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Analysis of tool wear in cryogenic machining of additive manufactured Ti6Al4V alloy

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ABSTRACT

Electron Beam Melting (EBM) technology applied to the titanium alloy Ti6Al4V is attracting interest in the biomedical industry since it allows producing surgical implants requiring a reduced number of subsequent machining steps. Even if the microstructural features of the EBM Ti6Al4V induce higher tool wear than the wrought Ti6Al4V, no evidences can be found in literature concerning the tool wear analysis when machining the EBM alloy, especially under dry and cryogenic cutting conditions, which are of particular interest for the biomedical industry allowing the reduction of the parts cleaning steps.

The aim of the paper is to evaluate the tool wear mechanisms arising when semi-finishing turning the EBM Ti6Al4V under dry and cryogenic conditions using a coated tungsten carbide insert at varying cutting speed and feed rate. The tool wear behaviour was investigated at fixed turning times using different analysis techniques. Scanning electron microscopy analyses were performed to measure the flank wear at the nose region, and energy dispersive X-ray spectroscopy was employed to investigate the workpiece material elements adhered on the cutting edge and rake face of the tool. 3-D optical profilometer analysis of the rake face was carried out to evaluate the abrasive and adhesive wear; the width of the adhered layer was measured by removing through chemical etching the workpiece material from the insert, allowing the quantification of the adhesive wear in comparison to the abrasive one.

The obtained results demonstrate that the higher cutting speed and feed rate the higher the tool wear; nevertheless, it was found the cryogenic cooling allowed reducing the adhesive wear mechanism of the workpiece material on the tool cutting surfaces in comparison with dry cutting, proving the feasibility of utilizing the cryogenic cooling to reduce the tool wear when machining the EBM Ti6Al4V.

1. Introduction

In the recent years, Additive Manufacturing (AM) technologies are increasingly being adopted for the production of near-net-shape products made of titanium alloys. The biomedical and aerospace fields are those that more take advantages of these innovative manufacturing technologies to produce surgical implants, as knee and hip prosthesis, or aero engine parts, as fuel nozzles and turbine blades. The chance to realize complex shape parts with trabecular structures and complex internal cavities just in one manufacturing step, therefore limiting the waste of bulk material to be removed, and at the same time obtaining improved mechanical properties in comparison with traditionally casted or hot forged and machined products, are persuading more and more companies to invest in AM technologies, such as the Electron Beam Melting (EBM), Direct Melting Laser Sintering (DMLS) or Selective Laser Melting (SLM). Despite one of the main goals of AM technologies is the reduction of the manufacturing steps, finishing machining operations can be still required to shape the mechanical joining features and mating components with the aim of obtaining those geometrical tolerances and surface characteristics that are difficult to achieve with the sole AM technologies

Ti6Al4V parts manufactured through EBM have been recently introduced in the aerospace and biomedical fields. While the influence of the EBM process parameters on the part obtainable characteristics have been quite extensively studied [1,2], in literature there are very few works concerning experimental investigations on the machinability of EBM Ti alloys, and neither an exhaustive discussion about tool wear degradation can be found. Bordin et al. [3] compared the machinability of EBM and wrought Ti6Al4V in semi-finishing external turning, when using a PVD coated tungsten carbide insert in conventional flood cooling conditions. The EBM Ti6Al4V resulted to be more difficult to machine than the wrought alloy for all the tested cutting conditions resulting in a worse surface integrity, which was evaluated in terms of surface roughness and topography. Similar tool wear mechanisms were observed for both the alloys, namely attrition wear, adhesive and abrasion wear. Considering that the wrought and EBM Ti6Al4V have the same chemical composition [4], the peculiar microstructure of the EBM alloy

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characterized by higher hardness and lower ductility may provoke the increased tool wear rate.

Titanium alloys are in general characterized by a reduced machinability due to their high reactivity with most of the cutting tool materials, low thermal conductivity that limits the amount of heat generated to be dissipated by the chips, and high specific strength up to temperatures of approximately 600 °C [5]. Hence the adoption of a suitable cutting fluid is necessary to prevent a rapid tool wear [6]. During the last decades, several researchers have being working to improve the Ti6Al4V machinability [7], by testing different tool substrate and coatings [8] and lubricating strategies, such as High Pressure Water Jet Assistance (HPWJA) [9] and cryogenic cooling [10]. However, the adoption of either conventional flood cooling or HPWJA in machining Ti6Al4V surgical implants implies costly and time consuming cleaning procedure before delivering the products.

Dry machining would represent the optimum solutions with an eye towards both sustainability and economization of the manufacturing process, nevertheless worse results compared to conventional lubrication and innovative lubricating strategies were found in most cases [10,11].

