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Development of a Shape-Adaptive Robot Gripper using Magnetorheological Fluids and Additively Manufactured Cylinders

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Abstract

Manipulating fragile objects of different shapes is a major robotics challenge. This led to the development and investigation of various gripper concepts with different flexible materials. This concept study focuses on the development of a shape-adaptive gripper that uses additively manufactured cylinders with variable heights and Shore hardness to achieve optimal adaptability and ripping force. The cylinders are filled with magnetorheological fluid (MRF), the properties of which are controlled by a standard electromagnet operating at 24 volts and 2 amps. The proposed concept aims to systematically investigate the influence of cylinder height, MRF volume, and material hardness on adaptability and gripping stability. Cylinders of varying heights allow for variations in MRF volume, enabling analysis of the fluid's volumetric behavior under the influence of a magnetic field. The Shore hardness of the additively manufactured structures is incrementally adjusted to optimize the balance between flexibility and structural stability. The electromagnet stimulates the MRF, altering its viscosity and stiffness to enable effective adaptation to various object geometries. The concept combines the properties of flexible materials and active fluids in a modular design, making it relevant for diverse applications such as robotics and automation.

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Abstract. Manipulating fragile objects of different shapes is a major robotics challenge. This led to the development and investigation of various gripper concepts with different flexible materials. This concept study focuses on the development of a shape-adaptive gripper that uses additively manufactured cylinders with variable heights and Shore hardness to achieve optimal adaptability and gripping force. The cylinders are filled with magnetorheological fluid (MRF), the properties of which are controlled by a standard electromagnet operating at 24 volts and 2 amps. The proposed concept aims to systematically investigate the influence of cylinder height, MRF volume, and material hardness on adaptability and gripping stability. Cylinders of varying heights allow for variations in MRF volume, enabling analysis of the fluid's volumetric behavior under the influence of a magnetic field. The Shore hardness of the additively manufactured structures is incrementally adjusted to optimize the balance between flexibility and structural stability. The electromagnet stimulates the MRF, altering its viscosity and stiffness to enable effective adaptation to various object geometries. The concept combines the properties of flexible materials and active fluids in a modular design, making it relevant for diverse applications such as robotics and automation.

Key words: Magnetorheological fluid (MRF), Smart Structures, Multiphysics Problems, Magnetic Field Distribution, Shape-Adaptive Gripper, Additive Manufacturing

1 INTRODUCTION

The ongoing development of shape-adaptive grippers for the precise manipulation of fragile handling objects with variable geometries represents a central challenge in robotics and automation. The use of magnetorheological fluids (MRF) offers specific advantages in this context, such as rapid, reversible, and contactless changes in viscosity and the resulting stiffness. These properties enable gripper systems to dynamically adapt their mechanical characteristics, which is particularly relevant for handling delicate and geometrically diverse objects [1]. By combining flexible structural elements with actively tunable rheological properties. An adaptive object manipulation can be achieved.

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Studies highlight the advantages of these systems, particularly in terms of their rapid and reversible adjustment of rheological properties in response to an applied magnetic field. Previous research has examined gripper systems optimized for the manipulation of delicate objects, as well as hybrid concepts that combine pneumatic actuators with MRF to achieve targeted stiffness control [2, 3]. These studies demonstrate the high potential of MRF for adaptive gripping systems and emphasize the need to further optimize relevant design parameters [4].
In this contribution, the magnetic interaction between an external magnetic field and cylindrical thermoplastic polyurethane (TPU) structures filled with magnetorheological fluid is investigated by simulation. The focus is on analyzing the influence of cylinder height and wall thickness on the resulting structural stiffening of the MRF. While MRFs are conventionally used in damping systems under high shear rate conditions, this work concentrates on the low shear regime where the structural reorganisation of the particles under static magnetic field exposure is investigated [2].
The present investigation contributes to this field by analyzing the underlying physical mechanisms governing magnetic field interactions with structured TPU cylinders and magnetorheological fluids. To illustrate the underlying gripper concept, a schematic representation of the system setup is provided in Figure 1.

