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Faculty of Electrical Engineering

BACHELOR THESIS

Applications of Novel Magnetic Materials in the Design of Electric Current Sensors

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ZADÁNÍ BAKALÁŘSKÉ PRÁCE

I. OSOBNÍ A STUDIJNÍ ÚDAJE

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II. ÚDAJE K BAKALÁŘSKÉ PRÁCI

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Aplikace nových magnetických materialů při konstrukci senzorů elektrického proudu

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Applications of Novel Magnetic Materials in the Design of Electric Current Sensors

Pokyny pro vypracování:

Ověřte možnosti 3D tisku materiálů s příměsí feromagnetických částic. Charakterizujte magnetické vlastnosti a homogenitu vytvořených struktur a posuďte jejich aplikovatelnost pro senzory elektrického proudu. Zhodnoťte vhodnost použití vámi vytištěného jádra pro zvolený typ senzoru, vytvořte funkční vzorek a určete jeho metrologické parametry.

Seznam doporučené literatury:

P. Ripka, A. Tipek: Modern Sensors Handbook
H. Kronmüller, S. Parkin: Handbook of Magnetism and Advanced Magnetic Materials
R. Pallás-Areny, J.G. Webster: Analog Signal Processing
K. Draxler, P. Kašpar, P. Ripka: Magnetické prvky a měření
M.G. Larson, F. Bengzon: The Finite Element Method: Theory, Implementation, and Applications

Jméno a pracoviště vedoucí(ho) bakalářské práce:

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III. PŘEVZETÍ ZADÁNÍ

Student bere na vědomí, že je povinen vypracovat bakalářskou práci samostatně, bez cizí pomoci, s výjimkou poskytnutých konzultací.
Seznam použité literatury, jiných pramenů a jmen konzultantů je třeba uvést v bakalářské práci.

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Datum převzetí zadání Podpis studenta

Declaration

I declare that this thesis is my own work supervised by Ing. Václav Grim, MSc. and supported by the sources listed as references.

In Prague 1. ledna 2022 ....

David Ježek

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Abstract

The aim of this work is to verify the possibility of creating objects from materials with ferromagnetic particles using two types of 3D printing and mould casting. Furthermore, to determine the suitability of these materials for the construction of electric current sensors. For this purpose, the electric current sensors and magnetic materials are described in the theoretical part of the thesis. In the practical part, the methods for fabricating the objects are tested and evaluated. The resulting products are evaluated for their magnetic properties, homogeneity and it is assessed if the material is suitable for a fluxgate sensor.

Abstract (Czech)

Cílem této práce je ověřit možnost tvorby objektů z materiálů s příměsí feromagnetických částic za pomocí dvou typů 3D tisku a lití do formy. Dále určit vhodnost těchto materiálu pro konstrukci senzorů elektrického proudu. Za tímto účelem jsou v v teoretické části práce popsány senzory elektrického proudu a magnetické materiály. V praktické části jsou metody výroby objektů otestovány a zhodnoceny. Výsledné produkty jsou zhodnoceny podle jejich magnetických vlastností, homogenity a je posouzeno jestli je materiál vhodný pro fluxgate senzor.

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Nomenclature

B	Magnetic induction [T]
C	Curie constant [K]
E	Electric field [V/m]
F	force [N]
H	Magnetic field [A/m]
I	Eletric current [A]
L	length [m]
M	Magnetization [A/m]
N	Number of turns/components [1]
Q	Eletric charge [C]
R	Eletric resistance [Ω]
T	Temperature [K]
U	Eletric voltage [V]
V	Volume [cm^3]
$V_{\%}$	Volume fraction [1]
e	Elemental electric charge [C]
m	weight [g]
$m_{\%}$	weight fraction [1]
t	time [s]
v	velocity [m/s]

Greek symbols

μ_O	Vacuum permeability [N/A]
μ_r	Relative permeability [1]
Φ	Magnetic flux [Wb]
ρ	Density [$\mathrm{g} \cdot \mathrm{cm}^{-3}$]

$\rho_{\%}$	Density fraction [1]

List of abbreviations

3D	three dimensions
AC	alternate current
AMR	anisotropic magnetoresistance
CAD	computer-aided design
CMR	colossal magnetoresistance
CT	current transformer
DC	direct current
EDS	energy-dispersive X-ray spectroscopy
EELS	electron energy loss spectroscopy
FRM	feromagnetic resonance
GMR	giant magnetoresistance
MFM	magnetic force microscopy
MOKE	megneto-optical Kerr effect
MR	magnetoresistance
OA	operational amplifier
PCB	printed circud board
PLA	polylactic acid
SQUID	superconducting quantum interference device
TMR	tunneling magnetoresistance
TPU	thermoplastic polyurethane

1. Introduction

Electric current measurement plays an important role in many industries and research. The demands placed on electric current sensors therefore vary depending on their application. The basic requirement is the accuracy of the measurement of either AC or DC current. The development or improvement of existing current sensors is necessary to meet the increasing demands placed on them.

This work deals with the use of new magnetic materials for the construction of electric current sensors with a special focus on 3D printing. In the first part, we discuss methods for measuring electric current with a main focus on magnetic field sensors. The most commonly used types of magnetic field sensors, their design and properties are presented here. Next, we look at new magnetic materials as they relate to magnetic field sensor applications, with a focus on nanomaterials and magnetic composites. For composites, a mathematical model of their magnetic properties has been created. The experimental part of this thesis deals with the production of magnetic cores by mould casting and 3D printing. The magnetic properties of the created structures are described and the possibility of their use for electric current sensors is assessed. The last part describes the properties of the created fluxgate sensor and the issues of the used methods for creating magnetic structures.

2. Current measurement

Electric current is caused by the movement of charged particles through an electrical conductor or space. Charged particles (charge carriers) can vary depending on the type of environment they pass through. In the case of metallic conductors, the charge carrier is the free electron. In semiconductors, the charge is carried by electrons or holes. In electrolytes and plasma, charge is carried by ions and, in the case of plasma also by electrons. The passage of charge carriers through the environment generates a magnetic field and can cause physical or chemical changes in the environment.

The unit of electric current is the Ampere. It is the basic unit in the international system of units. It is defined using the second and the fixed numerical value of the elementary charge $e = 1.602176634 \cdot 10^{-19}$. It is based on the knowledge of the quantum Hall effect, which introduces resistance, the Josephson effect, which introduces voltage, and Ohm's law I=U/R. The basic mathematical formulations for electric current is $I = Q/t$.

Electric current can be divided into two groups according to how the charge moves. In the case of alternating current (AC), there is a periodic reversal of the direction of flow of charged particles as opposed to direct current (DC) for which the charged particles move in one direction.

Electric current measurement is concerned with determining how much current flows through a system or its phases. Measurement methods can be divided into two subgroups: direct measurements and indirect measurements.

2.1 Direct measurement

In the case of direct measurement, the measuring element is connected directly to the electrical circuit. This means that the sensor becomes part of the conductor carrying the measured electric current. In practice, two types of sensors are primarily used. The first type is a resistive current sensor, and the second type is based on a current to voltage converter (uses a transistor).

The main disadvantage of methods using direct measurement is the necessity to interrupt the conductor for which we want to measure the electric current. Also, the output of the sensor is directly electrically connected to the conductor carrying the current to be measured, which can be dangerous.

2.1.1 Current sense resistor

This type of sensor takes advantage of the fact that passing an electric current through a conductor causes it to heat up (called Joule heat) [1]. This energy conversion causes a voltage drop across the conductor that can be measured. From the measured voltage, the value of the measured current can then be easily back-calculated using Ohm's law. If high measurement accuracy is not required, then in certain cases the voltage drop can be measured directly on the original conductor which is usually made of copper. Thus, it is not necessary to disconnect the electrical circuit by connecting the sensor. Furthermore, compensation for the change in resistance caused by heating of the conductor is often used.

Advantages:

- simplicity
- low cost

Disadvantages:

- heat generation and associated cooling problems

2.1.2 Current-voltage converter

This type of sensor uses an operational amplifier (OA) for its operation. OA include transistors. The main advantage is that their connection to the measured circuit does not create a voltage drop. Furthermore, their connection to the circuit is usually quite simple.

The advantages and disadvantages of this type of measurement depend on the wiring of the OA in the system to be measured and the characteristics of the OA [11].

2.2 Indirect measurements

Sometimes it is not possible to use direct measurement of the electric current, which results from their disadvantages [14]. In these cases, we then use an indirect measurement that eliminates these disadvantages. However, since the sensor is not in contact with the conductor that carries the current to be measured, the output may depend on its position relative to the conductor, or the output may be affected by interference from the environment. These problems can be counteracted by appropriate sensor design (using a closed magnetic circuit with a measured conductor inside or using sensor arrays) or by processing the output signal.

2.2.1 Current transformer

A current transformer (CT) is a device capable of reducing or increasing AC. It contains windings, magnetic circuit and insulation. The magnetic circuit of CT (core) is usually made up of layers of high permeability material arranged to maximize the magnetic flux in the core and avoid eddy currents. In certain cases, the core may be made of air or may be a single piece of material. A CT standardly contains two windings: a primary and a secondary but may contain more.

The purpose of the primary winding is to convert electrical energy into magnetic energy in the form of magnetic flux. This flux is then conducted through the magnetic circuit (core) to the secondary winding, where electrical voltage is induced according to Faraday's law of induction:

$$u_s = -N_s \frac{\mathrm{d}\Phi}{\mathrm{d}t} \tag{2.1}$$

If the primary and secondary windings carry the same magnetic flux (ideal case) then from the law of conservation of energy and the law of induction we get the ideal transformer equation:

$$\frac{N_p}{N_s} = \frac{U_p}{U_s} = \frac{I_s}{I_p} \tag{2.2}$$

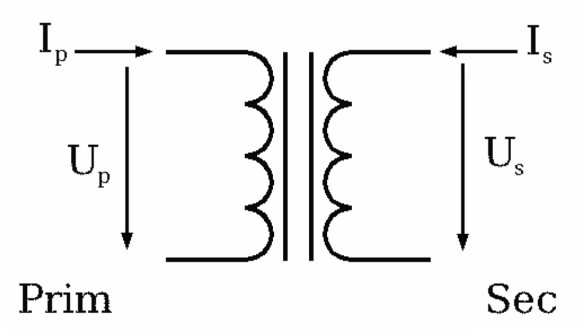

Figure 2.1: current transformer

For AC measurement using CT, it is suitable to select the correct core depending on the AC frequency. For low frequencies, cores wound from tape made of high permeability material are often used. Next, a primary must be made using a conductor that carries the measured current. If the value of the measured current is in the tens of amperes and above, it is possible to realize the primary winding with a single conductor passing through a hole in the core. The secondary winding should ideally be shorted, but for measurement purposes a small resistor or current-to-voltage converter is connected to it. The output signal is affected by the losses on the core, the resistance connected to the secondary winding and the resistance of the two windings themselves.

