Near-To-Net Shape Aerospace Extrusions

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Extruded shapes, generally, are ideal for the fabrication of long members of the aircraft that require constant cross sections. Most common aerospace extrusions include seat tracks that are produced using the work horse titanium alloy, Ti-6Al-4V (Ti-64). Titanium billets are extruded at very high temperatures (typically 300-400°F above beta transus) to the required shape and 100% machined to the finished part. In an effort to reduce the overall manufacturing costs including the buy-to-fly ratio, the R&D division of Plymouth Engineered Shapes (PES) has successfully developed an innovative process and manufactured near-to-net shape Ti-64 extrusions, about ~30ft. long, on a production scale that included shapes of varying geometries. This paper presents different near-to-net shapes extruded at PES, and provides the advantages in terms of cost savings over the standard extrusions. It will also discuss the mechanical properties, microstructure and the dimensional tolerances held over the length of the extrusion.

Keywords extrusions, titanium 6Al-4V (Ti-64), buy-to-fly ratio, near-to-net shape extrusions

Introduction

Extrusion is a compressive deformation process in which a billet is 'forced' (extruded) through a die in order to obtain a reduction in its cross section and convert to the desired shape. The length of the extruded part will vary, dependent upon the initial dimensions of the billet and the profile extruded. The extrusion process produces profile cross sections that are uniform over the entire length of the product and hence, is ideally suited for fabrication of long members. Currently, the extrusion process is capable of manufacturing innumerable shapes and profiles that are widely utilized in the aerospace industry. Superior strength to weight ratio, electrochemical compatibility with graphite in a graphite-reinforced organic-matrix composites, makes it convenient to employ titanium alloy extrusions for aerospace applications[1)].

It is well known that each preform process such as forging, casting and plate stock incurs a considerable loss of material during machining due to the excessive material envelope built around the finished product. Extrusions reduce the buy-to-fly ratio by a significant amount and provide advantages not offered by the alternative preform processes. Economic advantages include minimal tooling costs, reduced material usage, lower parts count resulting from the ability to extrude complex shapes over length in a single operation and less downstream machining and finishing. The quality benefits of extrusions include improved surface quality, fine tolerances, superior flatness and straightness that are critical for long-length structural operations[2)]. Proven applications for titanium extrusions in the aerospace industry include floor beams, seat tracks, engine pylons, pylon attachment beams, chords, stiffeners, stringers, spars, flap and slat tracks, hinges, mounting brackets, jet engine rings and related components and space vehicle components.

Considering the increased emphasis, PES has successfully developed methods to further reduce the buy-to-fly ratio of extrusions by manufacturing near-to-net shaped profiles, the advantages of which will be discussed in this paper.

The Extrusion Process

The extrusion process creates tremendous amount of geometric change and deformation of the work piece, more than other metal forming processes such as forging, rolling etc. As in any other metal forming operations, the forces involved and the material flow patterns that occur during the extrusion process are of primary concern in the analysis and development of this manufacturing process. Extrusion process takes into consideration a variety of factors, many of which will be specific to each particular operation. The type of alloy, size of the original billet, geometric cross section of the extruded part, ram speed, temperature of the billet are all important elements in the design and analysis of an extrusion operation. Typically, most titanium extrusion presses are water hydraulic and have remarkably high strain rates in the range of 10/sec or higher[3)]. A vast majority of titanium extrusions are performed above the beta transus to allow for lower flow stresses and the ability to form near-net products. A beta extruded titanium billet will yield in products with an elongated grain structure that is often recrystallized by hot stretch straightening and annealing. The resultant structure consists of recrystallized prior beta grains with colony alpha, which offers excellent combination of strength, fracture toughness and fatigue life.