2 Geometry and Materials

2.1 Geometry

The numerical simulations were carried out using the COMSOL 6.3 Multiphysics software. The simulation model consisted of a commercially available electromagnet, at the pole of which a cylindrical hollow body made of thermoplastic polyurethane was modeled. The wall thickness of the TPU cylinder was varied in a range from 0.2 mm to 1 mm in 0.2 mm steps. The height of the cylinder remained constant at 10 mm to allow a systematic analysis of the geometric influences on the magnetic field distribution. This configuration provides a standardized basis for investigating the interactions between the magnetic field and the MRF as a function of the geometry of the TPU hollow body, see Figure 2.

2.2 MR Fluid

Products considered included RHEOTEC, MRF-210 and MRF-132 DG, all supplied by *Arus MR Tech*. RHEOTEC was chosen due to its high sedimentation stability, response time of less than 10 ms, and controlled viscosity change within the relevant magnetic field range. It also features a homogeneous particle distribution and excellent long-term stability. The decisive factor was the higher iron content, which enables a stronger and more precise reaction to the magnetic field, a decisive aspect for the simulation in the low shear range.
In comparison, MRF-210 and MRF-132 DG exhibited lower iron content. This limited their suitability for the specific application, as the reduced concentration of magnetic particles resulted in a lower achievable change in viscosity and mechanical stiffness under applied magnetic fields.

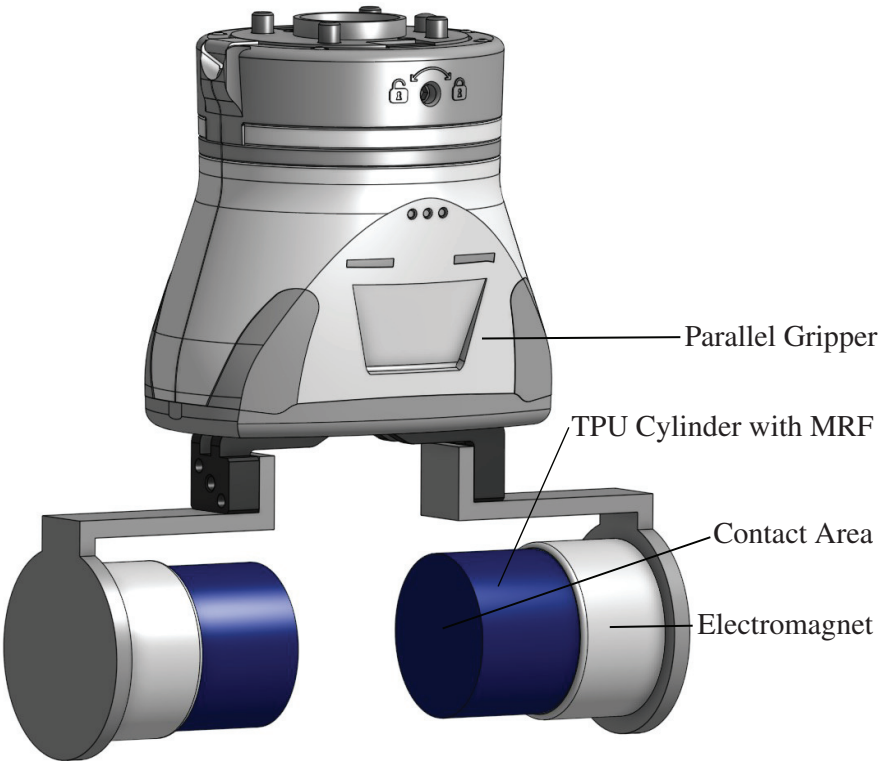

Figure 1: Schematic representation of the underlying gripper concept based on a model sketch using a parallel gripper.

2.3 B-H-Curve

The B-H curve describes the relationship between the magnetic flux density (B) and the magnetic field strength (H), serving as a fundamental basis for modeling magnetorheological materials.
The data points used in the simulation were extracted directly from the datasheet [5] and show a consistent slope in the low-field strength region (see Figure 3). To obtain intermediate values between the known data points, linear interpolation was applied using the following equation:

$$B = B_1 + \frac{(B_2 - B_1)}{(H_2 - H_1)} \cdot (H - H_1) \tag{1}$$

In this context, B_1 and B_2 denote the known magnetic flux densities corresponding to the magnetic field strengths H_1 and H_2, respectively. Linear interpolation was employed to establish a continuous relationship between these discrete data points. This interpolation method is considered appropriate and sufficiently accurate for the intended simulations, as the magnetorheological fluid exhibits an approximately linear behavior in the low shear regime.

