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Micro-milling machinability of DED additive titanium Ti-6Al-4V

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Abstract

This work investigates the micro-milling machinability of Ti-6Al-4V alloy produced by a Laser Engineered Net Shaping (LENS) additive manufacturing (AM) process with a specific focus on surface quality, cutting forces and burr formation. The effects of additive deposition parameters are also investigated since the material thermal history during processing can affect porosity and mechanical behavior of the samples, giving different milling performances. The material characterization of samples is done through micrographies, hardness tests and porosity evaluation. The roughness of the machined surfaces shows a statistical distinction between the AM and wrought titanium samples. Similar behavior is seen with the cutting forces, which increase with an increase of hardness of the AM samples. The results also show an increased trend towards burr formation in case of down milling of AM samples compared to wrought titanium samples. The future prospective is to take into account the machinability properties as functional material characteristics to optimize through the deposition process.

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Keywords: Machinability; Titanium alloys; Micro-milling; Additive manufacturing; Laser Engineered Net Shaping;

1. Introduction

The Additive Manufacturing (AM) has shown a great potential to create complex parts, starting from the addition of metal powder layer by layer and melting it by a heat source, such as a laser or an electron beam. Additive

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Manufacturing techniques can be classified in two main categories: (1) powder bed techniques, such as Direct Metal Laser Sintering (DMLS) and (2) blown powder techniques, such as Laser Engineered Net Shaping (LENS) / Direct Energy Deposition (DED). In particular, the LENS additive manufacturing technology was first developed by Sandia National Laboratories in the late 1990s [1]. The added value of this AM technology is the ability to produce and clad complex metallic geometries that are difficult to manufacture through conventional metal forming techniques and the capacity to provide increased mechanical properties of the components. However, the current AM processes available in industry are not able to achieve tight geometrical tolerances and good surface roughness and therefore, post-processing operations including grinding, milling, abrasive flow machining are usually required [2,3]. The milling process is shown to offer the best solution to finish external geometries for a wide variety of materials with reasonable surface quality. Several research studies have been performed to study the machinability of titanium alloys for several industrial applications [4-7]. The main problems of Ti-6Al-4V are related to its high strain-hardening behavior, chemical reactivity and low thermal conductivity, which accelerate tool wear. When scaling down the tool dimensions to micro-milling cases, these aspects worsen and this difficult-to-cut material requires specific cutting conditions [8-9]. On the other side, machinability of additive manufacturing metals is still not well understood and only very few and recent literature studies exist. Very recently, Guo et al. [10] focused their study on additive manufactured AISI 316L, whilst Montevecchi et al. [11] carried out cutting tests on wrought, LENS and WAAM (WireArc AM) processed AISI H13 samples, by analysing the subsequent cutting forces. The results highlight that AM materials are harder to machine as compared to the wrought state and show a significant increase in cutting forces. Machinability of AM Titanium and its alloys is even less explored. Tebaldo and Faga [12] studied the heat treatment effects on Ti48Al2Nb2Cr AM titanium obtained by electron beam melting, finding that the induced microstructural changes play a major role on the machinability. At the same time, Bruschi et al. [13] and Rysava et al. [14] recently studied micro-milling, micro-drilling and threading of titanium alloys produced by AM processes, finding that a proper selection of cutting process conditions is a key phase for achieving good machining results.

At the same time, there have been many research works about the characterization of mechanical properties of various types of titanium alloys manufactured by AM processes [15,16]. In particular, Kbryn et al. [15] studied the effect of process parameters including laser power and traverse speed on microstructure, porosity and texture of Ti-6Al-4V. The AM components were found to possess a columnar microstructure and a fine Widmanstätten microstructure. Their work also demonstrated that an increase in the laser power and traverse speed causes a decrease in porosity in terms of lack-of-fusion and gas entrapment.

The purpose of this research is to study the machinability of LENS AM Ti-6Al-4V by conducting micro end milling tests. Specifically, the machinability is evaluated by comparing LENS AM Ti-6Al-4V with wrought titanium in terms of roughness, cutting force and burr formation. The description of machines and materials, including material sample preparation and material characterization (micrography, porosity and hardness evaluation) is reported in Section 2 while the experimental work is detailed in Section 3. Results and machinability analyses are given in Section 4. Finally, the conclusions drawn from this work are presented in Section 5.

2. Machines and Materials

2.1. Machine

The micro-end milling operation for the roughness analysis are carried out on Microlution 310-S, the 3-axis micro-milling machine, which is capable of spindle speeds up to 50,000 rpm, 1 µm positioning accuracy, 0.02 µm resolution and a maximum acceleration of 5 g. Meanwhile, the cutting force and burr formation analysis are carried out on a 5-axis Kern EVO CNC machining center equipped with a Heidenhain iTNC530 numerical control (1 µm positioning accuracy).