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3D finite element modelling of surface modification in dry and cryogenic machining of EBM Ti6Al4V alloy

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ABSTRACT

The development of reliable numerical tools for predicting the machined surface integrity has become of primary importance nowadays. This paper introduces a novel customized FE model to predict microstructural changes generated during turning of the Electron Beam Melted (EBM) Ti6Al4V alloy under dry cutting and cryogenic cooling. The material peculiar fine acicular microstructure and the nano-hardness variation are modelled and implemented into a FE model by means of a User Subroutine. The developed FE model permits to predict the microstructure (alpha lamellae thickness), the plastic deformation (alpha lamellae deformation) and nano-hardness variations induced by machining operation under dry and cryogenic conditions.

Introduction

Within the manufacturing industry, Additive Manufacturing (AM) technologies are gaining more and more attention by several advanced industrial fields that are revolutionizing their standard schemes and strategies for manufacturing plastic and metal products. As an example, the necessity to reduce the fuel consumes is pushing airplane manufacturers to build stiffer and lighter components of the most modern aero engines by metal 3D printing techniques, being the Electron Beam Melting (EBM) one of the most used. Indeed, the AM technologies have enabled the manufacture of complex cross sectional areas like the honeycomb cells or other material parts that contain cavities and cut-outs reducing the weight to strength ratio [1]. The *Ti6Al4V* alloy has been one of the first alloys to be produced through the EBM process, thanks to the biomedical industry that foresaw its potential application for producing customized surgical implants. Moreover, since it is difficult if not impossible to fabricate open cellular structure (very similar to the bone marrow structures) from many metal or alloys (*Ti6Al4V*, *TiAl* or *Co*-base alloys) using conventional micro-casting or sintering technologies, the EBM or other AM processes permit to create these complex structures [2]. Recently, the researchers have demonstrated that AM processes can produce metal parts with mechanical performances different from the wrought ones. In particular, the hardness and wear resistance of the AM metals have revealed to be superior to conventional casting ones because the AM techniques can produce excellent surface wear properties due to low levels of residual stresses induced by the process itself [3]. In recent years, many researches are being published regarding the EBM process applied to the *Ti6Al4V* alloy [4], nonetheless most of the works have been focused on the forming process and not on the post processing operations, mainly machining operations, which are needed to achieve the final product geometry and functionality. Although these operations are drastically reduced when adopting AM techniques, their effect on the final material properties and workpiece surface integrity cannot be neglected. For instance, Bordin et al. [5] carried out semi-finishing turning operation on the EBM *Ti6Al4V* and compared its machinability with the one of the wrought alloy, investigating the tool wear, surface integrity, chip morphology and material microstructure changes as a function of the cutting parameters. They highlighted that the tool wear induced by the EBM material is more severe compared with the wrought one as well as higher values of surface roughness were measured when cutting the EBM alloy. The chip segmentation was observed for both the alloys and a constant width layer of deformed microstructure was observed for both the alloys as well. Moreover, both the wrought and EBM alloys showed higher value of surface hardness at increasing both the cutting speed and feed

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rate as a consequence of the materials strain hardening behaviour induced by the machining operations. Besides the experimental approaches that consist in performing machining tests and then analyzing the surface integrity, more and more sophisticated numerical approaches based on the Finite Element (FE) method are being developed to reduce costly and time-consuming experimental tests [6]. Great progresses have been accomplished on this topic, developing models that take into account the material dynamic changes arising during the machining operation, such as the dynamic recrystallization (DRX) phenomenon when turning the wrought *Ti6Al4V* alloy, by coupling the material flow stress equation with the Severe Plastic Deformed (SPD) layer properties [7,8]. Being these models strongly influenced by the material properties, they cannot be directly applied to simulate machining operations carried out on the same alloys made by AM techniques because of their different microstructures. As regards the EBM *Ti6Al4V* alloy, a fine peculiar microstructure of long and thin lamellae [9] organized in a basket wave morphology is generated instead of equiaxed grains as for the wrought material [10]. Therefore, considering the growing interest for the EBM *Ti6Al4V* alloy products, the availability of numerical models that can accurately simulate machining operations are of fundamental importance.

This work is aimed at setting the basis for developing three-dimensional numerical models to predict the surface integrity properties of machined EBM *Ti6Al4V* components. An empirical model for predicting the alpha phase lamellae thickness is developed on the basis of microstructural measurements. This empirical model is implemented into the FE code by a User Subroutine and the microstructure alterations are then coupled with the material flow stress equation to consider their effects during the cutting process at varying cooling conditions and cutting process parameters. An iterative procedure is utilized for calibrating the implemented empirical equations related to the alpha phase lamellae characteristics. Finally, the developed numerical model is validated on the basis of the outcomes of machining trials other than those used for its calibration.

