Journal of Materials Processing Tech. 264 (2019) 422–437

Contents lists available at ScienceDirect

Journal of Materials Processing Tech.

journal homepage: www.elsevier.com/locate/jmatprotec

Novel rotating-vibrating magnetic abrasive polishing method for double-layered internal surface finishing

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ARTICLE INFO

Associate Editor E. Budak

Keywords:
Additive manufacturing (AM)
Internal surface finishing
Selective laser melting (SLM)
Inconel 718
Magnetic field
Surface integrity

ABSTRACT

Components with complex internal surfaces are increasingly important for gas and fluid flow applications in aerospace and automotive industries. Recently, as an emerging manufacturing technology, three-dimensional (3D) additive manufacturing (AM) technology enables one-step fabrication of these complex internal surfaces. Although 3D AM technology eliminates the need for complex assembly process, due to the poor surface and sub-surface integrity, achieving a favourable surface condition is challenging. Therefore, a post-polishing process is essential for these 3D AM complex internal surfaces. This paper presents a novel rotating-vibrating magnetic abrasive polishing method to finish a kind of complex internal surface which has a double-layered tube structure made by selective laser melting (SLM) of Inconel 718. The principle of the method was illustrated and the material removal process was modelled. The feasibility of the method was verified and the surface evolution mechanism under different motions was revealed. The effects of process parameters on material removal and surface quality were evaluated quantitatively. The results showed that material was uniformly removed from both of the external surface of inner tube and internal surface of outer tube. The uneven surface caused by partially melt powders during SLM process was smoothed and the surface roughness was reduced from about 7 μm Ra to less than 1 μm Ra. Relatively higher material removal efficiency and lower surface roughness were obtained through combining rotation and vibration motions. The surface quality was improved representing by the increase of surface nanohardness and release of residual stress after polishing. There was no subsurface deformation and damage observed so that a damage-free surface was obtained.

1. Introduction

The requirements of components with complex internal surfaces are increasing for gas and fluid flow applications in aerospace and automotive industries. Reviews of abrasive processes by Tan et al. (2016) and Hashimoto et al. (2016) highlighted some of the applications such as turbine spray nozzles, hydraulic manifolds and cooling channels which have complex internal surface with curved feature, narrow portion and fluctuating volume. Concerning mechanical properties and functionality such as high-temperature strength and high resistance of corrosion, these components are usually made of Inconel alloys. However, due to the extreme toughness and work hardening characteristics, it is significantly difficult in machining Inconel alloys especially for those having complex structures. In summaries given by Ezugwu (2005) and Thakur and Gangopadhyay (2016), the numerous research in machining of Inconel alloys spanning a decade is a testament to its poor machinability and also great industrial demand. As described by Rahman et al. (1997), incorrect cutting conditions can cause severe effects on tool life of an insert when machining Inconel 718. Dudzinski et al. (2004) explained the technical and environmental challenge in coolant use and proposed a high-speed dry machining method.

A solution to overcome the difficulty is the utilisation of three-dimensional (3D) metal additive manufacturing (AM) technology. As an emerging manufacturing technology, 3D metal AM technology becomes an essential commercial manufacturing technology and enables a myriad of geometric features such as porous cores, shell as well as

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https://doi.org/10.1016/j.jmatprotec.2018.09.024
Received 21 April 2018; Received in revised form 19 September 2018; Accepted 19 September 2018
Available online 27 September 2018
0924-0136/

internal structures considered challenging prior to its inception. Reviews on metal AM by Gibson et al. (2010), Guo and Leu (2013) and Frazier (2014) have all highlighted the one-step fabrication of complex internal surfaces as a key advantage. Although 3D metal AM technology eliminates the necessity for complex assembly process, due to the poor surface and sub-surface integrity represented by rough surface finish and defective layers, achieving an industrially applicable surface condition is challenging. Strano et al. (2013) reported that the surface roughness of Inconel 718 components fabricated by selective laser melting (SLM) process is more than 7 μm Ra which is attributed to partially melted powder layers and inherent pores of the SLM process, and the poor surface roughness is not satisfactory for certain applications in aerospace and automotive industries. Therefore, a post-polishing process is essential for these 3D AM complex internal surfaces to achieve high quality internal surface finish.

