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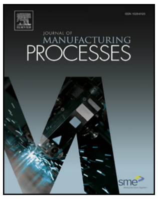

Localized magnetic fluid finishing of freeform surfaces using electropermanent magnets and magnetic concentration

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ABSTRACT

We report a novel magnetic concentration setup for localized finishing of freeform surfaces based on employing electropermanent magnet arrays configured using a recently developed magnetic concentration principle. The setup, without the use of any rotating or moving component, is capable of creating a localized spatiotemporal magnetic field variation a specialized magnetic fluid to polish a target 1.5 cm^2 area on the workpiece surface. Using a computational mechanistic model as well as experimental studies, we show that the current configuration of electropermanent magnets is capable of amplifying the magnetic strength by almost 3 times near the workpiece surface in comparison to no magnetic concentration. We also show that by modulating the strength, including toggling the polarity of electropermanent magnets, we demonstrate the sloshing motion of the fluid at a targeted region without requiring any rotating part. Experimental investigations on the localized removal of acrylic paint from a cylindrical workpiece surface suggest that the method can be used to polish localized, hard-to-access freeform geometries.

1. Introduction

Recent advances in additive and hybrid manufacturing technologies have created several opportunities to manufacture intricate, freeform components with differential surface morphology and microstructure to deliver enhanced performance [1]. The ability of these technologies to fabricate custom components with near-net shape and enhanced functionalities has elicited a strong interest, especially from the automobile, aerospace and biomedical implant industry. These technologies are estimated to garner a market size of $4 billion in 2017 and is expected to surpass $13 billion by 2025 [2].

However, with increasing part complexity, assurance of surface quality and mitigation of defects, such as porosity, have emerged as major challenges. For instance, biomedical implants (e.g., knee and hip implants) require specular surface finish ($S_a < 20\,\text{nm}$) to promote wear mitigation at the joints and other bearing surfaces. In contrast, a rough, textured surface is desired along the large swathes of the part to promote osseointegration, i.e., direct structural and functional integration between ordered living bone and the surface of a load-carrying implant [3]. In the aerospace and automobile industry, additive manufactured components, including impeller blades and exhaust manifolds—that have free-form, hard-to-access geometries—require finished surfaces to allow undisrupted flow. However, conventional machining and polishing approaches cannot be employed for the finishing of hard-to-access surfaces.

Realization of area-specific texturing and finishing of such complex shapes and structures to meet the desired functionalities necessitate localized finishing and targeted modification of freeform surfaces. Conventionally, the industry has employed manual hand-held polishers for localized finishing. Such processes tend to be laborious and demand extreme dexterity. Alternatively, localized electro-chemo-mechanical etching methods have been investigated [4–6], but they require specialized masks or physical barriers to confine material removal at desired locations. While localization is hard to achieve with free-abrasive finishing methods, many geometric features, such as internal cavities and channels are inaccessible to hand-held polishers.

Advancements in magneto-viscoelastic fluids offer an interesting opportunity [6–15] to combine the best features of handheld finishing (flexible downforce, localization) with the accessibility provided by fluids to create a fast, automated and localized finishing of hard-to-access locations. Significant research exists on utilizing the abrasive-mixed magnetorheological fluid (MRF) as a magnetic abrasive brush to finish planar surfaces. Conventional magnetic polishers are mostly limited to flat geometries or require the application of complex robotic

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arms or CNC machines to finish curved surfaces and capillaries [16–18] using the magnetic abrasive brush. However, only limited research has focused on creating spatiotemporal variation in the magnetic fields that could be utilized to finish hard-to-access, free-form geometries. Recent results on the concentration of magnetic field lines [19–22] and advancements in electropermanent magnets [23–26] open new avenues to achieve localized finishing of hard-to-access locations by controlling the spatiotemporal variation in the magnetic fields, and hence the fluid property and flow characteristics.

In this research work, we develop a novel magnetic concentration setup based on configuring a battery of electropermanent magnets capable of creating a localized spatiotemporal variation in the magnetic field near the workpiece surface. Using computational-mechanistic models as well as an experimental study, we show that the current configuration of electropermanent magnets is capable of amplifying the magnetic field strength by almost 3 times near the workpiece surface. In addition, we also show that by modulating the strength and toggling the polarity of electropermanent magnets, it is possible to generate the required downforce and sloshing motion of the fluid at targeted locations without requiring any rotating part (unlike in most conventional magnetic polishing setups). The remainder of the paper is organized as follows: In Section 2, we present a brief summary of the recent developments in the finishing of free-form geometries with emphasis on MRF. In Section 3, we discuss the concept of magnetic concentration followed by computational and simulation studies. Overview of the experimental setup and details are provided in Section 4. Results from our current investigations are presented in Section 5 that show the efficacy of the magnetic concentration approach. Concluding remarks are presented in Section 6.

