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Development of a rolling finishing system to deliver net shape components from titanium structural extruded shapes

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ABSTRACT

The high cost of manufacturing with titanium is the predominant barrier to wider adoption of the material into new applications, despite attractive material properties. The manufacture of long structural shaped product for framing applications has largely been relegated to lower cost alternative materials. Producing comparable structures from titanium requires different manufacturing processes due to the material's response during thermo-mechanical deformation. Traditional bulk rolling of titanium into shapes has proven enigmatic due to the occurrence of shear banding and cracking from significant levels of non-uniform deformation and sensitivities to temperature non-uniformities. The current manufacturing method of long structural shapes is through an extrusion process. The inability to deliver thickness and surface quality dictate the machining of all surfaces to deliver complete components. This machining operation is the most significant cost driver for the components due to material loss and difficulty of machining titanium. This experimental effort proved a novel system, for the processing of titanium, that couples the two processes to deliver capabilities that neither could independently. The coupling of these two systems enabled mitigations of shortcomings of the individual systems. Thicknesses and surface quality aligned with a finished or net shape component were achieved without requiring a machining operation. In the experimental effort, a series of specimen were processed under varying temperature and deformation rates during rolling. These process variables are correlated to resulting material quality and to complexities associated with the coupling of the rolling and extrusion operations.

1. Introduction

Titanium's high cost is a hindrance to acceptance into a broader range of applications warranted by material properties [1]. A titanium material technology review revealed the need for piecewise technological improvements to enable more widespread titanium usage. Barriers lie in the recent inability to scale up attempts at improving the manufacture of titanium alloys and the optimization of the existing Kroll process in practice [2].

Given the lack of progress in reducing the cost of titanium raw material, the more efficient utilization of titanium must play a paramount role in offsetting the cost of finished components. Material losses compound already high material costs. Boyer breaks down the cost contributions comprising a titanium component derived from a forging. In the example, the input materials and machining operations constitute approximately 67% of the finished component's cost as shown in Fig. 1 [3].

Attempting to address the high cost of machining titanium, an optimization study defined best practices but failed to eliminate much of the burden of the process. The difficulty and cost of machining titanium were attributed to its properties and persisted regardless of optimization [4]. The clearest path to reduce this cost is by reducing the activity of machining outright.

The manufacture of long shaped metal components, such as beam, is the focus of this experiment due to their importance in modern structural applications. These structures have most commonly utilized steel in their construction. Additionally, the predominant manufacturing method utilizes a shape rolling mill and large bulk inputs. The rolling process represents one of the common production methods for simple geometries from titanium as well. Non-complex cross section geometries such as sheet, plate, strip, and bar currently utilize rolling in their production in some capacity, if not entirely [5]. The response of the material provides an inhibition to creating more intricate shapes with the rolling process.

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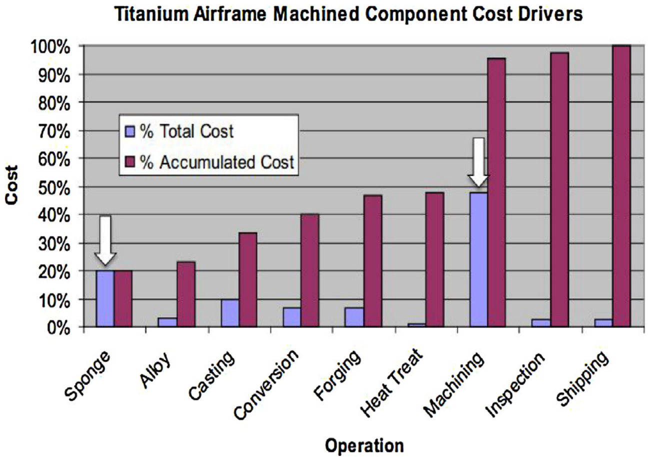

Fig. 1. Breakdown of titanium component's manufacturing costs [3].

Titanium's response to rolling is considerably different than that of other materials and must be treated differently during processing. At typical rolling temperatures, significant levels of non-uniform work input result in instabilities and compromised material in the form of shear banding or cracking [5]. Consequently the production of a complex shape from a generic mill input will unavoidably require non-uniform work input through the section occurring over numerous passes, as input is typically large generic solids [6]. Shear banding is attributed to titanium's low thermal conductivity, high flow stress and sensitivity of flow stress to temperature. Deformation generated adiabatic heating is not easily distributed through the material and results in localized softening which causes localized deformation. This effect is exaggerated at lower temperatures due to higher levels of adiabatic heating [5]. A further complication arises from titanium's tendency to cool rapidly from surfaces. Titanium workpieces have roughly a third of the processing time of a typical steel component before reheating is required. The effects of processing titanium with temperature gradients through the workpiece are severe and typically result in cracks, poor surface quality, and distortion due to residual stresses [7]. Titanium displays an additional phenomenon which occurs when imparting work in a single direction. The hexagonal closed packed crystal structure exhibits a high degree of anisotropy. Deformation in a single predominant orientation aligns these crystals and results in anisotropy, or crystallographic texture [8]. Typically anisotropy in rolling manifests in a reduction in strength in the longitudinal direction and a loss in ductility in the transverse direction [9]. The cumulative response of titanium to rolling deformation has thus far prevented the processing of titanium shaped sections in the same manner as steel counterparts.