Advantages:

- simplicity and easy installation
- low cost

- long life with invariant parameters

2.2.2 Rogowski coil

A Rogowski coil is a device for measuring AC or high frequency electrical pulses. It consists of a wire coiled into a helix. The wire coming out of one end of the helix is pulled through the inside of the helix so that one end of the helix contains both ends of the wire. The resulting structure is attached to a hard toroid or flexible material. For measurement, it is placed around the conductor to be measured.. The Rogowsiki coil does not contain a ferromagnetic core. Its principle of operation is similar to CT and when it is in the air then Ampere's law applies to it

$$\oint_L B \,\mathrm{d}l = \mu_0 \, i_L, \tag{2.3}$$

where L is central line of coil. For the measurement it is recommended that the coil is wound accurately and its cross-section is constant along its length. The output signal from the coil should be adjusted using an integrator. Two types of integrators are used, passive and active. A passive integrator can be used for a large range of output signals and consists of passive electronic elements (resistor and capacitor in series). In the case of an active integrator, its electrical circuitry contains a amplifier with feedback to improve its output signal when the input signal is small.

Advantages:

- rigid or flexible design
- absence of metal core (linearity of measurement, response to fast changing currents)
- low cost
- easy temperature compensation

Disadvantages:

- necessity of signal processing by integrator

2.2.3 Fluxgate

A fluxgate is a type of sensor that measures a static or low frequency magnetic field. Its basic structure consists of three parts: excitation winding, core and sensing winding. According to the orientation of the excitation winding relative to the sensing winding, the Fluxgate sensor is divided into two types: parallel and orthogonal [9]. The principle of operation in both cases is the same. It uses the periodically varying permeability of the soft ferromagnetic core, which is caused by the periodic current passing through the excitation winding. Thus, when the sensor is exposed to an external magnetic field, the soft core becomes more saturated in the direction of the field. When saturated, the permeability of the core will decrease and therefore the measured magnetic field will decrease. The induced voltage on the sensing winding then contains the second and higher harmonic components of the excitation frequency. The desired part of the sensor output is the voltage amplitudes of the higher harmonic components, which correspond to the external magnetic field.

It is advisable to choose the correct shape of the fluxgate sensor for measuring the electric current. The most used type is the "parallel" type with ring cores. The conductor which leads the measured current through the opening of the ring cores.

Advantages:

- simple design
- high accuracy
- long life with invariant parameters

Disadvantages:

- inability to measure AC with a frequency of more than a few kHz
- signal post-processing

2.2.4 Hall effect sensor

A Hall effect sensor is a type of sensor that detects the presence and strength of a magnetic field using the Hall effect. It consists of a strip of material (usually a semiconductor) that is connected to a power circuit and a measuring circuit. For best results it is recommended that the direction of electric current, magnetic field and voltage gradient are perpendicular to each other. Hall effect depends on the fact that when a permanent magnetic field is applied to the conducting strip, the movement of the charge carriers is influenced by the Lorentz force:

$$F = q(E + v \times B) \tag{2.4}$$

For the measurement of electric current, it is usually used to place the Hall sensor in a gap in the magnetic circuit (core), which is around the conductor that carries the measured electric current. To improve the linear response of the sensor, a compensating winding is often added to the magnetic circuit, which then allows the Hall sensor to act as a zero flux indicator. This configuration makes the measurement more accurate, reduces dependence on the sensor position and increases resistance to interference. Another circuit option is to use multiple Hall sensors arranged around a given conductor, which avoids errors due to core characteristics.

Advantages:

- simplicity and possibility of use in PCB connections

Disadvantages:

- accuracy

2.2.5 Magnetoresistance sensors

Magnetoresistance (MR) based sensors can use several principles: anisotropic (AMR), giant (GMR), tunneling (TMR), colossal (CMR) and other Mrs.

The AMR effect is based on the change in electrical resistance of ferromagnetic materials (Permalloy) depending on the angle between the direction of current flow and magnetization. This is caused by simultaneous action of magnetization and spin-orbit interaction.

The GMR resistance depends on the arrangement of the ferromagnetic layers with relation to the magnetization vector. The overall resistance is relatively low for parallel alignment and relatively high for antiparallel alignment.

The TMR effect is based on the tunneling of electrons from one ferromagnetic layer to another through the extremely thin insulation (few nanometers) between them. If the magnetization is parallel, there is a higher chance of electron tunneling and if it is antiparallel, the chance is reduced.

The CMR effect is a property of some materials (manganese-based perovskite oxides) in which the MR is orders of magnitude higher.

A magnetic circuit cannot be used to measure electric current using MR because the size of the MR sensor would cause too large a gap in the circuit. A large gap in the magnetic circuit will make the sensor susceptible to environmental influences (current, magnetic field). Therefore, wiring the sensors in a Wheatstone bridge is used to increase sensitivity and reduce thermal dependence.

2.2.6 SQUID

A SQUID (superconducting quantum interference device) is a very accurate magnetometer based on two superconductors separated by a Josephson junction. SQUID converts the flux threading its loop into voltage. This uses a macroscopic quantum phenomenon in which electrons tunnel through the Josephson junction.

For SQUID measurements, the device needs to be well shielded from the surrounding magnetic fields. It has a non-linear magnetic flux to voltage conversion characteristic. It excels at detecting flux changes, but a sensor array is required to detect current. Due to the need for shielding and cooling to achieve superconductivity, its operation is demanding.

2.2.7 Magnetooptical sensors

Magnetooptical sensors use the Faraday effect. This effect causes rotation of the plane of polarization by passing a linearly polarized beam through the magnetooptical sensor film to which an external magnetic field is applied. The sensors can be divided according to the magnetooptical material into uniform and fibre.

For the sensor to function properly, polarized light is required to enter the sensor, which can be achieved by using a polarizer or polarized light source. The resulting polarized light is captured by a detector which usually has a plane of polarization rotated 45 degrees with respect to the input. This angle determines how much the sensor responds to the change in polarization and the strength of its signal (the larger the angle, the more the sensor responds to the change, but the output signal is reduced).

Advantages:

- high dynamic range and bandwidth
- high resistance to interference

3. Magnetic materials

3.1 Classification

Classification of materials is based on the physical nature of magnetism in substances. When particles with an electric charge move, a magnetic field is created in their surroundings. Electrons and protons have an electric charge and move, so we can say that a magnetic field is created around them. The existence of magnetism is a natural property of all substances therefore in this sense every substance has magnetic properties [10]. The motion of an electron in its orbit around the nucleus produces the orbital magnetic moment of the electron. The spin motion of the electron induces the spin magnetic moment of the electron. Protons also move along certain orbits which induces the orbital magnetic moment of the proton. This orbital angular momentum is much smaller than the orbital angular momentum of the electron because the motion of the proton is also much smaller than the motion of the electron. The total magnetic moment of an atom is given by the vector sum of the magnetic moments of all electrons and protons. This moment then determines the magnetic properties of the material and the behaviour of the substance in a magnetic field [3].

According to the magnetic properties of the materials, they can be divided into five categories. The most common magnetism is paramagnetism and dimagnetism. At room temperature, most elements fall into these categories, but that doesn't mean their compounds do. Antiferromagnetism can also be observed for pure elements. Ferromagnetism is then only seen in compounds such as Ferrite (oxide). From these we still derive ferrimagnetic materials.

The first two groups mentioned show no magnetic interactions and are not magnetically ordered. For the remaining groups, magnetic ordering can be observed provided the required temperature is met. The last two groups mentioned can then be described as magnetic.

3.1.1 Diamagnetism

Diamagnetics are substances composed of atoms whose resulting magnetic moment is zero. The application of an external magnetic field to the substance causes a change in the motion of electrons which causes the formation of a magnetic field that acts against the external field. This property causes a decrease in the magnetic field in the substance from which it follows that these calves have a negative susceptibility.

All substances have a diamagnetic effect, but this can be masked by a paramagnetic or ferromagnetic effect. These include Cu, Zn, Ge, Hg, H, noble gases and type I superconductors.

3.1.2 Paramagnetism

Paramegnetic substances consist of atoms or ions that do not have fully occupied orbitals with electrons. This gives rise to a magnetic moment, but due to the thermal vibrations of the lattice of the paramagnetic substance the moments are oriented randomly. The resulting moment of a given substance is then zero. When an external field is applied to a paramagnetic material, the magnetic moments of the atoms/ions are partially arranged in the direction of the field. This causes the material to have positive magnetization and susceptibility. The above properties imply that the magnetization is dependent on the temperature of the material. This dependence is described by Curie's law:

$$M = \frac{C}{T} H \tag{3.1}$$

Examples of paramagnetic substances are Al, Sn, O, Cr, Na, Mg, Pt, copper sulphate, ferric chloride, ferric oxide and manganese chloride.

3.1.3 Ferromagnetism

In ferromagnetic substances, so-called magnetic domains (Weiss domains) are formed, which are regions in which the magnetic dipoles are identically oriented. The magnetic moments of the domains are randomly oriented in the substance, so the resulting moment is zero. By applying an external magnetic field, these domain moments are oriented in the direction of the field. Substances can maintain their magnetization to varying degrees even after the cancellation of the magnetic field. According to this, we can divide ferromagnetics into "soft", which can magnetise but do not want to remain magnetised, and "hard", which do.

Like paramagnetics, ferromagnetics are subject to random effects caused by heat. The limiting temperature that determines whether a material has ferromagnetic properties or not is called the Curie temperature. Exceeding it, the material loses its ferromagnetic properties and become paramagnetic.

An important property of ferromagnetic materials is magnetic hysteresis. This is a closed curve that describes the magnetization of a material as a function of the magnetic field. To plot the magnetic hysteresis, one magnetization cycle is required. The cycle starts by applying a magnetic field to the material so that saturation occurs. Then, by gradually changing the magnetic field, saturation is achieved in the opposite direction, which is performed twice to close the curve. Important values include the maximum magnetization, the residual magnetization (at zero magnetic field) and the magnetic field value for which the magnetization is zero. The shape of the loop is also important for use in sensors.

