Recycling of titanium alloy swarf directly into wire using the Conform™ continuous extrusion process

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Abstract

Conform™ is an extrusion process, which has been in use since the 1970s. Although it is primarily used with aluminium or copper rod/powder feedstocks, work at the Univ. Sheffield over the last decade has involved the use of titanium feedstocks for various applications. This paper expands on this knowledge by utilising low cost, aerospace titanium alloy swarf, which is the largest waste product from the manufacturing of aerospace titanium components. Swarf is fed into a Conform™ extrusion machine at room temperature and is fully consolidated into round wire/rod profiles in one, solid-state step, using modified tooling for titanium. Such wire can be used for additive manufacture or welding wire. To date there has been numerous successful trials in this challenging process, including the production of both 10 mm commercially pure titanium rod (from powder) and, more importantly, the production of 5 mm diameter Ti-6Al-4V wire from swarf. The material produced has since been characterised using light and electron microscopy and mechanical properties determined using tensile testing and microhardness indenting.

1 Introduction

Titanium alloy forgings are intensively machined, in some instances up to 90% of the forging is removed to swarf. In fact, many aerospace manufacturing companies generate greater weights of titanium swarf than components due to such poor buy-to-fly ratios. Therefore, it's no surprise that over the last few years there has been more interest the reuse and recycling of titanium alloy machined swarf in order to reduce manufacturing costs. And with increasing aircraft orders and more titanium alloy components being employed, such recycling technologies are becoming ever important. Also over the last few years, wire fed additive manufacturing routes have received increasing sponsorship, as an alternative route to achieve near net shape in fewer processing steps. Such processes include wire-arc additive manufacturing (WAAM) [1] and Arconic's Ampliforge process [2], for example. Such wire fed routes also require post or in-situ thermomechanical processing to refine the microstructure. However, one drawback of such processes is the high cost of the titanium alloy wire feedstock which is produced through the expensive Kroll Process route. Therefore, there is a market need for low cost Ti-6Al-4V wire for welding operations as well as these emerging AM routes.

Continuous extrusion or Conform™ has been used since the 1970s for the recycling of waste material - primarily aluminium and copper alloys [3]. Recently, work has been done into the Conform™ of materials such as titanium and various feedstock morphologies. Traditionally, rod feedstocks were used but work at the University of Sheffield [4] has been carried out using powder and particulate feedstocks. In this paper, we demonstrate the successful adaption and use of the technology for the recycling of Airbus Ti-6Al-4V machining swarf or chips directly into wire. This is the first time that the continuous extrusion technology has been used for such feedstock.

2 Experimental Approach

All trials were completed using an experimental BWE Ltd Conform™ 350i machine based in Ashford, Kent and shown in figure 1.

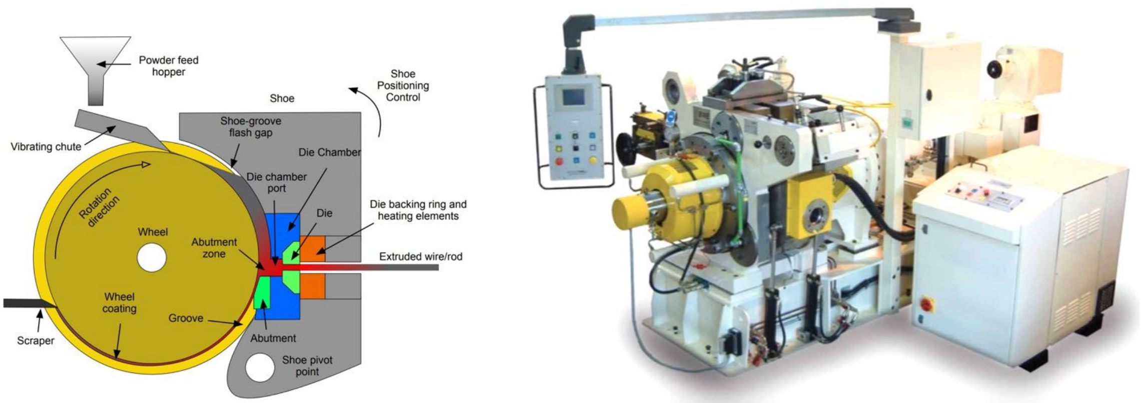

Figure 1 Schematic of continuous extrusion Conform^{TM} and a photograph of a BWE Conform^{TM} 350i (from [5])

Prior to any full-scale trials, finite element modelling and discrete element modelling are used to optimise the tooling geometries for the swarf flow stress, particulate size and morphology (examples of the outputs in figure 2). This is to enable 'right first time' tooling to save initial processing costs. Following this, all tooling was precision machined at Ian Cocker Precision Engineering in Sheffield, UK (Figure 3).