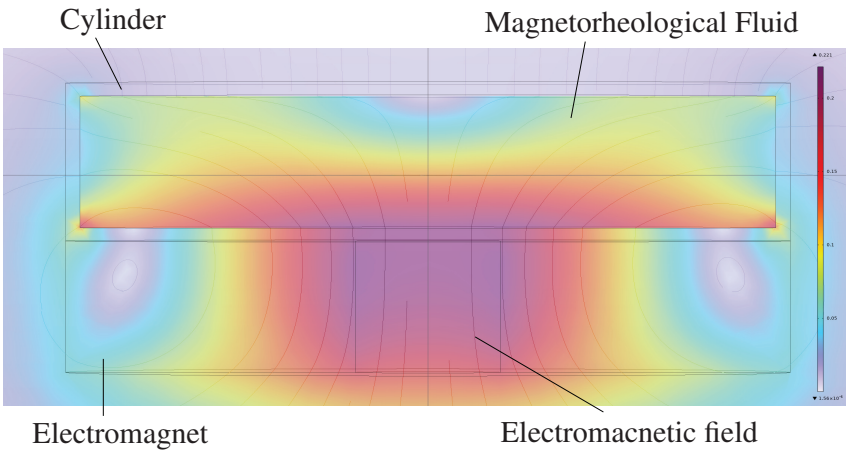

Figure 2: Distribution of the magnetic flux density in an MRF-based setup influenced by an electromagnet. The color scale denotes the magnetic flux density, with red indicating high and blue indicating low field strengths.

2.4 Relative permeability

The experimental analysis of the relative permeability $\mu_r(H)$ shows that it can be described by the function :

$$\mu_r(H) = \mu_{r0} - \left(\frac{H}{H_{\text{ref}}}\right)^n \tag{2}$$

At low field strengths, the initial magnetic behavior of the material is characterized by $\mu_{r0} = 10.89$, which describes its permeability in the unsaturated state. The reference field strength $H_{\text{ref}} = 1118.27\ \text{A/m}$ defines the scaling of the saturation processes and indicates the field strength at which the permeability significantly decreases from its initial value. A lower H_{ref} value is associated with an earlier onset of magnetic saturation, while a higher value reflects a more gradual reduction in permeability. The exponent $n = 0.372$ quantifies the nonlinear reduction of permeability as a function of the magnetic field strength. This function served to verify and quantify the behavior of the B-H curve, providing a mathematical description of how the permeability evolves with increasing magnetic field strength. The derived permeability function can be interpreted as a material-dependent field equation describing the B-H curve. The resulting permeability function (2) is used to validate the B–H behavior and describes the field-dependent evolution of the magnetic properties. It represents a material-specific model for characterizing the nonlinear magnetization process.

