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The response of the high strength Ti–10V–2Fe–3Al beta titanium alloy to laser assisted cutting

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ABSTRACT

Metal cutting is a process that uses tools to create new surfaces by imparting intense shear stresses and high strain rates on the work material. Consequently, the mechanical properties of the work material directly influence its machinability, and high strength materials such as titanium are notoriously difficult to cut. Laser assisted machining (LAM) is a promising solution to reduce the cutting pressures when machining difficult-to-cut materials. The method involves using a laser beam to locally heat and reduce the flow stress of the material ahead of an advancing cutting tool, making the metal shearing process easier. To date there is limited, if any, published literature on using the technology to improve the machinability of metastable β-titanium alloys. It remains unclear whether these materials will respond to laser assisted machining since many are specifically designed to exhibit high temperature strength. This paper compares the conventional and laser assisted machining method for the high strength Ti–10V–2Fe–3Al β-titanium alloy over a wide range of cutting parameters. The effect of the laser beam on the cutting force, cutting temperature and chip formation is discussed. The effectiveness of the LAM process in reducing the cutting pressure of Ti–10V–2Fe–3Al alloy is also compared against other alloys including commercial-purity titanium and Ti–6Al–4V.

1. Introduction

Titanium alloys are in high demand due to their superior combination of physical and mechanical properties such as high specific strength and corrosion resistance. Most of the current and potential applications involving titanium alloys require significant machining. Of all of the titanium alloys, metastable β-titanium alloys are becoming particularly attractive for a number of high-value added applications due to their unique range of properties. These alloys retain the β-phase upon quenching from above the β-transus, however, a variety of other phases including ω and α-variants can occur during heat treatment below the β-transus. Metastable β-alloys can exhibit diverse properties depending on the composition and phase constituents. Some metastable β-alloys are pseudoelastic owing to the reversible $\beta \rightarrow \alpha'$ transformation. These alloys can offer super elastic ductility, low stiffness and shape memory behaviour. Other alloys are α-precipitation hardened and offer the highest range of strengths within the titanium based alloys [1]. They offer potential advantages such as flexibility in heat treating thicker sections to high tensile strengths, providing superior fatigue strengths and ease of fabrication [2]. Metastable β-titanium alloys also offer high temperature strength in forgings and springs, which extends the useful in-service temperature beyond traditional titanium alloys such as Ti–6Al–4V [3].

A metastable β-titanium alloy was first applied on the Lockheed SR – 71 Blackbird in the early 1960s and now β-alloys are used in numerous applications including springs, nacelles, sine – wave spars for the empennage, rotor system structure and linkages in helicopters, landing gear, fuselages, and fasteners [2]. The Ti–10V–2Fe–3Al β-titanium alloy was first developed in the early 1990s for high strength forgings to be used on the Boeing 777. Since then the alloy has been extensively applied in landing gear and other applications for its high strength forging capabilities and corrosion resistance, resulting in significant weight and cost reductions [4]. Recent applications of this alloy are the mast and main motor system of the helicopter, arrestor hook structures for military aircrafts, flap tracks for Embraer passenger jets, boogie beams, torque links, and spoiler fittings [2].

The favourable properties that make metastable β-alloys attractive for many applications inherently means that these materials

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Table 1
Chemical composition of the β-titanium alloy workpiece.

Al	V	Fe	N	C	O	Ti
3.20	10.23	1.79	0.008	0.02	0.06	Bal

are difficult to machine. Titanium alloys are problematic to machine because of their high strength, hardness, chemical reactivity and low thermal conductivity. The high material strength requires high cutting forces to instigate plastic shear, and consequently, high cutting temperatures result. The problem is exacerbated for metastable β-alloys that are specifically designed to exhibit high temperature strength. Not surprisingly, Arrazola et al. [5] have reported that metastable β-titanium alloys are the most difficult of all titanium alloys to machine.

A recent technological development to improve the machinability of various materials is known as laser assisted machining (LAM). In this technique, the laser beam acts as an external heat source to locally heat and soften the workpiece material ahead of the advancing cutting tool. This creates a rise in temperature in the shear zone, reducing the hardness, flow stress and work hardening characteristics of the workpiece material, thereby facilitating ductile plastic deformation during machining and enhancing the productivity [6].

The laser assisted machining method has been widely investigated and Sun et al. [7,8] and Dandekar et al. [9] have reported to improve the machinability of various α/β or α-alloys such as Ti–6Al–4V and commercial purity (CP) titanium. However, it remains unknown whether the process is suitable for metastable β-alloys because such materials are specifically designed to maintain strength at high temperatures, hence, the machinability of these materials may not improve using the LAM process. The purpose of this paper is to investigate whether the cutting pressure of the high strength Ti–10V–2Fe–3Al β-titanium alloy can be reduced using the laser assisted machining method. The cutting forces and temperatures over a wide range of cutting parameters including cutting speed and feed rate is investigated and compared to conventional machining. The cutting pressures during laser assisted machining the β-titanium alloy at a range of strain rates are compared to CP Ti α-alloy and Ti–6Al–4V α/β-alloy.

