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Effects of Milling Process Parameters on Cutting Forces and Surface Roughness when Finishing Ti6al4v Produced by Electron Beam Melting

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Abstract**—**Electron Beam Melting (EBM) is a metal powder bed-based Additive Manufacturing (AM) technology, which uses computer-controlled electron beams to create fully dense three-dimensional near-net-shaped parts from metal powder. It gives the ability to produce any complex parts directly from a computer-aided design (CAD) model without tools and dies, and with a variety of materials. However, the quality of the surface finish in EBM process has limitations to meeting the performance requirements of additively manufactured components. The aim of this study is to investigate the cutting forces induced during milling Ti6Al4V produced by EBM as well as the surface quality of the milled surfaces. The effects of cutting speed and radial depth of cut on the cutting forces, surface roughness, and surface morphology were investigated. The results indicated that the cutting speed was found to be proportional to the resultant cutting force at any cutting conditions while the surface roughness improved significantly with the increase in cutting speed and radial depth of cut.

Keywords**—**Electron beam melting, additive manufacturing, Ti6Al4V, surface morphology.

I. INTRODUCTION

AM widely known as three dimensional (3D) printing, is one of the most developed technologies in recent years; it is a set of emerging technologies that are becoming a serious competitor to machining and forming technologies. It holds great promise to revolutionize manufacturing [1]. AM has several advantages which are the creation of complex geometries and internal features that cannot be produced using subtractive methods [1], maximum material savings [2], build speed [3], reduced machine set-up and tooling [4], product customization, controlled porous structures [2]. By contrast, a current limitation of AM is there are limited processing planning and build control options [5], surface finish, geometry limitations [3], processing defects [6], degraded dimensional control [4].

AM is a promising technology for the fabrication of metallic parts. Due to the fact that material is added in layers, parts of almost any geometry can be realized [7]. It is used for making a real three-dimensional object, with plastic or ceramic or metal thereby combination, which may be subjected to various applications [8]. The ability of AM technology to produce actual functioning parts is also a contributing factor to its newly acquired popularity [9]. It is a method of manufacturing that forms parts from sheets, wire or powder in a process that proceeds layer by layer [6]. AM is creating a new chapter in the manufacturing industry with the possibility to transform digital information into physical components [10]. AM has shown great potential for energy consumptions, reducing material wastes, and life-cycle impacts [11].

Many industries, including biomedical and aerospace, are increasingly turning to the metal AM to fabricate customized parts with complex geometries. However, there are several challenges to wider adoption of AM components in the industry, part accuracy, fatigue, part feature tolerances, and durability of the parts being among the most important challenges. Ensuring surface roughness is the main challenge for AM of real structural and functional parts, Numerous key challenges such as high surface roughness still exist [12]-[14]. To improve the surface finish of metal, some finishing operations are needed such as laser polishing [15]-[23], traditional machining [24], [25], vibratory finishing/ tribofinishing [26], electrolytic polishing and chemical polishing [24], and shot-peening [27]-[29]. There are many process parameters that can be altered to get the required surface quality of parts. Some of these parameters are scan spacing, laser power, build orientation, scan speed, layer thickness, part bed temperature, scan length and etc. [30].

Safdar et al. [31] investigated the effect of thickness of part and variation in process parameter settings of the EBM system on surface roughness/topography of EBM for Ti-6Al-4V. The result shows that every part produced by the EBM system has detectable surface roughness. The surface roughness Ra varies between 1-20 µm for different samples depending upon the process parameter thickness and setting. The Ra value decreases with an increase in scan speed and offset focus, and increases with increasing beam current and sample thickness. Greitemeier et al. [32] studied the effects of inherent surface roughness on the fatigue performance for Ti–6Al–4V samples. They compared the results by DMLS and EBM for surface roughness effects with the process parameters i.e. Machine type, Power, Scan speed, and Layer thickness. The roughness values for the EBM specimens are higher (Ra: 27 µm) compared to the DMLS specimens (Ra: 13 µm). Masuo et al. [33] studied the effects of surface roughness, Hot Isostatic Pressing (HIP), and defects process on the fatigue strength of a Ti-6Al-4V by DMLS and EBM. The defects were gas porosity and those made by a lack of fusion. Many pores were formed near the surface eliminated by the HIP. Surface roughness is

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more detrimental than defects that commonly exist in AM materials.

