Paper ID #36050

Design and Analysis of Magnetic Field Homogeneity of 3D Printed Helmholtz Coil

Dr. Anju Gupta, University of Toledo

Dr. Gupta is an Assistant Professor in the Department of Mechanical, Industrial and Manufacturing Engineering (MIME) at the University of Toledo. She serves on the Thermal-Fluid Sciences; and Materials, Design and Manufacturing focus areas in MIME. She is also a faculty member of the the Center for Hypertension and Precision Medicine located in College of Medicine and Life Sciences. Dr. Gupta also serves on UToledo's water Task Force for Lake Erie research.

She received her PhD in Chemical Engineering from University of Rhode Island. Her Interfacial Thermal and Transport lab focuses on Thermal Analysis: including phase change studies, heat transfer, calorimetry, and thermal separation processes; and Manufacturing: process-structure- property correlations of advanced materials, thermal analysis of materials, high-temperature coatings, thermal interface materials, and temperature-sensitive biomolecules.

Dr. Gupta has received funding from ACS PRF and NSF. Her graduate students are recipients of prestigious Ohio Space Grant and University Fellowships. Dr. Gupta has co-authored nearly 30 peer-reviewed scientific and education journals, and her work as been featured on the journal covers. Dr. Gupta's current collaborators span from National Institute of (NIH), Oak Ridge and Idaho National labs, Ohio Aerospace Institute (OAI), Masten Space, and Materion. She has served as an ad hoc reviewer for NSF, NASA, ACS proposals, and several high impact scientific journals. She is an active member and volunteer of AIChE, ACS, NATAS, and ASEE.

Magnetic Field Homogeneity of Helmholtz Coil integrated with a Hotplate for High Temperature Sintering: A Multidisciplinary Senior Design Project

*Chaitanya Mahajan [1], Seyed Alireza Rozati [2], Anju Gupta [2]**

[2] Department of Industrial and Manufacturing Engineering, Kettering University, 1700 University Avenue, Flint MI 48504, *Email: cmahajan@kettering.edu*

[2] Department of Mechanical, Industrial and Manufacturing Engineering, University of Toledo, 2801 West Bancroft Street, Toledo, OH 43606, *Email: seyedalireza.rozati@rockets.utoledo.edu, anju.gupta@utoledo.edu*

Abstract

This senior design project centered on the design, fabrication, and testing of the Helmholtz Coil to generate uniform magnetic field that was used to align ferromagnetic metal ink based functional surfaces. Helmholtz coils are utilized to generate homogeneous magnetic fields for a number of applications due to their ease of construction and tunable magnetic fields. This makes them particularly suitable for calibrating sensors and a variety of other applications using low frequency magnetic fields. This study presents theoretical and experimental analysis of magnetic field homogeneity of circular Helmholtz coils pairs with respect to diameter of coils, length and applied current. The thermal behavior of the Helmholtz coils is presented by means of IR thermal imager. This multidisciplinary project provided hand-on experience in the manufacturing engineering, measurements and instruments, and materials science and engineering.

Introduction

ABET requires engineering programs to induce professional and technical among students at all levels. Senior design courses provide an excellent avenue to challenge advance undergraduate students to apply core concepts to create a functional product. This paper describes a materials and manufacturing engineering focused senior design project performed at the Mechanical, Industrial, and Manufacturing Engineering Department at the University of Toledo (UToledo) in collaboration with Kettering University. This objective of this project was to create a device that will generate a uniform magnetic field required to align ferromagnetic inks that are being developed under several collaborative research efforts between the two institutions. This unique co-institutional senior design project was designed to address the challenges of securing industry senior design project partnership due to COVID-19 pandemic and lockdown. These disruptions resulted in limited participation from several industries who have been historically supporting the senior design projects. In the pursuit of providing a holistic experience to their senior design team primarily focusing on communication and partnership with external entities, the faculty advisor outreached their research collaborators at Kettering University (KU). KU being a primarily undergraduate institution emphasizes on “practice meets theory in equal measure” served as the client for the senior project. This also presented an opportunity for exchange of ideas on senior design course assessment and outcomes between the two institutions.