3.1.4 Antiferromagnetism

Antiferromagnetic materials are similar to ferromagnetic materials except that the interaction of neighbouring elements results in a anti-parallel arrangement of their magnetic moments. Due to this, the resulting magnetic moment of the material is zero, thus these materials seemingly behave in the same way as paramagnetic materials. As with ferromagnetic materials, when a certain temperature (Néel temperature) is exceeded they become paramagnetic.

3.1.5 Ferrimagnetism

Ferrimagnetism is similar to ferromagnetism and antiferromagnetism due to the arrangement of magnetic moments in the substance. It differs in that even if the magnetic moments in the substance are anti-parallel, their magnitude is different. This is due to the different composition in the building block of the substance.

Ferrimagnetic substances exposed to a variable magnetic field exhibit a hysteretic loop. In contrast to ferromagnetic materials, they usually have a lower saturation value.

Ferromagnetic materials include cubic ferrites composed of iron oxides.

3.2 Characteristic properties of magnetic materials

3.2.1 Permeability

Permeability (μ) is a physical quantity that expresses the effect of a particular material or environment on the resulting effects of an applied magnetic field. In some cases it can be considered as a material constant although its magnitude is dependent on temperature, the strength of the applied field and changes in the electric field. The basic formula is:

$$\mu = \frac{B}{H} \tag{3.2}$$

We usually describe materials using relative permittivity (μ_r), which is the value of the ratio of the permittivity of the material and the permittivity of vacuum ($\mu_0 = 1.26 \cdot 10^{-6}$):

$$\mu_r = \frac{\mu}{\mu_0} \tag{3.3}$$

3.2.2 Magnetization characteristics

The magnetization characteristics include the aforementioned hysteresis loop and the initial magnetization curve.

3.2.3 Curie point

The Curie point is the temperature at which a material loses its permanent magnetic properties, which can (in most cases) be replaced by induced magnetism.

3.2.4 Magnetostriction

Magnetostriction is the property of a material to change its dimension based on exposure to a magnetic field. The change can be in shape or volume.

3.3 New magnetic materials

The creation of new magnetic materials is a complex process. Currently, considerable attention is being paid to nanomaterials because of their unique properties. Nanomaterials are defined as materials that have a size in the range of 1 to 100 nm in at least one of their dimensions.

3.3.1 Magnetic Nanowires

Introduction, possible application

Magnetic nanowires feature unique properties that have attracted the interest of different research areas [8]. Their nanoscale structure makes them suitable for high-density magnetic recording, high-frequency devices, sensors, biotechnology, and medicine.

A magnetic nanowire is a single domain structure with a diameter of the cross-section in order of a nanometre. Their magnetic properties are connected to crystalline, shape anisotropy, geometry, and build material.

Fabricationn

Fabrication of magnetic nanowires can be divided into direct synthesis and template-assisted synthesis. Direct synthesis can use focused electron beam-inducted deposition .[2] or vapor deposition [6]. Template-assisted synthesis commonly uses nanoporous alumina membrane as a template due to its simplicity and versatility [13]. Aluminum-based templates are usually fabricated by a two-step anodization process, which could create highly ordered pores. The template is afterward filed by material or materials using electrochemical deposition. Magnetic nanowires are obtained by dissolving template.

Characterization

Characterization of magnetic nanowires is based on their magnetic, electrical, and physical properties. Due to advances in their fabrication and nano-manipulation, it is possible to create a system based on them. To utilize such system, comprehensive characteristics of magnetic nanowires or magnetic nanowires arrays are needed. Therefore, there are different methods for that. In the case of magnetic nanowires arrays, their collective characteristics provide only some insight into the magnetic properties of the single nanowire. That is caused by magnetic interactions between individual nanowires. Characterization of a single magnetic nanowire is more challenging caused by its overall small structure.

The basic characterization of magnetic nanowires is physical characterization. It serves as an examination of fabricated magnetic nanowires by check their geometry and composition using electron microscopy techniques (scanning electron microscopy, transmission electron microscopy), energy-dispersive X-ray spectroscopy (EDS) and electron energy loss spectroscopy (EELS).

For electrical characterization, is magnetic nanowire placed between two electrodes for the direct measure. There are two methods for achieving this. The first method is to place the nanowire on two existing electrodes, which required nanowire manipulation. The second method uses scattered nanowires, for which electrodes are created. The requirement for both methods is to establish proper electrical contact. In the measurement, afterward, the electric current must be limited in order not to damage the nanowire.

Magnetic characteristics of the nanowire can be determinate by anisotropy probing, magnetometry, and magnetization imaging. For anisotropy, probing can be used ferromagnetic resonance (FRM). This technique use resonance arising, when the frequency of alternating magnetic field, which is applied transversely, is equal to material Larmor frequency. Direct magnetic measurement of the nanowire can be done by fabricating micro-SQUID around it or by using the magneto-optical Kerr effect (MOKE). MOKE technique is used more often than the SQUID technique. Magnetization imaging is usually done by magnetic force microscopy (MFM).

3.3.2 Ferromagnetic nanoparticles

Ferromagnetic particles are a class of particles with the ability to be magnetized by an external magnetic field.

Nanoparticles and their subclass magnetic nanoparticles and nanowires are the type of particles with an overall size in the order of nanometer. Properties of nanoparticles mostly differ from their larger counterparts. Due to the possibility of optimization of their chemical and physical properties, they are suitable for various applications.

The fabrication of nanoparticles heavily depends on their structure. Fabrication methods are based on chemical reaction, gas or plasma condensation, or pyrolysis.

3.3.3 Soft Magnetic Composites

Soft magnetic composites are a combination of magnetic particles and electrically insulating material that have a structural supporting function. Their properties depend strongly on the arrangement of magnetic particles in their material [12]. Some of their desired unique properties are low eddy current loss, isotropic ferromagnetic behavior, thermal characteristic, material memory, simpler fabrication of complex 3D structures, weight, and cost reduction of products.

3.4 Magnetic materials for 3D printing

3D printing is a method for creating three-dimensional objects by depositing source material. Depositing is typically done layer by layer. Source material can be in liquid, solid, or loose form, depending on which type of printing method is used. The object creation process can be divided into three parts. The first part is about obtaining a 3D model by scanning an existing object or creating it with a computer program. The acquired 3D model is then managed for printing (adding structure supports, determinate the fill, creating instruction to the printer). The second part is about printing objects according to instructions. In the final part acquired object could be cleaned, cured, or the structural supports be removed.

Magnetic materials for 3D printing are a subclass of soft magnetic composites, except direct 3D printing using magnetic material.

3.4.1 Photopolymers

Photopolymers, although known as light-activated resin, are a subclass of polymers. Their physical properties change when they are exposed to light. In 3D printing are used photopolymers, which in contact with light, change their form from liquid to solid. Commonly used light in 3D printing is ultraviolet and is specifically targeted using a liquid-crystal display. Due to their liquid form, it is possible to add some particles to alter the properties of the resulting material.

3.4.2 Magnetic filaments

Filaments are pre-formed materials for 3D printing in the form of filament-like structures. Their magnetic versions are fabricated by infusing magnetic particles in the form of powder to base material. Base material enters the process in the form of colorless plastic pellets. Pellets with additives are afterward melted and properly mixed. The melt is extruded in the form of thread and enters the cooling area. After cooling, the filament is processed to usable form by winding.

4. Mathematical model

Mathematical modelling deals with the description of all relevant factors of a given situation and makes it possible to reveal the essential relationships between the elements of the system under study [5]. There are various mathematical models of existing systems. These models can be of two types: analytical or discrete (finite element).

Analytical models are simple to compute, but for practical applications they often do not provide enough accuracy. This is due to the approximation that may be necessary to create the model.

In the case of finite element methods, the system is discretized. From the obtained elements and their interdependencies, the inherent properties of the whole system can be deduced.

As part of this work, it is useful to estimate the properties of the magnetic composite, specifically the permeability. For its estimation we will use the mixing laws [4]. These laws estimate the property that describes a given composite material depending on its components, their quantity and their arrangement.

Since permeability is a volumetric property and the representation of the substances in the composite is given in weight percent as a standard, it is necessary to calculate the volume representation of the substances. For a two-substance composite the following applies:

$$\rho = \frac{m}{V} \quad \wedge \quad V_{\%} = \frac{V_1}{V_2} \quad \rightarrow \quad V_{\%} = \frac{m_{\%}}{\rho_{\%}}$$

The mathematical models will consider extreme cases of the arrangement of two substances in a composite. In the first case, the axis is a serial arrangement. The substances in this arrangement form thin layers lying on top of each other. The property of the composite is then measured through the layers. In the second case, the property of the composite is measured along the layers (parallel) and in the third case it is measured through the random distribution of material in the composite.

Serial:

$$\mu_{composite}^{-1} = \sum_{i=1}^{N} V_{\%} \mu_i^{-1} \tag{4.1}$$

Parallel:

$$\mu_{composite} = \sum_{i=1}^{N} V_{\%} \mu_i \tag{4.2}$$

Random:

$$\log(\mu_{composite}) = \sum_{i=1}^{N} V_i \log(\mu_i) \tag{4.3}$$

Figure 4.1 shows the dependence of the permeability on the volume fraction of both substances in the composite. The carrier substance of the hypothetical composite has a permeability equal to 1 and the magnetic substance has a permeability of 100.