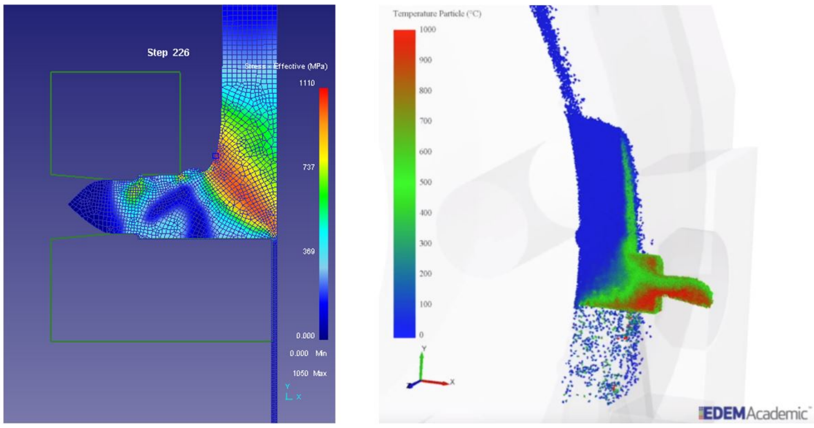

Figure 2 Example of (a) DEFORM and (b) EDEM simulation used to inform tooling design for the Conform^{TM} of Ti-6Al-4V swarf

The tooling arrangement (see Figure 3), with the exception of the wheel, is loaded into the shoe and then preheated to approximately 500°C.

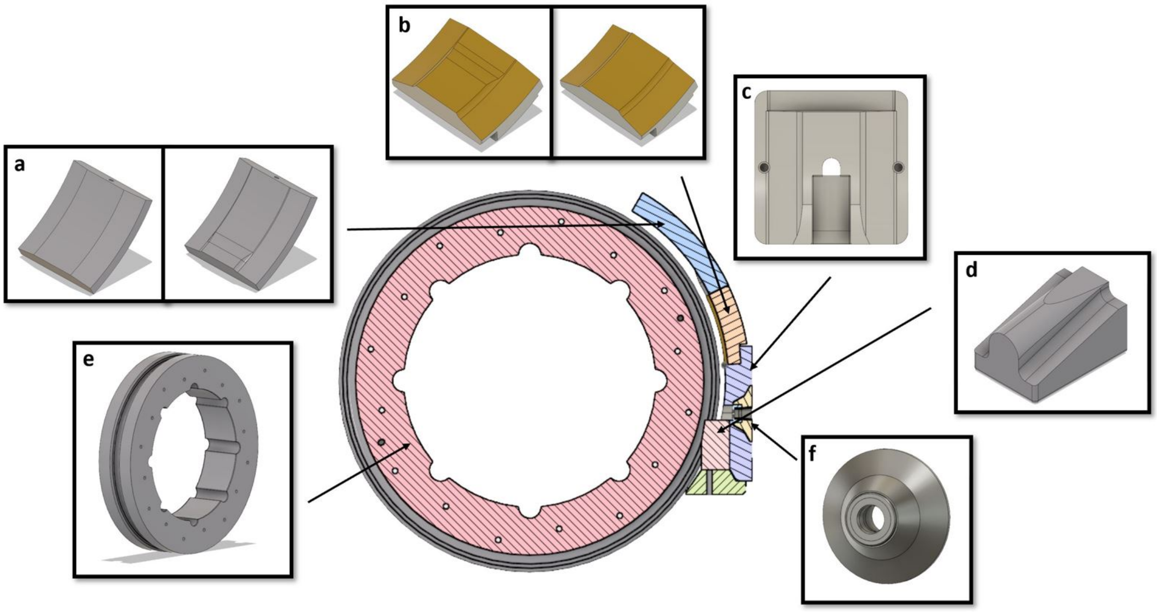

Figure 3 Tooling Schematic (where, a = entry block extension; b = entry block; c = die chamber; d = abutment; e = wheel; and f = die)