Functional surfaces are the requirement of several industrial and engineering applications. Specifically, surface patterning with metallic structures is an important tool for different biomedical [1] and engineering applications [2]. Traditional patterning techniques such as soft lithography [3], microcontact printing [4] or stencil micropatterning [5] have been used to fabricate microstructures, however, they require expensive tooling and multi-step processes which increase the fabrication time. With the recent advancement in additive manufacturing techniques, considerable efforts have been demonstrated to pattern desired structures on different surfaces [6-8]. The simplicity, cost-effectiveness, and freedom of changing the design on the fly make additive manufacturing techniques the best option available for patterning surfaces. Most of these techniques uses materials in the form of inks or pastes and are often classified as either nanoparticle inks or precursor inks. Metallic inks of copper, nickel, and silver are most used to fabricate features for electronics and sensing applications. For magnetic applications, metals such as iron, cobalt, and nickel are prime candidates due to their magnetic properties. Among these, nickel shows good corrosion resistance and electrical conductivity. Nickel ink when sintered or reduced in presence of homogenous magnetic field, produces aligned structures in the direction of the magnetic field [2]. Patterned surfaces with such alignment show potential for anisotropic properties which opens door for biomedical applications. Therefore, a need exists to reduce and/or sinter such inks in presence of uniform magnetic field. A uniform magnetic field is one that has the same strength and direction at all points [9]. In practice, a uniform magnetic field can be difficult to create. One of the common ways to produce magnetic field that is uniform over a specific region is to use a Helmholtz coil. A Helmholtz coil is a device composed of two identical coils made of a ferromagnetic material that becomes electromagnets and produces a nearly uniform magnetic field between them when current is passed through them. These coils are placed a coil’s radius apart from each other. Due to ease of assembly and compact nature of the apparatus, Helmholtz coils are useful laboratory and testing tools.

The objectives of the senior design project were to a) create collaborative senior design opportunities between the two institutions due to limited industry partnerships availability during the, and b) design a Helmholtz coil to be used with a temperature changing device between its two coils. The senior design team, graduate student, and faculty advisors were located at the UToledo. The senior design took on roles of project managers, safety manager, designer, and tester. The online teaching and meeting tools developed during the onset of COVID-19 pandemic were leveraged to maintain communication between the participants on weekly basis. The advisors and the students met in-person at the University of Toledo’s Senior Design Clinic. Additionally reports and presentations documents were communicated through a shared drive. The end product of this project involved a hot plate integrated with the Helmholtz coil to achieve high temperature sintering (< 300 °C) in presence of uniform magnetic field. Nickel ink was drop casted on a copper chip and sintered at high temperature. The sintering of the nickel ink in presence of uniform magnetic field generated aligned pattern. Such nickel structures can be easily manipulated during the sintering process in presence of magnetic field to produce different novel structures for wide range of applications. This paper focuses on the design and product development aspects of the multidisciplinary senior design project centered on concepts of advanced manufacturing, heat transfer, measurements and instrumentation, and material science and engineering.

Design and Fabrication:

The coils were fabricated by wrapping a magnet wire (BNTECHGO 16 AWG Magnet Wire) onto the plastic bobbins with outer diameter of 6 inches made of UHMW polyethylene plastic. The two coils were set a distance apart that is equal to the radius of the coils, marked on the base plate of the design. This distance helps the uniformity of the magnetic field. The coils were identically wrapped and connected in series, so when a current is run through the coils, it generates the magnetic field. The base and mounts of the coils were made of aluminum 6061 as seen in Figure 1. A magnetic sensor (PocketLab Voyager) was used to measure the magnetic field with respect to time and position. The sensor holder was 3D printed using the PLA filament, and it moves along the track through the centerline of the coils to gather the graphs for the full range of the magnetic field. A 60 W mini hotplate was used to achieve sintering at high temperatures. The hotplate has a temperature range up to 300 °C and was placed such that the sintering takes place in the centerline of the coils.