The extrusion process can produce a long uniform shaped product that improves material usage compared to many other forms. The extrusion process also utilizes temperatures above the beta transus to enable better die fill and more complex geometries. When the material is above the beta transus the strain rate sensitivity, flow stress, and adiabatic heating propensity reduce significantly [10]. An additional effect is seen in the isotropy of the material. Unlike lower temperature deformation, above the beta transus of alpha-beta titanium alloys, dynamic recovery actively occurs during the entire deformation process [11]. The presence of recrystallization and fully body centered cubic (BCC) material enables greater plastic accommodation without internal defects compared with deformation below the beta transus [10]. The inverse correlation to forging strain rate to resulting grain size establishes the basis for rapid deformation during beta extrusion [12].

A potential negative to the beta processing of titanium involves beta grain size. Rapid beta grain growth is experienced when alpha-beta alloys even briefly exceed the beta transus temperature [13]. Excessive grain size could cause significant losses in material formability. The extrusion process partially mitigates this through high strain rate deformation. The beta grain size shows an inverse correlation to the imparted strain rate during deformation during dynamic recrystallization [12]. In this way, the extrusion process can generate relatively fine-grained lamellar material in the form of long, complex shapes. However, extruded product is not considered a net shape component since machining to finished form is still required because of surface finish and minimum achievable thickness [8,14]. During surface sliding with other materials, titanium exhibits significant incidence of seizure and galling [15]. The high temperatures of the extrusion process dictate the use of molten glass to lower friction levels and enable surface sliding without defects [16]. These lubricants also result in lower optimized surface quality due to a buildup on tooling and attachment to the workpiece. The use of glass lubricants causes surface texturing associated with liquid entrapment within the surface of the workpiece [17]. Furthermore, a more recent extrusion process study presented the optimized capability of beta extrusion as being capable of delivering thicknesses down to 3.50 mm robustly [14]. To achieve thickness and surface quality requirements of typical titanium structures, full machining is employed to extruded material.

A prior attempt was employed to finish an extrusion with a drawing process. The extrusion segment was below currently published robust limits and demonstrated significant difficulties in delivering material. The extrusion of "T" shaped segments with features as thin as 1.59 mm (.063″) were produced as an input to a drawing process. Various manufacturing difficulties included die failures, prolonged shape establishment, inconsistent surface quality, bent stem, and stalling of extrusion press [18]. Coupled with the extrusion effort, a subsequent effort developed a warm drawing process to finish the extrusions of titanium. This effort involved drawing extrusions using dry lubricants and tungsten draw tooling. The drawing process was performed between 466–543 °C at speeds of 61–71 mm/s. The effort demonstrated surface condition improvement and minimum successful drawn thicknesses down to 1.15 mm [19].

The avoidance of liquid entrapment was accomplished by using dry lubricants during drawing. Lowering the coefficient of friction as much as possible is also important to achieving quality surfaces in the drawing process [20]. Prior studies identified that a mixture of dry lubricants including molybdenum disulfide and graphite provide the most friction reduction up to 649 °C [17]. The lubricating properties of molybdenum disulfide and other atomistic sheet type lubricants have been known to degrade at elevated temperatures in the presence of oxygen [21]. The expected coefficient of friction with molybdenum disulfide is nearly equal to that of the dry condition at temperatures above 850 °C (1562 °F) [16]. Processing below this temperature for lubrication purposes would not align with material processing windows. As described in Fig. 2, shear banding is expected to begin below 900 °C. Furthermore, the more catastrophic cracking phenomenon should occur with temperatures lower than 750–800 °C (1382–1472 °F) and high strain rates [22].

An effective method of titanium manufacture should account for all aspects of processing the alloy system and identify complexities that arise from coupling various manufacturing systems together. In the prior art, the extrusion process was operating outside of the later identified robust capability for extrusion [14,18]. Furthermore, lowering drawing temperatures to achieve surfaces with available lubricants resulted in deformation within processing regimes known to induce shear banding and cracking [16,22]. The current effort demonstrates that final reductions with a rolling