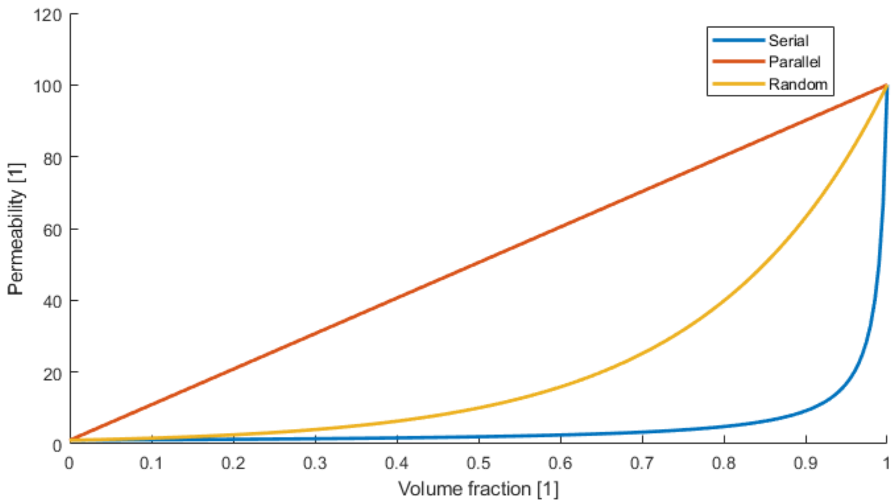

Figure 4.1: graph of mathematical models of the dependence of permeability on volume fraction

5. Experiment

The aim of the experimental part of this work is to create an electric current sensor that contains a core made of a ferromagnetic composite. Three methods were chosen to create the ferromagnetic core: 3D printing using filament, 3D printing using resin [7] and resin casting in a mould.Three sizes of cores were created:

- large with inner diameter 19.5 cm, outer diameter 20.5 cm and circular cross-section
- medium with inner diameter 9.5 cm, outer diameter 10.5 cm and circular cross-section
- small with inner diameter 3.6 cm, outer diameter 4.2 cm and rectangular cross-section (0.6 x 0.5 cm)

A control non-magnetic core was created for each size. The resulting magnetic cores were screened for their magnetic properties and further assessed for their suitability for the chosen sensor.

5.1 Mould casting

One of the methods used to produce magnetic cores is mould casting. Two types of moulds have been made for this purpose. The first type was made using 3D filament. The second type was made from two metal plates into which the desired shape was cut. Only the large and medium cores have been made. EPOX G20 was used as the carrier material. The additives were magnetite micro-powder, iron mico-powder and nickel-zinc-ferrite nano-powder.

The printed moulds, which were made of Polylactic acid (PLA) proved to be problematic due to their lack of rigidity and heat resistance. The metal mold did not show any significant deficiencies. Cores made from EPOX G20 often contained air bubbles. These may have been caused by the mould design or the dynamic properties of the resin/additive mixture. Two methods were tried to eliminate this problem. The first method consisted of heating the resin/additive mixture and the mould. This method showed a slight improvement. The second method consisted of using a vacuum chamber in which the casting into the mold was done. The use of this method exacerbated the bubble problem as the resin began to evaporate in the vacuum.

Another problem of producing cores by this method is the sedimentation of the magnetic powder. This problem was more pronounced for the magnetite micro-powder than for the nickel-zinc-ferrite nano-powder and depended on the position of the mold during solidification.

The pictures in the attachment show the produced cores and their defects.

5.2 Filament 3D printing

The production of cores using a filament 3D printer consists of creating a 3D model using Computer-aided design (CAD) software (Autodesk inventor), selecting the filament and then printing it. The Original Prusa i3 3D printer was used. Large and small sizes cores were printed in this way. The cores which were circular in cross section were printed in two parts and then glued together. Protopasta filament, which is made of PLA and iron dust, was used for the production, as well as filament made of TPU and hard ferrite.

Printing with magnetic filament presents several difficulties. The first problem can be the need to print at a higher temperature and the associated thermal deformation problems of the printout. Another problem is the ability of the filament to behave as an abrasive, which has caused scratching of the heat-break and subsequent filament jamming in the print head. Last but not least, it is almost impossible to make your own composite filament without the necessary equipment.

The cores printed by this method are practically almost homogeneous, the only shortcomings in homogeneity can be attributed to the printer's inability to fill the required volume. This problem is small and can be neglected compared to the homogeneity problems of other methods.

Pictures of the small cores produced by this method can be found in the attachment.

5.3 Resin 3D printing

Manufacturing cores using a resin 3D printer involves creating a 3D model and slicing it, mixing a composite of photopolymer and magnetic additives and then printing it. In addition, post-processing of the product is suitable, which includes cleaning and curing.

The Prusa SL1 3D printer was used in this experiment because of its ability to tilt the resin tank. The initial thought was that tilting the resin tank after each layer has cured is sufficient to mix the magnetic particles. However, after the first attempts to print the core, the sedimentation of all types of particles used proved to be too great.

To avoid sedimentation of the mix, two methods were tried. The first method used ultrasonic mixing, but its use did not produce a change in sedimentation rate. The second method used physical mixing of the resin directly in the resin tank of the 3D printer.

5.3.1 Mixing system

The mixing system is based on pumping the resin using a peristaltic pump between each curing cycle of the printer. For this purpose, the firmware of the 3D printer (Linux basted) was modified so that it could communicate with the mixing system. The communication was created using a standard USB-serial driver via ttyUSB0. Using this communication, a signal is sent after each curing of a layer is completed to a microcontroller (Arduino UNO), which controls a stepper motor with a peristaltic pump using a driver (BIGTREETECH TMC2130 V3.0). Furthermore, the peristaltic pump can be controlled by a button on the Arduino to fill or empty the mixing system. The full code for Arduino UNO is included in the attachment of this work.

Translated with www.DeepL.com/Translator (free version)

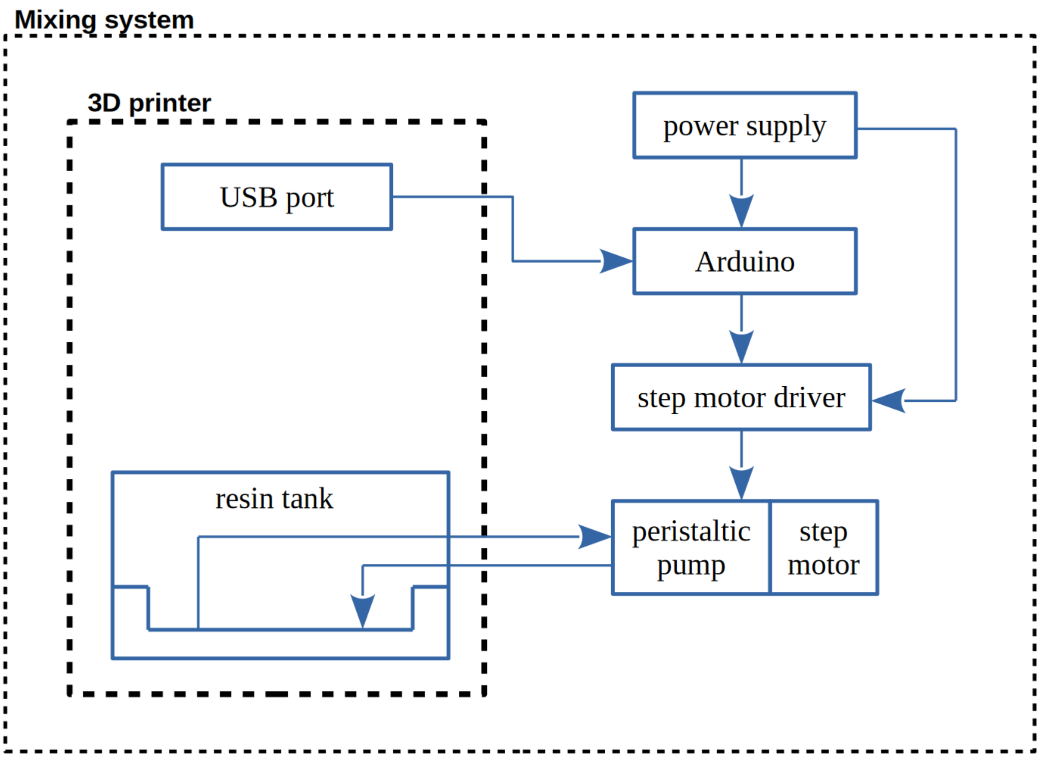

Figure 5.1: connection of the mixing system to the 3D printer

Four flow diffusers are used for the best possible mixing of the tank contents. They are oppositely positioned and because they are all connected to one peristaltic pump they work in pairs in reverse. One pair draws in the contents of the tub and the other pair returns it. For better mixing, the flow direction is reversed after each mixing cycle. Furthermore, the printing platform was trimmed to prevent sedimentation of particles on its upper side. This allows the particles to sink to the bottom of the tank where the flow from the mixing system can disperse them.

In the attachment of this work you will find pictures of the mixing system and other modifications on the 3D printer.

5.3.2 Prints

Due to the limited size of the printing patform, only small cores were printed. Prusa transparent tough resin, ferrite powder and flakes of nanocrystalline material were used to print them. In the case of the flake-resin composite, the print had flakes only in the first layer. Because the flake print exhibited extremely rapid sedimentation and the flakes were cutting the tubing in the peristaltic pump, their use was abandoned. Ferrite printing proved to be much more promising. Up to 10 wt% of powder in the print was achieved, although at this concentration the bonding of the individual layers of the print began to weaken. This meant that even a small change in powder concentration (e.g. a small unbroken lump) caused the print to spoil.

Despite the fact that the mixing system was designed to be easily disassembled, using this method is challenging. Due to sedimentation in different parts of both the 3D printer and the mixing system, it is advisable to clean both devices. This greatly prolongs and complicates the manufacturing process.

Using this method, cores with zero magnetic content, cores with 0.05 mass fraction of ferrite micropowder, and cores with 0.1 mass fraction of ferrite micropowder were created. For both concentrations, sedimentation of the magnetic powder in the resulting core was observed. Pictures of these cores are in the attachment.

