmatech/profile.html (accessed on 31 October 2011).

12. Williams, N. Parmatech: The MIM industries first commercial producer, and still going strong. *Powder Inject. Mould. Int.* **2010**, *4*, 5.
13. Bellamy, H.T. Production of Molded Metallic Articles; U.S. Patent 2397831, 2 April 1946.
14. Ewart, P. The Formulation of Titanium—Based Metal Feedstocks and the Fabrication of Parts Using the Powder Injection Moulding Process. Ph.D. Thesis, The University of Waikato, Hamilton, New Zealand, 2015.
15. Clarke, J.L. (Ed.) *Structural Design of Polymer Composites: EUROCOMP Design Code and Handbook*; CRC Press: Boca Raton, FL, USA, 1996.
16. U.S. Department of Defense. Polymer Matrix Composites: Materials, Usage, Design and Analysis. In *Composite Materials Handbook*; MIL-17; U.S. Department of Defense: Washington, DC, USA, 2002; Volume 3.
17. Ebel, T. PMTi 2017 Xi'an: Titanium MIM comes of age as Additive Manufacturing drives awareness. *Powder Inject. Mould. Int.* **2017**, *11*, 61–73.
18. Laschowski, B.; McPhee, J. Body segment parameters of Paralympic athletes from dual-energy X-ray absorptiometry. *Sports Eng.* **2016**, *19*, 155–162.
19. Cavacece, M.; Smarrini, F.; Valentini, P.P.; Vita, L. Kinematic and dynamic analysis of a sit-ski to improve vibrational comfort. *Sports Eng.* **2005**, *8*, 13–25.
20. Al Muderis, M.; Aschoff, H.H.; Bosley, B.; Raz, G.; Gerdesmeyer, L.; Burkett, B. Direct skeletal attachment prosthesis for the amputee athlete: The unknown potential. *Sports Eng.* **2016**, *19*, 141–145.
21. Ewart, P.D.; Ahn, S.; Zhang, D.; Park, S.J.; German, R. Poster Progam, PowderMet2011. In Proceedings of the International Conference on Powder Metallurgy and Particulate Materials, San Francisco, CA, USA, 18–21 May 2011.
22. Adelman, S.; Otto, S.; Strangwood, M. Modelling Vibration Frequency and Stiffness Variations in Welded Ti-Based Alloy Golf Driver Heads. In *The Engineering of Sport 6*; Moritz, F., Haake, S., Eds.; Springer: Munich, Germany, 2006.
23. Timms, T.; Mase, M.; West, C. Player Fitting of Golf Equipment Using a Calibration Club. In *The Engineering of Sport 6*; Moritz, F., Haake, S., Eds.; Springer: Munich, Germany, 2006.
24. Daniel, T.; Kamperman, N.; Ajoku, U.; Hopkinson, N.; Caine, M. Benchmarking Stiffness of Current Sprint Spikes and Concept Selective Laser Sintered Nylon Outsoles. In *The Engineering of Sport 6*; Springer: Dordrecht, The Netherlans; Munich, Germany, 2006.
25. Burgess, S.; Lodge, C. Optimisation of the chain drive system on sports motorcycles. *Sports Eng.* 2004, *7*, 65–73.
26. Easterling, K.E. Skis. In *Advanced Materials in Sports Equipment*; Easterling, K.E., Ed.; Springer: Dordrecht, The Netherlans, 1993.
27. James, D.A. The Application of Inertial Sensors in Elite Sports Monitoring. In *The Engineering of Sport 6*; Moritz, F., Haake, S., Eds.; Springer: Dordrecht, The Netherlans; Munich, Germany, 2006.
28. Easterling, K.E. Bicycles. In *Advanced Materials in Sports Equipment*; Easterling, K.E., Ed.; Springer: Dordrecht, The Netherlans, 1993.
29. Plueddeman, C. Superbike: So radical it was banned until Barcelona, the forkless, monocoque-framed Lotus Sport bicycle turns high-tech into Olympic gold. *Popular Mechanics,* February 1993.
30. Moxson, V.S.; Froes, F.H. Components via Powder Metallurgy. *J. Mater.* **2001**, *53*, 39–41.
31. Ewart, P.; Zhang, D.; Ahn, S. Removal of the Water Soluble Components from Titanium and Titanium Alloy Powder Compacts produced by MIM. In *Powder Metallurgy of Titanium*; Qian, M., Ed.; Trans Tech Publications: Brisbane, Australia, 2012; p. 6.
32. Ewart, P.; Jull, H.; Kunnemeyer, R.; Schaare, P. Identification of contamination levels and the microstructure of metal injection moulded titanium. *Key Eng. Mater.* **2016**, *704*, 161–169.