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A novel magnetically driven polishing technique for internal surface finishing

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ABSTRACT

This paper presents a novel magnetically driven polishing tool for internal surface finishing. Differing from the existing magnetic abrasive finishing or magnetic field assisted finishing (MAF) methods; this new technique performs material removal inside a tube using a spherical magnet with abrasives driven by external bar magnets. This configuration of magnets not only simplifies the design but also allows more flexibility in the potential application to internal finishing of manifolds. The physical principle was introduced and polishing experiments were conducted to investigate the effect of magnetic abrasive particles and abrasive size based on the two major criteria of surface roughness and material removal. The results unequivocally substantiated the capability of the developed method with a more than 98% improvement in surface roughness for ring polishing and an 86% improvement for section polishing. An analytical model was devised to illustrate the material removal mechanism of the proposed internal polishing technique based on the experimental results. The technique developed in the paper shows signs of future success in finishing internal surface of complex components in a wide range of industrial applications.

1. Introduction

Fine finish of internal surface is in high demand for a wide range of applications in semiconductor, medical, chemical, aerospace, and automobile industries. Typical examples are those with a functional internal surface such as sanitary pipes, catheters, gas bombs, oil pipes, engine manifold, etc. With the rapid development of additive manufacturing (AM), more complex structures with internal functional surfaces can be readily fabricated, e.g. conformal cooling channels [1]; however, the inferior surface finish of the AM-ed components gives rise to substantial demands for internal finishing. Conventional machining technologies could not provide an effective solution for the finishing of such internal surfaces due to the restricted accessibility of the complex topography and geometric limitations. Hence, these internal surfaces are mainly finished by non-conventional machining techniques such as abrasive flow machining (AFM) or abrasive flow finishing (AFF) [2–4]. AFM is capable of finishing complex surfaces that are inaccessible by hand. This process exhibits great potential in surface processing of additively manufactured (AM) components. Cheng et al. [4] developed a multiphysics simulation model for predicting the dimensional accuracy in AFM of bladed rotor blade. The proposed model was well supported by the results of the comparative experimental study. In the meantime, electrolytic and chemical polishing (ECP) [5], magnetic abrasive finishing or magnetic field assisted finishing (MAF) [6–11] and their derivatives such as magnetorheological abrasive flow finishing (MRAFF) [12], and electrolytic MAF (EMAF) [13], have also been developed to finish internal surfaces. Nevertheless, the finishing process based on abrasive flow, such as AFF, AFM, MRAFF, etc., may encounter certain limitations due to the pressure drop along the direction of abrasive media flow, which results in an uneven material removal when it is applied to finishing long tubes. ECP is a high-efficiency finishing technique for metal workpieces but the time-consuming fabrication process of a customised anode for a particular type of curved tubes impedes its further application. Among these three non-conventional finishing techniques, MAF seems to be the most promising technique for fine finishing of internal surfaces in various applications. The material removal in the MAF process is driven by a combination of movements, including the translational, reciprocating, and rotary motions of the magnet(s) and workpiece at different rates and directions simultaneously which can be implemented by a dedicated design of the finishing systems. A body of investigations into the internal polishing of straight tubes and bent tubes using MAF can be found in the literature which are summarised in Table 1. Even though some of the current MAF techniques can be successfully applied to finishing straight tubes and even 90° bent tube disregarding the complexity of setup, their capability for finishing more complex internal surfaces, such as

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Nomenclature

Symbols

D_r	Depth of polished ring [μm]
F_M	Magnetic force on internal magnet [N]
F_m	Magnetic force on MAP [N]
F_f	Friction force on internal magnet [N]
F_f'	Friction force on abrasive [N]
F_h	Hydraulic force on abrasive [N]
F_n	Normal force on internal magnet [N]
F_n'	Normal force on abrasive [N]
K_p	Preston coefficient
n_{M_e}	Rotation speed of external magnets [rpm]
n_{M_i}	Rotation speed of internal magnet [rpm]
n_T	Rotation speed of tube [rpm]
P	Normal pressure applied [N]
V	Relative speed between abrasive and workpiece surface [m/s]
W_r	Width of polished ring [μm]