From the literature review, it can be seen that currently, the major issue is the considerable surface roughness and inaccuracy of the additively manufactured metallic parts. The post-finishing operations like machining are needed to be applied to the 3D printing parts to achieve the required surface finish and accuracy. It can be seen from the literature that only a few studies have been reported concerning the machinability of the additively manufactured components to achieve the improved surface roughness of the 3D printed parts.

II. EXPERIMENTAL

The Ti6Al4V titanium alloy was produced in a block of 30 mm*30 mm*10 mm by EBM. Chemical composition of the Ti6Al4V ELI powder used and some of its mechanical properties, as informed by the manufacturer, are shown in Table I. Three-axis vertical machining center (DMC 635 V Ecoline) from DMG Mori, Germany was used for the experiment. A KISTLER piezoelectric dynamometer table (type 5697A) was employed for measuring cutting forces in three coordinate directions (X, Y, and Z) during machining. The setup of the end milling is shown in Fig. 1. Solid carbide end mill tools with a 10 mm diameter and 4 flutes were used: cutting speeds (50, 80, and 100 m/min), constant axial depths of cut 0.4 mm and two radial depths of cut (2.4, 4.8 mm), and constant feed rate 30 mm/min. To measure surface roughness parameter (Sa), 3D optical Profilers (ContourGT-K) from Bruker Nano Surfaces Division were used. For each machined surface, an average of five readings of surface roughness was recorded. Measurements of cutting forces and surface roughness were performed at the initial cut for each machining condition when the cutting tool is considered fresh. To characterize machined surface morphology, a scanning electron microscope (SEM) from Jeol Japan (Model JCM 6000Plus) was used. During the experimental trials, only one insert was mounted on the cutter, the cutting length of each test was 30 mm, and the wear effect of the insert was neglected because of the short cutting time.

TABLE I
CHEMICAL COMPOSITION OF THE TI6AL4V ELI POWDER AND ITS MECHANICAL PROPERTIES

Contents (wt.%)						Mechanical properties	
Al	V	C	Fe	O	Ti	Yield strength (MPa)	Modulus of elasticity (MPa)
6.04	4.05	0.013	0.0107	0.13	Bal.	930	120,000

III. RESULTS AND DISCUSSIONS

A. Analysis of Cutting Forces

Cutting forces in all coordinate directions (Fx, Fy, and Fz) were obtained (Fig. 2). Fig. 3 shows that cutting force decreases to some extent at higher cutting speed (V). Cutting temperature increase which lowers the required force for plastic deformation and reduces rubbing at the contact area between tool and chip is the possible cause. This result reveals cutting speed and cutting force relation which agrees with Oxley's theory [34]. It also criticizes the hypothesis proposed by Daymi, et al. [35], which disregarded cutting speed in the analysis and calculation of cutting force. Oxley [34] reported that cutting force decreases with cutting speed increase to a minimum value and then increases when higher cutting speeds are set due to material's strain characteristics. Fig. 3 also illustrates that Fz and Fy are dominant cutting forces while Fx is insignificant amongst three cutting force components, the graphs indicate that cutting force Fz shows more sensitivity to cutting conditions. Results also show that Fz and Fy exhibit a decreasing trend for all conditions while Fx almost behaves constantly when cutting speed is varied. Increasing cutting speed slightly reduces cutting force, in agreement with the results reported by Oxley [34], means Fz is the major component for cutting force while Fy is the main component of thrust force (Ft).

