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Predicting surface quality of γ-TiAl produced by additive manufacturing process using response surface method †

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Abstract

Electron beam melting (EBM) has been found to be a promising technology for producing complex shaped parts from gamma titanium aluminide alloys (γ-TiAl). The parts produced by this process are projected to have dimensions very close to the desired final shapes. However, the surface roughness of the parts produced by EBM is excessively rough. In many applications, it is necessary to improve the quality of manufactured parts using a convenient post process. This paper determines process parameters of end milling when it is used as a post process for the parts produced by EBM. Design of experiments has been used to study the effect of the selected input parameters of end milling (spindle speed, feed rate, depth of cut and coolant type) on the surface roughness of γ-TiAl parts. Response surface methodology is used to develop a predictive model for surface roughness. Effects of the selected milling process are investigated. This paper also optimizes the selected process parameters to minimize the value of the obtained surface roughness.

Keywords: EBM process; End milling; Response surface method; Factorial design; Surface quality

1. Introduction

Additive manufacturing (AM) has emerged as a promising fabrication technology for metal parts [1]. AM Technologies can fabricate complex shaped components using three dimensional Computer aided design (CAD) data starting from a precursor powder that is consolidated layer-by-layer. Working layer-by-layer according to the given CAD model offers a high geometrical freedom and the possibility to create very complex parts with internal cavities and channels. The consolidation can be reached by sintering or by melting using either a laser or an electron beam as an energy source.

Titanium aluminides alloy (TiAl) fall in the class of materials known as intermetallic alloys that are, compounds mainly formed by two metals. Their crystal structure and properties are completely different from their parent metals [2]. TiAl alloys based on the gamma phase (Gamma Titanium alloys) are new intermetallic alloys that contain 44-48 atomic percent Al (32-35 in weight percent), with element additions of Cr, or Mn to increase ductility, and Nb to improve strength and oxidation resistance. Gamma titanium aluminide alloys (γ-TiAl) have unique properties such as low density, high strength, high temperature, specific strength, high stiffness and good corrosion, creep, and oxidation resistance that are highly attractive for dynamic applications at high temperatures [3, 4]. γ-TiAl alloys show approximately half the density of Ni superalloys, high strength/weight ratio, and high refractoriness. Furthermore, they show fatigue resistance values close to 100% of yield strength [6].

Classic examples of applications of γ-TiAl include turbine blades, turbo charger wheels and valves for combustion engines, seal supports, cases, metal cutting tools, missile components, nuclear fuel, divergent flaps in nozzles of high speed gas turbine engines and artificial joint prostheses. Due to its attractive properties mentioned above, it has been considered as a potential replacement for Ni-based superalloys at temperatures ranging from 600 to 900ºC. Heat resistant γ -TiAl have been identified as possible alloys for high-performance automotive components, and they are intended for a wide usage in aerospace applications, especially in the hot parts of aircraft engines [5, 6].

In spite of their numerous advantages, γ-TiAl alloys show some drawbacks such as low ductility, which typically ranges between 0.3 and 4% in terms of elongation, brittleness, and low inherent formability at room temperature, together with low fracture toughness [7].

Electron beam melting (EBM) is an additive manufacturing

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technique, developed by Arcam AB in Sweden [8], which produces net-near shape products. An EBM melts powder on a powder bed according to a computer-made 3D-drawing, and the structure is built up layer by layer. Surface roughness is a fundamental problem in EBM process, which require a proper post process to improve surface quality to meet the desired specifications.

Up to our knowledge, there no research work has been done on the determination of milling parameters for γ-TiAl parts produced by EBM process. This paper investigates the process parameters of end milling operations when finishing γ-TiAl parts that have been produced by EBM process. Response surface method (RSM) is used to predict surface roughness of γ-TiAl parts machined using end mill process when the inputs are cutting speed, depth of cut, feed rate and coolant type. The rest of the paper is organized as follows: Sec. 2 is devoted to literature survey. Sec. 3 presents the different steps of the suggested methodology for producing the considered parts and investigating the process parameters of end mill. Sec. 3 also presents the analysis of the obtained results. Finally, Sec. 4 concludes the paper and suggests research directions for future research work.