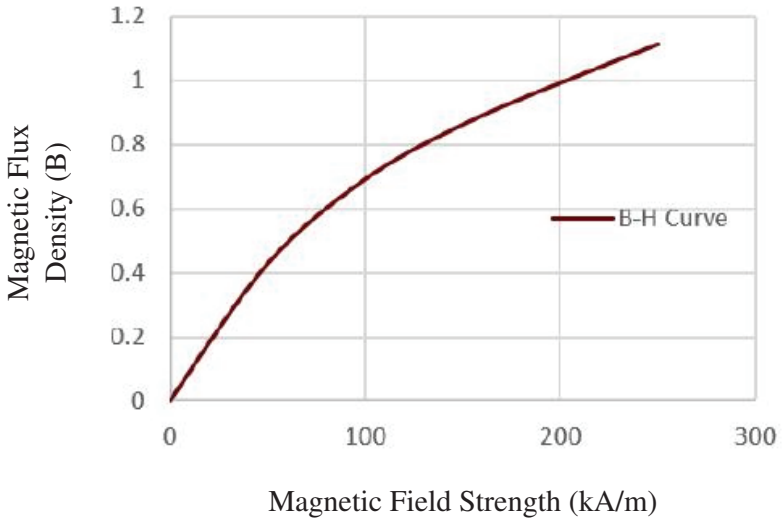

Figure 3: B-H curve for AMT-RHEOTEC+ MRF interpolated in COMSOL

2.5 Thermoplastic Polyurethane

TPU exhibits an elongation at break of up to 500%, high wear resistance under repeated mechanical stress and frictional contact, and dimensional stability within a temperature range of $-40°\mathrm{C}$ to $+80°\mathrm{C}$ [6]. These characteristics ensure reproduction of complex geometries in additive manufacturing. In addition, TPU contributes to reducing weight, material consumption, and production time, while supporting the realization of application-specific designs that can be flexibly adapted to varying requirements [7]. TPU is considered neutral, with a relative permeability of approximately $\mu_r \approx 1$ and negligible magnetic susceptibility.

3 Method of Study and Physics Used in COMSOL

3.1 Simulation Approach

The simulation was conducted as a stationary analysis at the moment of magnetic field activation. A detailed examination of the magnetic field distribution and the magnetic field strength within the magnetorheological fluid was carried out. The complex interaction between the electromagnet, the TPU cylinder, and the MRF was investigated in order to systematically characterize the mutual influences.

3.2 Magnetic Analysis

Ampère's Law was used in COMSOL for the magnetic analysis to accurately calculate the magnetic field distribution within the material. Ampère's law describes the relationship between an electric current and the resulting magnetic field and is expressed in its differential form as:

$$\nabla \times \mathbf{H} = \mathbf{J} \tag{3}$$

$\mathbf{H}$ denotes the magnetic field strength and $\mathbf{J}$ the current density. The magnetic field is generated by an electromagnet operating at 24 volts and 2 amps, with a total of 1,680 turns. These parameters are critical in determining the strength and distribution of the magnetic field generated. The coil wire parameters were defined based on literature data. The electrical conductivity was set to 6×10^7 S/m, and the cross-sectional area to 1×10^{-6} m^2 [8]. These material properties ensure efficient current conduction and allow a simulation of the magnetic field. The resulting magnetic flux density $\mathbf{B}$ is determined by the nonlinear magnetization behavior of the material, which follows the B-H curve. Instead of the linear relation where μ_r is a constant relative permeability:

$$\mathbf{B} = \mu_0 \mu_r \mathbf{H} \tag{4}$$

The magnetic material behavior is described by a nonlinear constitutive relation given by:

$$\mathbf{B} = f(|\mathbf{H}|) \frac{\mathbf{H}}{|\mathbf{H}|} \tag{5}$$

This equation accounts for the nonlinear response of the material to the applied magnetic field strength $\mathbf{H}$. The function $f(|\mathbf{H}|)$ represents the material's B-H curve, ensuring that the dependency of the magnetic flux density $\mathbf{B}$ on the magnitude of $\mathbf{H}$ is accurately captured.
Electrical conductivity was taken into account to capture the interaction between electric current and the magnetic field. The relationship between current density $\mathbf{J}$ and the electric field $\mathbf{E}$ is governed by Ohm's law, which is expressed as:

$$\mathbf{J} = \sigma \mathbf{E} \tag{6}$$

where σ is the scalar electrical conductivity of the material, assuming isotropic electrical behavior of the magnetorheological fluid (MRF). Ampère's law was implemented as a fundamental component of the simulation framework to resolve the magnetic field distribution and its effect on the MRF. This allowed a detailed analysis of the interactions between the electromagnetic field, the material properties of the cylinder, and the MRF filling.

4 Results

The simulation results illustrate the influence of the wall thickness of the additively manufactured TPU cylinders on the magnetic flux density distribution in the magnetorheological fluid (MRF). Figures 4 and 5 depict the magnetic flux density distribution for cylinders with wall thicknesses of 0,2 mm and 1 mm respectively.