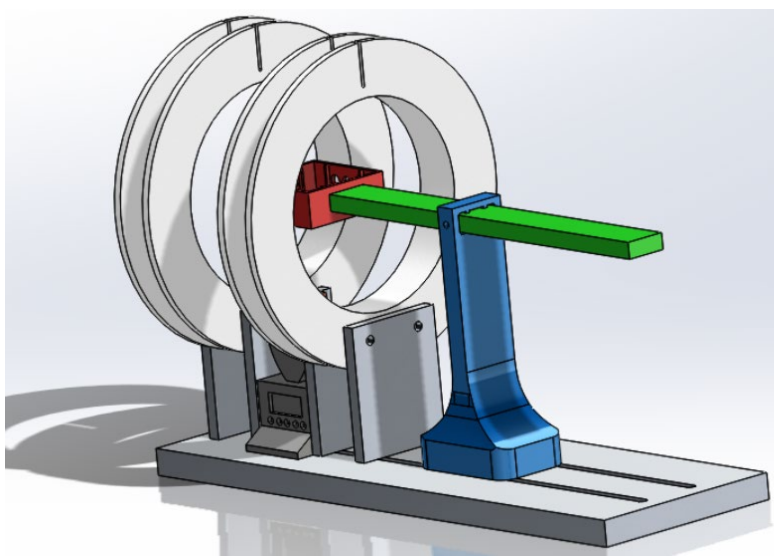

Figure 1: Final Prototype CAD Design

Feasibility Test:

To validate the design and assembly of the Helmholtz coil, the magnetic sensor was used to monitor the magnetic field strength with respect to the coil position. Theoretical values for the magnetic field of two Helmholtz coil with respect to the current passed was determined using Equation 1.

$$B = \mu_0 \frac{8 * I * N}{\sqrt{125} * R} \qquad Eq. 1$$

Where B= magnetic field strength, I= coil current (amps), N= Number of turns in each coil (138 turns), R= coil radius and distance between the coils (0.055 m), and μ_0= vacuum permeability ($4\pi \cdot 10^{-7}$ T*m*amp^{-1}).

Figure 2 shows the magnetic field strength with respect to the sensor position. The start of the coils is around 0.05 m and 0.125 m. During this distance, the magnetic field is uniform and sits around -6000 µT. The percent variation between the theoretical and measured magnetic field is 8.03%. The differences increase with the magnitude of the magnetic field. This could be due to the smaller size of the coils with an increasing current, so the field actually has a smaller magnitude than the theoretical. Increasing the size of the coils would increase the number of wraps in the wire, which would increase the strength and stability of the magnetic field. The magnetic field is uniform and stable in-between the coils, and steadily increases as the amps increase, but also stops recording after the limit of the sensor has been reached. The field strength increased by around 1000 µT with each 0.5 amp increase.