2. Background and literature review

The application of a magnetic field for localized finishing was first recorded in 1938 for the finishing of the inner surface of welded joints of a barrel; especially to remove oxide scales using magnetic abrasive particles [27]. After almost half a century, it was Kordonski [28] who used MRFs for the finishing of optical glasses. Subsequent efforts focused more on the global finishing using MRF along with the development of a much broader class of magnetic fluids (MFs). Several MF finishing methods have been developed based on employing varying magnetic configurations as well as different variants and concentration of magnetic abrasives and/or fluids [16–18,29–31]. For example, Shinmura et al. [32] employed bonded magnetic abrasives to polish steel and silicon nitride cylinders. Fox et al. [29] investigated the effects of using unbonded magnetic abrasives in a cylindrical magnetic abrasive finishing process and noted an increase in the material removal rates (MRR) but a rougher surface. It was also determined that (a) imparting axial vibration to the workpiece resulted in a better surface finish (i.e., smaller average surface roughness (S_a)), and (b) increasing the magnetic flux density yielded a better MRR and surface finish [29]. Kim et al. [30] used a pressurized jet of magnetic abrasive particles through a nozzle to finish the internal surface of a workpiece with a non-circular cross-section. A comprehensive survey of the methods can be found elsewhere [33,34].

Despite these significant advances, most of the current implementations of MF finishing methods either rely on some external mechanism to apply the necessary downforce or involve rotating parts to induce relative motion between the workpiece surface and the abrasive mixed-MF [35]. This significantly hinders their applicability to free-form and hard-to-access geometrical surfaces. In addition, localization of the finishing action is also restricted by the geometrical constraints of the external mechanism/part used to induce the required downforce and relative motion.

Recently, several developments have focused towards addressing these challenges by developing specialized robotic arms or CNC machines. For example, Yamaguchi et al. [16], employed MRF to finish the internal surface of a capillary tube. Although magnetic field strength was used to apply the necessary downforce, the workpiece (capillary tube) was mechanically rotated by a pneumatic motor-gearbox setup to generate the relative motion between the abrasive-laden MRF and the internal surface of the tube. In addition, the finishing of complexly shaped tubes required specialized robotic arms to create the necessary relative motion between the abrasive particles and the workpiece surface. More recently, Jain and Sidpara [35], demonstrated a methodology to polish the free-form surface of a knee implant to nanometer roughness. The finishing action was realized by using a CNC milling machine with the machine tool head attached to a neodymium magnet carrying the MR fluid. This forms a flexible ball end MR finishing tool. The diameter of magnetic finishing tool was kept sufficiently small so that the contact area was “locally flat”. A specific tool path was then generated following the workpiece geometry, to polish the whole region while constantly adjusting the z-axis. However, the downforce was provided using the finishing tool, rather than the magnetic field. Other noteworthy implementations to achieve localization or internal finishing involve controlling the geometry, shape, and optimal placement of magnetic tool, [1,35], masking, and magnetic abrasive jet finishing [30].

Although significant efforts have been made towards developing specialized tools and configurations, little emphasis has been made towards understanding the principles underlying the generation of spatiotemporally varying magnetic fields without requiring movable parts, as well as the effects these fields have on the complex rheology of MFs. Recent developments in transformation optics based magnetic concentration, along with the advances in rheological and hydrodynamic understandings of the MFs, together with the advent of electropermanent magnets (EPM) [23–26], offer exciting possibilities to simultaneously control the local dynamics (flow and downforce) as well as the rheological properties of MF in both space and time. In the following section, we present the concept of magnetic concentration and EPM, and explicate how these can be used to create spatiotemporal variation in the magnetic fields obviating the need for any movable/rotating part.

3. Magnetic concentration and computation study

Spatiotemporal variation and concentration of magnetic field lines are critical to allow MFs (a) to adequately stiffen in the presence of concentrated magnetic field lines and consequently exert the required shear stress and normal force at desired locations to cause material removal, (b) flow to hard-to-access regions and execute sloshing action without the need for additional moving parts. In addition, abrasive-mixed MFs need to stay as a cohesive mixture (e.g., the abrasives should not segregate from the magnetic matrix) and expose more abrasives towards the workpiece surface. In this section, we present a detailed overview of the concept of magnetic concentration along with the electropermanent magnet configuration to achieve the aforementioned functionalities.

3.1. Physical principle of magnetic field localization

To localize and concentrate the magnetic field lines at an arbitrary location in space, we borrow the concept of magnetic energy harvesting and concentration proposed by Navau et al. [22]. It is in fact, an adaptation of the principle of Transformation Optics (TO) [36,37], a novel approach that allows customizing the path of electromagnetic waves by partitioning the corresponding space into regions of varying permittivity and permeability. An elementary realization of this principle is the distorted path of magnetic field lines or electromagnetic ray, such as light, when incident on one face of a sandwich of glass slabs with varying refractive indices as shown in Fig. 1. TO takes advantage of the form-invariance of Maxwell's equations under any space-coordinate transformation, as discussed in Section 3.2, to achieve a