- Cylinder with 0.2mm wall thickness (Figure 4): The MRF exhibits a higher magnetic flux density compared to the cylinder with a thicker wall. Due to the shorter distance to the magnetic field source, the field strength within the fluid is increased, leading to a stronger magnetization effect.

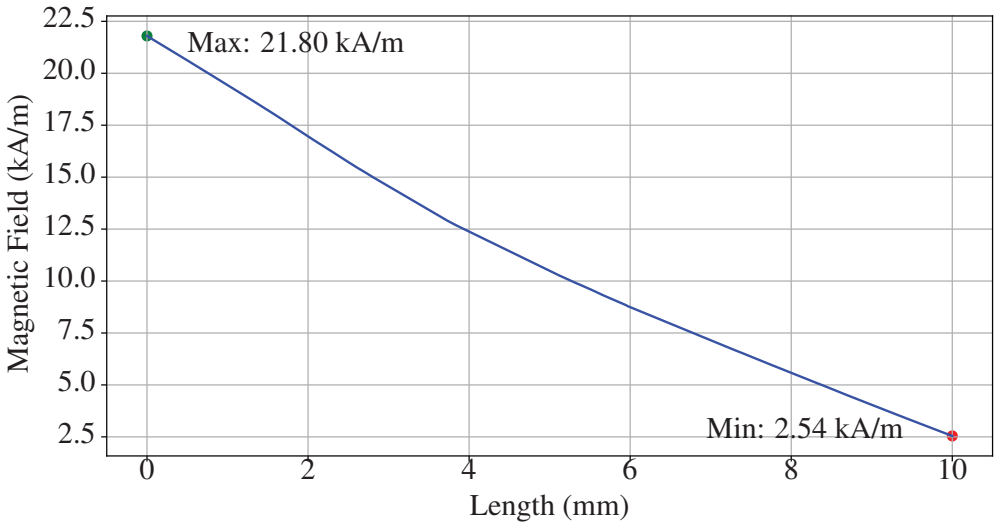

Figure 4: Magnetic field strength in the MRF for TPU wall thickness 0,2 mm

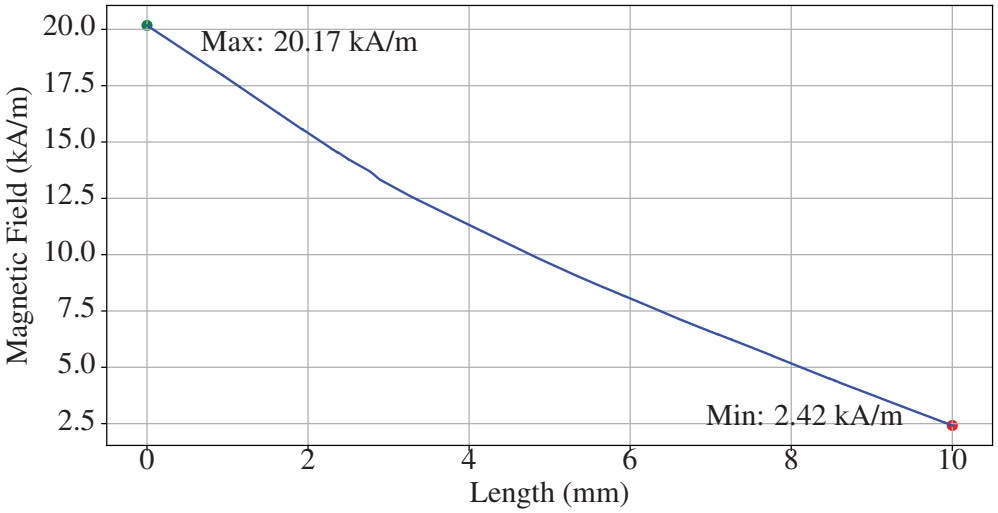

Figure 5: Magnetic field strength in the MRF for TPU wall thickness 1 mm

- Cylinder with 1.0mm wall thickness (Figure 5): In this case, a lower magnetic flux density is observed within the MRF compared to the thinner-walled cylinder. The increased wall thickness results in a greater distance between the MRF and the magnetic field source, reducing the magnetic field strength inside the fluid.