Material and methods

Experiments

The machining tests were conducted on a Mori Seiki® NL 1500 CNC lathe equipped with a self-designed cooling line to supply Liquid Nitrogen (LN_2) in the cutting zone. EBM *Ti6Al4V* cylindrical specimens printed along their symmetrical axis direction were turned under dry cutting and cryogenic cooling adopting three values of the cutting speed (50, 80 and 110 m/min) and a constant feed rate (0.1 mm/rev). The turning length was calculated for each turning trial ensuring a minimum machining time of 20 s to reach a steady state condition for the cutting temperature and forces. The adopted cutting tool was a Sandvik Coromant® CNMG 120404-23 H13A uncoated tungsten carbide insert, mounted on a PCLNR/L 2020k12 tool holder supplied by the same manufacturer. The turning trials were repeated three times to guarantee a statistical repeatability. The experimental set-up used for conducting the machining test is shown in Fig. 1.

The effective cutting angles and the tools geometry were measured with a Sensofar Plu-Neox™ optical profiler by scanning the tool insert mounted on the tool holder. The effective cutting angles resulted of being equal to 7° and 8° for the rake and clearance angles, respectively, while an approaching angle of 95° was defined by the tool holder geometry. A fresh cutting edge was adopted for each cryogenic and dry turning test, thus neglecting the tool wear effect even in such short turning lengths. A Kistler®-type 9257 B three components piezoelectric dynamometer was mounted on the lathe revolver for the acquisition of the cutting forces along the cutting speed and feed directions. An infrared camera FLIR A6000-series was fixed on the tailstock allowing the acquisition of the thermal field from a frontal position with regard to the workpiece. The cryogenic delivery system aimed at supplying the Liquid Nitrogen (LN_2) directly to the cutting zone. The LN_2 is carried through a vacuum insulated pipe and a nozzles system composed by two cooper nozzles with an internal diameter of 0.9 mm that direct the flow towards the tool rake face and the primary cutting edge with an inclination of 45° (Fig. 1). 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. More detailed information about the experimental approach is described in a previous work published by the same authors [11], in which the cutting forces and temperatures were experimentally acquired to preliminarily calibrate the material flow stress and friction models. Material samples in the as-built and machined conditions were mounted in an epoxy resin, polished and etched with the Kroll's reagent to highlight the grain boundaries. The microstructure was

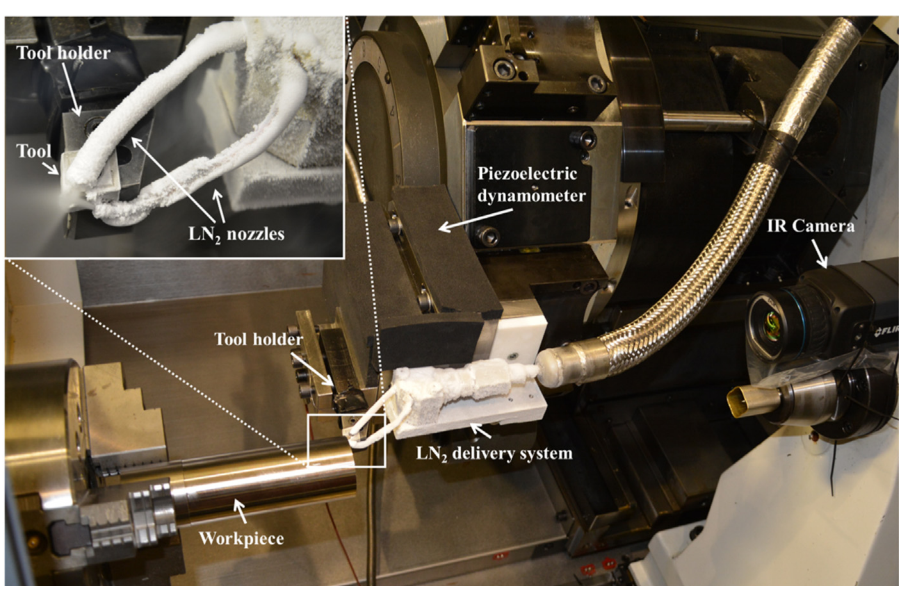

Fig. 1. Experimental set-up for machining test.