When the tool chamber temperature has stabilised, the Airbus Ti-6Al-4V swarf chips (figure 4) are poured into the apex of the groove via a vibrating hopper. It is important to note that swarf is fed into the machine at room temperature as the wheel initially rotates at a constant speed. The swarf heats by frictional effects as it is sheared at the abutment and when steady state conditions are achieved, through manipulation and monitoring of (1) wheel speed, (2) wheel temperature and (3) particulate feed rate, the consolidated material in the die chamber will extrude through the die at temperatures of greater than 900°C. The extruded wire is then fed through a water trough to quench as shown in Figure 4. Extrusion rates are of the order of 1-3 metres per minute for a 10 mm diameter wire, depending on the optimised wheel speed. The extruded wire has an oxide scale, as no inert gas atmosphere is used to shield the hot titanium product from the die exit. This is something that can be implemented during further industrialisation of the process. However, the oxide scale has been found to be beneficial during the subsequent wire drawing stages, when cold drawing down to diameters less than 5 mm diameter: The oxide scale tends to break down in the cold drawing die, leaving a bright cold drawn finish to the final wire. Examples of the extruded product from swarf as well as hydride-dehydride feedstocks and further cold drawn product are also shown in Figure 4.

Figure 4 Photograph of (a) Ti-6Al-4V swarf feedstock provided by Airbus; (b) titanium wire exiting the Conform^{TM} machine and entering trough; and (c) various titanium wires produced via the Conform^{TM} process

3 Characterisation and Mechanical testing

Firstly, all wire product from the Conform^{TM} process has good levels of strength and ductility from a handling standpoint. Wire can be coiled easily, which from a WAAM or welding process perspective is a positive result. In such processes, alloy chemistry is the primary requirement of the wire feedstock, mechanical properties are a secondary concern, as the wire will be melted. However, the authors have carried out some basic characterisation and mechanical testing to demonstrate the effectiveness of the solid state extrusion process.

The microstructure of the swarf wire is illustrated in Figure 5. A fine scale basketweave transformed β structure is observed in the Ti-6Al-4V wire. Such a structure indicates that the wire was severely plastically deformed and exited the die chamber above the β transus (~ 960 °C).

Tensile testing and microhardness testing were carried out on the swarf wire. Figure 5 shows a Vickers hardness map across the face of wire profile. Generally, the hardness levels are within that expected for Ti-6Al-4V which is a clear sign that negligible oxygen or nitrogen has been picked up during the solid-state extrusion process. Elongations to failure during tensile testing were found to be around 10%.

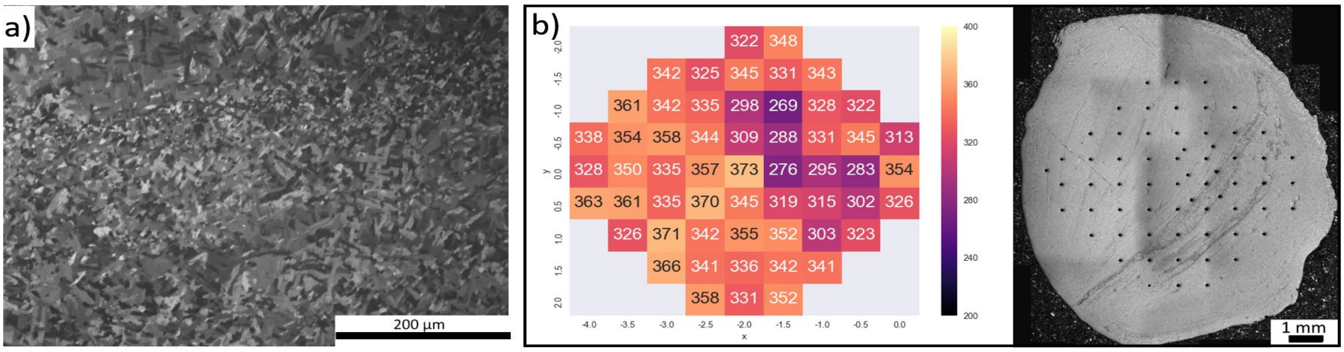

Figure 5 (a) Light micrograph of the cross-section of the extruded Ti-6Al-4V wire derived from swarf and (b) Microhardness of cross section of Ti-6Al-4V wire.

4 Conclusions

Continuous extrusion or Conform^{TM} has been demonstrated for the first time to effectively consolidate Ti-6Al-4V machine swarf or chips directly into 10 mm wire in one solid state process step. The wire had a good level of ductility and strength and can be further cold drawn to produce welding wire or wire fed AM product.

This technology can be further exploited to provide a route for recycling of the increasing amount of titanium alloy machine waste product that is being produced year upon year. Furthermore, process designers could use Conform^{TM} to directly feed downstream AM units. In the longer term, waste swarf product could be turned into near net shape parts in 3-4 processing steps: (1) Conform^{TM} of swarf to wire; (2) cold drawing of wire; (3) wire fed AM processing; (4) finish machining.

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