The magnetic flux density directly in front of the TPU surface was set to 200 mT in all simulations. The spatial distribution of the magnetic field is influenced by the geometry of the cylinder, leading to variations in the magnetization of the MRF.

In addition to geometric parameters, the effect of Shore hardness was also evaluated. Variations in the Shore hardness of the TPU did not exhibit any measurable influence on the distribution of the magnetic flux density. Due to its magnetic neutrality—characterized by a relative permeability of approximately $\mu_r \approx 1$ and negligible magnetic susceptibility—changes in mechanical surface properties such as hardness do not affect the propagation of the magnetic field. Consequently, the interaction between the magnetic field and the MRF is predominantly governed by geometrical aspects, particularly the distance to the field source.
This dependence is supported by a field analysis along the cylinder geometry. Figure 6 presents the spatial distribution of the magnetic field strength (in kA/m) and the magnetic flux density (in mT) along the arc length of an MRF-filled cylinder with a wall thickness of 0.2 mm. Both quantities decrease continuously with increasing distance from the electromagnetic source. The flux density decreases from an initial value of 200 mT to below 25 mT, while the magnetic field strength follows a similar trend with a smaller absolute variation. This indicates that the most pronounced magnetization occurs in close proximity to the magnetic field source.

Yield Stress and Magnetic Field Strength

Figure 7 illustrates the yield stress curve of the employed *AMT-RHEOTEC+ MRF* as a function of the magnetic field intensity. The curve confirms that the yield stress increases with rising magnetic field strength. At 50 kA/m, the yield stress is approximately 30 kPa, whereas at 200 kA/m, it exceeds 70 kPa. This shows that the MRF significantly stiffens under magnetization, allowing controlled adjustments in the stiffness of the gripper.
The previously discussed decline in the magnetic field intensity along the cylinder (Figure 7) implies that the yield stress is not uniformly distributed within the MRF volume. In regions with lower field strength, the MRF remains softer, while in areas with high magnetization, it exhibits increased rigidity. This phenomenon could be exploited to create localized stiffness gradients within the gripping element, optimizing adaptability to different object geometries.

5 Discussion

The results indicate that the wall thickness of the TPU cylinder has a significant influence on the magnetic field distribution and, consequently, on the magnetorheological properties of the fluid.