2. Literature review

Different techniques were proposed for machining γ-TiAl alloys. Aspinwal et al. (2005) [8] reviewed the machinability of y-TiAl intermetallic alloys when turning, grinding, High speed milling (HSM), drilling, Electric discharge machining (EDM) and Electric chemical machining (ECM). They concluded that surface integrity problems remained with turning and drilling. However, turn-milling can provide cylindrical surfaces that are crack-free. When HSM, temperatures of < 350°C were obtained with new tools and selected operating parameters. Also, a review of key advances in gamma titanium aluminides has been presented by Kothari et al. (2012) [9]. They included microstructure, deformation mechanisms, and alloy development. Traditional manufacturing techniques such as ingot metallurgy and investment casting were reviewed and advances via powder metallurgy based production techniques were discussed. In addition to solving production issues, authors also considered the issues of developing titanium aluminides with a balance of desirable mechanical properties. They found that the new processing techniques can probably achieve this balance by incorporating some of the mechanical property enhancement mechanisms such as, (1) Control of microstructural morphology, (2) Small alloying additions, such as Nb, Cr, and B, (3) Reduction of grain size to sub-micrometer to nanometer range, and (4) Reinforcement with discontinuous particulates or fibers.

Gamma titanium aluminides alloys are considered as difficult-to-cut materials, because of their high hardness and brittleness, low thermal conductivity, high chemical reactivity, and strong tendency to hardening [7]. Poor machinability and, furthermore, the high manufacturing costs, limit the widespread use of those materials in the market.

Cryogenic cooling with liquid nitrogen and minimum quantity lubrication in longitudinal external turning operations of γ-TiAl were investigated by Klocke et al. (2013) [10]. Their investigation indicated that cryogenic cooling- in comparison with all the other lubrication conditions studied - is a promising way to lower tool wear and furthermore to limit surface and sub-surface defects.

Milling experiments have been conducted for gamma-TiAl by Priarone et al. (2012) [11]. They considered the relation between cutting performance (such as tool wear, surface hardness and roughness, and chip morphology) and machining parameters (such as cutting speed, feed, and lubrication conditions (dry, wet, and minimum quantity lubrication). They concluded that minimum quantity lubrication was by far the method that allowed extending tool life, R_a and R_t increased with the tool wear and also dependence on cutting speed and feed, and chip morphology, chip length and width dependence mainly on cutting speed.

Priarone et al. (2013) [12] have also conducted drilling experiments on a particular γ-TiAl fabricated via electron beam melting. Cutting performances were measured in terms of tool wear, surface roughness, dimensional and geometric errors. Analysis of the results showed that tool wear is strongly affected by the cutting speed. For the highest cutting speed in the explored range, catastrophic failure was observed. Chipping and material adhesion were the main drivers to tool failure. Surface roughness was found to be decreased if feed decreases and cutting speed increases. For hole quality, cylindricity error was found to increases with increasing of cutting speed and tool wear.

Full factorial experiment when turning Ti-45Al-2Mn-2Nb +0.8 vol. % TiB2 was conducted by Sharman et al. (2001) [13]. Workpiece surfaces/subsurface were evaluated in relation to microstructural alterations, strain hardening/microhardness changes, and 2D surface roughness (Ra). It was found that, a significant reduction in surface damage could be obtained using more abusive parameters comparing to the previous studies. Bentley et al. (1999) [14] studied the effect of grinding and High speed milling (HSM) on the fatigue strength of the γ-TiAl intermetallic alloy. Results showed that HSM significantly increased fatigue strength by as much as 200 MPa over polished samples. Measurement and analysis of workpiece subsurface micro-hardness and microstructure indicated that the high run-out values correlated to high hardness and plastic deformation of the near surface lamellae.

Beranoagirre et al. (2012) [15] carried out a complete set of milling tests for γ-TiAl. They considered the relationship between tool wear, cutting speed and feed per tooth. Results showed that the cutting speed must be ranging between 50 and 70 m/min and feed per tooth between 0.05 and 0.06 mm, for tungsten carbide tools with (AlTi)N coating. Beranoagirre et al. (2013) [16] presented the results from grinding tests on two types of Gamma TiAl alloys. The tests were performed with three different tools, in terms of grain size and composition.