For internal surface finishing, in general, there are major five kinds of established finishing processes which are internal cylindrical grinding, abrasive flow machining (AFM), fluid jet machining (FJM), magnetic abrasive finishing (MAF) and fluidized bed machining (FBM), three of which are reviewed by Tan et al. (2016). Internal cylindrical grinding, as a conventional technology, has been widely used in industry for many years, but it is limited to straight internal structures with relatively large diameters considering tool size and coolant supply. AFM is one of the most prominent process for finishing inaccessible surfaces with a wide range of materials. In AFM, the pressurized semi-solid-laden media with hard abrasive particles is forced to flow in a restricted area and abrade the target surface in repeated cycles. The finishing pressure depends on the fluid dynamics of the media. However, it is limited to some geometries such as blind holes. It is also difficult to achieve uniform material removal on channels with varied geometries or features. Furthermore, Jain et al. (1999) and Tan et al. (2016) have reported contamination issues arising from abrasive particles embedding onto the workpiece surface, and removed materials mixing into the abrasives. FJM pumps abrasives towards target surfaces through an adjustable nozzle at certain pressures to remove materials, and it has been widely used in mold, ceramics and optics finishing. Axinte et al. (2014) presented a review of the state-of-the-art, while Beaucamp et al. (2012), Beaucamp and Namba (2013) conducted dynamic multiphase modelling of FJM and demonstrated super-smooth finishing of diamond turned hard X-ray molding dies using FJM. Kim et al. (1997) developed a magnetic abrasive jet machining system for precision internal polishing of circular tubes. Cheung et al. (2017) presented a multi-jet polishing process for inner surfaces finishing through adopting a rod-shaped nozzle. Compared with AFM, it has the unique advantages of high machining accuracy and flexibility, undergoes no contamination issues, but it is still limited to deep and bind holes with narrow gaps. MAF is a precision non-traditional finishing process that the finishing is controlled by magnetic field. In MAF, the media is pressed against the surface by magnetic force and is dragged along the surface for finishing. Magnetic abrasive particles acting on a workpiece are influenced by magnetic poles, thus forming a flexible magnetic abrasive brush. However, as emphasised by Jain (2009), Hashimoto et al. (2016) and Tan et al. (2016), MAF's biggest limitation is the restriction of the materials that can be processed. FBM is a recently developed non-traditional finishing process utilizing fluidized bed hydrodynamics. Fluidized bed is formed when a bed of solid abrasive particles is controlled under fluid flow and material is removed by the flow of an abrasive solid emulsion over the internal surface. Due to the fluid-like behaviour, internal surfaces are achievable and can be finished, as demonstrated by Barletta (2006). The limitation of FBM is the existance of debris remaining on the machined surfaces. Tan et al. (2016) indicated the embedding of abrasive splinters onto the machined surfaces for soft and ductile workpieces such as aluminium and polyvinyl chloride (PVC). Furthermore, in FBM, Barletta (2006) showed that surface improvement on the internal surface is significantly less than the external surface. For fluidized bed assisted abrasive jet machining (FB-AJM), Barletta et al. (2007), Barletta (2009) further concluded that the integration of abrasive jet principles results in the incapability on bent internal surface finishing.

As mentioned above, each process has its limitations. Compared with the other two technologies, MAF does not require complex facilities, making it easier to be realized, and more reliable and applicable to industry. In the past years, some research work such as those by Singh et al. (2005) and Jain (2009) have been done to understand the MAF process behaviour and surface pattern generation. Shinmura et al. (1990) and Shinmura and Yamaguchi (1995) firstly presented a new finishing process and through modification demonstrated its feasibility on finishing of stainless steel tube and clean gas bomb. Kim and Choi (1996) analysed magnetic pole arrangement and pole number variations. Kang and Yamaguchi (2012) developed a multiple pole tip system to increase the finishing area, thus efficiency. Besides, Yoon et al. (2014) proposed a few possible pole arrangements which vary from a conventional single north (N)-south (S) pole system. Additionally, Yamaguchi et al. (2011) explored and demonstrated MAF's capability to finish the internal surfaces on the tubes of various sizes and materials. However, to date, research efforts are mainly focused on internal finishing of one-layer tube structure, there is still no solution for internal finishing of double-layered tube structure. Recently, Frazier (2014) and Flynn et al. (2016) have proposed hybrid manufacturing through combining 3D printing and machining technologies such as milling and grinding. Although this technology shows potential to fabricate double-layered tube structure, it is still very challenging when the gap between the tubes is less than a few hundred micrometres.

To solve the problem, in this paper, a new rotating-vibrating magnetic abrasive polishing method is proposed to finish a kind of complex internal surface which has a double-layered tube structure fabricated by selective laser melt (SLM) Inconel 718. The critical challenge of this research issue is to access and improve the internal surface finish of the tubes while maintaining the forms of inner and outer tubes. This paper introduces the principle and material removal process of the method, details of sample preparation, experimental setup and conditions. Then followed by the magnetic field distribution analysis, experiments were carried out to verify the feasibility of the method, evaluate the effects of process parameters on surface quality and material removal, and validate the material removal model. Conclusions were obtained on inter-relations between surface/subsurface quality and process parameters.

2. Methodology

2.1. Principle of the method

Fig. 1(a) shows the schematic illustration of the method for internal finishing of double-layered tube structure. The set-up consists of a pair of magnets located externally to the workpiece as well as a diametrically magnetised cylindrical magnet located at the centre of the workpiece, along the axial direction. The magnetic abrasives were supplied to the gap between the outer and inner tubes. From the cross-sectional views (Fig. 1(b)), due to the magnetic field, the magnetic abrasives conglomerate according to magnetic flux lines and are attracted towards to the external surface of inner tube and internal surface of outer tube, forming a flexible magnetic abrasive brush. The source of magnetic field can be an electromagnet or permanent magnet, and the size and grade of the magnets can be adjusted to fit the dimension of workpiece. The magnetic forces acting on the magnetic abrasives exert polishing forces on the internal surfaces. Under the polishing forces, the cutting edges of hard abrasive particles abrade the workpiece surface. Then subsequent rotation of workpiece and linear vibration of magnets induces relative motion between the abrasive particles and workpiece, causing materials to be removed by magnetic abrasives in the form of fine abrasion. Therefore, the surfaces between the outer and inner tubes can be polished.