Cryogenic machining may indeed represent an efficient solution for machining biomedical components thanks to the advantages it offers. This cooling strategy allows the reduction of the cutting temperature by supplying liquid nitrogen at −192 °C directly on the cutting zone, hence reducing the tool wear and permitting the adoption of more severe cutting parameters. Moreover, liquid nitrogen gasifies during machining, leaving the workpiece, chips and machine interior clean and dry, hence reducing the cleaning and sterilizing costs of biomedical surgical implants, to be carried out when adopting standard emulsion cooling. Recently, many scientific works present in literature have shown the potential of the cryogenic lubricating strategy in machining difficult-to-cut metals as Inconel 718, tool steels and Ti6Al4V [12,13], most of them referring to rough cutting conditions. Dry machining of Ti6Al4V generates high temperatures in the cutting zone even in finishing or semi-finishing cutting conditions [14], thus the application of liquid nitrogen as cooling mean might give benefits in terms of tool wear and surface integrity even with less sever cutting parameters.

The aim of this study is to investigate the tool wear mechanism and modes of PVD coated tungsten carbide inserts when turning an EBM Ti6Al4V under dry and cryogenic cooling strategies in semi-finishing cutting conditions. The tool wear was evaluated experimentally by means of SEM and EDS analysis coupled with optical profilometry. The effects of the applied lubricating conditions on the machined surface integrity with regard to biomedical applications are also presented.

2. Experimental procedure

2.1. Material

The metal alloy object of the investigation is the titanium alloy Ti6Al4V obtained by Electron Beam Melting (EBM). The chemical composition of the as-built alloy is shown in Table 1: the comparison with the one of the wrought Ti6Al4V according to the ASTM F1472 [15] standard demonstrates a negligible difference in the percentage of all the chemical elements. The EBM material was produced by means of an ARCAM® Q10 machine, specifically designed for the industrial production of surgical implants. Five cylindrical specimens with a diameter of 40 mm and length of 230 mm were 3D printed having their symmetrical axis parallel to the beam direction, thus normal to the layers melting direction. The microstructure of the as-built material was analysed by preparing and etching the samples with the Kroll's etchant. In the as-built condition, the material shows a fine acicular microstructure mainly consisting of α phase fine lamellae organized in a basket wave morphology with 7% of bcc β phase in an hcp matrix (Fig. 1). The microstructure is the result of the rapid solidification and subsequent annealing due to the thermal cycle of the working zone [16]. No microstructural defects as cavities and cracks were detected on both the parallel and perpendicular directions with respect to the growing direction in the bulk material. The mechanical properties of the EBM Ti6Al4V are presented in Table 2: higher values of ultimate tensile stress, hardness and a reduced elongation at fracture compared to the wrought alloy might foresee a reduced machinability. Before machining, the samples were subjected to a preliminary rough turning operation to remove the 1 mm thick porous surface layer generated by the EBM process, thus allowing the same reference surface roughness of 1.2 μm and a constant diameter of 38 mm for each machining trial.

Table1
Chemical composition of the EBM Ti6Al4V (%weight).

Chemical composition (wt%)							
Al	V	C	Fe	O	N	H	Ti
6	4	0.03	0.1	0.15	0.01	0.003	Bal

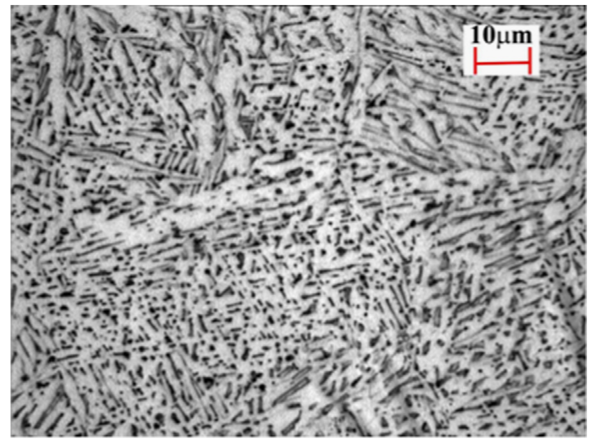

Fig. 1. Microstructure of the EBM Ti6Al4V in the as-built condition.

2.2. Machining tests

The machining experiments were run on a Mori Seiki NL1500™ CNC lathe equipped with a cooling line assembled for the cryogenic cooling (see Fig. 2). The liquid nitrogen is stored in a non-conventional high pressure LN2 storage Dewar equipped with security valves and pressure regulator. A high vacuum insulated pipe carries the cutting fluid to the cutting zone. Previous researches on cryogenic turning have proved higher cooling efficiency of LN2 if multiple cooling directions are adopted simultaneously [17,11]. According to the literature findings, the proposed experimental set-up consists of two flows of LN2 directed onto the rake and flank faces with a direction of 45° by means of external copper nozzles with an internal diameter of 0.9 mm (detail in Fig. 2). The position and the direction of the nozzles with respect to the tool faces were optimized after several rough turning trials conducted on wrought Ti6Al4V workpieces. The supplying pressure was set equal to 15 bars, resulting in a mass flow of 0.9 kg/min. The adopted insert was a semi-finishing TiAlN coated tungsten carbide insert CNMG120404SM-GC1105 (substrate composition: 93% WC and 7% Co) supplied by Sandvik–Coromant®, with a radius of 0.4 mm, rake and clearance angles are of 7° and 0°, respectively.