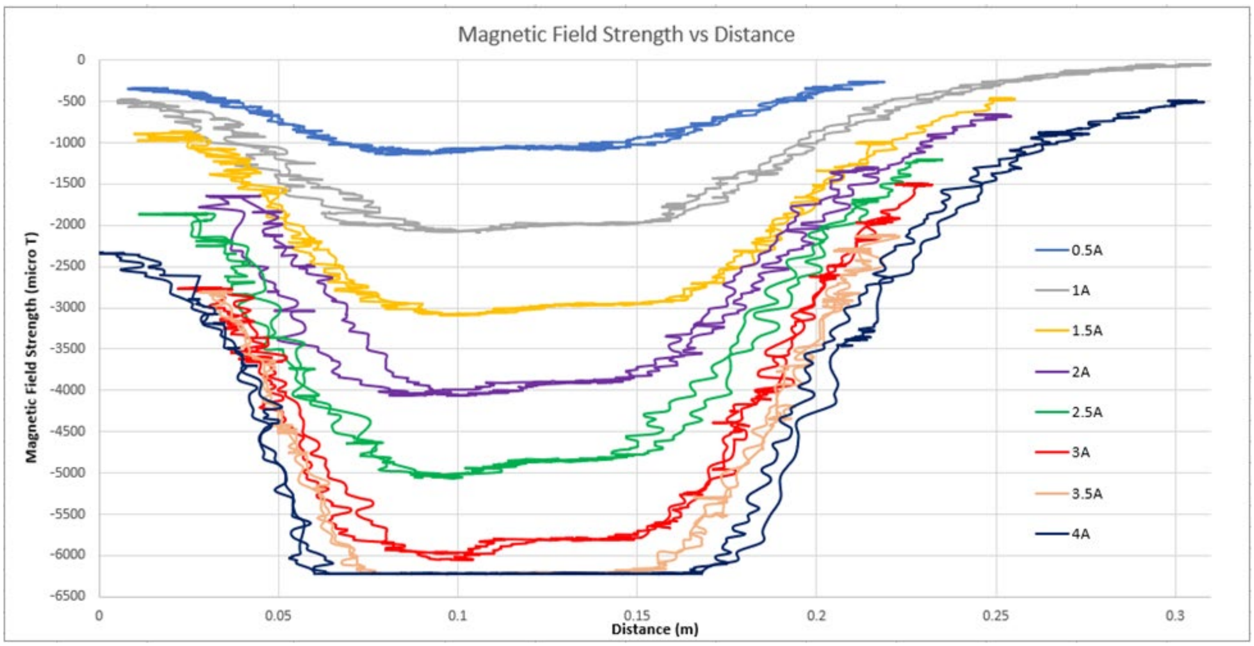

Figure 2: Magnetic field strength vs distance

High Temperature Sintering:

To observe the effect of sintering in presence of uniform magnetic field, nickel MOD ink was formulated as described by Mahajan et al. [2]. Nickel MOD ink is a homogenous particle free solution which when sintered at 240 °C reduces to elemental nickel in forms of nanoparticles. The alignment of these nanoparticles is influenced by the direction of the magnetic field. A copper chip was used as a substrate on which the nickel ink was drop casted. 10 µl of ink was placed and spread on the surface of the copper chip. The chip was later placed on the mini hot plate and positioned in between the two coils such that nickel ink is at the centerline of the two coils.