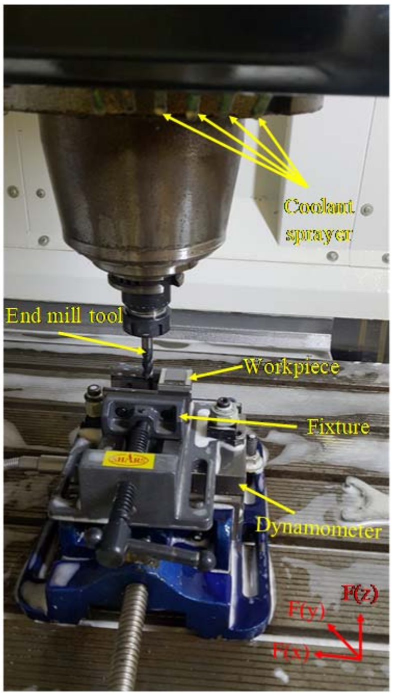

Fig. 1 Experimental setup for the milling test

B. Analysis of Surface Roughness

The effects of cutting speed on machined surface roughness under different radial depths are presented in Fig. 4. The roughness of machined surfaces was scanned and measured with 3D optical Profilers (ContourGT-K) from Bruker Nano Surfaces Division. For repeatability, five measurements at different locations for each surface were made. As the cutting speed increases, it can be observed that the surface roughness decreases cutting speed 80 m/min, the trend of curves is identical with the variation of cutting forces in Fig. 3. Also, we see that the small radial depth of 2.4 mm has higher surface roughness than 4.8 mm. It can be concluded that there are obvious correlations between cutting forces and surface roughness. With the increase of the cutting speed, the cutting edge of the tool wears rapidly which leads to the increase of the cutting edge radius and it has a great effect on the cutting forces. At the same time, tool wear can induce severe deformation of the crystalline grain in the subsurface. Though the surface roughness is only one aspect of the surface integrity, the results still have certain reference significance for machinability evaluation and cutting parameter optimization.

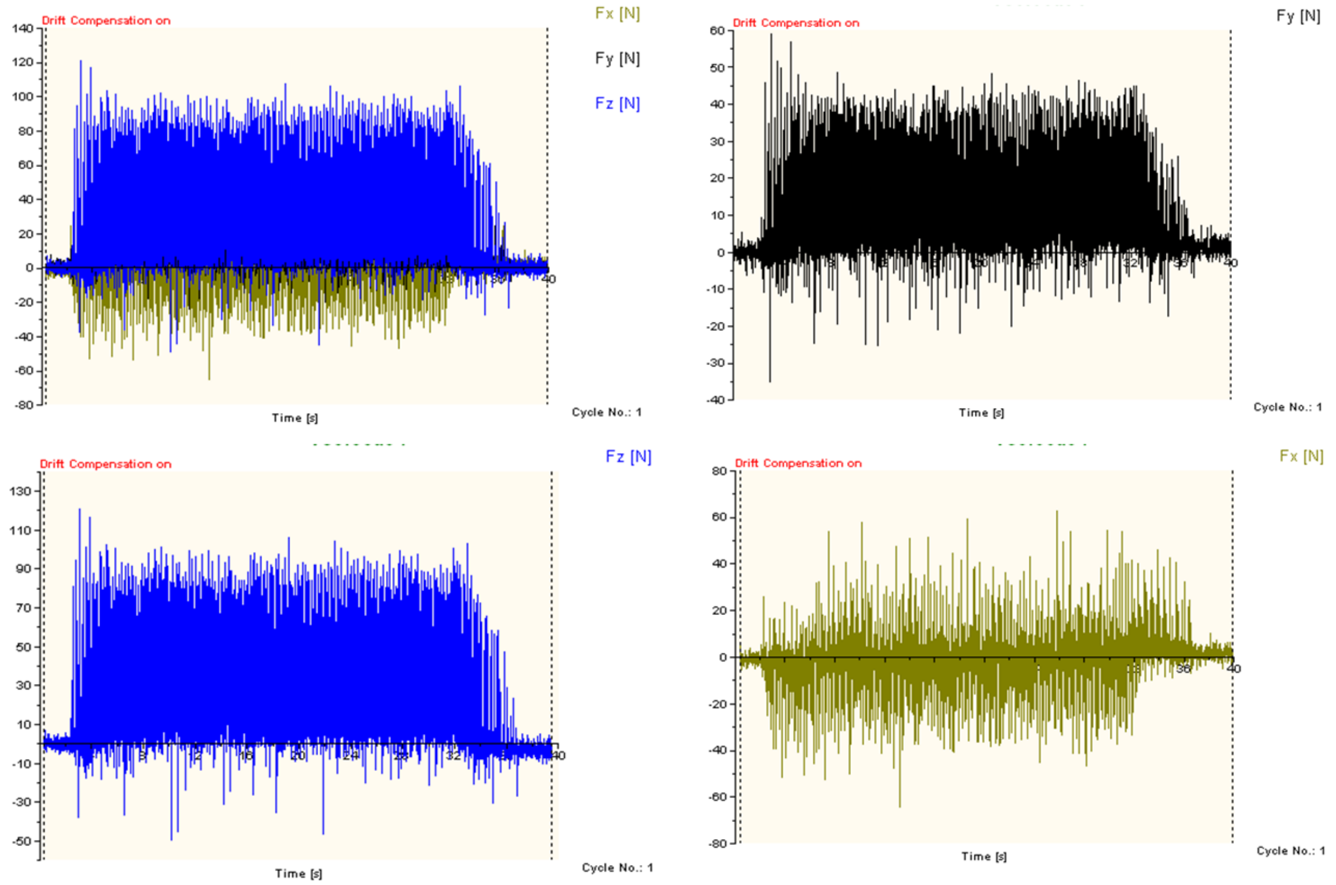

Fig. 2 Instantaneous cutting forces in three directions: V = 50m/min, radial depth 4.8 mm