Abbreviations

2D	2-dimensional
Al_2O_3	Alumina
AFF	Abrasive flow finishing
AFM	Abrasive flow machining
AM	Additive manufacturing
CMP	Chemical mechanical planarisation
CNC	Computer numerical control
Co	Cobalt
DC	Direct current
ECP	Electrolytic and chemical polishing
EMAF	Electrolytic magnetic abrasive finishing
Fe	Iron
FEMM	Finite Element Method Magnetics
H_2O	Water
ID	Internal diameter [mm]
Ly12	Ly12 aluminium alloy
MAF	Magnetic abrasive finishing or magnetic field assisted finishing
MAPs	Magnetic abrasive powders
MR	Material removal [μm^2]
MRR	Material removal rate [μm^2/min]
MRAFF	Magnetorheological abrasive flow finishing
OD	External diameter [mm]
Ra	Surface roughness (arithmetic mean height) [μm]
rpm	Revolutions per minute
S-N-S-N	South-north-south-north pole configuration
SEM	Scanning electron microscope
SiC	Silicon carbide
SS316	Stainless steel Grade 316
SUS304	Stainless steel Grade 304
TiC	Titanium carbide
WA	White alumina
WC	Tungsten carbide
wt %	Weight percent

conformal cooling channels, is limited.

In this paper, a new flexible finishing technology was developed to finish the internal surfaces of non-ferromagnetic materials with an innovative design of the polishing tool. A cost-effective and adaptable setup was built to validate the proposed internal finishing technique. Experiments were conducted to investigate the effects of the type of magnetic abrasive powders (MAPs) and abrasive size on the finishing characteristics such as surface roughness, surface texture and material removal. The experiments also evaluate the effect of MAPs on finishing performance. Material removal mechanism is analysed based on the experimental results. At last, the capability of the new finishing method was testified in a full-length section polishing trial with the modified setup on a two-axis turning lathe. The focus of this paper is on the development and validation of the working principle of the new internal finishing method. The application of this new method in finishing complex internal surfaces will be explored by integrating it into a multi-degree-of-freedom tool in the future work.

2. Working principle and experimental procedure

The working principle of the proposed internal surface finishing method is shown in Fig. 1. A sphere magnet is placed inside a tube while a pair of bar magnets with the configuration of S-N-S-N is parallelised to the axis of the tube. Being connected to a rotary shaft, the bar magnets rotate along their centre axis to drive the rotational movement of the sphere magnet inside the tube in the opposite direction by the magnetic force. In addition, the magnetic force exerted by the external bar magnets on the internal sphere magnet results in a normal pressure on the internal surface of the tube. The combination of this normal pressure and relative tangential movements between the sphere magnet and tube will in turn give rise to material removal. It is worth noting that according to the 2D magnetic-field simulation conducted with the software Finite Element Method Magnetics (FEMM 4.2), the magnetic flux density at the near side of the tube is stronger than that at the distal side away from the external bar magnets as

Table 1
Representative techniques of magnetic abrasive finishing of internal surfaces.

Research work	Tube geometry	Material	Magnetic abrasives	Primary motion	Material removal rate (mg/min)	Surface roughness, Ra (nm)
Yamaguchi et al. (2007) [14]	Straight	SUS304	Iron + WA	Workpiece rotating; magnet reciprocating and feeding	0.025–0.03	20
Sato et al. (2007) [15]	Straight	Copper	MRF slurries		NA	2.9
Yamaguchi et al. (2004) [9]	Straight	Ceramic	Electrolytic iron + diamond		~1	20
Kim et al. (2003) [16]	Straight	SUS 304	WC + Co		NA	50
Wang and Hu (2005) [6]	Straight	Ly12, 316L, brass	Al_2O_3/Fe TiC/Fe		1–15, 0.5–12, 3.5–73	240
Yun et al. (2016) [17]	Straight	Ceramic	Iron + diamond		6–9.5	30
Das et al. (2010) [18]	Straight	Stainless steel	Electrolytic Fe + SiC	Magnets rotating; abrasive media reciprocating	18–23 mg per 1000 cycles	16
Umehara et al. (1995) [19]	Straight	Brass	Magnetic fluid + SiC	Magnet rotating and feeding	0.28 μm/min	40
Yamaguchi et al. (2001) [8]	Bent	SUS304	Iron + WA	Magnet rotating and feeding	3.3–3.7	30