Metal extrusion processes, in the manufacturing industry, can be broadly classified into two main categories – direct and indirect. PES employs the direct or forward extrusion process, where the die and the ram are in the opposite ends and the billet travels in the same direction as the ram. Typically, the cross section of the work billet is much larger than the cross section of the extruded part. To relate the cross section of the work piece to that of the extruded product, a value commonly termed as “extrusion ratio” was established that is defined as the ratio of the area of the original billet cross section (A_o) to that of the extruded product (A_f). The extrusion ratio, or reduction ratio, can be expressed as (A_o/A_f). Depending on the final geometry of the part, there exists a wide range of extrusion ratios for extruding different titanium products. As mentioned earlier, almost all titanium extrusions will require a hot straightening operation after the completion of the extrusion process.

Experimental Materials and Processing

Different grades of titanium alloys can be produced by the extrusion process, but majority of the commercial aerospace industry, commonly utilizes Ti-6Al-4V (Ti-64) for a large number of its applications. Therefore, the primary focus for this paper is limited particularly to Ti-64 extrusions and related characteristics. Ti-64 billets, with nominal composition per AMS 4935[4)], ranging from 177mm (7.0”) to 225mm (8.9”) in diameter were induction heated to a temperature above the beta transus and extruded to different geometric profiles. The dies used for the extrusion process are designed and manufactured in-house using modified tool steel. Figure 1 shows the profile of a shape/die used for extrusion. The parameters for the extrusion process are selected based on the billet size, extrusion ratio, the profile to be extruded etc. Typical extrusions are ~ 9 – 12m long (30-40ft), depending on the initial size of the billet. The extruded products are then subjected to hot straightening and annealing, in accordance to AMS 4935 to achieve the mechanical properties and key characteristics such as flatness across the width of the part, straightness (bow/camber) and twist along the full length of the extrusion. To enhance the machinability, the finished extrusions are chemically treated to remove the thin layer of the surface alpha case. The sequence of operations is schematically illustrated in Figure 2.

Figure 1. The profile of the die shown here provides the geometry of the shape to be extruded. Manufactured in-house from modified tool steel, the die is able to withstand intense heat and pressure generated during the extrusion process.

Figure 2. The titanium billets are subjected to beta heat treatment followed by extrusion using the required dies, thermally straightened, surface alpha case chemically removed and packed for shipment.

Results and Discussion

Two different seat track profiles (Ext-A and Ext-B), as shown in Figure 3, were selected for the optimization process. The weight per foot of the extrusions in both cases along with their respective buy-to-fly ratio is shown in Table 1. Although specifics of the die design techniques are proprietary, results indicate over 70% reduction in the weight for Ext-A and over 28% reduction in buy-to-fly ratio for Ext-B after optimizing to a near-to-net shape. Optimized profiles of the seat tracks after design enhancements are shown in Figure 4. The specimens for mechanical testing and microstructure were obtained from the location as indicated in the figure. Room temperature mechanical testing was performed according to ASTM E8[5)] and optical microscopy was performed using Keyence digital microscope. As observed in Table 2, the results of the mechanical testing are in full compliance with the strength requirements of AMS 4935 for both profiles, in standard and near-to-net extruded conditions. As expected, the microstructure was resultant from a beta processed Ti-64, with colony alpha along the recrystallized beta grain boundaries. Micrographs shown in Figure 5 are excised off of Ext – A, before and after optimization to a near-to-net shape extrusion. Very similar microstructure was observed on samples from Ext – B. A summary of grain size measurements is provided in the Table 3.

To further explain the advantage of near-to-net extrusions, buy-to-fly ratio was theoretically calculated for the both the seat track shapes, if they were to be machined from a bar stock, and the comparison is graphically represented in Figure 6. Near-to-net shape extrusions provide approximately 135% and 195% reduction in buy-to-fly ratio for Ext – A and Ext – B respectively when compared to the bar stock, thus allowing for substantial trimming in machining time and scrap and increasing tool life[6)].