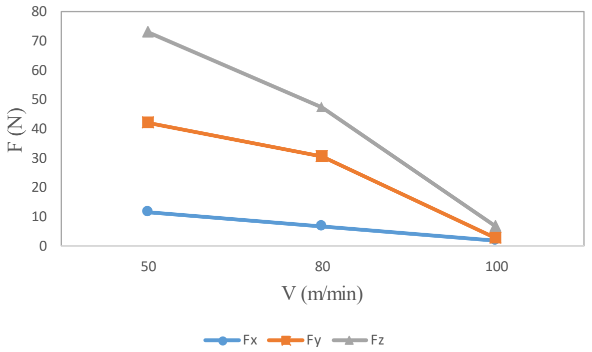

Fig. 3 Cutting forces vs. cutting speed at radial depth 2.4 mm

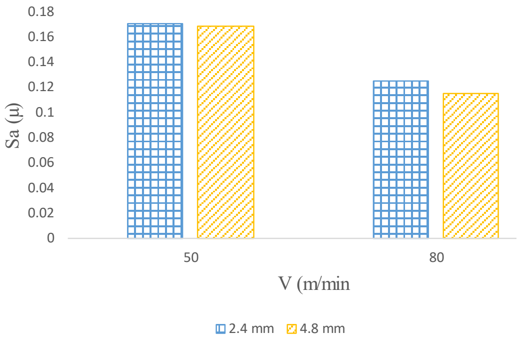

Fig. 4 Sa under different cutting parameters

C. Surface Morphology

Ti6Al4V is produced by EBM set at 80 m/min cutting speed and 2.4 mm radial depth of cut. Highly machined surface quality can be observed. The main damages observed on the surface of the machined workpiece include redeposited materials and tool feed marks. Redeposited material was detected on milled surfaces machined. This defect originates from small portions of material being attached to the machined surface during the cutting process. It seems that the high heat generated at the interface between the tool and chip makes redeposited materials to be welded onto a machined surface, eventually causes the rougher surface [24]. In general, the formation of redeposited particles depends on the machining conditions such as cutting speed and radial depth of cut which affect the chip formation and generation of the fine chip particles. The experimented cutting conditions led to a high-temperature cutting zone and the formation of a redeposited material defect.

Surface images also display tool edge marks formed along the tool feed direction. The scratched pattern is the print of cutting edge created on a machined surface which can be attributed to the low quality of tool edge or built-up edge. High speed and low radial depth of end milling process usually brings about plastic deformation of the alloy during side milling which results in developing feed marks on the machined surface and causes poor surface finish.

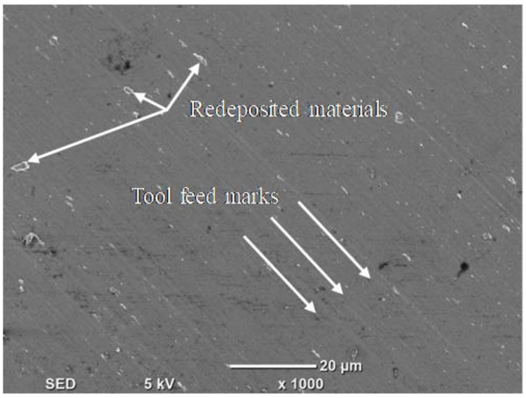

Fig. 5 SEM images of the machined surfaces at the cutting speed of 80m/min and radial depth of cut of 2.4 mm

IV. CONCLUSION

AM of Ti6Al4V parts is carried out through EBM technology. In order to improve the surface finish of EBM produced parts, vertical milling is performed along the parts. Based on the results and discussion related to cutting force analysis and surface roughness analysis, and based on the investigation conducted on the effect of various cutting conditions during milling, it can be remarked that:

- The resultant cutting force is proportional to cutting speed at any cutting conditions.
- An increase in cutting speed at the higher radial depth of cut improves surface roughness.
- The overall fine surface finish was obtained, but redeposited materials and tool feed marks were also detected on the machined surface to some extent.

It can be concluded that there are obvious correlations between cutting forces and surface roughness.

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