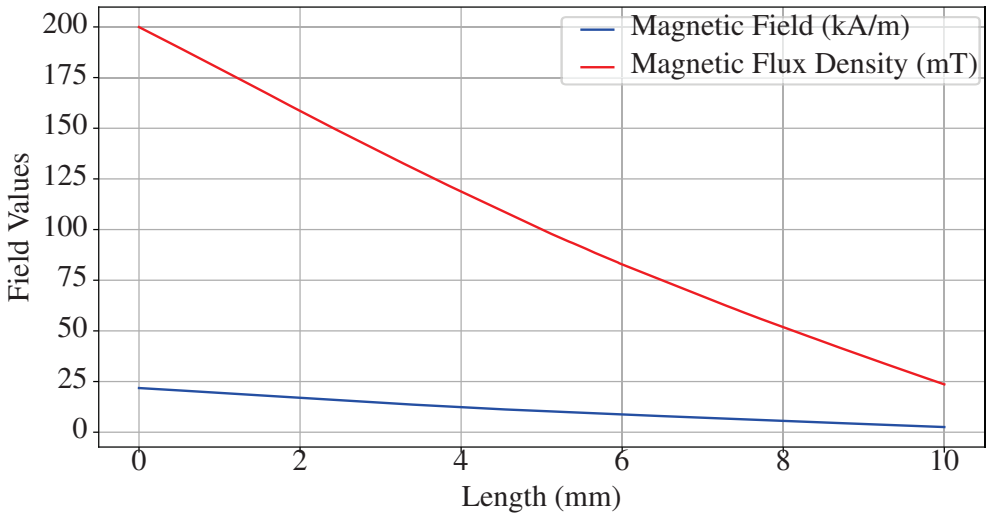

Figure 6: Magnetic field strength in the MRF for TPU wall thickness 0,2 mm

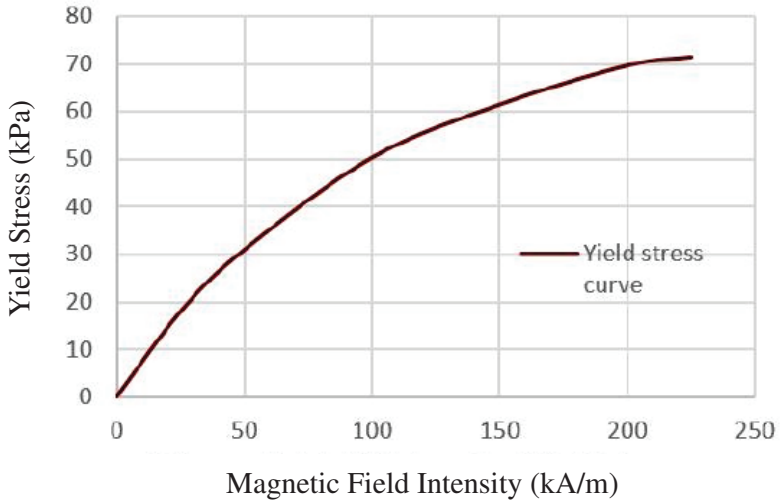

Figure 7: Yield strength vs. magnetic field strength for AMT-RHEOTEC+ MRF

Influence of Wall Thickness on MRF Magnetization

A thinner wall thickness 0.2 mm enhances MRF magnetization due to its proximity to the magnetic field source. This results in a higher field strength within the fluid and a more pronounced increase in viscosity. In contrast, a thicker wall (e.g., 1 mm) increases the distance between the MRF and the magnetic field, thereby reducing the magnetic field strength within the fluid.

Additional Confirmation through the Magnetic Field Distribution Diagram (Figure 6)

The diagram quantitatively demonstrates the decrease in magnetic flux density along the arc length of the cylinder with a 0.2 mm wall thickness. This supports the hypothesis that an increased wall thickness—and thus a greater distance of the MRF from the magnetic field source—leads to reduced magnetization. The activation of the MRF decreases with increasing distance from the magnetic field, directly affecting the adaptability of the gripper.
The observed decrease in magnetic flux density is not solely attributable to the geometric distance from the magnetic field source but is also influenced by the relative permeability μ_r of the MRF. Since μ_r describes a material's ability to conduct a magnetic field, it directly impacts the field distribution within the fluid.
The investigated MRF exhibits a nonlinear dependency of relative permeability on the applied magnetic field strength. This phenomenon implies that, in addition to the diminishing magnetic field intensity with increasing distance from the field source, the material's internal magnetizability is also subject to alteration. A higher relative permeability amplifies the fluid's magnetization, whereas a lower μ_r results in attenuated magnetization.

Relationship with Yield Stress (Figure 7)

The yield stress illustrated in Figure 7 shows that the MRF experiences a significant increase in stiffness at higher magnetic field strengths. The previously discussed decrease in magnetic flux density along the cylinder implies that the MRF in the region farther from the electromagnet exhibits a lower yield stress compared to areas closer to the magnetic field source. This effect can be utilized for optimizing the gripper by selectively generating regions with different stiffness levels to facilitate efficient shape adaptation.

6 Conclusion

This contribution provides insights into the role of TPU cylinder wall thickness in governing the magnetization behavior and mechanical response of MRFs. The results demonstrate that reducing the wall thickness enhances MRF activation due to increased proximity to the magnetic field, whereas increasing the thickness diminishes magnetization and subsequently affects yield stress. These findings have direct implications for the design of MRF-based adaptive systems, particularly in applications requiring controlled stiffness variations, especially in low-shear conditions.
Future research will focus on refining experimental validation, investigating alternative material

compositions, and optimizing structural designs to maximize adaptability and performance in practical applications. Additionally, additive manufacturing technologies could be leveraged to fabricate complex, functionally graded structures with precisely controlled wall thicknesses, enabling further advancements in adaptive gripping systems and other MRF-based applications.

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