Machining of titanium extrusions requires extreme control of tolerances on key characteristics such as transverse flatness, straightness, twist and angularity along the full length of the extruded part. With reduction in the envelope due to near-to-net shaped profiles, holding these tolerances along the length of the extrusion is of paramount importance, to successfully machine the final part. Due to the constraints of limited space, and for the convenience of presenting, the transverse flatness tolerances only on the north and south ends of the standard and near-to-net extrusions are presented in Table 4. However, the maximum level of bow and twist observed over the full length of the extrusion are shown in the table. It can be noticed that the average values of the critical characteristics are not only well within the allowable limits, but the near-to-net extrusions manufactured at PES also offer much tighter tolerance limits than specified in AMS 2245[7)], thus making them exceptionally favorable for machining.

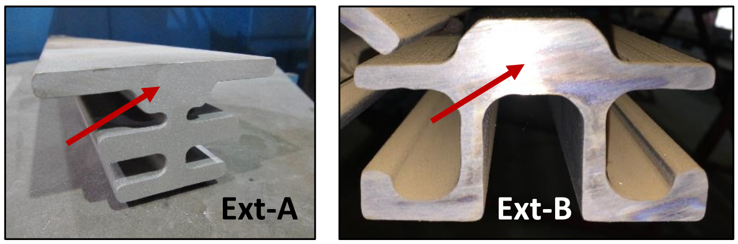

Figure 3. Ext-A (left) and Ext-B (right) are the two different seat track profiles used for this study. Arrow points to the locations from where the tensile and the microstructure samples were excised off.

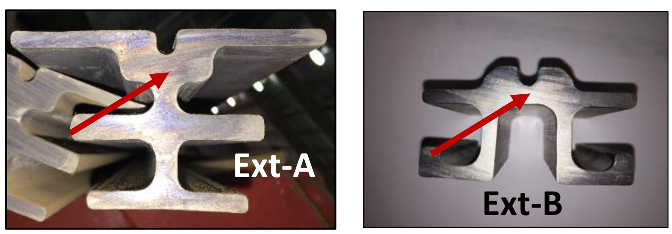

Figure 4. Near-to-net shape extrusions: Ext-A (left) and Ext-B (right)

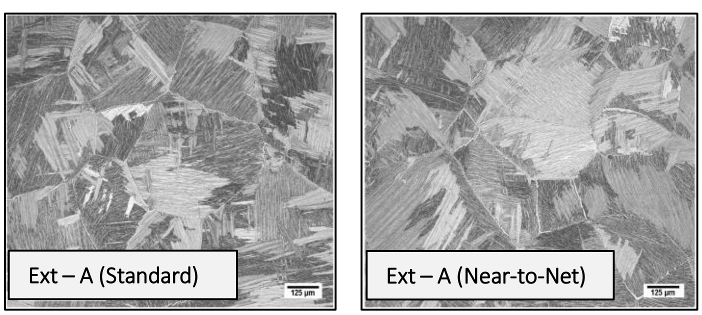

Figure 5. Optical micrographs excised from the longitudinal direction of Ext-A, standard (left) and near-to-net shape condition (right)