2. Experimental procedure

2.1. Workpiece material

The Ti–10V–2Fe–3Al titanium alloy was cast using vacuum arc melting process (remelted 3 times). The Φ620 mm cast ingot was then forged in the β-field above 830 °C, deformed 60%, and then deformed 70% in the dual phase zone in order to reduce the grain size of the coarse cast grain structure. The material was finally forged to Φ110 mm in the dual phase zone and subsequently reduced to Φ50 mm. The chemical composition of this titanium alloy is shown in Table 1.

The forged bar was then solution heat treated at 750 °C for 3 h followed by air cooling, then aged at 510 °C for 8 h followed by air cooling (STA). Fig. 1 shows the optical microstructures of the Ti–10V–2Fe–3Al alloy after heat treatment. The solution treatment is a standard sub-β transus treatment that produces equiaxed-α of approximately 1–2 μm and the ageing produces very fine acicular-α within retained β-grains. The hardness of the material is 375 ± 10 HV.

2.2. Machining setup

The experimental equipment for the machining trials comprises of five components and a photograph of the hardware is shown in Fig. 2. Machining was performed on a 3.5 hp Hafco Metal Master lathe (Model AL540) under dry cutting conditions. An uncoated tungsten carbide tool (CNMX1204A2-SMH13A type) supplied by Sandvik is used in this study as shown in Fig. 3. Its rake angle was +15°, angle of inclination was −6° and the entry angle was 45°.

A 3-component force sensor (PCB Model 260A01, made by PCB Piezotronics, Inc.) was used to measure the dynamic cutting forces with an upper frequency limit of 90 kHz. The forces measured are the feed force in the X direction, thrust force in the Y direction and main cutting force in the Z direction, denoted by F_x, F_y and F_z respectively.

Data logging software Scope® was utilised with a sampling rate of 16 kHz. Noise with a magnitude of 5 mV (corresponding to forces of 2 N, 2 N and 10 N in the X, Y and Z directions, respectively) was detected with this system. The force data was analysed in the same acquisition software Scope®. For each set of force measurements along the feed, thrust and main cutting directions, seven measurements were taken over a sampling period of <30 s and the average of these measurements have been reported. A new tool was used for each test and because the sampling period was short, tool wear is considered negligible. Therefore, the effects of tool wear on the cutting forces can be neglected (the interested reader is referred to Ref. [10] for a discussion of tool wear mechanisms during thermally enhanced turning). The force obtained was in mV (millivolts), and is

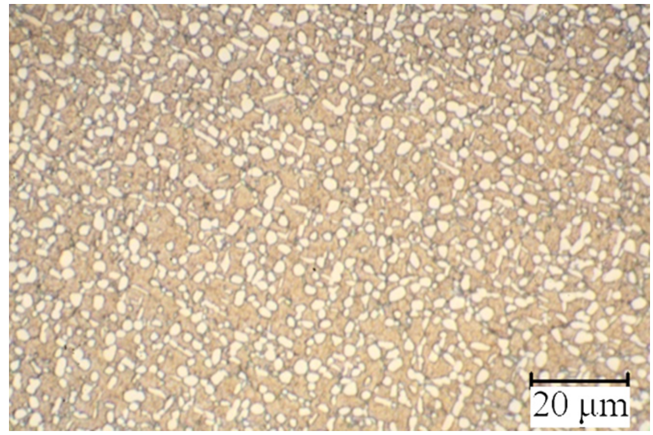

Fig. 1. Microstructure of Ti–10V–2Fe–3Al solution treated and aged material.

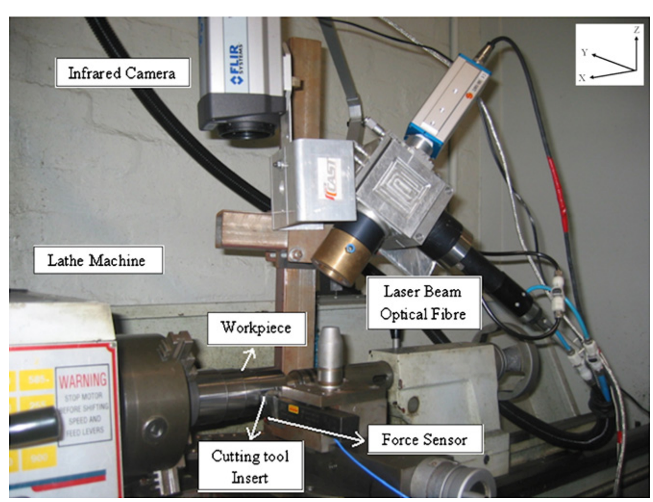

Fig. 2. Basic experimental setup for the machining trials.