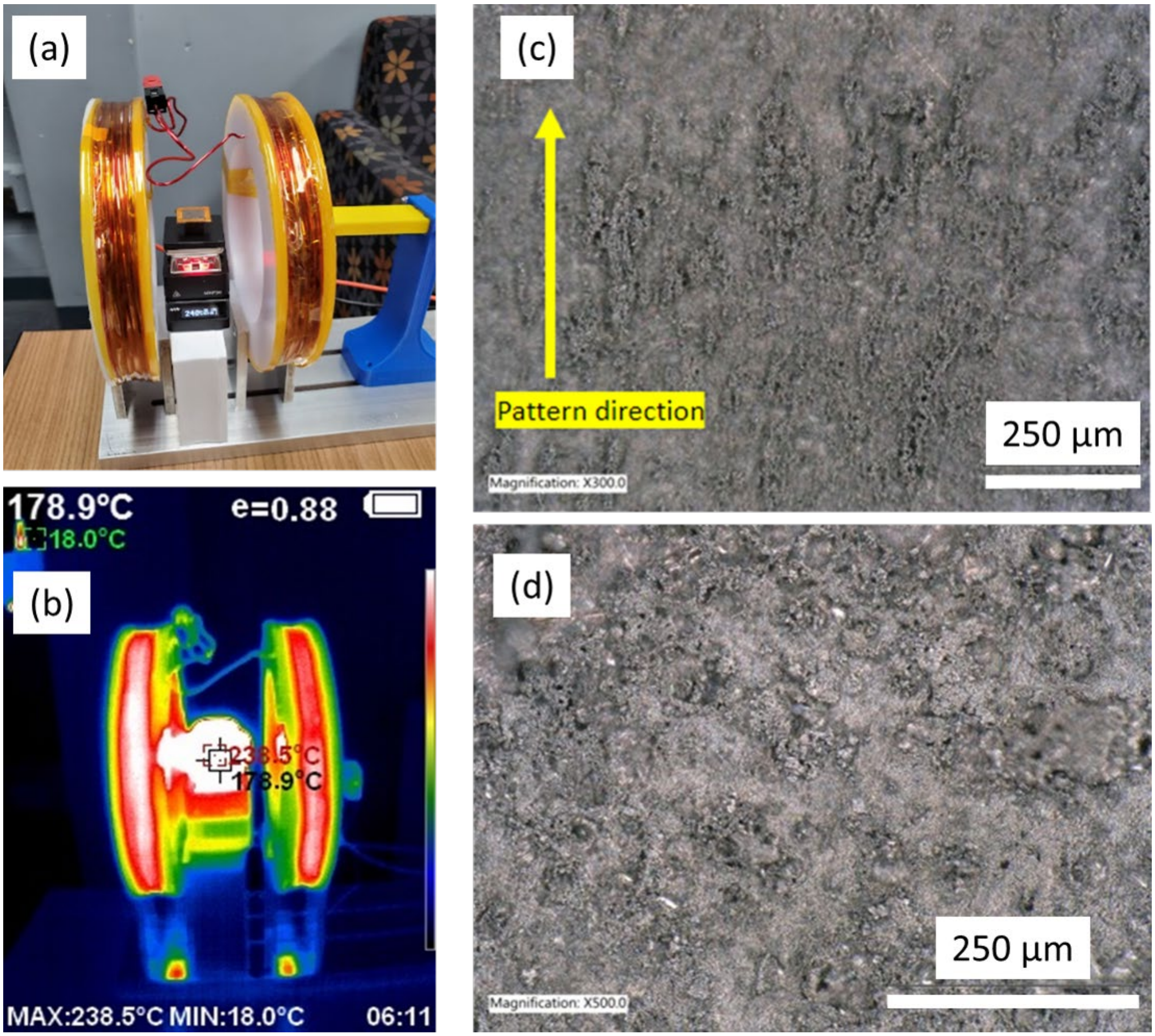

Figure 3: (a) Setup of the copper chip on the hotplate. (b) IR thermal imager confirming the temperature of the hotplate. (c) Micrograph of aligned nickel nanoparticles due to presence of homogenous magnetic field. (d) Micrograph of unaligned nickel nanoparticles due to absence of homogenous magnetic field.

Figure 3 (a & b) shows the setup of the copper cube on the hot plate, right when it got up to the correct temperature of 240 °C. Samples sintered in the presence of magnetic field showed prominent alignment as seen in Figure 3 (c). No such alignment was observed when the ink was sintered in absence of magnetic field (Figure 3 (d)). The client requirements were meet by successfully designing and fabricating the Helmholtz coil with temperature changing hotplate to achieve high temperature sintering.

Conclusions and Future Work:

This senior design project between the two institutions presented a unique opportunity of collaboration, communication, and exchange of ideas for a holistic senior design experience during the COVID-19 disruptions. The traditional role of an industry client was fulfilled by an external research collaborator from KU who was well-versed with educational outcomes, and the practical aspects of the senior design project. The senior design students successfully demonstrated magnetic field homogeneity of the Helmholtz coil integrated with a hotplate. The uniform magnetic field generated by the coil produced aligned nickel nanoparticles in the direction of the magnetic field. No such alignment was observed with the nanoparticles in the absence of the magnetic field. For future work, the size of the bobbins could be increased to allow sintering of the large substrates. With larger bobbins, the coils would be able to withstand a higher current and therefore higher heat, for longer periods. When the current setup was left at 5.5 amps for an extended time, the coils got very hot and needed a cool-down period. Lastly, another sensor that can measure a higher magnitude of magnetic field strength would be more beneficial in this project, so the higher currents which induced higher magnetic field magnitudes values could be obtained, in addition to the theoretical values.

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