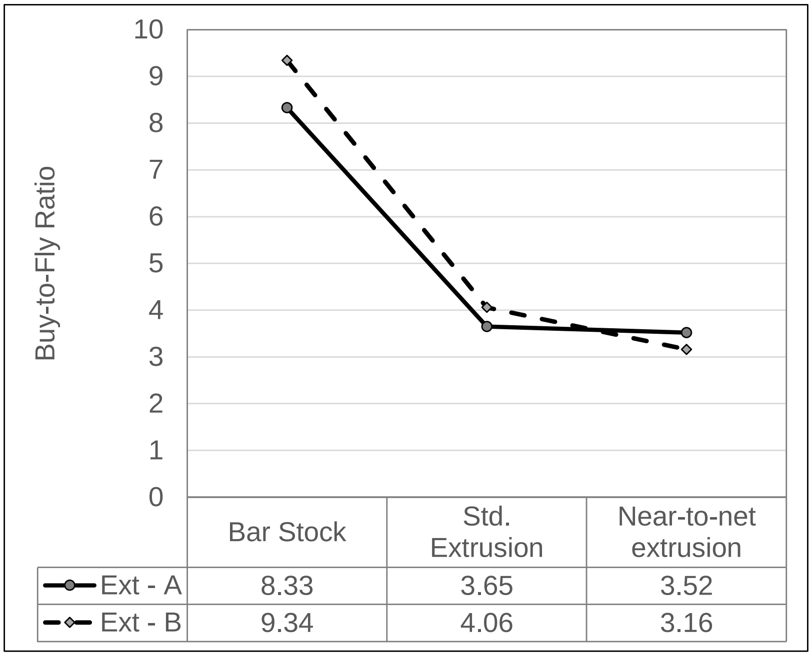

Figure 6. Significant reduction in buy-to-fly ratio is observed when utilizing near-to-net extrusions compared to the other manufacturing techniques.

Table 1. Comparison of key extrusion parameters and savings realized in terms of weight and buy-to-fly

Product Type	**ID**	**Ext. Ratio**	**Wt/ft, lb**	**Buy-to-Fly**	**Reduction, %**	
					Wt/ft	Buy-to-Fly
Standard Extrusions	Ext – A	14.2	8.45	3.65		
	Ext – B	22.4	5.90	4.06		
Near-to-Net Extrusions	Ext – A	15.4	4.95	3.52	70.7	3.7
	Ext – B	21.1	5.61	3.16	5.2	28.5

Table 2. Room temperature mechanical properties of the extruded products

Product Type	**ID**	**YS, ksi**	**UTS, ksi**	**El, %**	**RA, %**
Specification	AMS 4935	120.0	130.0	10.0	20.0
Standard Extrusions	Ext – A	126.5	140.0	15.0	29.0
	Ext – B	135.0	148.0	20.0	27.0
Near-to-Net Extrusions	Ext – A	125.6	139.4	16.1	28.6
	Ext – B	134.3	139.2	20.4	28.1

Table 3. Grain size measurements performed in accordance ASTM E112[8)]

Product Type	**ID**	**Orientation**	
		Long.	Trans.
Standard Extrusions	Ext – A	ASTM 1.0	ASTM 1.0
	Ext – B	ASTM 1.5	ASTM 1.0
Near-to-Net Extrusions	Ext – A	ASTM 1.0	ASTM 1.0
	Ext – B	ASTM 1.0	ASTM 1.0

Table 4. Average tolerances on the key characteristics offered by the PES extrusions

Product Type	**ID**	**Location**	**Flatness, in**	**Max. Bow, in**	**Max. Twist, deg**
Standard Extrusions	Ext – A	North	0.012	0.045	0.5°
		South	0.014		
	Ext – B	North	0.000	0.022	0.7°
		South	0.000		
Near-to-Net Extrusions	Ext – A	North	0.013	0.055	0.3°
		South	0.008		
	Ext – B	North	0.000	0.010	0.7°
		South	0.000		

Summary

Plymouth Engineered Shapes (PES) has successfully developed unique and efficient techniques to reduce the buy-to-fly ratio by manufacturing near-to-net shape extrusions on a production scale, and further the benefits realized with improved savings in machining time and tool life. Two different near-to-net shaped seat track extrusions provided approximately 135% and 195% reduction in buy-to-fly ratio compared to similar profiles, if machined from a plate or bar stock. Microstructure, room temperature mechanical properties and extrusion critical characteristics such as transverse flatness and straightness were in accordance to AMS 4935 and AMS 2245 respectively for the near-to-net shape extrusions. Considering the merits of titanium alloys along with the substantial advantages offered by the near-to-net shaped profiles, the authors strongly believe that these extruded products offer significant economic benefits to the aerospace industry, especially in the areas where long structural members are utilized on the aircraft.

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