5.4 Measurements

To measure the properties of the magnetic cores, the all cores were wound with 0.6 mm diameter copper wire. The wound cores were then connected to an HP 4284A precision LCR meter and their inductance at 1kHz was measured. To calculate the relative permeability we use:

$$\mu_r = \frac{L_{magnetic}\, N^2_{nonmagnetic}}{L_{nonmagnetic}\, N^2_{magnetic}} \tag{5.1}$$

	N [-]	L [μH]	μ_r [-]	$M_{\%}$ [-]	$V_{\%}$ [-]	μ_{serial} [-]	$\mu_{parallel}$ [-]	μ_{random} [-]
Epox	1276	291.62	1.00	0.00	0.00	1.00	1.00	1.00
Epox + Ni-Zn-ferite	965	156.92	0.94	-	-	-	-	-
TPU + hard ferrite	1810	640.43	1.09	0.40	0.236	1.30	14.92	2.63
Epox + magetite	1006	189.58	1.05	0.10	0.020	1.02	6.87	1.12
Protopasta	1277	484.31	1.66	0.33	0.078	1.08	390.92	1.94

Table 5.1: Large cores

From the results it can be seen that the fitted relative permittivity varied for the most part between the value calculated by the series model and the model for the random arrangement. For use in a fluxgate current sensor, the relative permittivity would need to be at least an

	N [-]	L [μH]	μ_r [-]	$M_{\%}$ [-]	$V_{\%}$ [-]	μ_{serial} [-]	$\mu_{parallel}$ [-]	μ_{random} [-]
Epox	465	71.57	1.00	0.00	0.000	1.00	1.00	1.00
Epox + magetit (vertical)	460	71.56	1.02	0.10	0.020	1.02	6.87	1.12
Epox + magetit (horizontal)	462	75.18	1.06	0.10	0.020	1.02	6.87	1.12
Epox + Fe	470	83.35	1.14	0.20	0.026	1.03	130.97	1.25

Table 5.2: Medium cores

	N [-]	L [μH]	μ_r [-]	$M_{\%}$ [-]	$V_{\%}$ [-]	μ_{serial} [-]	$\mu_{parallel}$ [-]	μ_{random} [-]
Resin	167	11.34	1.00	0.00	0.000	1.00	1.00	1.00
Resin + Ferrite (5%)	169	11.47	0.99	0.05	0.010	1.00	3.87	1.06
Resin + Ferrite (10%)	168	11.88	1.04	0.10	0.019	1.01	6.74	1.12
Protopasta	169	16.63	1.43	0.33	0.078	1.02	390.92	1.94

Table 5.3: Small cores

order of magnitude higher. From the above models, it follows that the volume fraction of magnetic material would have to be at least 0.5 in the random model and at least 0.9 in the series model. These values are practically impossible to achieve with current 3D printers but could be achieved by mould casting. To practically verify the unusability of the resulting cores, a hysteresis loop was subsequently measured for the sample with the highest relative permittivity and a dual-core fluxgate electric current sensor was created. The hysteresis loop was not observable only the magnetization curve. Measurements using the fabricated fluxgate current sensor showed no correlation between the magnitude of the current and the sensor output, and there were up to 70% fluctuations in the measured component of the signal.

6. Conclusions

The work is focused on the creation of new magnetic materials and their processing using 3D printing and moulding methods. It also discusses the possibility of using these materials and methods to create electric current sensors.

The practical part of this thesis is divided into four parts. The first three parts focus on the creation and processing of magnetic composites, where each part describes one method. The first method presented is casting a composite of resin and magnetic particles into a mould. Except for the initial mold making, this method is simple and, depending on the resin used, can be fast. However, its widespread use is still hampered by manufacturing defects (sedimentation, partial non-filling of the mould). Another method is printing using a filament 3D printer. This is a simple method, but the use of this method can be problematic until the problem of damage to the 3D printer parts by the composite filament is resolved. The last method is printing using a resin 3d printer. This is the most complex method used because of the vulnerability of the print.

The last part is about measuring and evaluating the results. All the magnetic cores created have a relative permeability too low to be used for fluxgate type current sensors. The values of the measured relative permeability were in principle consistent with the series mathematical model and the random arrangement model. This is because each magnetic particle in the composite is encased by at least a weak layer of resin. The feasibility is further checked by two experiments. For these experiments, protopaste cores (iron + PLA filament) were used because they exhibit the highest relative permeability. The first experiment attempted to measure the hysteresis loop and the second was to measure the electric current using a fluxgate sensor made from two of these cores. Both experiments proved the theoretical prediction that the materials created could not be used for a fluxgate sensor.

In order to continue the work, it would be advisable to improve the methods used. For casting into the mould, it would be possible to build a device that would rotate the mould during the solidification of several axes, which could prevent the sedimentation of magnetic particles. This could also allow the use of a lower-viscosity resin. In the case of a filament printer, it would be advisable to replace all components that may be damaged by friction against the composite filament. It would also be appropriate to create a custom composite filament. For the last method, several different methods could be used to improve, for example: speeding up the curing of the layers (by increasing the power of the UV light or increasing the reactivity of the potopolymer) or improving the mixing system (mixing in all directions of the tank or optimising the mixing time).

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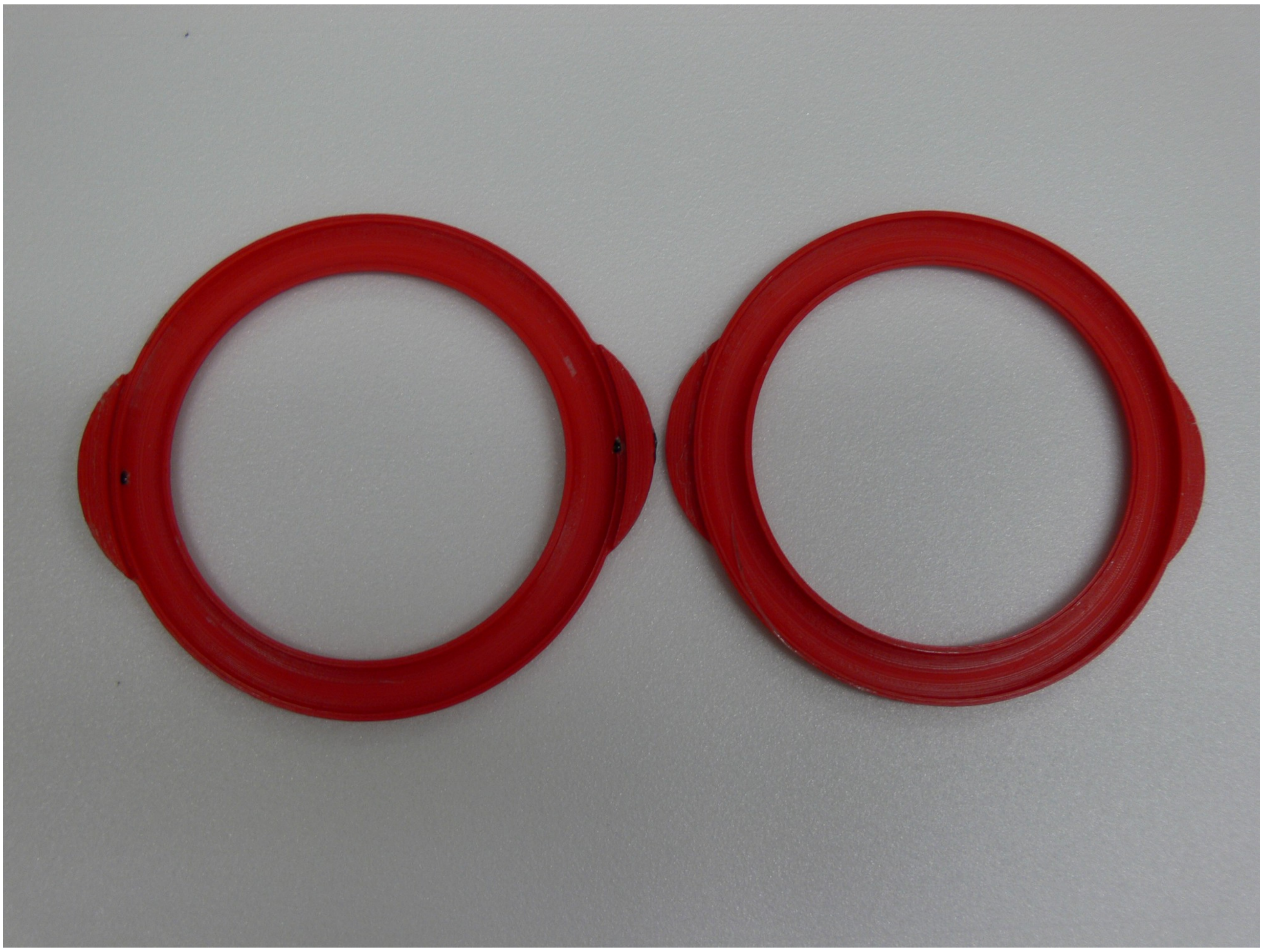
Attachments

Arduino UNO code:

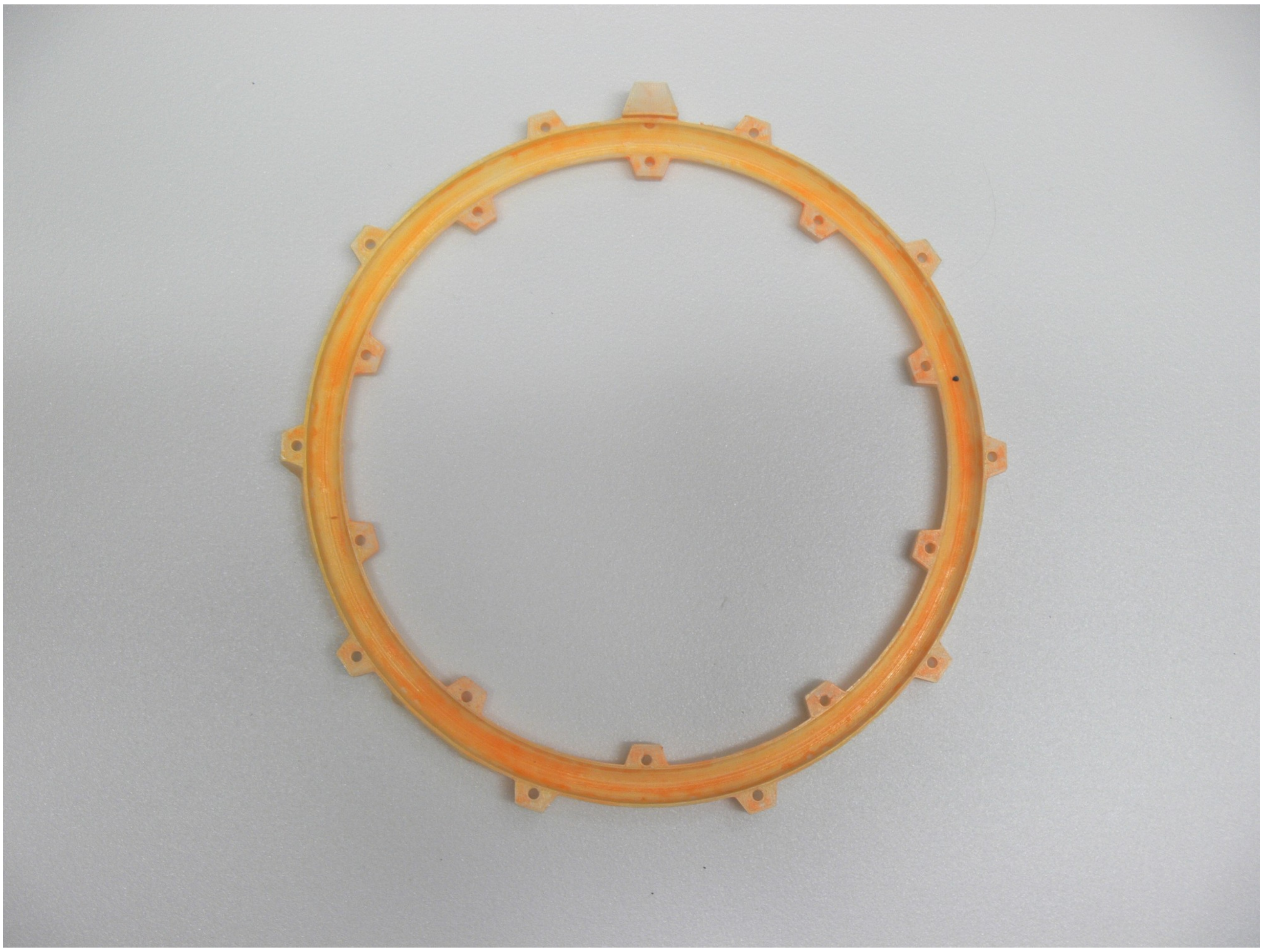
```
// Define pin connections & motor's steps per revolution
const int dirPin = 2;
const int stepPin = 3;
const int diodPin = 4;
const int ErrPin = 5;
const int btnPin = 6;
const int minSpeed = 500; //period f=1/T
const int MaxSpeed = 25; //period f=1/T
const int acc = 1;
bool start_btn = false;
bool start_serial = false;
bool change = false;
int curSpeed = 2000;

void setup()
{
  // set up Serial library at 9600 bps
  Serial.begin(115200);
  // Declare pins as Outputs
  pinMode(stepPin, OUTPUT);
  pinMode(dirPin, OUTPUT);
  pinMode(diodPin, OUTPUT);
  pinMode(ErrPin, OUTPUT);
  pinMode(btnPin, INPUT_PULLUP);

  digitalWrite(dirPin, HIGH);
}

int motor_step(int curSpeed, const int MaxSpeed, const int acc)
{
  digitalWrite(stepPin, HIGH);
  delayMicroseconds(curSpeed);
  digitalWrite(stepPin, LOW);
  delayMicroseconds(curSpeed);
  if(curSpeed > MaxSpeed)
    {
      curSpeed -= acc - int(acc * MaxSpeed / curSpeed);
    }
    else
    {
      curSpeed = MaxSpeed;
    }
  return curSpeed;
}

void loop()
{
```

```
  if(!digitalRead(btnPin))
  {
    start_btn = true;
  }
  else
  {
    if(Serial.available())
    {
      switch(Serial.read())
      {
        case 'S':
          start_serial = true; //start
          if(digitalRead(2) == HIGH){digitalWrite(dirPin, LOW);}
          else{digitalWrite(dirPin, HIGH);}
          digitalWrite(diodPin, HIGH);
          break;
        case 'F':
          start_serial = false; //finish
          digitalWrite(diodPin, LOW);
          break;
        default:
          break;
      }
      digitalWrite(ErrPin, HIGH);
      delayMicroseconds(1000);
      digitalWrite(ErrPin, LOW);
    }
    start_btn = false;
  }


  if(start_btn or start_serial)
  {
    curSpeed = motor_step(curSpeed, MaxSpeed, acc);
  }
  else
  {
    curSpeed = minSpeed;
    delayMicroseconds(100);
  }
}
```

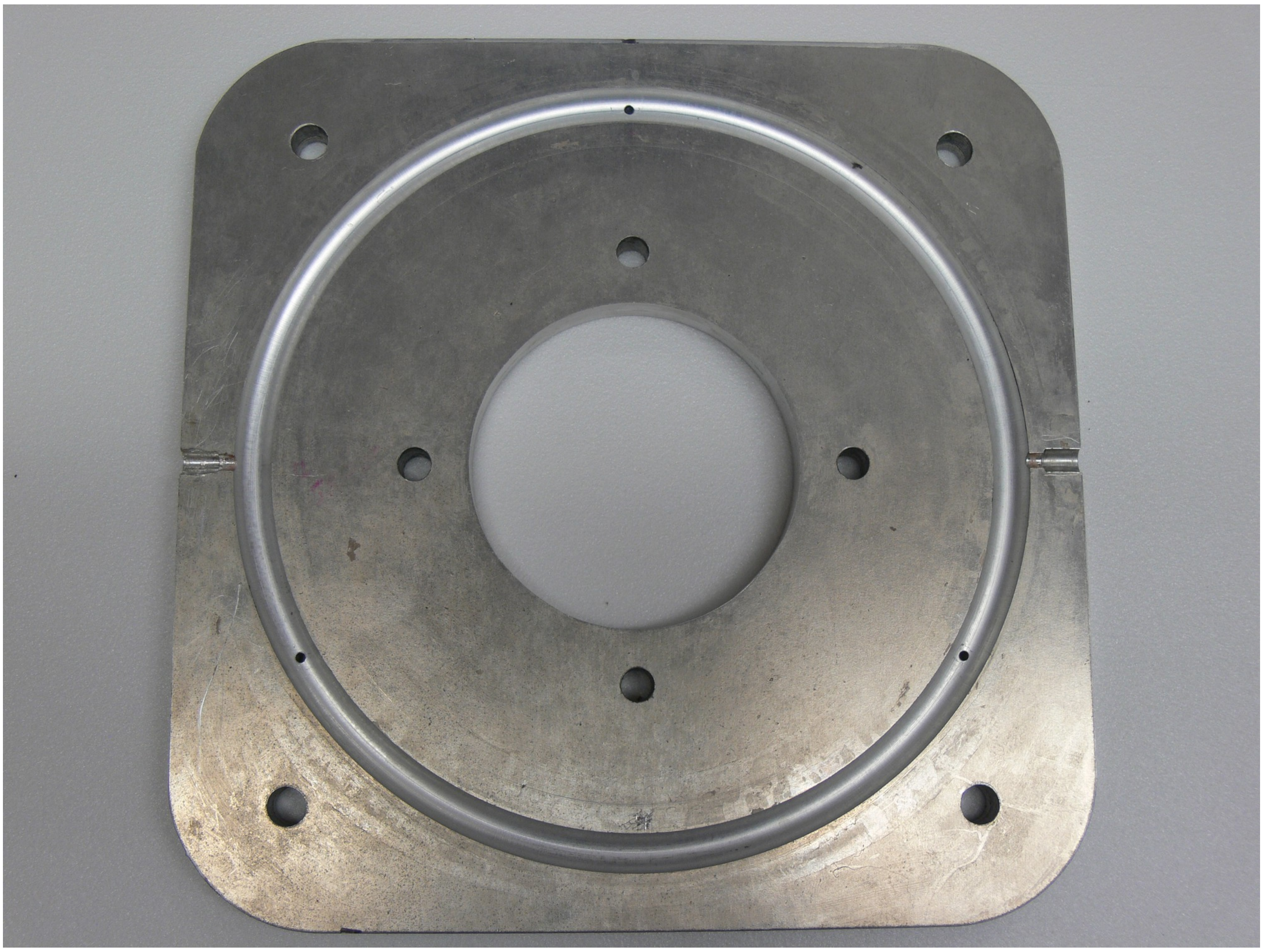
Medium PLA mould:



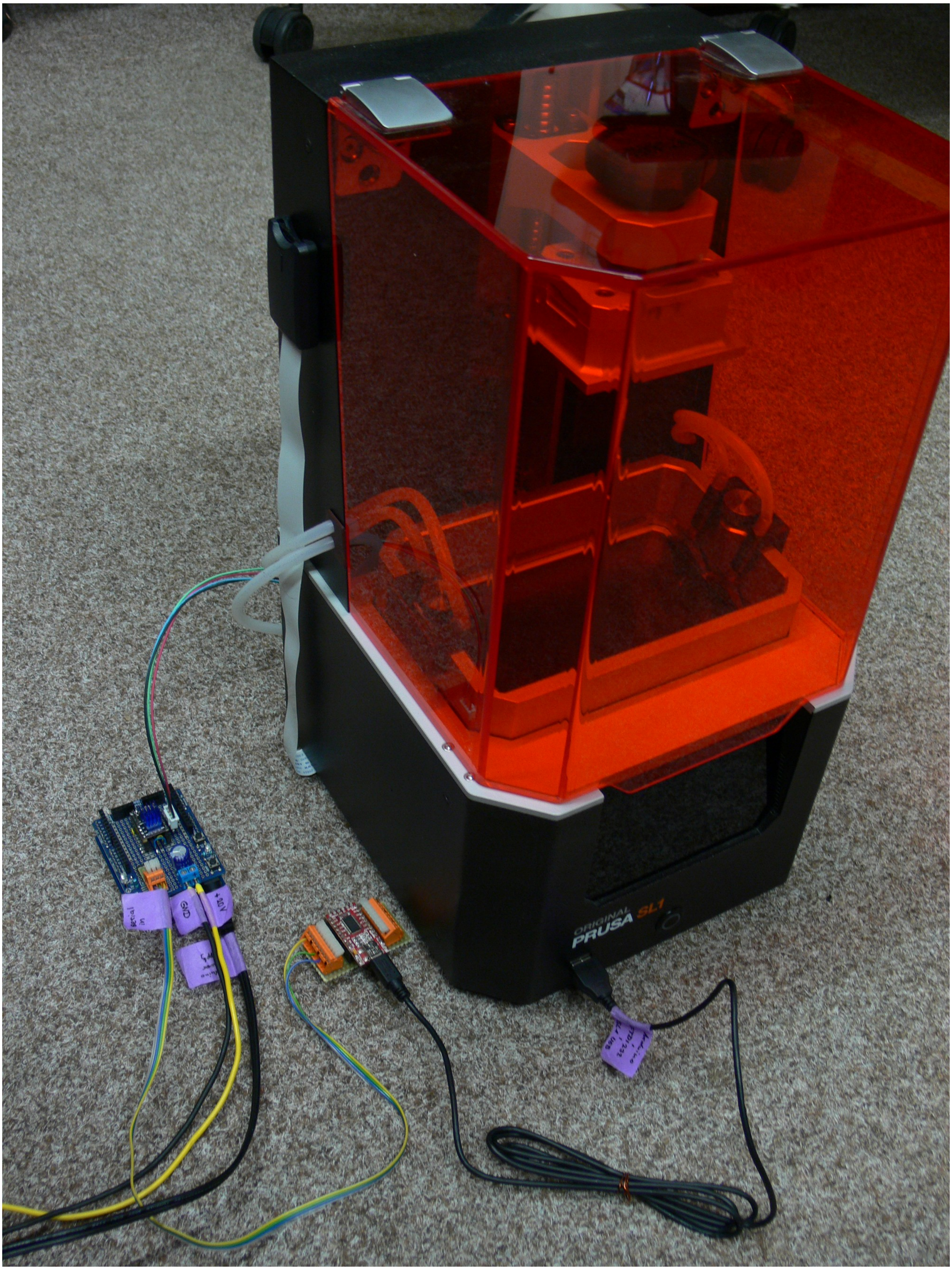
Large PLA mould:



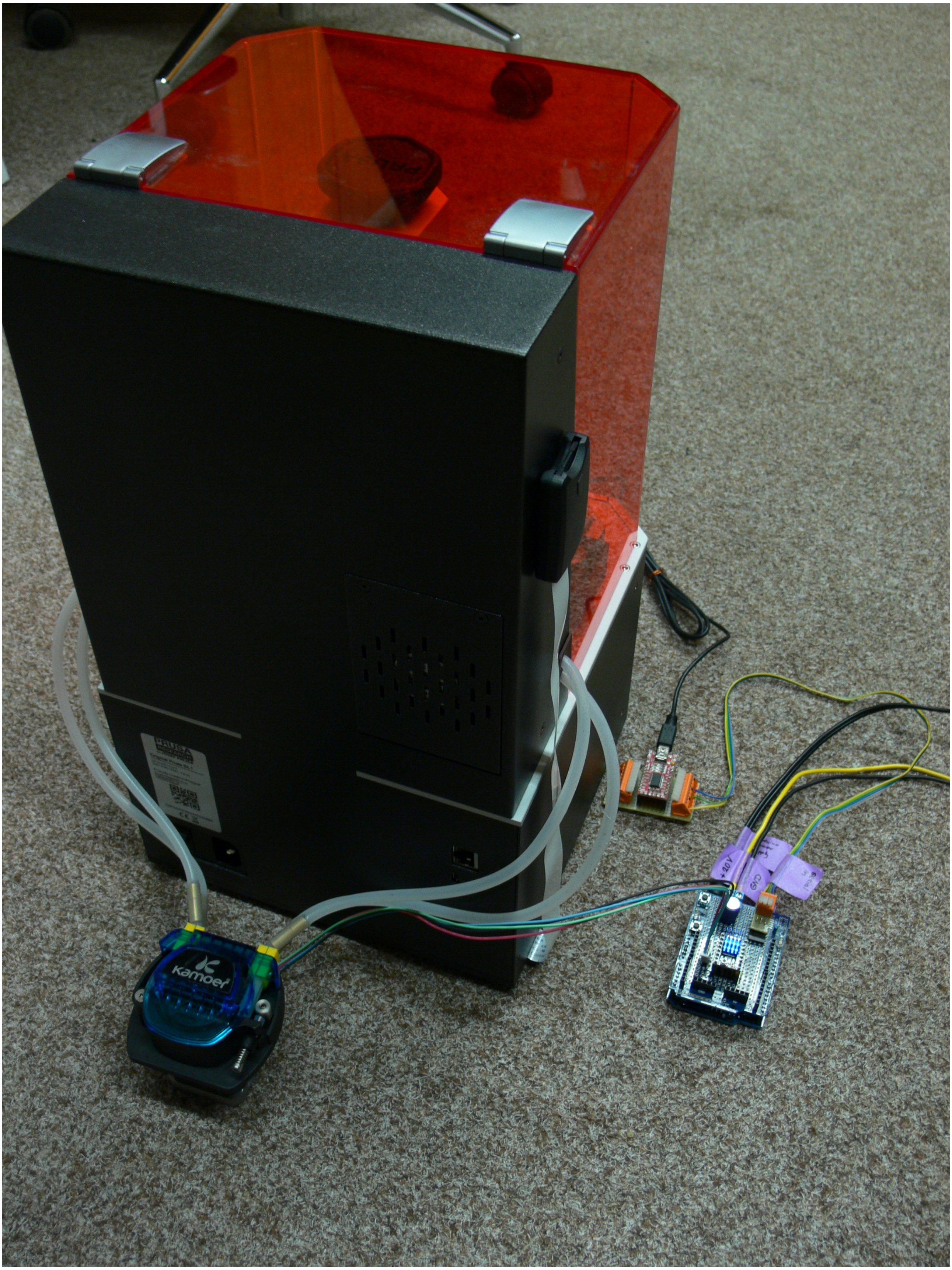
Large metal mould:



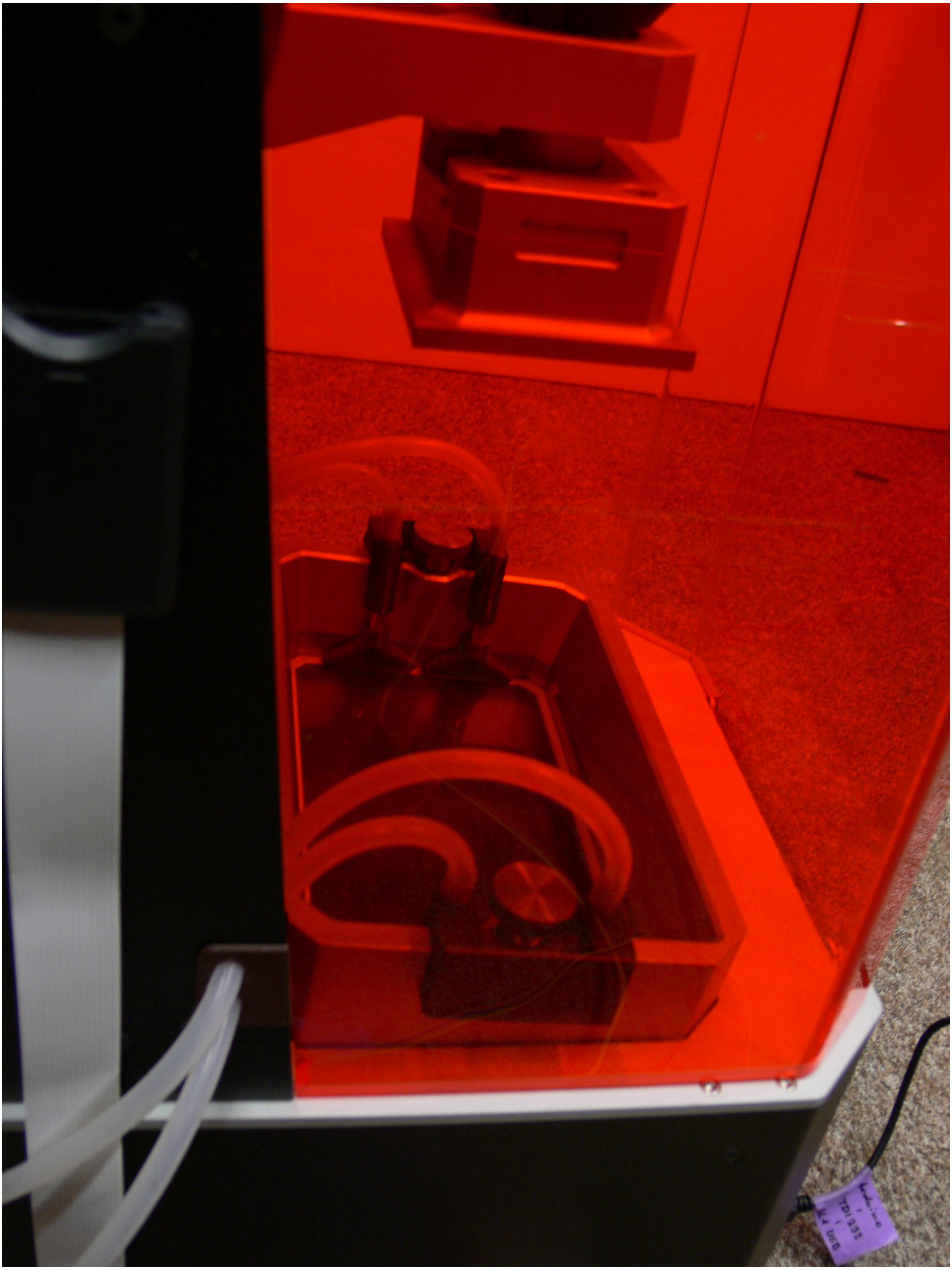
SL1 printer + mixing system:



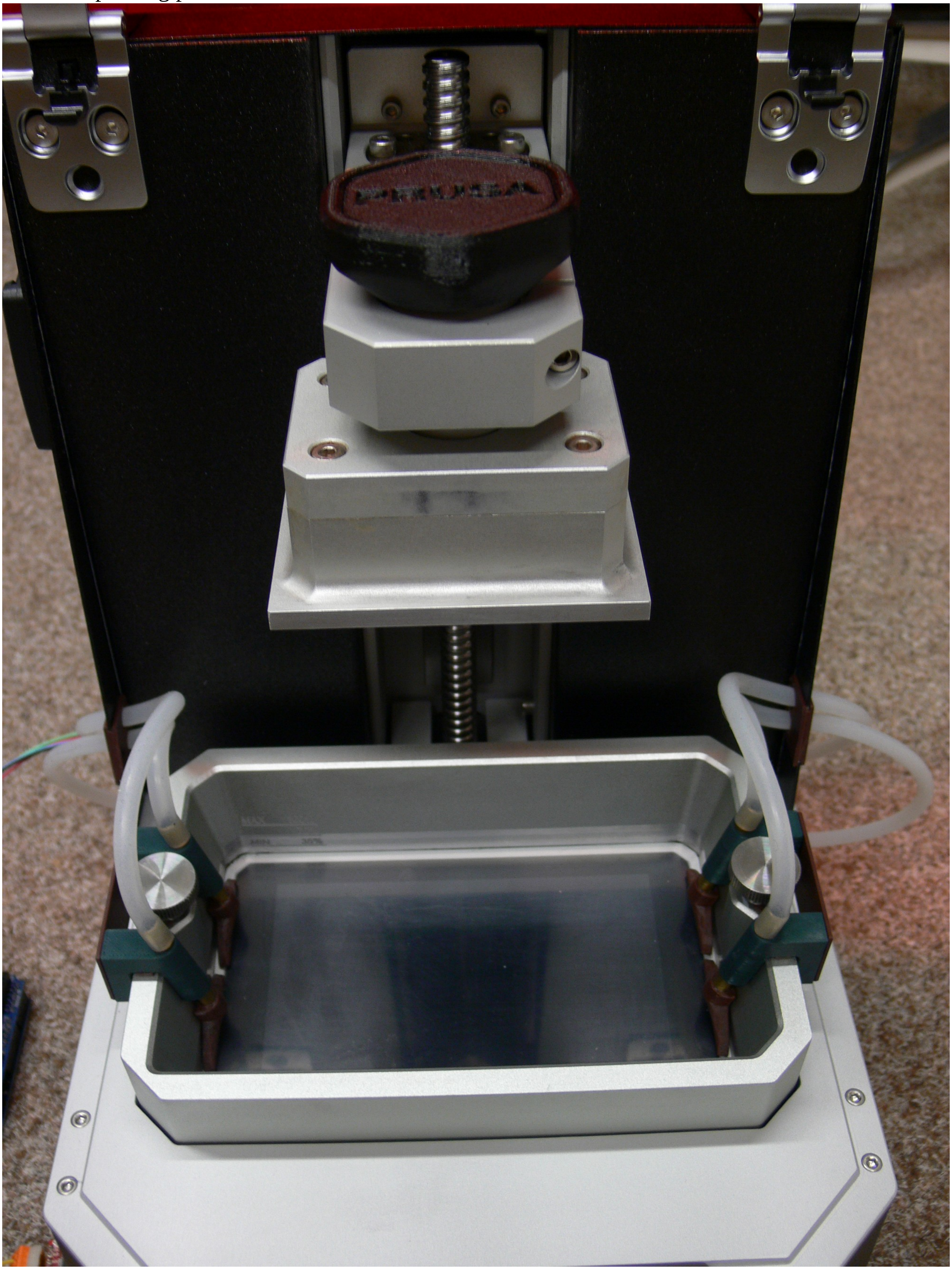
SL1 printer + mixing system:



SL1 printer + mixing system (zoom on resin tank):



Trimmed printing platform:



Trimmed/normal printing platform:

Medium core, mould casting, 80 Epox + 20 Fe:

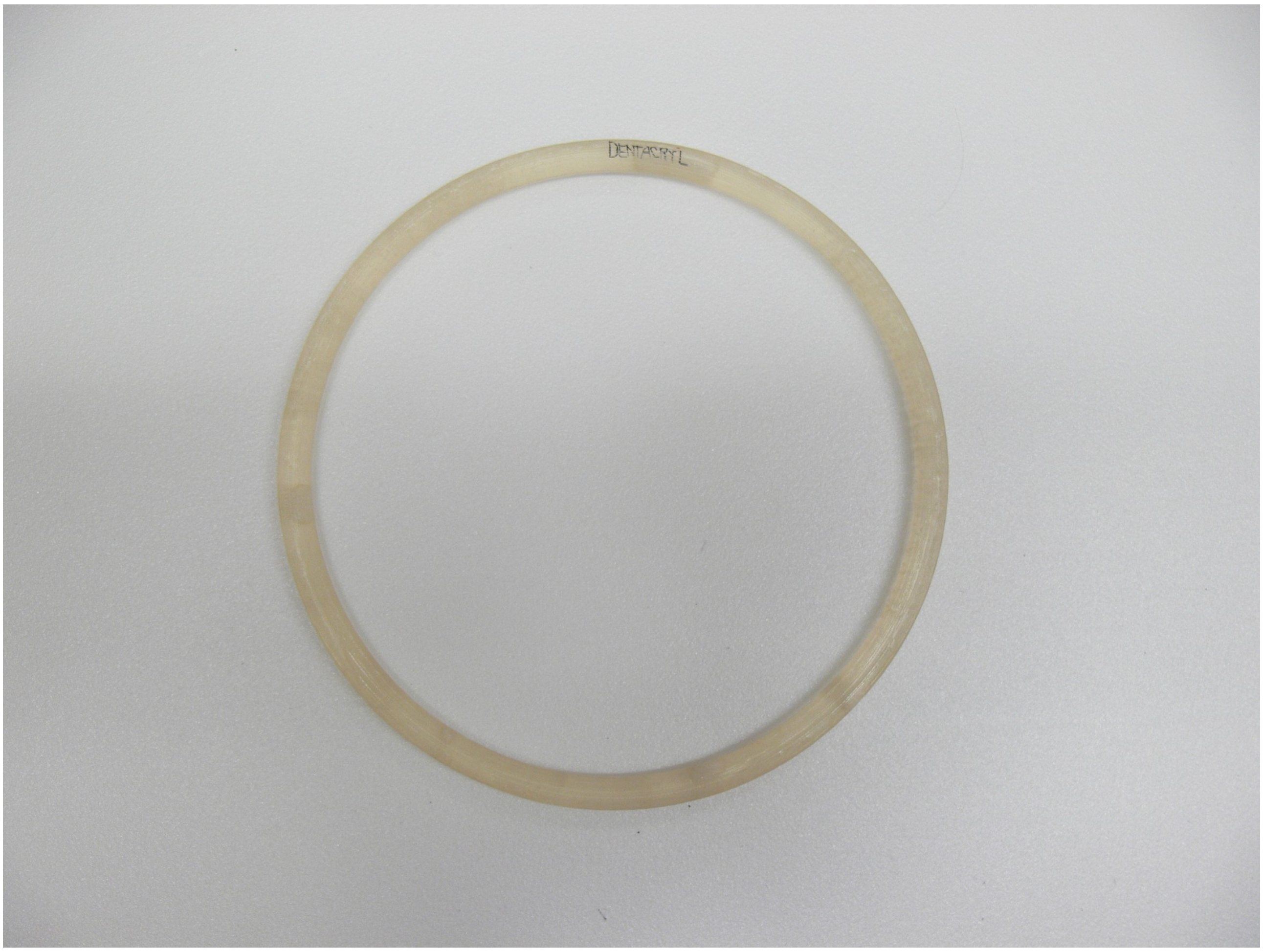
Medium core, mould casting, 90 Epox + 10 Magnetit:

Large core, heated mould casting, 90 Epox + 10 Magnetit:

Large core, vacuum mould casting, 90 Epox + 10 Fe:

Large core, vacuum mould casting, 80 Epox + 20 Fe:

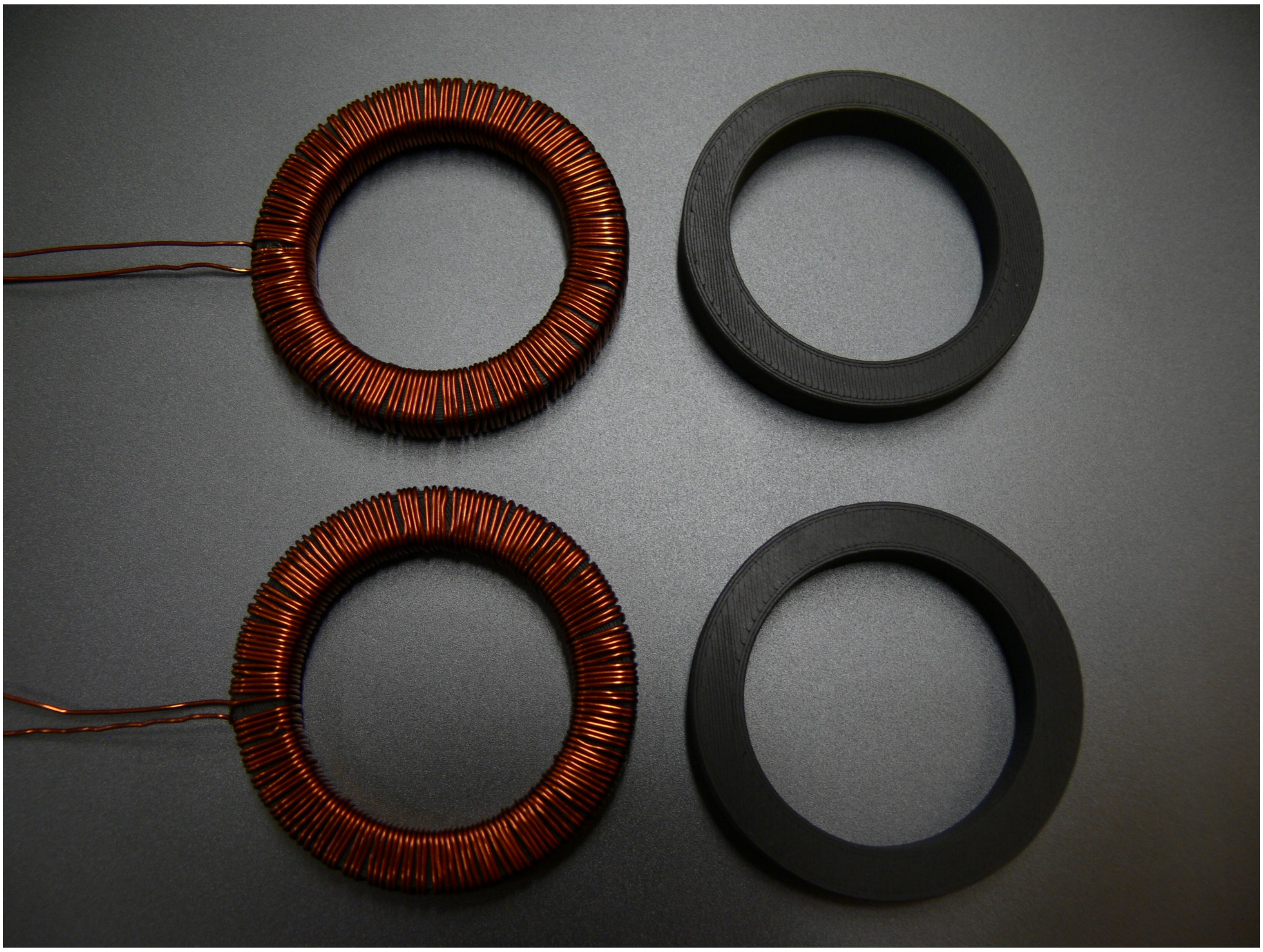
Nonmagnetic large core, mould casting:



Large core, mould casting, Epox + Nickel-zinc-ferrite:

Large core, wound up:

Small cores, 3D printed, Protopasta filament:



Small cores:

Fluxgate electric current senor with two cores: