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DEPARTMENT OF PHYSICS



**DESIGN AND PRODUCTION OF PROTOTYPE SOLENOIDAL
SUPERCONDUCTOR COIL MADE WITH MgB_2 WIRE TOWARDS
POSSIBLE USAGE IN WASTEWATER TREATMENT**

DOCTOR OF PHILOSOPHY, PHYSICS

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BOLU, 4/21/2025

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PREFACE

This study offers a thorough exploration of the production and characterization of magnesium diboride (MgB_2) superconductors, focusing specifically on elongated monofilamentary wires. Using the *in-situ* powder-in-tube (PIT) method, we aimed to optimize the fabrication process and evaluate the superconducting properties of these wires. The research details protocols for preparing a precise mixture of boron and magnesium powders, followed by careful filling into iron tubes and subsequent drawing and rolling. We successfully constructed and adapted a conduction cooling system, overcoming several challenges along the way. Additionally, we investigated the winding of these wires onto ETP copper formers to create non-insulated (NI) single and multilayer coils, complemented by controlled heat treatments. Characterization techniques were employed to assess superconductivity transitions, critical current levels, and resistivity. The coils successfully generated a magnetic field within the conduction cooling system during testing. The study also examines the effects of bending on wire degradation, providing valuable insights for future designs. Ultimately, this work advances the understanding of MgB_2 wires and highlights their potential applications in wastewater treatment, paving the way for further research and essential recommendations for future endeavors.

MAHRAN A.A. SHAHADEH

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ABSTRACT

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PHD THESIS

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This study investigates the production of elongated monocoil wires of magnesium diboride (MgB_2/Fe), emphasizing their superconducting properties. The wires were manufactured *in situ* using the powder-in-tube (PIT) method, with systematic evaluations of their electrical characteristics under various magnetic fields. Techniques such as groove rolling, wire drawing, and electro-thermal heat treatment enhanced the wires' strength and flexibility, resulting in 180 meters of MgB_2/Fe wire with a diameter of 1.0 mm. The data regarding the produced wire were analyzed through current-voltage and temperature-resistance graphs, alongside metallographic examinations. Bending tests determined suitable bending diameters, with a safe threshold exceeding 200 mm. Non-insulated (NI) wires were wound onto insulated ETP copper formers. The study also involved winding single and multilayer NI solenoid coils and constructing a cryogenic chamber for conduction cooling. This system effectively cooled the coils, enabling the investigation of critical parameters such as coil temperature, maximum superconducting current capacity, and magnetic field generation. The cryostat, evacuated to a pressure of 10^{-5} mbar, achieved temperatures of 50–60 K without liquid nitrogen and as low as 26.6 K with liquid nitrogen, supporting currents of up to 70 A despite residual heating effects. Additionally, this work explores the potential applications of MgB_2 superconductors in wastewater treatment, examining how magnetic fields can enhance the removal of heavy metals from industrial sewage via magnetic separation. Key factors like magnetization in wastewater and magnetic gradients are discussed, highlighting the feasibility and future prospects for using superconductors in advancing wastewater treatment technologies.

KEYWORDS: Superconducting wire, MgB_2 coils, Non-insulation, Conduction cooling cryostat, Bending process, Degradation Ratio, Wastewater treatment.

ÖZET

ATIKSU ARITIMINDA OLASI KULLANIMA YÖNELİK OLARAK PROTOTİP SOLENOİDAL SÜPERİLETKEN BOBİN TASARIMI VE

MgB₂ TEL KULLANILARAK ÜRETİMİ

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Bu çalışma, magnezyum diborid (MgB₂/Fe) uzun monocore tellerinin üretimini araştırmakta ve süperiletken özelliklerine vurgu yapmaktadır. Teller, toz-içinde-tüp (PIT) yöntemi kullanılarak yerinde üretilmiş ve çeşitli manyetik alanlar altında elektriksel özelliklerinin sistematik değerlendirmeleri yapılmıştır. Groove rolling, tel çekme ve elektro-termal ısıtma işlemi gibi teknikler, tellerin dayanıklılığını ve esnekliğini artırarak 1.0 mm çapında 180 metre MgB₂/Fe teli elde edilmiştir. Üretilen tel ile ilgili veriler, akım-gerilim ve sıcaklık-direnç grafikleri ile metalografik incelemeler aracılığıyla analiz edilmiştir. Bükme testleri, uygun bükme çaplarını belirlemiş ve güvenli eşik değeri 200 mm'yi aşmıştır. İzole edilmemiş (NI) teller, izole ETP bakır kalıplara sarılmıştır. Çalışma ayrıca tek ve çok katmanlı NI solenoid bobinlerinin sarılmasını ve iletim soğutması için bir kriyojenik odanın inşasını içermektedir. Bu sistem, bobinleri etkili bir şekilde soğutarak bobin sıcaklığı, maksimum süperiletken akım kapasitesi ve manyetik alan üretimi gibi kritik parametrelerin araştırılmasına olanak tanımıştır. 10⁻⁵ mbar basınçta vakumlu kriyostat, sıvı azot olmadan 50–60 K ve sıvı azot ile 26.6 K'ye kadar sıcaklıklar elde etmiş, artık ısı etkilerine rağmen 70 A'ya kadar akımları desteklemiştir. Ayrıca, bu çalışma, atık su arıtımında MgB₂ süperiletkenlerinin potansiyel uygulamalarını incelemekte ve manyetik alanların endüstriyel atık suların ağır metallerin manyetik separasyon yoluyla çıkarımını nasıl artırabileceğini araştırmaktadır. Atık sularındaki magnetizasyon ve manyetik gradyanlar gibi anahtar faktörler tartışılmakta, süperiletkenlerin atık su arıtım teknolojilerinin ilerletilmesinde kullanılabilirliği ve gelecekteki perspektifleri vurgulanmaktadır.

ANAHTAR KELİMELER: Süperiletken tel, MgB₂ bobinleri, Yalıtımsız, İletim soğutma kriyostatu, kriyostatı, Bükme işlemi, Bozulma oranı, Atıksu arıtımı.

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LIST OF ABBREVIATIONS AND SYMBOLS

MgB₂	: Magnesium Diboride
PIT	: Powder In Tube
NI	: Non-Insulated
LTS	: Low Temperature Superconductors
HTS	: High Temperature Superconductors
T_c	: Critical Transition Temperature
$T_{c \text{ offset}}$	: Offset Superconducting Transition Temperature
$T_{c \text{ onset}}$	: Onset Superconducting Transition Temperature
J_c	: Critical Current Density
J_{ce}	: Engineering Critical Current Density
B_{irr}	: Irreversibility Field
B_{c2}	: Upper Critical Field
B_{c1}	: Lower Critical Field
I_c	: Critical Current
ρ	: Resistivity
YBCO	: Yttrium Barium Copper Oxide
BSCCO	: Bismuth Strontium Calcium Copper Oxide
XRD	: X-Ray Diffraction
SEM	: Scanning Electron Microscopy
MRI	: Magnetic Resonance Imaging
SEM	: Scanning Electron Microscope
XRD	: X-ray Diffraction
MF	: Magnetic Field
SMF	: Static Magnetic Field
SQUID	: Superconducting Quantum Interference Device
WWT	: Wastewater Treatment

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1. INTRODUCTION

Superconducting magnets are used to produce uniform and high magnetic fields (Tachikawa et al., 1987; Schneider-Muntau et al., 2004; Markiewicz et al., 2006; Twin et al., 2007; Rossi et al., 2018; Bai et al., 2020; Zhou & Tang, 2023). The conventional superconductor NbTi is the most used material in superconducting magnets but the need for higher magnetic fields and the increasing cost of helium necessitates the use of other superconductors in applications such as accelerators, MRI, NMR, and resistive fault current limiters (Baig et al., 2014; Parizh et al., 2016). Nb₃Sn and MgB₂ superconductors enable conduction cooling and have important potentials for superconducting magnet applications. Nb₃Sn with a critical temperature (T_c) of 18.3 K is more suitable for conduction cooled high field magnets operating around 8 K. However, the high cost of Nb₃Sn makes it less feasible for realization of conduction cooled low field magnets (e.g., MRI magnet with 1.5T or 3T) compared to low cost MgB₂ with T_c of 39 K (Baig et al., 2014; H. S. Kim et al., 2015; Yao & Ma, 2021). Quench detection and protection are ongoing issues in superconducting coils, especially for those of high- T_c . A local hot spot can reach high temperatures before being detected and damage the superconductor (Marchevsky, 2021). There are many quench detection techniques using resistive voltage and non-voltage detections (T. Wang et al., 2021). Studies have shown that non-insulated (NI) high- T_c superconducting coils can protect themselves against overcurrent via non-insulated turn-to-turn resistive contact, but this has been claimed to be more effective in small pancake coils than in a large magnet (Hahn et al., 2018; Mulder et al., 2024). The slow charging and discharging rates of NI high- T_c pancake coils remain an issue to be solved (Y. Wang & Song, 2016). The realization of conduction-cooled MRI magnets using MgB₂ requires active quenching protection because the thermal normal zone propagation velocity of MgB₂ is much slower than that of NbTi (Ye et al., 2015).

In the study of Kim et al., Cr coated MgB₂ wires were proposed to improve the charge/discharge rates and self-shielding of partially insulated MgB₂ magnet (Y. G. Kim et al., 2018). The charge /discharge rates of these partially insulated MgB₂ magnets were found to be about ten times faster compared to the magnet made with uncoated wire (Y. G. Kim et al., 2019). The aim of this study is

to test non-insulated MgB₂ superconducting coils in a newly designed conduction cooling system. The tentative six-layer NI nested coil with independent MgB₂ winding layers where the applied current is shared among the layers (Yetiş & Belenli, 2022). Nested coils eliminate the need for long wires in large solenoid coils, allowing the use of shorter wires with better core uniformity. Possibility of use of shorter wires can provide a great advantage in coil production, especially using IMD MgB₂ wires, which have problems with longitudinal uniformity (D. Wang et al., 2016; Kováč et al., 2021; Yetiş et al., 2022). Another advantage of the nested coil design can be the reduction of the time required for current passage between the windings in non-insulated coils (Noguchi et al., 2013) because the currents are shared immediately at the beginning and end of the windings.

Superconductors have revolutionized many areas thanks to the absence of electrical resistance. They are used in a wide range of applications, including medical imaging, particle accelerators, transportation, energy storage, power transmission, fault current limiters, magnetic separation, research magnets, fusion reactors, quantum computing, high-field magnets, electric motors and generators, SQUIDs, cryogenic systems, and industrial heating. Superconducting magnet technology is considered as a physical method that utilizes variations in magnetism to achieve the materials separation based on their behavior in a non uniform magnetic field. This approach is environmentally friendly, efficient, and has minimal impact on the physical and chemical properties of raw materials. It is primarily employed in the processing of magnetic ferrous minerals in water and wastewater treatment (WWT) (Baig et al., 2014; Parizh et al., 2016; Ku et al., 2024).

In 2024, the United Nations International Children's Emergency Fund (UNICEF) and in cooperation with the World Health Organization (WHO) highlighted that water scarcity and quality are critical global challenges. Approximately, 2.2 billion people lacked access to safely managed sanitation during a year of 2022. Rapid industrial growth has led to the degradation of water sources, and we need to act much faster to achieve universal access to basic drinking water by 2030, necessitating a six-fold increase in safely managed services (Zhou et al., 2011; Drechsel et al., 2015; UNICEF & WHO, 2024). One approach to physical treatment is magnetic field (MF) technology, an efficient and cost-effective method that enhances WWT performance. While some research has

examined the impact of MF on WWT, the results remain complex and not entirely understood. To address these challenges, MF enhanced the treatment methods which have been proposed as a means to improve WWT processes due to their high efficiency, low energy requirements, and environmental advantages (Mohammed et al., 2014).

1.1 MgB₂ Superconductors

1.1.1 Superconductivity Phenomena

The pioneering discovery of superconductivity can be attributed to Kamerlingh Onnes, who observed this phenomenon in mercury at extremely low temperatures using liquid helium in 1911 (Onnes, 1911). A fundamental characteristic of superconductivity is its ability to exhibit zero electrical resistance once the temperature falls below a specific T_c . Materials that display this remarkable behavior are referred to as superconductors. The key feature of superconductivity lies in the abrupt drop in electrical resistance below the T_c , resulting in lossless electrical transmission. This extraordinary property has revolutionized various fields, particularly in the domain of power transmission and storage, offering immense potential for technological advancements and energy efficiency. However, it is important to note that even when a superconductor remains below its T_c , subjecting it to a high magnitude of electrical current can cause it to transition back to the normal resistive state. This transition occurs due to the formation of a MF around the superconductor wire in response to the flowing electrical current. The strength of this MF intensifies as the current within the wire increases. The maximum MF value at a given temperature is referred to as the critical magnetic field (H_c). Based on the aforementioned analysis, it becomes apparent that there exists a maximum current value that a superconductor can effectively carry. This critical current density (J_c) is contingent upon the temperature at which the superconductor is operating. Therefore, T_c , J_c , and H_c represent three pivotal parameters that characterize a particular superconducting material (Nagamatsu et al., 2001; Bardeen et al., 2002).

1.1.2 Superconductivity of MgB₂

1.1.2.1 Background

The discovery of MgB_2 superconductivity can be attributed to Akimitsu Jun and his research team (Nagamatsu et al., 2001), despite the compound itself being known since 1950. MgB_2 is a simple metallic binary compound that exhibits the highest T_c among all known superconductors to binary alloys. With a $T_c \approx 39$ K, MgB_2 surpassed the T_c of inter-metallic superconductors that were prevalent during that time. This groundbreaking announcement sparked widespread enthusiasm within the global scientific community, igniting a surge of research interest ranging from investigations into fundamental physics properties to practical applications. The exceptional characteristics of MgB_2 superconductor make it an attractive material for a diverse range of applications, including large-scale systems and electronic devices. Key attributes that contribute to its appeal include its high T_c , large coherence lengths (ξ), J_c , simple crystal structure, and high upper critical fields (H_{c2}). Additionally, MgB_2 exhibits transparency of its grain boundaries to current flow (Larbalestier et al., 2001). Researchers have successfully fabricated MgB_2 into various shapes, such as bulks (Takano et al., 2001; Narozhnyi et al., 2002), single crystals (Lee et al., 2002; Karpinski et al., 2003), thin films (Blank et al., 2001; Kang et al., 2001), wires (Jin et al., 2001; Pradhan et al., 2001), and tapes (Grasso et al., 2001; Fang et al., 2003).

1.1.2.2 The Properties of MgB_2

In comparison to traditional metallic low-temperature superconductors (LTS) and copper oxide high-temperature superconductors (HTS), MgB_2 stands out due to its distinctive characteristics. Notably, MgB_2 exhibits a significantly higher T_c than LTS, while also experiencing fewer challenges associated with anisotropy and weak links at grain boundaries, which are inherent in HTS (Masui et al., 2003).

The crystal structure of MgB_2 is depicted in Figure 1.1, revealing its simple binary compound nature and a hexagonal AlB_2 type structure resembling other borides. The unit structure comprises alternating hexagonal layers of magnesium atoms and graphite-like honeycomb layers of boron atoms. The magnesium layers separate the boron planes, with each magnesium atom positioned between the centers of the hexagons forming the boron lattice planes. Within each boron layer, a hexagon consists of six boron atoms, resulting in an overall 1:2 Mg-B ratio within the unit cell. The entire material structure of MgB_2

exhibits anisotropy (Eltsev et al., 2002; Masui et al., 2003), with the B-B distance within the plane being significantly shorter than the distance between layers.

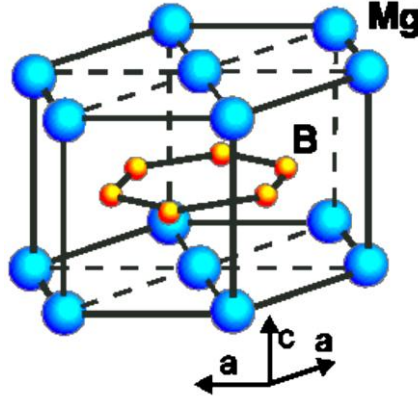


Figure 1.1. Hexagonal crystal structure of MgB_2 (Buzea & Yamashita, 2001).

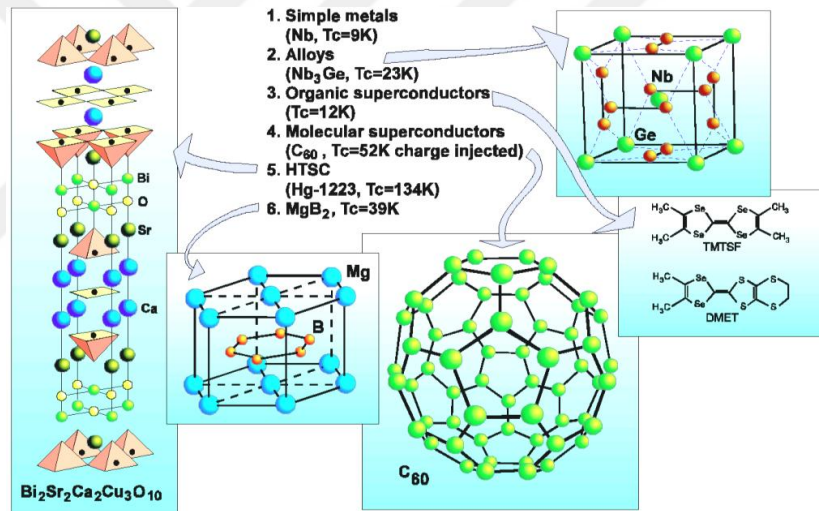


Figure 1.2. MgB_2 crystal structures and some others practical superconductors (Buzea & Yamashita, 2001).

Figure 1.2 provides a comparison of the crystal structure of MgB_2 with other practical superconductors. Similar to graphite, MgB_2 manifests pronounced anisotropy in the B-B lengths, with the distance between boron planes being considerably longer than the in-plane B-B distance. At ambient temperature, the lattice parameters are $a = b = 0.3086 \text{ nm}$ and $c = 0.3521 \text{ nm}$. Consequently, the electromagnetic properties exhibit anisotropy due to the crystal structure, with the coherence length in the a-b plane exceeding that along the c-axis. This disparity

leads to a lower value of the H_{c2} when the MF is directed along the c-axis, perpendicular to the plane (Buzea & Yamashita, 2001).

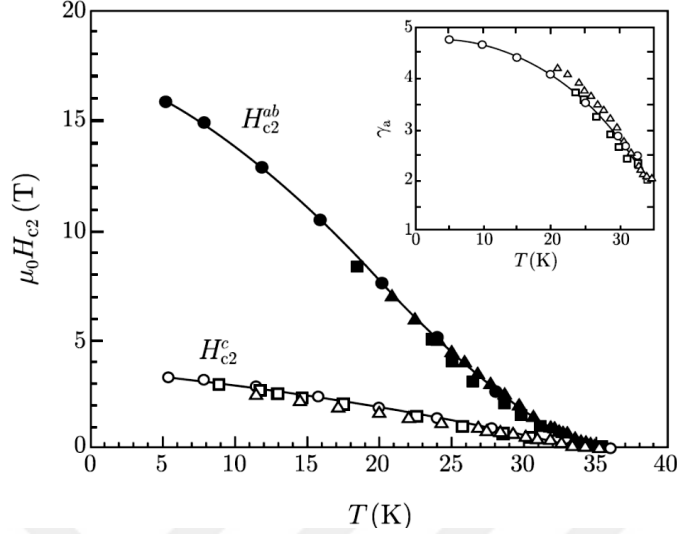


Figure 1.3. Temperature dependence of H_{c2} of MgB_2 single crystal (Lyard et al., 2002).

The inset of Figure 1.3 illustrates the anisotropy of the H_{c2} , revealing an approximately two-fold increase in the anisotropy factor at the T_c , which further amplifies with decreasing temperature. In polycrystalline MgB_2 , random grain orientations average out anisotropy, improving performance in real devices. MgB_2 wires are polycrystalline; anisotropy is not a serious problem. MgB_2 exhibits moderate anisotropy in its superconducting properties, though it is significantly less anisotropic compared to high-temperature superconductors (e.g., YBCO or BSCCO). Hexagonal structure is similar to cubic, so normally it does not cause much anisotropy. MgB_2 has a hexagonal crystal structure, Boron honeycomb layers, and Magnesium layers. This layered structure creates weak anisotropy in properties like J_c and H_{c2} . Understanding and characterizing this anisotropy is crucial for comprehending the material's response to external MFs and optimizing its performance in various applications. The estimated coherence lengths derived from the H_{c2} of MgB_2 are notably larger compared to those of high-temperature superconductors. Specifically, $\xi_c(0)$ is approximately 9.6 nm, while $\xi_{ab}(0)$ is approximately 2.0 nm. This significant difference suggests that the flux pinning properties of MgB_2 may resemble those of traditional metallic superconductors rather than high-temperature superconductors (Lyard et al., 2002).

Table 1.1 provides a comprehensive overview of the typical parameters of MgB_2 in comparison to other practical superconductors. Numerous magnetization and transport measurements have been conducted to investigate the behavior of MgB_2 , and the results consistently indicate the absence of weak-link electromagnetic effects at grain boundaries (Larbalestier et al., 2001) and fast flux creep (Thompson et al., 2001). Transport measurements carried out under high MFs using dense bulk samples have yielded J_c values that align closely with those obtained from magnetization measurements (Dhallé et al., 2001). This correspondence lends support to the notion that the inductive current flows coherently throughout the entirety of the sample, unaffected by the presence of grain boundaries. Consequently, the motion of flux lines within the material will play a decisive role in determining the dependence of J_c on both MF and temperature. The absence of weak-link behavior at grain boundaries in MgB_2 is a significant advantage, as it enhances the overall electrical transport properties and ensures the coherence of the superconducting current across the material. These findings contribute to a more comprehensive understanding of the underlying mechanisms governing the superconducting properties of MgB_2 , paving the way for further exploration and optimization of its flux pinning and current-carrying capabilities.

Table 1.1. Basic properties of the practical superconductors (Vinod & Upendran, 2010).

Parameter	NbTi	Nb ₃ Sn	MgB ₂	YBCO	Bi-2223
T_c (K)	9	18	39	92	110
Anisotropy	Negligible	Negligible	1.5~5	5~7	50~200
J_c at 4.2 K (A/cm ²)	$\sim 10^6$	$\sim 10^6$	$\sim 10^6$	$\sim 10^6$	$\sim 10^7$
H_{c2} at 4.2 K (T)	11–12	25–29	15–20	>100	>100
H_{irr} at 4.2 K (T)	10~11	21~24	6~12	5~7 (77K)	0.2 (77K)
Coherence length $\xi(0)$ (nm)	4~5	3	4~5	1.5	1.5
Penetration depth $\lambda(0)$ (nm)	240	65	100~140	150	150
Resistivity $\rho(T_c)$ ($\mu\Omega\text{cm}$)	60	5	0.4	150~800	40~60

1.1.2.3 The Phase Diagram of MgB_2

The temperature-composition phase diagrams hold paramount importance as they serve as indispensable tools for guiding the fabrication, composition

selection, and application of various materials and chemical products. Figure 1.4 illustrates the temperature-composition phase diagrams for the Mg-B system under ambient pressure (Z. K. Liu et al., 2001).

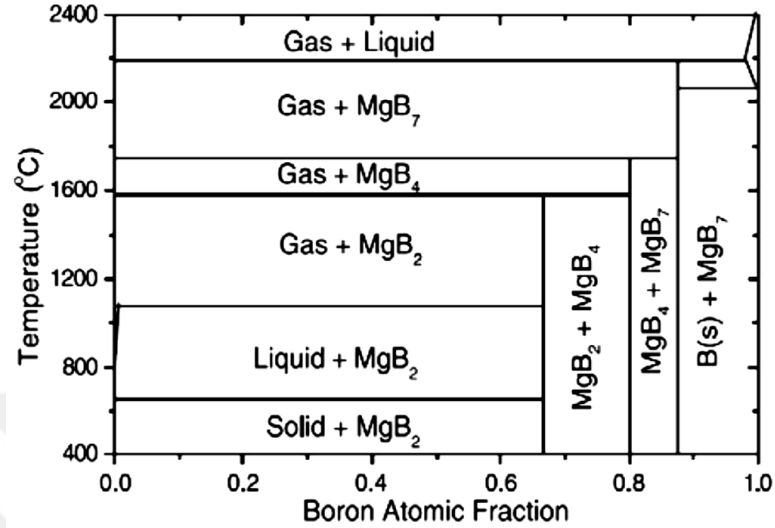


Figure 1.4. The (Mg-B) diagrams under the Mg vapor pressure of 1 atm (Z. K. Liu et al., 2001).

In the diagram, the regions labeled as Solid, Liquid, and Gas correspond to the Mg-rich solid phase, liquid phase, and gaseous phase, respectively. A comprehensive analysis of the figure reveals compelling insights into the behavior of this system. When the temperature exceeds 650 °C and the atomic ratio of Mg to B surpasses 1:2, the Mg component undergoes a melting process, coexisting with the solid phase of MgB₂. Conversely, within the temperature range below 1090 °C and with a Mg:B atomic ratio ranging between 1:4 and 1:2, the MgB₂ phase coexists with another compound known as MgB₄. Notably, there exist substantial composition windows where both Mg in the liquid phase and MgB₂ in the solid phase coexist, further emphasizing the intricacies and diversity within the Mg-B system. The temperature-composition phase diagrams provide critical insights into the stability and compatibility of various phases within the Mg-B system under ambient pressure conditions. This knowledge is invaluable for guiding the fabrication processes, optimizing the composition selection, and facilitating the targeted application of materials and chemical products based on the Mg-B system. These phase diagrams offer a fundamental understanding of the thermodynamic behavior and phase transformations occurring in the Mg-B

system, empowering researchers and engineers to make informed decisions regarding the synthesis and application of materials within this system (Yan et al., 2004).

1.1.3 Doping of MgB_2

In the absence of an external MF (i.e., self field conditions), pure MgB_2 exhibits transport J_c of approximately 10^6 A cm^{-2} in various forms such as bulks, films, wires, and tapes, even at moderately low temperatures ranging from 20 to 25 K. Figure 1.5 illustrates the relationship between T_c , J_c , and H_c for MgB_2 , NbTi , and Nb_3Sn , respectively. Notably, the J_c value of pristine MgB_2 experiences a rapid decline as the external MF increases. This behavior can be attributed to the material's limited flux pinning strength in a MF and its relatively low H_{c2} (Holúbek et al., 2008).

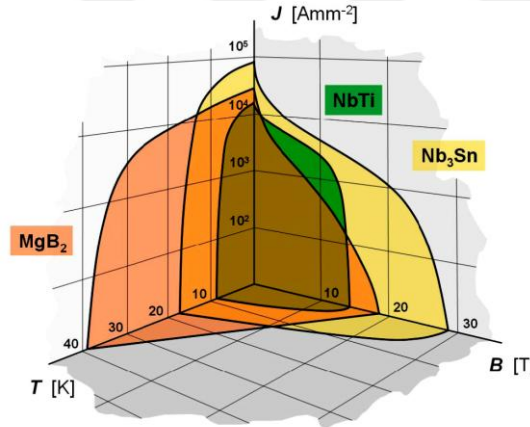


Figure 1.5. Critical surfaces of some superconductors includes MgB_2 (Holúbek et al., 2008).

Numerous techniques have been explored to enhance the (J_c - B) characteristics and flux pinning properties of MgB_2 . These techniques encompass irradiation (Bugoslavsky et al., 2001; Silver et al., 2004; Putti et al., 2005), chemical doping (Dou et al., 2002; Sumption et al., 2005; Agatsuma et al., 2006; Xu et al., 2010), MF annealing (Dou et al., 2006; Y. Ma et al., 2006), and ball-milling methods (Xu et al., 2006; Romano et al., 2009; Dancer et al., 2010), among others. Among these techniques, chemical doping has been regarded as a convenient and effective approach to enhance the J_c - B properties of MgB_2 .

Chemical doping has the potential to induce alterations in the electronic state, lattice constants, and crystallinity of the material. Furthermore, if the

impurity particles introduced through doping possess a moderately small grain size and are dispersed throughout the MgB_2 matrix, they can serve as effective pinning sites. Chemical doping presents a promising avenue for tailoring the superconducting properties of MgB_2 , particularly by improving its flux pinning capabilities and enhancing its J_c - B characteristics. By altering the material's structure and introducing impurities in a controlled manner, researchers aim to overcome the limitations associated with pristine MgB_2 and unlock its full potential for various technological applications (Cheng et al., 2003; Ueda et al., 2004; Chen et al., 2005; Yamamoto et al., 2005; J. H. Kim et al., 2007; X. Zhang et al., 2007).

1.1.4 The Fabrication Method of MgB_2 Superconducting Wires

Since the initial discovery of superconductivity in MgB_2 in 2001, significant advancements have been made in the development of MgB_2 superconductor wires. These advancements have culminated in the successful demonstration of kilometer-long MgB_2 wires in magnets and coils. As a result, ongoing efforts are now focused on utilizing MgB_2 wires in the construction of superconducting devices, and commercially available MgB_2 wires are already accessible for this purpose.

1.1.4.1 Powder-in-Tube Technology

The powder-in-tube (PIT) technique, widely employed for the fabrication of HTS BSCCO conductors, has been utilized in numerous laboratories to produce MgB_2 wires and tapes of industrial lengths (Yamada et al., 2006). The PIT process offers several key advantages, including its cost-effectiveness and simplicity in fabrication. Additionally, it represents a highly developed and stable technique for producing superconducting wires and tapes with a multi-filamentary structure. Such multi-filamentary configurations typically exhibit superior current-carrying and mechanical properties compared to mono-filamentary counterparts, owing to the reduced dimensions of individual filaments. Furthermore, multi-filamentary wires and tapes demonstrate greater resistance to tensile and bending strains, along with improved thermal stability due to the smaller dimensions of the filaments. However, the hardness and brittleness of MgB_2 pose significant challenges when employing the PIT process for the production of industrial-scale wires and tapes. Notably, the process of drawing or rolling multi-filamentary

MgB₂ wires or tapes into smaller sizes is highly demanding. Consequently, in the case of practical high-current MgB₂ multi-filamentary wires and tapes, the filaments are typically around 30 µm in size (Malagoli et al., 2009), considerably larger than those found in Nb₃Sn wires. The schematic representation of the fabrication process is depicted in Figure 1.6.

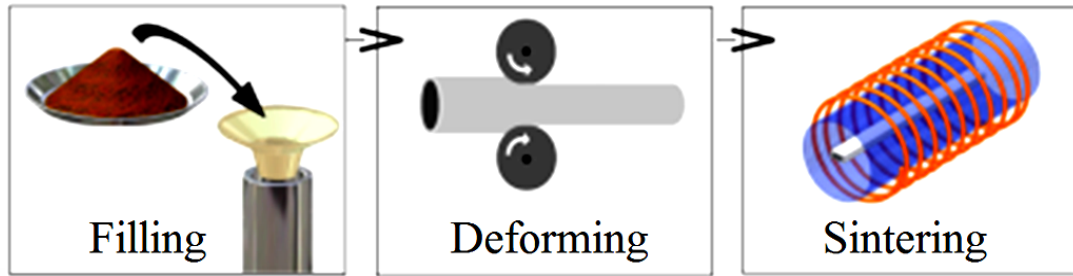


Figure 1.6. A simple fabrication of powder in tube method.

The literature describes two approaches for PIT fabrication: *in-situ* and *ex-situ* methods as follows:

***In-situ* PIT Technique:** The *in-situ* powder-in-tube (PIT) technique involves the initial step of filling metallic tubes with elemental Mg and B powders, followed by subsequent deformation and heat treatment processes. Notably, this approach requires lower heat treatment temperatures to achieve high J_c , thereby expanding the range of viable sheath materials. In the *in-situ* route, boron-rich phases may be present due to incomplete precursor reaction. The *in-situ* process offers several advantages, including its lower reaction temperatures, and increased flexibility in incorporating dopants or other additives into the wire. The lower reaction temperature is particularly advantageous as it helps mitigate the likelihood of powder-barrier reactions. Furthermore, the chemical compatibility between the filled tube and the powders at the MgB₂ reaction temperature is crucial for ensuring a successful overlap-closed configuration.

***Ex-situ* PIT Technique:** An alternative approach for fabricating MgB₂ wires and tapes is the *ex-situ* PIT technique. This method involves the direct filling of metallic tubes with reacted MgB₂ powders, followed by cold deformation processes. Subsequently, heat treatment within the temperature range of 600-1000 °C is typically employed to induce superconductivity and enhance the core density of the cold-worked tapes or wires, thereby promoting the formation of well-connected grain structures. Moreover, it is important to note that the high

annealing temperature associated with the *ex-situ* PIT technique limits the choice of sheath materials. This limitation arises from the need to prevent chemical reactions between the sheath and filament, particularly in the context of future multi-filamentary wires with significantly smaller filament dimensions. The resulting reaction layer thickness typically falls within the range of 1-25 μm , which is contingent upon the specific sheath material employed and the temperature of the applied heat treatment.

1.1.4.2 The Sheath Materials

Practical superconductors typically comprise multiple filaments of superconducting material embedded within a highly conducting matrix. The process of reducing the size of compound wires is often accomplished through drawing, rolling, or extrusion. For flexible alloys like Nb-Ti superconductors, this represents a straightforward and viable approach. However, MgB_2 , similar to Nb_3Sn and BSCCO, is a hard and brittle intermetallic compound, making direct deformation more challenging. To address the difficulties associated with the deformation of such brittle superconducting materials, the PIT process is employed, utilizing a suitable sheath material. The resulting wire may not possess the same level of flexibility as conventional metal wire, but it is typically sufficient for various applications. In this process, the choice of sheath material assumes critical importance. While high thermal and electrical conductivity metals like Ag and Cu have been utilized successfully for fabricating Nb_3Sn and BSCCO wires, they are not suitable for Mg-B mixed powders due to the heightened chemical reactivity of Mg and B. The reaction between Mg-B and these metals, such as Ag, Cu, and Al, during intermediate or final annealing results in the formation of an evident reaction layer between the superconducting core and sheath material. These reaction layers can diminish the superconducting properties or compromise the thermal stability of MgB_2 wires. Therefore, it is imperative to avoid or minimize the formation of such reaction layers by employing an appropriate sheath material. The selection criteria for sheath materials generally revolve around the following principles: chemical stability, exceptional plasticity, higher thermal and electrical conductivity, and lower material cost. Various metals, including Ni, Cu, Fe, Nb, Ta, and stainless steel (SS), have been employed as sheath materials for MgB_2 wires by different research teams. Composite sheaths, such as Cu/Ta, Cu-Ni, Fe/SS, Fe/Ni, and

Fe/Cu, have also been utilized to enhance the mechanical strength of MgB₂ wires. Considering all the aforementioned factors, Fe, Nb, and Cu emerge as ideal sheath materials for the fabrication of MgB₂ wires. Fe offers a lower cost and sufficient mechanical strength, while Nb exhibits a reduced propensity for reacting with Mg or B. Furthermore, Cu combines low cost with excellent thermal stability (Kumakura et al., 2001; Fu et al., 2002 ; Tanaka et al., 2005).

1.1.5 Long Length MgB₂ Wires Fabrication

Presently, several companies specialize in the fabrication of MgB₂ wires and tapes. One notable example is Columbus Superconductors, which achieved a significant milestone in 2006 by producing MgB₂ tapes with lengths reaching up to 1.6 km. These tapes were fabricated using the *ex situ* powder-in-tube method. In this process, fully reacted MgB₂ powders were carefully packed into pure nickel tubes, which underwent cold working to form an extended wire. The monofilament wire was subsequently cut into multiple segments and reassembled inside a second nickel tube, which contained an inner core made of oxygen-free high conductivity copper (OFHC) and an iron diffusion barrier. The inclusion of the copper core and iron barrier aimed to prevent undesirable diffusion of copper into the nickel and MgB₂ during subsequent heat treatment. To achieve the final rectangular shape of the tape, the composite underwent further cold working through drawing and rolling processes. The manufactured tapes typically exhibited dimensions of 0.65 mm thickness and 3.65 mm width. Subsequently, a high-temperature heat treatment (900 °C) was applied to sinter the MgB₂ grains and enhance the J_c (Stenvall et al., 2007; Razeti et al., 2008; Abramson et al., 2011).

1.1.6 MgB₂ Coils

There are many types of superconducting coils, including solenoid, dipole, quadrupole, racetrack, and toroid coils, each fabricated for various applications as specified in Table 1.2. Among these, the solenoid is the most widely used type. The toroid coil generates a MF in the azimuthal direction and is employed for superconducting magnetic energy storage (SMES). The racetrack coil consists of two parallel sides and two semi-circles at each end, allowing it to approximate the field of a dipole, making it suitable for motors and maglev systems (Matsumoto A

et al., 2003). Racetrack coils are particularly important in applications such as MRI and accelerators due to their elliptical shape. Notably, the first commercial superconducting magnet, which produced a 4 Tesla MF, was manufactured by Oxford Instruments in 1962. The racetrack coil made from $\text{MgB}_2/\text{Cu}_{30}\text{Ni}$ monocoil wire generates a MF of 0.44 T at 12 K and 0.29 T at 20 K (Sumption et al., 2006). Many scientists are working on applications using MgB_2 to achieve higher and more homogeneous MFs.

Table 1.2. Various coils and their B_{max} for Applications (Matsumoto A et al., 2003).

Coil	B_{max} (T)	Applications
Solenoid	45	High-field research
	23.5	NMR
	5	MRI
	~1.5	Magnetic Separation
Dipole	~15	High-energy physics (HEP)
Quadrupole	0	HEP
Racetrack	4-5	PowerElectric Devices
Toroid	~16	Fusion
	5-10	SMES

1.1.7 The Typical Application of MgB_2 Superconductor

The application range of MgB_2 superconductors can be broadly classified into two main regions: the "low field" applications that utilize cryogenic free systems and operate within a temperature range of approximately 20 K, and the "high field" region where the conductor can potentially surpass the MF capabilities of current NbTi materials around 8 T at 4.2 K (J. H. Kim et al., 2007).

ASG, a leading company in this field (Spina et al., 2024), embarked on the design of an MRI magnet based on MgB_2 conductors, which was significantly ahead of the expected industrialization of the conductor itself. The design of the magnet underwent modifications to align with the evolving characteristics of the MgB_2 conductors during the engineering study. Furthermore, this endeavor presented a unique opportunity to initiate the winding of the first double pancake and assemble the magnet within a few weeks of producing the cable of substantial length that was suitable for practical use. The completed magnet underwent initial testing, which yielded positive results. The preliminary findings confirmed that the 18 km of conductor used for coil winding adequately fulfilled the

requirements of the MRI system. Remarkably, the magnet achieved its intended nominal current of 90 A and central field strength of 0.5 T without the need for any training procedures (Razeti et al., 2008).

A series of MgB_2 Fault Current Limiter (FCL) prototypes were developed in the LIMSAT Italian project, supervised by CESI. Test results matched expected behavior, with non-inductive windings achieving I_c around 600 A under AC transport currents in liquid helium and neon across frequencies of 2-500 Hz. Various prototype solenoids were created using different conductors, achieving central MFs up to 5 T. A solenoid wound with an already reacted conductor on a 135 mm inner diameter reached the short sample limit at 20 K without training, achieving a central field of 1 T at 16 K. These results demonstrate the potential of MgB_2 superconductors for Fault Current Limiters, showcasing their high I_c and versatility for practical applications in power systems (Dalessandro et al., 2007).

1.2 Magnetic Field and Wastewater Treatment

1.2.1 Wastewater

Wastewater, or sewage, is water discarded which is driven from various sources and activities, the effective management is vital for public health and life. The rising volume of municipal wastewater, led by population growth and economic developments; including industrial wastewater, highlights the need for integrated water resource management to convert wastewater into a valuable resource (Drechsel et al., 2015). Qadir et al. reported that 380 billion m^3 of wastewater is produced annually, with projections indicating an increase of 24% by 2030 and 51% by 2050. This wastewater contains valuable nutrients and energy, which could potentially meet 13.4% of global agricultural demand and provide power for 158 million households. Addressing these challenges necessitates collaboration between public and private sectors to enable resource recovery within a circular economy (Qadir et al., 2020). A review of 53 datasets estimated average concentrations in wastewater at 43.7 mgL^{-1} nitrogen (N), 7.8 mgL^{-1} phosphorus (P_2O_5), and 16.5 mgL^{-1} potassium (K_2O). Nutrient potential was expressed in teragrams (Tg), with economic values based on 2018 prices such as urea (US\$ 249/t), triple-superphosphate (US\$ 347/t), and potassium chloride (US\$ 216/t). The energy value was estimated at 0.14 m^3 of methane (CH_4) per m^3 of wastewater (a caloric value of 35.9 M Joule/ m^3) (Mateo-Sagasta et al., 2015;

Qadir et al., 2020). Treating wastewater can incur significant costs, as it is essential to effectively remove pollutants to ensure the water is clean and reusable. Common contaminants in wastewater effluents include heavy metals, surfactants, organic compounds, salts, and soluble bases (Rashid et al., 2021). Current conventional treatment methods often fail to completely eliminate these pollutants; instead, they may concentrate or convert them into different phases (Yahya et al., 2018). Nevertheless, ongoing progress is being made to develop new strategies for WWT that will help meet the need for clean water (Ahmed & Haider, 2018). Numerous physical techniques are utilized for WWT, with mass transfer strategies serving as the basis for these pollutant removal methods. These techniques are preferred due to their simplicity, flexibility, high efficiency, and potential for pollutant recycling. Additionally, physical treatment is often viewed as more reliable than other methods since it does not depend on living organisms (Foroutan et al., 2019; Wong et al., 2019; Samsami et al., 2020). The discharge of wastewater has resulted in significant environmental issues, such as deteriorating water quality and eutrophication of aquatic systems (Arbib et al., 2014). Although traditional treatment methods have proven effective for various types of wastewater, they often fall short when dealing with industrial wastewater, which typically contains high concentrations of heavy metals, dyes, and toxic substances (Gonçalves et al., 2017).

1.2.2 Heavy Metals

Heavy metals such as cadmium, arsenic, chromium, zinc, nickel, copper, mercury, and lead are major freshwater pollutants, posing serious health risks due to their toxicity and persistence (Hunsom et al., 2005). Industrial activities release these metals, which are highly soluble and can accumulate in aquatic life and the human food chain (Hunsom et al., 2005). Various treatment methods have been developed, including membrane filtration, adsorption, ion exchange, chemical precipitation, nanotechnology, and electrochemical processes. Access to clean water is increasingly critical as availability declines from pollution and population growth, even in resource-rich areas. While rainwater harvesting offers short-term relief, effective WWT and reuse are essential. Wastewaters contain toxic pollutants classified as organic, inorganic, and biological, with a focus on removing inorganic heavy metal ions to prevent environmental discharge.

Excessive metal accumulation can cause serious health issues, such as skin irritations from zinc and cancers from nickel. Thus, effective treatment is crucial for reducing pollutants to safer levels. Heavy metals can persist in the body for long periods due to their non-biodegradable nature (Montgomery & Elimelech, 2007; Hahladakis et al., 2013). Azimi et al. examined methods like membrane filtration, ion exchange, chemical precipitation, and adsorption, while electrochemical methods include electrocoagulation and electrodeposition. Photocatalysis and nanotechnology also play roles in treatment. Preferred methods are cost-effective and environmentally friendly, although biological processes mainly target biodegradable substances rather than heavy metals (Azimi et al., 2017).

1.2.3 Magnetic Field and Treatment

The application of MFs in WWT is emerging as a promising technique due to its capacity to enhance various physicochemical processes. MFs can modify the behavior of contaminants, improving their separation and removal efficiency. They enhance flocculation and settling of suspended particles by exerting attractive forces on paramagnetic and ferromagnetic particles, promoting their agglomeration and removal from wastewater. Moreover, MFs can improve the effectiveness of biological treatment processes by modulating the growth and activity of microorganisms that degrade organic pollutants. Research shows that MFs enhance bacterial activity, leading to faster degradation rates, primarily by facilitating oxygen transfer, which is crucial for aerobic bacteria (Batstone et al., 2015).

Additionally, MFs reduce energy consumption and operational costs in WWT by influencing the physical properties of water, such as surface tension and viscosity, thereby lowering energy needs for filtration and pumping. They also aid in regenerating adsorbents and enhancing the efficiency of membrane technologies, further decreasing operational costs. Importantly, MFs are not standalone solutions but complementary technologies that can be integrated with traditional methods such as coagulation, precipitation, adsorption, and biological processes. This combination has demonstrated promising results in enhancing treatment efficiency and contaminant removal. While the potential of MFs in WWT is significant for improving water quality and achieving sustainable

solutions, further research is necessary to optimize these systems for various contaminants and wastewater matrices. Embracing such innovative technologies can lead to more efficient and sustainable wastewater management, benefitting public health and the environment. On another note, N. S. Zaidi et al. conducted a review focused on water magnetization and its applications in WWT. They critically examined magnetically assisted treatment approaches, comparing their performance to conventional systems. The literature indicates that MFs significantly enhance solid-liquid separation by promoting the aggregation of colloidal particles, while also improving biological properties such as bacterial activity. These enhancements contribute to the overall efficiency of water and WWT processes (N. Syamimi et al., 2014).

This study examines the applications of MFs in calcium carbonate crystallization, water purification, coagulation and sedimentation of colloidal particles, and WWT, emphasizing their potential benefits and limitations while calling for further research in this area. MFs have shown effectiveness in separation processes by influencing the characteristics of contaminants, thereby enhancing purification efficiency when combined with other techniques (Ambashta & Sillanpää, 2010). Various magnetic technologies utilize permanent magnets or high-gradient magnetic separation (HGMS) in methods like magnetic seeding, magnetic adsorption, and electromagnetic devices, each affecting system performance differently (N. Syamimi et al., 2014).

However, the mechanisms behind these applications are not fully understood, leading to conflicting theories in the literature. For example, while Kronenberg et al. (1985) proposed molecular nucleation as a key principle, it does not explain how this occurs or the varying effects of magnetism (Kronenberg, 1985). To address these gaps, four critical factors in the use of MFs: magnetization and MF manifestation, the presence of a magnetic gradient, the influence of Lorentz force, and the phenomenon of magnetic memory (Spiegel, 1998). Magnetic technology has enjoyed extensive utilization across diverse domains for several decades. Within the realm of water and WWT, magnetic technology has found notable applications. This section aims to elucidate the specific areas where magnetic technology has been employed in this field as following:

(CaCO₃): The precipitation of calcium carbonate (CaCO₃) is significant due to its applications as a pigment, brightener filler, and adsorbent in various industries. Literature indicates that applying a MF can transform CaCO₃ clusters in supersaturated solutions, shifting their predominant form from calcite to aragonite. This transformation accelerates aragonite growth while suppressing calcite formation. Additionally, magnetic treatment can help mitigate scaling by promoting homogeneous nucleation of CaCO₃. However, precise exposure to the MF is crucial when treating water with silica to ensure effective crystallization while minimizing scaling effects. CaCO₃ scale deposition leads to operational challenges, including pipe blockages, membrane clogging, and reduced efficiency in heaters and heat exchangers. Various methods have been used to address scaling, such as electrochemical processes, seeding, acid addition, and chemical inhibitors. However, these chemical treatments can pose health risks, prohibiting their use in drinking water systems. As a result, physical methods like magnetic treatment of hard water have emerged as effective strategies to prevent encrustation from mineral salts (Alimi et al., 2009).

Water purification: Water management practices include various categories based on the source, such as natural, domestic, and industrial wastewater management. Each category requires distinct strategies for reuse or disposal, with water purification being a common approach. Purification techniques encompass adsorption, biotechnology, catalytic processes, membrane processes, ionizing radiation, and magnetically assisted processes. Table 1.3 presents various studies examining the effects of MFs on water.

Table 1.3. The magnetic field influences on water.

The Impact of Magnetic Fields on Water Purification	References
Exposure to a SMF of(0.4–0.6) T accelerated precipitation and improved sludge coagulation by reducing electrokinetic potential.	(Krzemieniewski et al., 2004)
SMF of 0.0025 T lowered the conductivity of deionized water, attributed to changes in the ionic hydration shell.	(Akopian & Aïrapetian, 2005; Holysz et al., 2007)
Water's structural stability and viscosity are closely tied to its hydrogen bonding.	(Iwasaka & Ueno, 1998)
SMF exposure from (0 - 10) T increased hydrogen bonds by up to 0.34%, decreasing the self-diffusion coefficient while enhancing viscosity and stability.	(Chang & Weng, 2008)
A 6 T magnetic field strengthened hydrogen bonds in H ₂ O and D ₂ O by inhibiting thermal motion through the Lorentz force, termed “enhanced-dynamic magnetic susceptibility.”	(Inaba et al., 2004)
Moderate MFs (less than 1 T) can also promote hydrogen bond	(Cai et al., 2009)

synthesis.	
MFs may weaken hydrogen bonds between water clusters but enhance bonding within the clusters.	(Toledo et al., 2008)
Magnetized water has a lower friction coefficient than unmagnetized water, indicating reduced hydrogen bond strength.	(Y. Wang et al., 2013)
MFs alter hydrogen bonding dynamics in water, enhancing reactions like improved adsorption.	(J. Ma et al., 2018)

Wastewater Treatment: Rapid population growth has significantly increased water consumption, worsening water pollution. Researchers have explored various methods, including MFs, to address these challenges. While studies show that higher MF intensities improve the removal of organic compounds such as a 30% increase in phenol removal at 450 mT (Jung et al., 1993), mixed effects on bacterial biodegradation are noted. Sakai et al. (Sakai et al., 1994) found that a submerged filter system using magnetically anisotropic media achieved up to 94% removal of sewage with a COD of 200 mg/L. However, the optimal MF intensity for enhancing bacterial activity and biodegradation remains unclear, necessitating further research. The intensity typically ranges from 1 mT to 1 T, with higher levels potentially hindering bacterial growth. Each bacterium has a unique susceptibility to MFs, which can affect treatment performance. Flow mode also influences treatment effectiveness. Recirculating wastewater through MFs has been shown to improve contaminant removal compared to single-pass exposure (Szcześ et al., 2011). This is due to magnetic memory enhancing interactions between charged particles, facilitating solid-liquid separation. For biological treatment, single-pass flow is generally more effective.

1.2.4 Magnetization of Water

Water, the most common solvent, is highly susceptible to magnetization. MFs significantly influence its self-diffusion coefficient and evaporation rate, as well as the cluster size of water molecules. These changes are linked to alterations in molecular structure, including particle polarization and electrokinetic potential. For instance, Krzemieniewski et al. (2004) reported that exposure to a static magnetic field (SMF) of 0.4–0.6 T led to faster precipitation and improved coagulation of sludge due to reduced electrokinetic potential (Krzemieniewski et al., 2004). Additionally, Hakobyan and Ayrapetyan (2005) showed that a SMF of 0.0025 T could lower the conductivity of deionized water, attributed to changes in the ionic hydration shell (Akopian & Aĭrapetian, 2005; Holysz et al., 2007).

Water's structural stability and viscosity are closely tied to its hydrogen bonding (Iwasaka & Ueno, 1998). Chang and Weng found that SMF exposure from 0 to 10 T increased hydrogen bonds by up to 0.34%, which decreased the self-diffusion coefficient while enhancing viscosity and stability (Chang & Weng, 2008). Inaba et al. noted that a 6 T MF strengthened hydrogen bonds in H₂O and D₂O by inhibiting thermal motion through the Lorentz force, termed “enhanced-dynamic magnetic susceptibility” (Inaba et al., 2004). Moderate MFs (less than 1 T) can also promote hydrogen bond synthesis (Cai et al., 2009). However, Toledo et al. suggested that while MFs may weaken hydrogen bonds between water clusters, they enhance bonding within the clusters (Toledo et al., 2008). Wang et al. found that magnetized water has a lower friction coefficient than unmagnetized water, indicating reduced hydrogen bond strength (Y. Wang et al., 2013). Overall, MFs alter hydrogen bonding dynamics in water, enhancing reactions like improved adsorption (J. Ma et al., 2018).

1.2.5 Magnetic Water

Magnetic water treatment (MWT) modifies the physical and chemical properties of water through MF exposure, offering benefits such as scale prevention, improved soil quality, enhanced plant growth, increased crop yields, water conservation, and WWT. This process restructures water molecules into small hexagonal clusters, facilitating their movement through cell membranes while blocking toxins, making magnetized water biologically advantageous. A review by Ali et al., highlighted MWT's applications and mechanisms, emphasizing the need for controlled lab and field studies to advance these techniques (Ali et al., 2014). The use of electromagnetic fields (EMFs) has expanded in various sectors, including environmental management and industry, with MWT recognized for its potential benefits amid rising water demands and droughts. Research shows that MWT improves irrigation water quality, enhances crop yields, prevents scale formation, and treats wastewater, while also exhibiting antimicrobial properties beneficial for food processing (Gholizadeh et al., 2008). Magnetic wastewater treatment (MWWT) employs EMFs to enhance treatment processes, offering safety, environmental friendliness, low costs, and no proven harmful effects. EMFs modify water properties, promote sludge precipitation, and improve the removal of phosphorus and organic compounds. Combining cleaning

agents with MWWT can reduce their usage by up to 75% (Ren et al., 2021). Research on EMFs in WWT includes magnetite slurry, magnetic particles, and pulsed electric fields. Most MWWT systems use magnets or electromagnets to remove pollutants like phosphates and heavy metals, with magnetic particle technology effectively recovering metals from wastewater. Additionally, SMFs are gaining interest, though further studies are needed on their effects on organic substrate biodegradation, particularly regarding nitrogen compounds (Cuartero & Fernández-Muñoz, 1998).

Magnetic particle technology is a key method in MWWT due to its absorption and coagulation capabilities. It is effective for recovering metals from electroplating rinse water, sewage sludge, and hydrometallurgical effluents. This process involves attaching pollutants to a magnetic carrier, typically magnetite, which allows for efficient separation and reuse. A significant study by Sakai explored a submerged filter system using magnetically anisotropic tubular media for sewage treatment. By adding ferromagnetic powder to activated sludge, biofilm formation was enhanced through magnetic attraction, achieving 72% to 94% COD removal from sewage with a concentration of 0.2 g/L over an 8-hour retention time, with biofilm formation occurring in just 15 minutes (Sakai et al., 1994).

1.3 Superconductors and Wastewater Treatment

Water pollution is a significant challenge in the 21st century, highlighting the need for effective protection of water resources. Superconducting magnetic separation systems are increasingly essential for WWT. A newly developed large bore conduction-cooled magnet enhances these capabilities, building on magnetic separation techniques used since the 1970s for applications like heavy metal ion removal. With only 2.5% of Earth's water being fresh and climate change threatening water availability, compact systems for sewage and groundwater treatment are crucial (Ohara et al., 2001). These superconducting systems offer advantages over conventional activated sludge treatment, such as higher efficiency, faster processing, and reduced costs. Conduction-cooled magnets are more convenient and cost-effective than liquid helium-cooled options (W. Ma et al., 2012). Following K. Watanabe's introduction of the first conduction-cooled magnet in 1992, advancements have resulted in commercially available cryogen-

free systems that generate high MFs. Optimal performance requires a MF above 0.7 T. While large bore magnets typically rely on liquid helium, conduction-cooled designs face challenges that require further research. The manufacturing process utilizes dry winding technology for insulation and stability, ensuring secure conductor placement (Seo & Morita, 2006).

A study for H. Liu et al. which developed a superconducting magnet with NbTi solenoid coils, featuring a 400 mm horizontal warm bore and a maximum central field strength of 2.56 T. The cooling system employs a two-stage 1.5 W 4K GM cryocooler, taking approximately 65 hours to cool to 4.8 K. MF testing confirmed the magnet met design specifications. The magnet includes a 460 mm inner bore solenoid made from multi-filamentary NbTi/Cu wires sourced from Western Superconducting Technologies Co., Ltd. Each wire has a diameter of 0.55 mm, is insulated for at least 2.5 kV, and coated with 0.025 mm of varnish. Operating at 65 A, the solenoid generates a central field of 2.56 T, with simulations indicating a possible peak of 3.4 T, although the field rapidly decreases outside the winding, properties of superconducting wire for coil. Given the coil's large diameter, a 20% safety margin is included to address potential instabilities. The coil is wound onto an aluminum former with an axial slit to minimize eddy current heat generation and simplify assembly. The former measures 378 mm in thickness and height, with 14 mm thick end plates for a seamless weld. To enhance conductance, the thickness of epoxy and fiberglass layers is minimized, and a 1.5 mm thick, 22 mm wide layer of copper braided strips is applied outside the wire layer, secured with collars. A 5 mm thick binding layer of fiberglass tapes and DW-3 epoxy resin, under a maximum tension of 120 N/mm², manages hoop stress from the Lorentz force. The magnet coil is connected to two pairs of diodes for cooling protection. After multiple energization cycles, three quench incidents were noted at 55 A (2.16 T), 62 A (2.44 T), and 69 A (2.72 T). The magnet successfully operated at 65 A, generating 2.56 T without quenching, and during the 69 A quench, the maximum temperature rise was kept below 70 K, ensuring effective protection (H. Liu et al., 2017).

In 2023, Nicola Di Costanzo et al. studied the increasing global production of sewage sludge and evaluated anaerobic digestion as a sustainable management strategy. This process generates methane-rich biogas and nutrient-rich digestate. The research investigated the impact of a high-intensity SMF of 1.5 T on the

chemical composition of sewage sludge and its methane production. Key variables included flow rate, the mixing ratio of magnetized to non-magnetized sludge, and total solid content. Results indicated that exposure to the SMF decreased methane production by 24% and reduced concentrations of ionic species (NH_4^+ , NO_3^- , PO_4^{3-} , SO_4^{2-} , and Mg^{+2}) in the sludge's liquid phase. However, the SMF also facilitated the precipitation of valuable compounds like struvite. While the high-intensity SMF negatively affected methane generation, it aided in nutrient recovery, supporting circular economy principles. Further research is needed to elucidate the mechanisms behind these effects and optimize sewage sludge management (Di Costanzo et al., 2023).

1.3.1 Magnetic Separation of Industrial Wastewater

Magnetic separation techniques have been used since the 1840s in the mining industry to concentrate magnetic ore and remove magnetizable particles from slurries. The advent of high-field superconducting magnets in the 1960s led to the development of superconducting separators, initially for refining kaolin clay. Recently, interest has grown in environmental applications, resulting in the construction of superconducting separators for water purification and sulfur removal from coal. The effectiveness of these separation processes depends on optimizing parameters like particle size, magnetic susceptibility, applied magnetic force density, and flow velocity. The required force for effective separation is proportional to the magnetic flux density and its gradient, typically limited to 0.05 T/mm in open gradient magnetic separators (Gillet et al., 1999).

Hartikainen et al. explored open gradient magnetic separation as a continuous method without matrix elements. They built a separator with a liquid helium cryostat and interchangeable NbTi and Nb₃Sn coils to purify synthetic and genuine steel mill wastewater. This involved chemical treatment to make dissolved metals, such as chromium, iron, nickel, and molybdenum, suitable for magnetic separation using ferromagnetic magnetite. The study demonstrated the separator's efficiency, achieving an 82% separation efficiency for chromium in synthetic wastewater and a 55% reduction in molybdenum concentrations in

genuine wastewater as magnetic flux density increased, highlighting its potential for effective wastewater purification (Hartikainen et al., 2005).

C. He et al. (He et al., 2022) investigated an innovative up-concentration process for carbon-neutral WWT, minimizing reliance on gravity through advanced separation techniques. They proposed a pilot-scale enhanced magnetic separation (EMS) system aimed at maximizing energy recovery from municipal wastewater. This system utilizes magnetic-driven separation for quicker processing while employing adsorption to capture soluble substances. Jar tests confirmed the effectiveness of activated carbon in enhancing aggregate surface roughness. After a year of operating a 300 m³/d EMS system, over 80% of particulate organics and 60% of soluble organics were removed in just 10 minutes, with energy consumption at only 0.036 kWh/m³. Sludge analysis provided insights into organic concentration and microbial community structure, and anaerobic tests highlighted the potential of the concentrated products. The EMS system demonstrates significant advantages in time efficiency, space utilization, and competitive operating costs. Overall, the findings suggest that EMS is a promising technology for recovering organics from municipal wastewater, effectively adapting to different influent conditions and producing concentrated sludge suitable for energy recovery.

Baek et al. (Baek et al., 2012) explored an innovative WWT method that employs magnetic microbeads and a MF. They performed jar tests to evaluate the method's feasibility, showing that contaminants in wastewater attach to the microbeads during stirring, forming magnetic flocs that can be separated using an external MF. The study involved designing a separation system, with its performance analyzed through numerical simulations using an electromagnetic finite element method. This analysis accounted for various forces, including magnetophoresis, gravity, buoyancy, and drag. The proposed approach adds magnetic beads and reagents to the wastewater during stirring, leading to the formation of flocs around the beads, which are subsequently removed by the MF. This technique requires only a compact precipitation tank and reduces processing time due to the strong magnetic attraction. Experimental findings confirmed that the flocs could be easily manipulated using a standard electromagnet, and the inclusion of magnetic beads shortened the floc precipitation time. Numerical simulations of bead movement demonstrated that the magnetic force successfully

overcomes drag, allowing for precise control of bead trajectories. Overall, the results validate the method's feasibility and provide important insights for developing optimal WWT systems.

1.3.2 High Gradient Magnetic Separator

High Gradient Magnetic Separation (HGMS) is a widely utilized technique for separating magnetic particles. In HGMS, a magnetically susceptible wire bed is placed within an electromagnet. When a MF is applied, it creates non-uniformity, resulting in significant field gradients around the wires that attract and capture magnetic particles. The effectiveness of this process depends on the strength of these gradients, along with factors like particle size and magnetic properties (Sarıkaya et al., 2006). Ha et al. highlight that superconducting HGMS systems are particularly effective in removing pollutants and paramagnetic substances, such as iron oxides, due to their ability to generate higher MF strengths. For instance, cryocooled Nb-Ti superconducting magnets can achieve field strengths up to 6 Tesla.

The efficiency of HGMS has been demonstrated in steam condensers of thermal power stations, where contaminants like α -Fe₂O₃ (hematite) and γ -Fe₂O₃ (maghemite) were effectively removed, reducing water turbidity. Additionally, decreasing the wire diameter of the magnetic filter and increasing the mesh size improved turbidity removal, as these changes affect the magnetic gradient and enhance purification efficiency. Tuutijärvi et al. (Tuutijärvi et al., 2009) also demonstrated the successful adsorption of arsenic pollutants (As(V)) using a combination of magnetic separation and γ -Fe₂O₃ nanoparticles (Ha et al., 2011).

Superconducting magnetic separation is increasingly recognized for its potential in WWT technology. Research began in 1987 at Osaka University, leading to the development of a prototype separator for paper factories and successful laboratory demonstrations (Nishijima et al., 1987; Takeda et al., 2000; Nishijima et al., 2003; Kakihara et al., 2004). However, many pollutants in wastewater from industries such as paper, chemicals, pharmaceuticals, and food are organic substances that are not ferromagnetic and cannot be removed by magnetic separation alone. To facilitate this process, magnetic seeds must be added to the wastewater, allowing superconducting magnetic separation to treat it effectively. Surface modifications of the seeds enhance their interaction with pollutants. This method offers advantages over traditional treatments, including

lower costs, a smaller occupied area, and shorter operation times. The availability of commercial cryocoolers for superconducting magnets has further simplified and reduced the cost of establishing these systems (H. Zhang et al., 2011).

Some elements are crucial for human health such as Copper, but can be toxic and is often found among heavy metal contaminants in the environment. The release of industrial effluents containing heavy metals into water systems poses a serious environmental challenge. Traditional WWT methods such as iron exchange, electro-refining, coagulation, reverse osmosis, and chemical treatments face limitations in terms of cost, energy consumption, and sludge production. HGMS offers an effective and eco-friendly alternative for recovering metals from wastewater. This method utilizes magnetic force to separate pure metals without requiring coagulants. The effectiveness of HGMS is influenced by the matrix's geometric properties and saturation, as noted by Vincent-Viry et al. (Vincent-Viry et al., 2000). HGMS has proven effective for small, weakly magnetic particles. To increase the MF gradient, ferromagnetic wires can be incorporated, enhancing the force on particles. HGMS has been successfully applied in various industries. For example, Newns and Pascoe (Newns & Pascoe, 2002) demonstrated the removal of iron from kaolin. Xiong et al. (Xiong et al., 1998) applied pulsating HGMS in mineral processing, and a fully automated HGMS system has been developed for isolating proteins from whey (Meyer et al., 2005). Additionally, metal ions can be removed from wastewater using magnetic hydroxide flocs, which can be separated effectively. Arsenic removal was improved by 15% with the addition of cationic polyacrylamide during HGMS such as Okada et al. (Okada et al., 2004) successfully removed arsenic from geothermal water using iron (III) sulfate and HGMS. Oka et al. (Oka et al., 2008) achieved over 85% removal efficiency for ferrite precipitates in laboratory wastewater with HGMS. A study of S.K. Baik et al., investigated a HGMS that utilizes a matrix to create a high MF gradient, attracting (ferro) or (para) magnetic particles with significant magnetic force. This force, generated by the field gradient, is several thousand times stronger than that from magnetic flux density alone, making HGMS highly effective compared to other magnetic separators. The matrices are typically made of stainless steel wires with strong magnetization properties. This study focuses on a superconducting HGMS designed for wastewater purification using a stainless steel matrix. A

background MF of up to 6 T is produced by a superconducting solenoid, with stainless steel matrices arranged inside (Baik et al., 2012).

1.3.3 MgB₂ Superconductors

MgB₂ presents a compelling avenue for advanced applications due to its unique combination of superconducting properties, cost-effectiveness, and operational flexibility (Karaboğa et al., 2018; Yetiş et al., 2021; Gajda et al., 2021; Gajda et al., 2021). Characterized by a simple binary composition and a critically high $T_c \approx 39$ K, MgB₂ surpasses conventional LTS (Fair et al., 2012; Jensen et al., 2013). This elevated T_c enables operation within the 10–20 K range, allowing the use of energy-efficient cryocoolers rather than complex liquid helium systems- significantly reducing cooling costs and infrastructure demands (Abrahamsen et al., 2014). Furthermore, MgB₂ exhibits a high J_c and demonstrates mechanical adaptability in wire and tape configurations, making it a versatile candidate for applications spanning MRI, particle accelerator magnets, and next-generation power grids (Kováč et al., 2005) Zhuang et al., 2007; Häßler et al., 2010). While challenges in scalability and mechanical brittleness persist, advances in composite engineering and doping strategies (e.g., carbon nanotube integration) are rapidly enhancing its durability and high-field performance.

1.4 AIM AND SCOPE OF THE STUDY

This study aims to produce elongated superconductor monocoire wires of magnesium diboride (MgB_2/Fe) with optimal engineering shapes, focusing on their superconducting properties. The wires were manufactured *in situ* using the PIT method, and their electrical and mechanical properties were systematically evaluated under various MFs. MgB_2 is recognized as an economically viable and easily producible superconductor. To ensure the wires are suitable for coil winding, techniques such as groove rolling, wire drawing, and electro-thermal heat treatment were employed to enhance their strength and flexibility. Following successful fabrication of long MgB_2 wires in our laboratory, these wires were utilized to construct coils. These produced wires were wound into a continuous helical shape to form the coils. A cryogenic cooling system were employed to cool the NI coils, enabling the investigation of several key parameters, including the coil's temperature, maximum superconducting current capacity, and the MF generated at the center of the coils. This research endeavor aims to measure the magnitude of the MF when the coils were cooled to approximately 30 K using a conduction-cooled cryogenic system. Additionally, valuable insights and

recommendations regarding the potential utilization of MgB_2 coils-based superconducting magnets in further application were assessed in terms of their quality and capabilities. The acquired data were thoroughly analyzed through the construction of current-voltage and temperature-resistance graphs, while metallographic techniques were utilized to examine the wire structure. Numerous sub-objectives have been planned to ensure successful outcomes. These include producing MgB_2 wires of sufficient length for winding coils, winding the single-multilayers NI coils onto a copper former, adapting a cryogenic cooling system to facilitate conduction cooling of the superconducting MgB_2 coils for testing, and determining the MF strength at the center of this preliminary coil. Furthermore, an extensive review of existing literature were conducted to explore the feasibility of employing such coils in WWT applications.

2. MATERIALS and METHOD

2.1 Experimental Techniques

2.1.1 Initial Powder Mixture

The preparation of the Mg+2B powder mixture involved precise steps and considerations to ensure the desired composition and prevent the formation of magnesium oxide. High-purity magnesium powder, with a purity level of 99% and particle sizes ranging from approximately (149 to 74 μm), was utilized. The boron powder, composed of amorphous boron with a particle size of less than 1 μm and a purity level of (95-97%). To achieve the stoichiometric proportion required for MgB_2 , accurate weighing and mixing of the powders were carried out. A Mg + 2B powder mixture was milled and homogenized for 3 hours using a rotary ball mill with iron balls under an inert atmosphere. The milling process involved mixing and grinding the powders as shown in Photo 2.1. Recognizing the sensitivity of magnesium to oxidation, the entire process was conducted within a glove box under an argon atmosphere as in Photo 2.2.

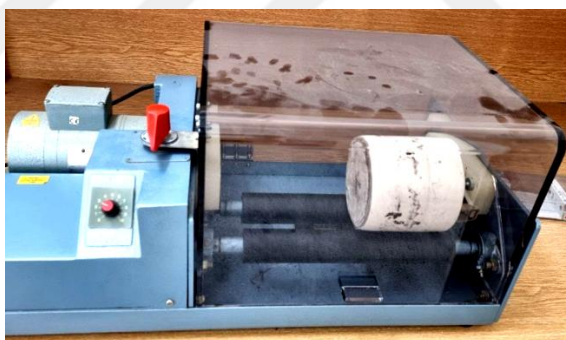


Photo 2.1. The ball milling machine.



Photo 2.2. The glove box.

2.1.2 Powder Filling/Packing

Regarding the iron tubes employed in the *In-situ* PIT method, selection criteria were applied. The chosen tubes possessed an outer diameter of 12 mm and an inner diameter of 9 mm, with a length of 1.25 meters. To ensure cleanliness and remove any potential contaminants, the iron tubes were cleaned in acetone with an ultrasonic cleaner for a duration of 30 minutes. Following these steps, one end of the iron tube was sealed using aluminum foil. The mixture of Mg+2B powder was then filled and packed into the tube as specified in Table 2.1. Finally, the other end of the tube was securely sealed with aluminum foil, completing the preparatory phase for subsequent processing.

Table 2.1. Mg +2B powder properties was filled into Fe tube.

Volume (cm ³)	95.3775
Mass (g)	146.108
Density (g/cm ³)	1.53342

2.1.3 Rolling and Drawing

We employed groove rolling machines to reduce the diameter to approximately 1mm as shown in Photo 2.3. Following this, we employed cold drawing (Photo 2.4) using progressively smaller dies to further decrease the diameter to 1 mm and extend the wire to about 180 meters as shown in Photo 2.5. These processes; groove rolling, cold drawing, and elongation which resulted in the final MgB₂ superconducting wire.



Photo 2.3. The groove rolling machine.



Photo 2.4. Drawing machine.



Photo 2.5. Various dies with different diameters.

2.1.4 Strain Relief Annealing

The annealing process significantly affects the microstructure, physical homogeneity, and chemical homogeneity, as well as the diffusion of boron, T_c , I_c , and H_c of the prepared MgB_2 samples. The investigations into heat treatment methods aimed at enhancing the superconducting properties of MgB_2 samples prepared through various techniques. The most commonly used method for preparing MgB_2 involves reacting magnesium and boron powder mixtures at temperatures ranging from 500 to 1000 °C, following the chemical equation $Mg + 2B \rightarrow MgB_2$ (Larbalestier et al., 2001; Monteverde et al., 2001).

The J_c of pure MgB_2 is strongly influenced by the heating rate, with better J_c values obtained at a slow heating rate of 100 °C/h. This slower rate allows the samples more time at temperatures below the melting point of magnesium, facilitating the formation of more MgB_2 through solid-state diffusion. The amount

of free magnesium is minimized upon reaching 650 °C, while fast heating rates and high temperatures can lead to magnesium loss and the formation of pores in the studied MgB₂ wire samples (Chen et al., 2005). Additionally, MgB₂ wire samples annealed at 770 °C and 810 °C exhibited more impurity phases, while temperatures of 830 °C and 850 °C are more favorable for forming the MgB₂ superconducting phase with sintering times of 5-30 minutes. The optimal heat treatment is at 830 °C for 15 minutes (Suo et al., 2007).

We applied heat treatment for strain relief annealing at 500 °C several times between drawing and groove rolling of MgB₂ superconductors to improve mechanical properties and superconducting performance. This process relieves mechanical stress, enhances wire structure, promotes better grain alignment, reduces defects, and ensures uniform thermal treatment for consistent superconducting properties.

2.1.5 Sintering for Phase Formation

2.1.5.1 MgB₂/Fe Wire

MgB₂ wires prepared using the *ex-situ* technique require heat treatment at approximately 950 °C, while wires prepared with the *in-situ* technique can be sintered at lower temperatures of 600-750 °C to complete the reaction (Dou et al., 2003; Fu et al., 2003). Sintering heat treatments of the MgB₂ wire samples were conducted using a Protherm Controller/Three Zone Programmable tube furnace. The samples were heat treated in a stainless steel tube at various temperatures for different periods in a high-purity Ar atmosphere. This 1.5 m long stainless steel tube, with a 35 mm outer diameter and 3 mm wall thickness, was used under Ar pressure. Vacuum and Ar inlets were connected via T-type connections. The furnace was evacuated for 10 minutes and then filled with Ar, repeating this process three times to eliminate any oxygen traces before treatment. All heat treatments were performed under high-purity Ar pressure to achieve the superconducting phase formation of MgB₂ wires as shown in Photo 2.6. We applied heat treatment for sintering at 650 °C or 700 °C to enhance phase formation in MgB₂ superconductors, improving mechanical and superconducting properties. This temperature range minimizes Mg loss, ensuring a more complete reaction. It also enhances microstructure and grain connectivity, which are crucial for J_c , while improving the uniformity and consistency of the MgB₂ phase.



Photo 2.6. Three Zone Programmable Furnace.

2.1.5.2 MgB₂/Fe Coils

Furnace preparation is a crucial step. It ensures optimal conditions for achieving the desired temperature and pressure during the heat treatment process. The following procedures were followed to prepare the furnace as seen in Photo 2.7:

1. Placing the coil: The coil was positioned in the middle of the cylindrical furnace, ensuring proper alignment for uniform heating.
2. Closing the furnace: The furnace was securely closed, creating a pressure of approximately 2 bars inside. This pressure served as a starting point for subsequent operations.
3. Argon gas: Argon gas was introduced into the furnace, with a flow rate controlled to maintain the desired pressure. The pressure gauge was monitored to detect any potential leakage.
4. Evacuation: The vacuum pump was activated to remove any air inside the furnace. The process of transferring Argon gas and evacuating it with the vacuum pump was repeated at least twice to ensure complete removal of air.
5. Increasing pressure: The pressure inside the furnace was gradually increased to 5 bars using Argon gas flow. This step prepared the furnace for the subsequent heat treatment process.
6. Setting the temperature: The furnace temperature was set to 680°C, the desired temperature for the heat treatment process.

7. Running the furnace: The furnace was operated, allowing it to reach the set temperature of 680°C. The stability of the furnace temperature was observed before proceeding with the actual heat treatment.

Figure 2.1 shows the temperature profile over time, with measurements taken every 10 minutes, to track the temperature increase in the closed cylindrical furnace before heat treatment. It illustrates the temperature rate and stability of the furnace, confirming that the desired temperature was reached and maintained before starting the heat treatment.

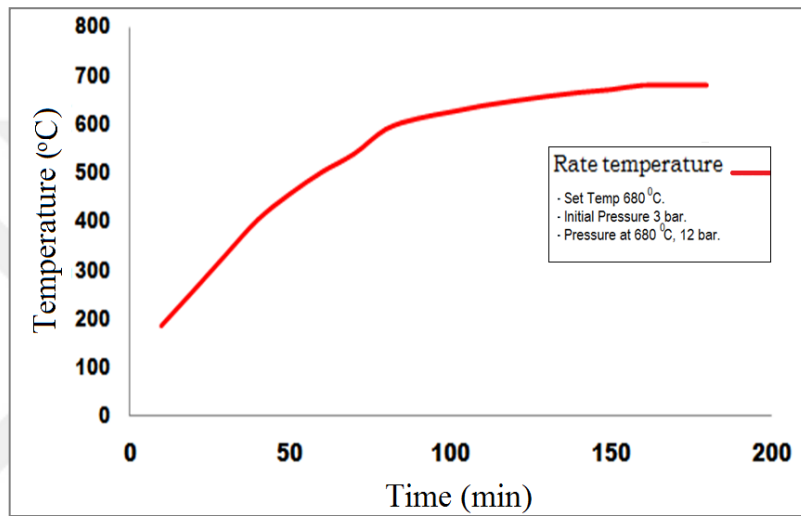


Figure 2.1. The growth rate temperature inside the furnace.



Photo 2.7. The furnace was used for sintering of wound coils with a set temperature of 680 °C.

2.1.6 Continuous Heat Treatment

The temperature profile of the furnace as shown in Photo 2.8 was obtained using a K-type thermocouple and a thermocouple reader. These measurements were conducted in 5 cm intervals and waiting for 5 minutes until thermall equilibrium is achieved accuracy and consistency. Figure 2.2 shows the correlation between temperature variations at five-minute intervals and corresponding distances along the furnace. We repeated this measurement three times. The difference between the upper and lower curves was observed. It was found that separation between temperature measurements along the furnace led to more accurate results, producing consistent curves. In contrast, when the measurement intervals were closer together in short time, distinct upper and lower curves emerged.

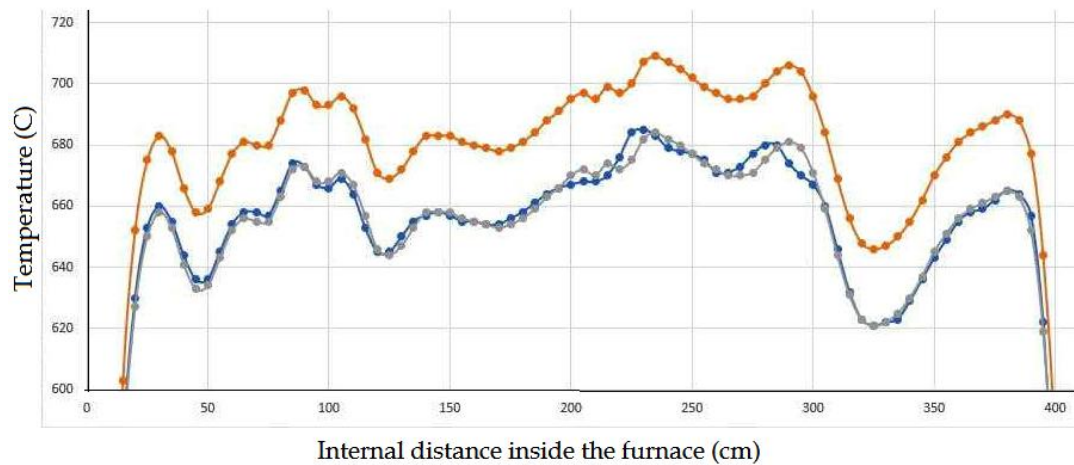


Figure 2.2. Temperature profile of the 4m long tube furnace.



Photo 2.8. The 4m long tube furnace used for continuous heat treatment.

2.1.7 Four Point Probe Method

The four-point probe technique is a method used to measure the electrical resistivity of a material. The technique involves using four probes that are placed on the surface of the material. A current is passed through the two outer probes, and the voltage is measured across the two inner probes. This technique eliminates the effect of contact resistance. Configured for a standard four-point probe measurement, we soldered four contacts on each MgB_2/Fe wire sample as shown in Figure 2.3.

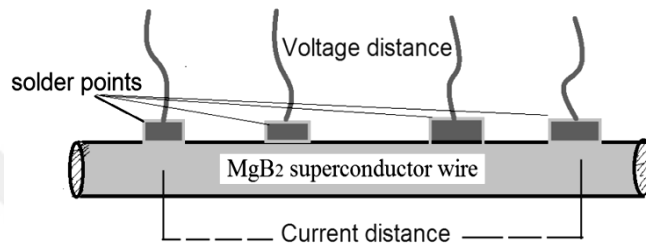


Figure 2.3. Determination diagram of voltage distance and current distance by using the standard four point probe method.

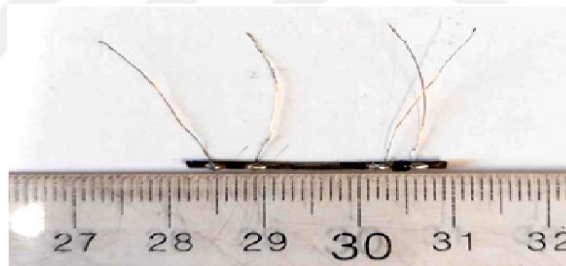


Photo 2.9. The distances between the inner voltage taps of the MgB_2/Fe samples were measured using this type of optical images.

Moreover, when a MF is applied, it becomes possible to measure the transport current and temperature dependence of resistivity. This technique facilitates the measurement of voltage and current distances, enabling characterization of the samples. Photo 2.9 visually demonstrates the application of this methodology in practice, shows the measurement setup and important parameters involved in the four point probe method.

2.1.8 Resistivity-Temperature & Current-Voltage Measurements

The DC resistivity measurements (ρ - T) and current-voltage (I - V) measurements for the samples were carried out using the four-point resistivity method, with a Keithley nanovoltmeter (Model 2182A) and a Keithley current source (Model 238). A constant DC bias current of (50 to 100) mA was applied to the samples within a temperature range of (10 to 50) K in a closed-cycle He cryostat. For accurate temperature control, a programmable temperature controller (Lakeshore 340) was used, providing stability and accuracy of (± 0.01 K). Standard Pb-Sn solder was utilized to attach the current and voltage contacts to the wire surface. The current flowed through the two outer electrical contacts, while the voltage drop across the two inner contacts was measured as the temperature changed. Transport currents in MFs were assessed using a standard four-probe configuration with a constant direct current (DC) varying between 0 and 1 A at cryogenic temperatures below the T_c under MFs up to 7 T perpendicular to the current direction. The (I - V) characteristics of the samples were measured at various temperatures using the standard four-probe method, both in self and applied fields, to determine the J_c of the wires. The ($1 \mu\text{Vcm}^{-1}$) criterion was employed for determining the I_c . The transport J_c was calculated as the I_c divided by the cross-sectional area of the MgB_2 wire, which was accurately measured with a micrometer. All data were recorded using LabVIEW software.

2.1.9 Metallographic Process

In the initial stage, small specimens of MgB_2/Fe wires were precisely positioned in a vertical or longitudinal orientation using a mounting machine, as shown in Photo 2.10(a). Following this, molds containing the prepared samples were carefully obtained. A series of polishing procedures were then executed on these molds, utilizing SiC grinding papers of varying grades, including 240, 600, 1200, and 2500, as illustrated in Photo 2.10(b). This polishing approach aimed to enhance the surface quality of the samples, ensuring optimal preparation for subsequent analyses. The surface characteristics of the samples were subsequently evaluated using an optical microscope, as demonstrated in Photo 2.11. The microscopic images obtained served as valuable references for later calculations, particularly for determining the cross-sectional area of the samples.

By analyzing these photographs, precise quantitative assessments were made, enabling accurate measurements of the cross-sectional dimensions of the samples.



Photo 2.10. (a) Mounting machine, and (b) polishing machine.



Photo 2.11. Optical microscope.

In addition to its role in calculating the cross-sectional area, the optical microscope served as a valuable tool for identifying potential manufacturing defects in the wire. The examination process included conducting practical tests as deemed necessary to validate the adherence to the required drawing process. The detection of cracks, fissures, and other defects that could compromise the integrity of the wire held significant importance. Photo 2.12, showcases a selection of scans obtained through the utilization of the optical microscope. These scans were instrumental in identifying any irregularities or imperfections that may have arisen during the wire fabrication process. By these tests, critical insights were gained, enabling the assessment and mitigation of any potential risks that could compromise the wire's structure.

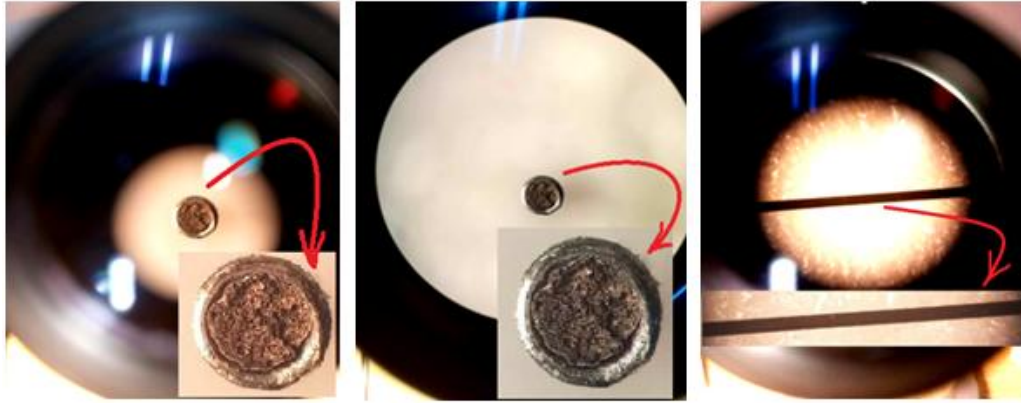


Photo 2.12. Optical tests for MgB₂/Fe wire under the optical microscope during drawing process.

2.1.10 Cryogenic Measurements

2.1.10.1 Cryogenic Tests in Magnetic Field

This measurement system enables the application of MFs ranging from zero up to 7 Tesla and the generation of direct currents (DC) within the range of (0 to 1) ampere. To commence the experimental procedure, heat-treated samples were carefully sectioned to a length of approximately 25 mm. Subsequently, ordinary Pb-Sn solder was utilized to establish voltage and current contacts on these samples. The prepared samples were then positioned perpendicular to the MF within the helium cryostat system. Prior to commencing the measurements, the samples were cooled in a zero MF to establish a baseline condition. The magneto-resistivity measurements were performed by applying a direct current of 50 mA across the samples within a temperature range of 4 to 45 K. This deliberate temperature range facilitated the determination of the T_c of the samples, providing crucial insights into their superconducting properties.

Furthermore, to ascertain the J_c and J_e of the samples, the voltage-current characteristics were measured at a constant temperature of 25 Kelvin. In order to utilize the cryostat system for carrying out these measurements, we procured samples from a long MgB₂ superconductor wire, and subsequently employed the standard four point probe method to solder four connected points. The four point probe method is a widely employed technique for characterizing samples in terms of their electrical conductivity or resistivity.

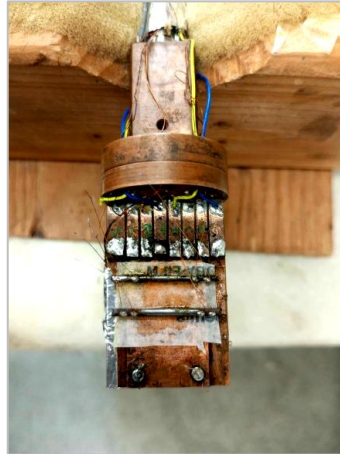


Photo 2.13. Four connected MgB_2/Fe samples with sensors were fixed on the holder before undergoing into the cryostat chamber.

The illustrated in Photo 2.13, depicts four distinct samples of MgB_2 wire, intricately connected to sensors affixed onto the holder, forming an integral component of the cryostat system. Upon carefully installing these samples, each possessing an approximate length of 25 mm, the holder is appropriately positioned within the cryostat chamber. The installation process entails the placement of two pairs of samples on each side fixed on the holder. Subsequently, ordinary Pb-Sn solder was utilized to establish voltage and current contacts on these samples. The prepared samples were then positioned perpendicular to the MF within the helium cryostat system as shown in Photo 2.14. Prior to commencing the measurements, the samples were cooled in a zero MF to establish a baseline condition.



Photo 2.14. Electrical characterization measurement and cryostat system.

2.1.10.2 Cryogenic Tests of Coils

The cryostat employed comprises four main distinct components, as visually depicted in Figure 2.4. These constituent parts effectively integrate with one another to form a cohesive and functional cryostat system as seen in Photo 2.15. The key units within this cryostat system include:

1. Helium compressor: This unit is responsible for generating and supplying the necessary pressurized helium gas, which plays a crucial role in achieving and maintaining the desired low-temperature environment within the cryostat system. The helium compressor ensures efficient circulation and cooling of the cryogenic medium.
2. Vacuum pump system: This integral component of the cryostat system facilitates the establishment and maintenance of a high-quality vacuum environment within the chamber. By effectively removing undesired gases and particulates, the vacuum pump system ensures optimal thermal insulation and minimizes heat transfer to the surroundings and also its role to prevent the oxidation conditions.
3. The chamber body and cool head: The chamber body serves as the central housing structure within the cryostat system, providing a controlled and isolated space for housing the experimental setup. The cool head, intricately connected to the chamber body, enables the efficient transfer of thermal energy and ensures the desired temperature stability within the system.
4. Electrical characterization measurement system: This system component is specifically designed to enable accurate and precise electrical measurements and characterization of the superconducting coil assembly. It incorporates a range of specialized instruments and probes, allowing for the evaluation of critical electrical parameters and performance analysis.

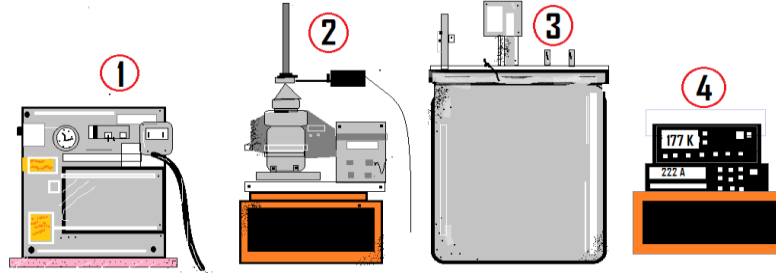


Figure 2.4. The cryostat system units: (1) He compressor, (2) vacuum pump, (3) the chamber body, and (4) electrical characterization measurement system.

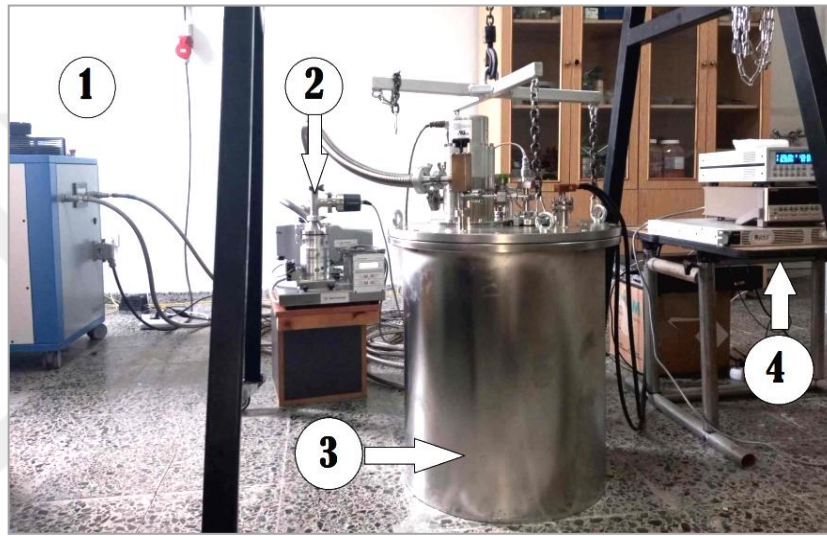


Photo 2.15. The cryostat system parts.

2.2 Wire Uniformity

This section indicates the uniformity of the MgB_2/Fe wires concerning their superconducting properties. These wires were subjected to a continuous heat treatment process at a temperature of $650\text{ }^\circ\text{C}$. The elongated wire was carefully guided through the furnace at a controlled speed of 2.5 cm/min with a set temperature of $750\text{ }^\circ\text{C}$. This approach aimed to receive the wire a heat treatment. The heat treatment procedures were systematically executed utilizing the furnace whenever the wire's diameter reduction rate reached approximately fifty percent. This procedure was implemented to guarantee the continuous and gradual drawing of the extended wire. Subsequently, two pieces (short and long) wires were selected from the main wire of MgB_2/Fe for further testing. The two pieces of wires were subdivided into four short samples: S_1 , S_2 , S_3 , and S_4 , as in Figure 2.5. These four samples were then tested in the cryostat system.

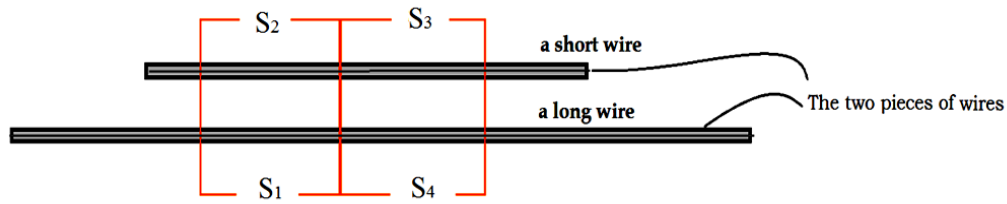


Figure 2.5. A method was used for subdivided of wire samples after heat treatment process arranging from 1 to 4 respectively.

Table 2.2 presents the measurements obtained using the cryogenic tests for the four samples (S_1 , S_2 , S_3 , and S_4) after heat treatment process. The table includes the current and voltage distances, as well as the total lengths of the samples. Photo 2.16, shows MgB_2/Fe samples (S_1 , S_2 , S_3 , and S_4) after heat treatment process. These samples were tested for their resistivity-temperature (ρ - T), and current-voltage (I - V) characteristics, and their (E - J_e) behavior was also prepared.

Table 2.2. Current and voltage distances measurements using the standard four point probe method, all measurements in unit of millimeter.

Sample Code	S_1	S_2	S_3	S_4
Current distance	18.60	17.03	17.87	18.38
Voltage distance	10.62	8.30	8.60	9.75
Total length	26.68	25.81	26.87	27.45



Photo 2.16. The heat treated MgB_2/Fe wire samples.

2.3 Effect of Bending for React & Wind Process

A series of experimental studies were conducted to determine the bending strain tolerance of MgB_2 superconducting wires (Kováč et al., 2016) and to identify the wire diameters that can be bent to larger sizes without compromising performance in the fabrication of "react & wind" coils. Studies also focused on the fabrication and transport properties of MgB_2 wires and coils (Yoo et al., 2018),

the superconducting properties of reacted mono- and multifilament MgB_2 wires in relation to bending diameters, utilizing a custom-made bending test probe were carried out (Tanaka et al., 2002). Additionally, the electromechanical properties of superconducting MgB_2 wires and bending radii were examined (Salama et al., 2005). In this study, we will investigate the performance before bending, after bending, and the degradation ratio. Significant performance losses are expected if the outer diameters of the coil formers are smaller than these specified diameter values. Subsequent to the fabrication of the elongated MgB_2 wire, a series of procedures and measurements were conducted on samples obtained by cutting sections from the wire to study it before and after undergoing bending processes into various diameters. The objective of these investigations was to examine and determine the appropriate diameter that would allow the long wire to be effectively wound onto a solenoid without compromising the superconductivity properties. This crucial procedure holds significant importance in the design of the solenoid coil, a pivotal aspect of our research aimed at achieving an optimally designed and flawlessly manufactured solenoid. The precise examination of the wire samples, taken from specific sections to measure it before and after the bending processes and study its properties, enables a comprehensive evaluation of their structural and functional characteristics. By subjecting the wire to different bending diameters, we aim to identify the diameter that ensures seamless winding onto the solenoid, without inducing any defects that would adversely impact the wire's superconducting properties. This rigorous investigation seeks to determine the optimal conditions for the subsequent winding process, ensuring the preservation of the wire's desirable attributes. The significance of this procedure lies in its direct impact on the design and manufacturing of the solenoid coil. By acquiring precise data on the appropriate diameter for winding the wire, we can advance our research towards the design of a solenoid coil that trying closely approaches the ideal parameters.

This precise approach aims to minimize defects and imperfections, ultimately contributing to the development of an optimally functioning solenoid with impeccable superconductivity properties.

2.3.1 Before Bending

Upon successful production of an elongated superconducting MgB_2/Fe wire through the PIT method, a subset of samples were designated for subsequent processing and analysis. The primary objective of this investigation was to comprehend the impact of bending on the I_c and ascertain the extent to which the bending process diminishes the I_c characteristics of the wire samples. By employing this method, we sought to quantify the degradation of the J_c values of the wires when subjected to bending at various diameters. The obtained findings pertaining to the degradation of J_c values upon bending hold significant relevance for their potential application as intermediate components in the construction of former coils.

To ensure an adequate length for the heat treatment process, the minimum required length of the wire was determined to be 8 times the desired sample length, i.e., $8 \times 25\text{mm} = 200\text{ mm}$. For instance, a wire with an initial length of at least 2 meters was selected for heat treatment. Subsequently, the 2-meter long heat-treated wire was sectioned into individual samples, each measuring approximately 25 mm, to facilitate subsequent testing within a cryostat system.

Figure 2.6, shows the methodology employed to cut 6 limited length wire samples, all of which were taken from the identical MgB_2/Fe superconductor wire, as depicted in Photo 2.17. This analysis aimed to ascertain the most appropriate and suitable bending diameter for utilization in the construction of the coil. These samples were subjected to cryogenic measurements under carefully controlled conditions, such as a predetermined temperature of 25K and a MF strength of 3.5, 3.8 and 4 Tesla.

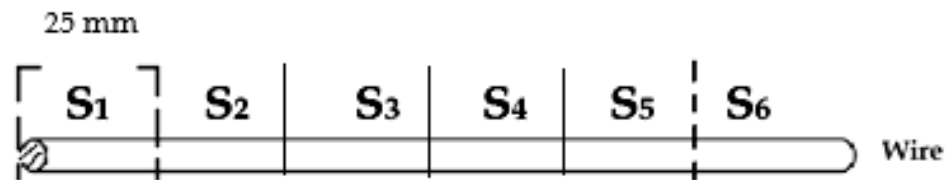


Figure 2.6. A way that was used for cutting samples arranging from 1 to 6 respectively.

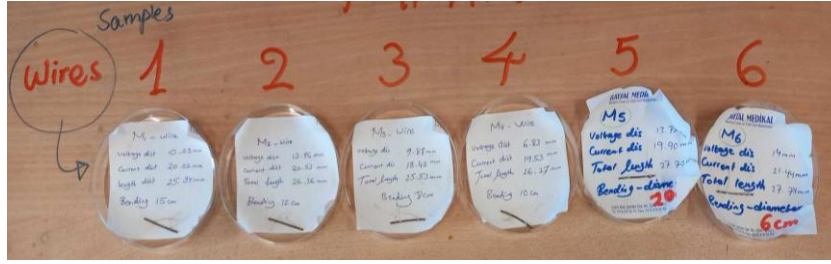


Photo 2.17. Samples of MgB_2/Fe wires.

Table 2.3 presents the measurement data obtained through the enlarged images of 6 samples before bending to measure the distances on the ruler. We then used these distances to convert the resistance measurements into resistivity ($J-E$). The total lengths of the samples used for the calculations of I_c and J_c . These measurements served as crucial inputs for subsequent calculations.

Table 2.3. The voltage taps distances of the MgB_2/Fe samples, in millimeter.

Sample Code	S_1	S_2	S_3	S_4	S_5	S_6
Voltage distance	10.23	13.96	9.88	6.83	13.72	14
Sample length	25.34	26.36	25.53	26.27	27.72	27.74

2.3.2 After Bending

The subsequent investigation involved the utilization of the same set of the six samples employed in the initial phase of the study. Then, these samples were bent to different diameters, the aim was to induce controlled mechanical bending deformation and assess its impact on the magnetic and electrical characteristics of the wires. The wires underwent a series of bending processes, encompassing a range of diameters including (200mm, 150mm, 120mm, 100mm, 80mm, and 60mm) as in Table 2.4. Experimental measurements and analyses were performed to quantify the changes in superconducting properties resulting from the bending process. Resistivity ρ , J_c , and T_c values were carefully determined to understand the impact of bending on the samples' superconductivity performance. The study aimed to identify the diameter that yielded the lead degradation in the superconducting characteristics. Table 2.5. specify the voltage distance measurements for 6 samples after bending.

Table 2.4. Bending diameter for wires in unit of (mm).

Sample Code	S ₁	S ₂	S ₃	S ₄	S ₅	S ₆
Bending diameter (mm)	150	120	80	100	60	200

Table 2.5. Voltage distances measurements for 6 samples after bending, and all data measurements in (mm).

Sample Code	S ₁	S ₂	S ₃	S ₄	S ₅	S ₆
Voltage distance	10.23	13.96	9.88	6.83	13.72	14
Total length	25.34	26.36	25.53	26.27	27.72	27.74

2.4 Wind & React Coils

2.4.1 Coil Fabrication

2.4.1.1 Coil Formers

Copper is a highly versatile metal characterized by its exceptional softness, malleability, and ductility. Its thermal and electrical conductivity are remarkably high, with a thermal expansion coefficient of $16.5 \mu\text{m}/(\text{m}\cdot\text{K})$ at 25°C , a thermal conductivity of $401 \text{ W}/(\text{m}\cdot\text{K})$ at 0°C , and an electrical resistivity of $16.78 \text{ n}\Omega\cdot\text{m}$ at 20°C . These unique properties make copper an ideal material for various applications, particularly in the realm of heat transfer and conduction. The coil formers were manufactured from electrolytic tough pitch (ETP) copper due to its high thermal conductivity as seen in Photo 2.18.

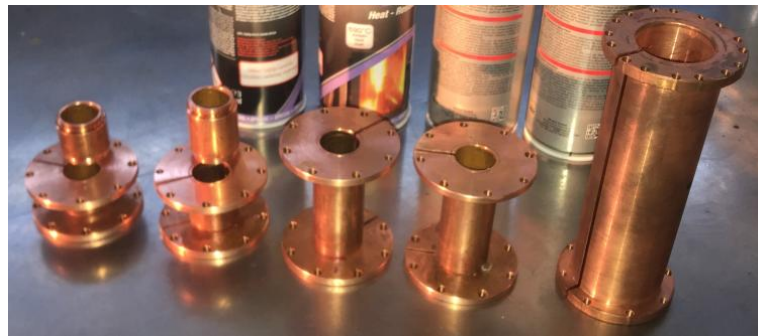


Photo 2.18. Coil formers made from ETP copper in various sizes.

The specific design of the copper former, as illustrated in the referenced Figure 2.7, serves to optimize the winding process and the overall performance of the superconducting coil assembly. The former's geometry and dimensions are

carefully engineered to accommodate the precise placement and alignment of the superconducting wires, ensuring a tightly-wound and mechanically stable coil structure. Photo 2.19 visually presents the top and vertical views for the Cu former.

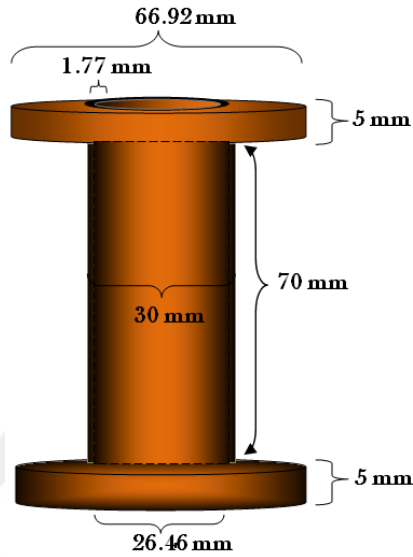


Figure 2.7. Design and dimensions of the copper former.



Photo 2.19. The top and vertical views for the copper former.

2.4.1.2 Coil Formers Insulation Process

Following the initial design of the copper former, the next step in the fabrication process involved applying an insulating process to the entire inner surface of the former. This insulating layer was crucial for electrically isolating the superconducting wires from the conductive copper substrate during the winding and subsequent operation of the coils. To firmly adhere the insulating process to the copper former, the assembly was subjected to a carefully controlled

heat treatment process. Specifically, the copper formers were electrically insulated with a high-temperature resistant coating, applied via spraying and cured at 180-200°C for a duration of 2 hours to ensure adhesion, as depicted in Photo 2.20. This heat treatment step served to cure and fix the insulating paint, ensuring a robust and reliable electrical isolation between the copper former and the superconducting wires.



Photo 2.20. Nabertherm Furnace.

2.4.2 Winding of Non-insulated MgB_2/Fe Coils

After the insulation of the copper former, the next step in the fabrication involved the strategic placement of thermal fleece around the internal edges of the former. As depicted in Photo 2.21, this additional insulating layer was incorporated to prevent any direct contact between the superconducting winding wires and the conductive copper substrate. The winding process was then executed using a specialized mechanical winding machine. The coil former was wound with a continuous, long length of MgB_2/Fe superconducting wire, which was wound in a layer-by-layer manner. Specifically, the first layer was wound in one direction, followed by the second layer in the opposite direction, and so on, until a total of the three layers were completed as in Photo 2.22. This systematic and deliberate winding approach ensured a compact, uniform, and well-organized coil structure within the coil former.

The final product of this coil former assembly featured two distinct ends, one for the input and the other for the output, facilitating the integration of the coil into the cryostat system. The careful attention to detail in the insulation, winding, and overall assembly of the coil former highlights the advanced engineering

principles underlying the fabrication of this superconducting coil system. The strategic use of thermal fleece and the controlled, layer-by-layer winding process contribute to the robustness and reliability of the final coil assembly.



Photo 2.21. The insulated Cu former and winding process.



Photo 2.22. The in-reacted coil former of 3 layers of MgB_2/Fe long wires.

Otherwise, a six-layer NI MgB_2 nested coil was fabricated by winding the wire onto the ETP copper former (150 mm in length and 60 mm in diameter) with a thin insulating layer between each layer. The coil was then sintered at 670°C for 2 hours under 20 bar of argon pressure. An ETP copper coil former, 20 mm in length, with copper flanges of 30 mm in diameter was used to produce a single-layer NI solenoid coil with 17 turns. The coil (NISC) was sintered at 670°C for 2 hours under 10 bar of argon pressure. The coil formers were manufactured from electrolytic tough pitch (ETP) copper due to its high thermal conductivity. The copper coil formers were then electrically insulated with a high-temperature resistant coating, applied via spraying and cured at $180\text{--}200^\circ\text{C}$ to ensure adhesion

as in Figure 2.8(a). A six-layer NI MgB_2 nested coil was fabricated by winding the *in-situ* $\text{Mg}+2\text{B}$ wires as shown in Figure 2.8(b) onto the ETP copper former (150 mm in length and 60 mm in diameter) with a thin insulating layer between each layer as in Figure 2.8(d). The coil was then sintered at 670°C for 2 hours under 20 bar of argon pressure. An ETP copper coil former, 20 mm in length, with copper flanges of 30 mm in diameter was used to produce a single-layer NI solenoid coil with 17 turns as seen in Figure 2.8(c). The coil (NISC) was sintered at 670°C for 2 hours under 10 bar of argon pressure.

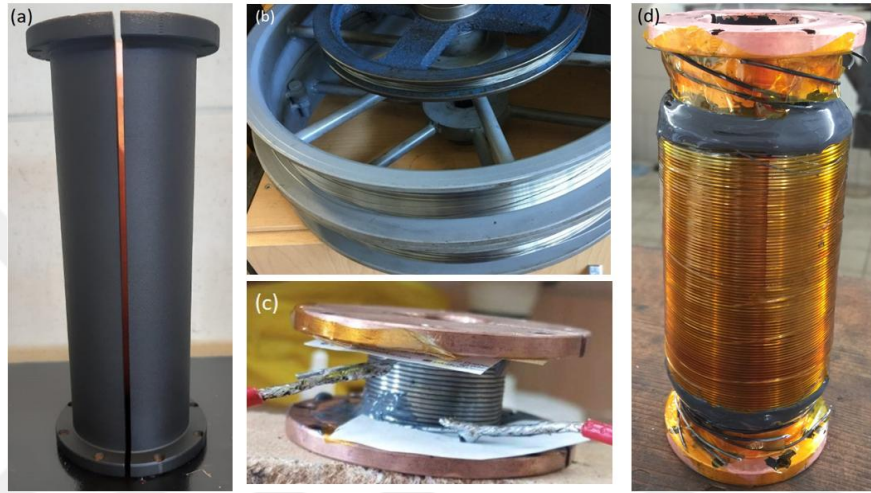


Figure 2.8. (a) Insulation coating on ETP copper former, (b) long in-situ $\text{Mg}+2\text{B}$ wires, (c) single layer NI solenoid coil and (d) a six-layer NI nested coil wrapped with Kapton tape.

2.4.3 Reacted Coils

Upon completing the insulation of the copper former and the winding of the MgB_2 superconducting wires onto formers, the subsequent step entailed subjecting the coil former to a heat treatment process, commonly referred to as a reacted coil. The sintering process for the reacted coil of MgB_2/Fe wire lasted approximately 2 hours at a temperature of 680°C under a pressure of 12 bars. However, prior to commencing this process, comprehensive cleaning, pumping, and evacuation procedures were executed within the furnace. These preparatory measures were undertaken in order to eliminate any impurities, particulates, and potential sources of oxidation within the furnace environment. Subsequently, the coil former was carefully placed within the furnace, which had been pre-set to a temperature of 670°C . To ensure precise control and accurate assessment of the

heat distribution versus time, the temperature monitoring regime was implemented, as illustrated in Figure 2.9. This monitoring process facilitated a comprehensive understanding of the thermal dynamics within the furnace during the heat treatment process.

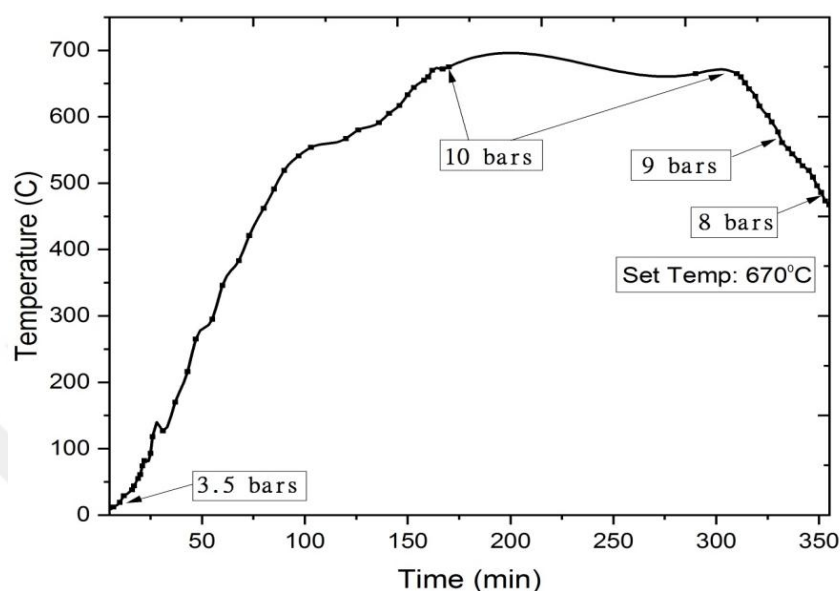


Figure 2.9. Internal heat distribution inside the furnace at a set temperature of 670°C.

Before mounting the coils into the cryostat, the subsequent step involved carefully removing the reacted coils from the furnace and made electrical connection tests in order to check if there is any potential short-circuit or not. It is noteworthy that this particular type of coil former was classified as a NI coil former; as the sole insulated surface existed within the interstitial region between the copper former body and the wound wires, facilitated by the application of a painted-insulated surface. The connection tests served as a critical quality control measure to ensure the functional integrity and electrical performance of the coil formers. By subjecting the coils assembly to this examination, any unintended electrical connections or short-circuits could be promptly identified and rectified.

Photo 2.23 visually presents a reacted coil former, comprising three layers of MgB_2/Fe long wires, subsequent to the completion of the heat treatment process. Notably, the coil form exclusively possesses two distinct ends, which were effectively secured using insulated glue to ensure structural integrity and

electrical insulation. Following this crucial step, the coil former stands prepared for installation within the cryostat system.



Photo 2.23. The reacted coil of 3 layers after heat treatment process.

2.5 Adapting the Conduction Cooling System

The cryostat is a cylindrical reservoir with a diameter of 50 cm and a height of 60 cm with all connections on it.. There is a steel cylinder on the outside and a steel flange on its top. They are entirely made of chrome steel. The outer vessel and flange are connected with metric 8 bolts. Sealing is ensured with a circular cross-section gasket on the contact surface. The bottom tank is empty and remains fixed on the ground. The flange has all the elements of the cryogenic cooling system connected to it, and they are moved up or down with the help of a mechanical pulley apparatus for mounting and dismounting samples. An O-ring is used for sealing between the outer vessel and the top flange to which the inner unit is connected. A large copper plate, connected to the underside of the steel top flange with GFRP rods, is in thermal contact with the liquid nitrogen vessel. This plate serves both as a structural element for attachments and a radiation shield, minimizing heat transfer from the room-temperature flange into the cryogenic environment.

The inner surfaces of the liquid nitrogen vessel are covered with multi-layer insulation (MLI) to further reduce radiative heat transfer. High-current rubber cables deliver the test current from the constant current source to current injection connections on the top flange. Braided ETP copper strips transmit the transport current from to current injection connections though the top flange to the

measurement volume. Braided ETP copper strips wound around the liquid nitrogen vessel in contact with the cold surface. These braids, with their low electrical resistance, generate minimal heat, which is effectively dissipated through thermal contact with the liquid nitrogen vessel. Two GFRP lamellae with low thermal conductivity, each supporting two parallel REBCO tapes, form a thermal break between the sample and cryostat terminals. ETP copper cables transfer current from this assembly to the coil windings. This configuration minimizes heat conduction to the test coil while enabling efficient current transfer. The superconducting current transfer elements are fixed to a large copper plate at the top of the cryostat and connected to the coil via ETP cables. This setup cools the HTS REBCO tapes and minimizes heat conduction from room temperature components to the 77 K test environment. Thin cables, routed through vacuum feed-throughs, provide connections for temperature and MF sensors. To minimize radiative heat transfer to the coil, the inner surfaces of the liquid nitrogen vessel are covered with MLI. A silicon diode temperature sensor is mounted on the copper plate to which the coil is attached. An electrically insulated braided strip, wound around the liquid nitrogen reservoir, is connected to the current connection point beneath the top flange. The ETP copper plate, in thermal contact with the liquid nitrogen reservoir, maintains a temperature of 77 K. Following assembly, the cryostat chamber is evacuated using a turbo-molecular vacuum pump (“Agilent Technologies” brand, model “TPS Flexy”). This vacuum insulation, combined with the cryostat's design, provides effective thermal isolation, enabling successful cryogenic testing of MgB_2 coils.

Figure 2.10 provides a detailed view of the cryostat's interior. The ETP copper element (1) serves as a thermal link between the MgB_2 coil (7-8) and the second stage of the cold head. A silicon diode temperature sensor (2) and a current-carrying ETP copper braid (3) are also visible. This arrangement ensures efficient cooling of the current leads up to connection point (11). To minimize heat conduction while transferring current, two parallel REBCO tapes bridge the connection between point (11) and point (5). A GFRP lamella (4) with low thermal conductivity provides mechanical support for these tapes, which are approximately 100 micrometers thick and capable of carrying currents greater than 150 A at 77 K. The transport current is then conducted to the coil windings via ETP copper cable (6). The copper element (1) is also suspended from a GFRP

rod (9) and fixed to a large copper plate (10) to prevent movement due to the gravitational force acting on the coil. MLI lining the inner surfaces of the liquid nitrogen vessel minimizes radiative heat transfer to the coil (12).

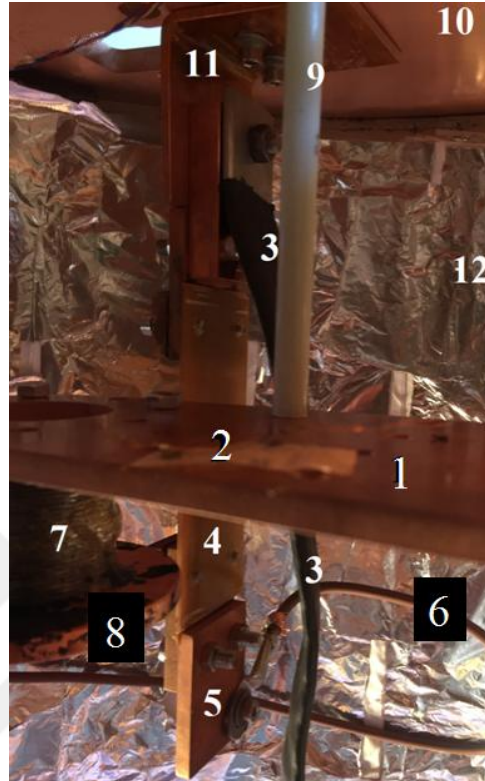


Figure 2.10. A detailed view of the cryostat's interior.

3. RESULTS

This chapter presents and discusses the fruitful findings from the experimental results, which include the successful production of elongated MgB_2/Fe wires and the uniformity of these wires regarding superconducting properties. It also investigates the relationship between wire diameter and bending performance, specifically identifying the point at which bending performance begins to deteriorate. Additionally, the chapter addresses the "wind and react" tests of MgB_2/Fe coils, the construction of the cooling conduction system, and the adaptation of this system for testing the coils.

3.1 Elongated MgB_2/Fe Wires

After employing groove rolling, wire drawing, and electro-thermal heat treatment, elongated moncore MgB_2/Fe wires using the PIT method were produced. The initial 12 mm diameter tube was reduced to approximately 1 mm through groove rolling and cold drawing. This process resulted in wire elongation to about 180 meters, ensuring the desired dimensions and structural properties of the MgB_2/Fe superconducting wires. The wire fabrication process involved the utilization of a drawing machine. To ensure the highest level of precision and maintain the quality of production, accurate measures were implemented to prevent any potential scratching or surface damage to the wire. This involved the continuous wiping and cleaning of the wire's surface throughout the successive stages of the drawing process.

The careful selection of the appropriate die was also paramount in upholding the wire's integrity and desired characteristics. The culmination of considerable effort and attention resulted in the successful completion of the wire fabrication process. To protect the wire and preserve its pristine condition, it was wound onto a wheel, as illustrated in Photo 3.1. The utilization of the drawing machine, coupled with the diligent maintenance of the wire's surface and the selection of suitable dies, ensured the preservation of the wire's quality. The

careful winding of the wire onto the wheel finalized the process, safeguarding the wire for future use.



Photo 3.1. A 180-meter-long MgB_2/Fe wire of a diameter of 1.02 mm is wound around a polyethylene pulley with a diameter of 550 mm.

3.2 The Heat Treated MgB_2/Fe

3.2.1 The $(\rho-T)$ Analysis for Heat Treated MgB_2/Fe

The samples of MgB_2/Fe were subjected to heat treatment process to induce a phase formation of MgB_2 and to gain superconductivity properties. Two pieces (short and long) wires were selected from the main wire of MgB_2/Fe for further testing. The two pieces of wires were subdivided into 4 short samples (25 mm) for each. The $(\rho-T)$ curves offer valuable insights into the superconducting properties and behavior of the heat treated MgB_2/Fe samples including S_1 , S_2 , S_3 , and S_4 with a diameter of 1.02mm. Figure 3.1 shows that the four samples have nearly the same resistivity values, with slight variations among them.

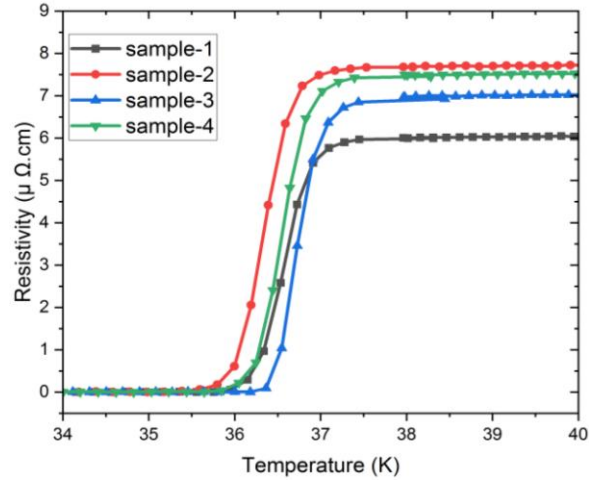


Figure 3.1. Temperature dependent resistivity (ρ - T) curves for the heat treated MgB_2/Fe samples with a diameter of 1.02 mm.

All of these samples underwent heat treatment, with two samples taken from the short piece and two from the long piece from the main heat treated MgB_2/Fe wire. The resistivity curve revealed that sample S_2 exhibited the highest resistivity value, while S_1 showed the lowest. This may have occurred during the repeated drawing processes of cold mechanical operations prior to the heat treatment, and the slight lack of uniformity in thermal treatment along the length of the produced wire may also contribute to this issue.

3.2.2 The (E - J_e) Analysis for Heat-Treated MgB_2/Fe

The (E vs J_e) curves for the heat-treated superconducting wires (S_1 , S_2 , S_3 , and S_4) were obtained under MF strengths of (3 - 4) Tesla at 25K. These curves illustrate how varying MFs affect each sample, providing insights into their superconducting behavior. Analyzing the curves reveals distinct patterns and correlations between MF strength and electrical response, facilitating a comprehensive assessment of each sample's superconductivity properties. Figure 3.2, Figure 3.3, Figure 3.4 and Figure 3.5 analyze the performance of each sample under different MF strengths after heat treatment at 680°C, measured at 25K. The figures show that as MF intensity increases, the superconducting properties of the samples deteriorate. Notably, optimal performance occurs around 3 Tesla, indicating that this MF strength enhances superconducting properties. These findings underscore the importance of selecting the right MF to optimize superconducting performance.

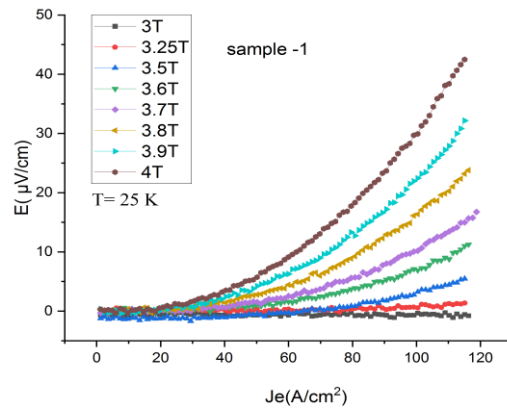


Figure 3.2. The E vs. J_e curves obtained for S_1 after heat treatment process under various MFs at 25 K.

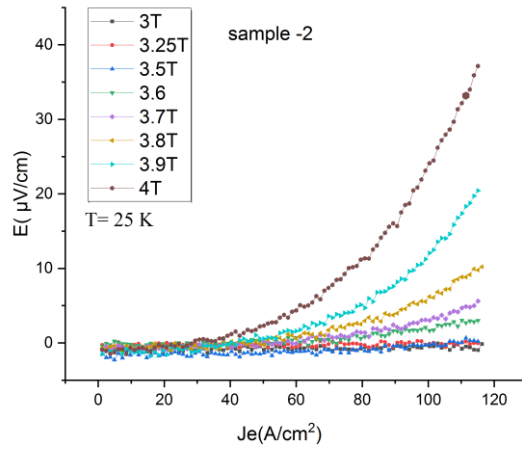


Figure 3.3. The E vs. J_e curves obtained for S_2 after heat treatment process under various MFs at 25 K.

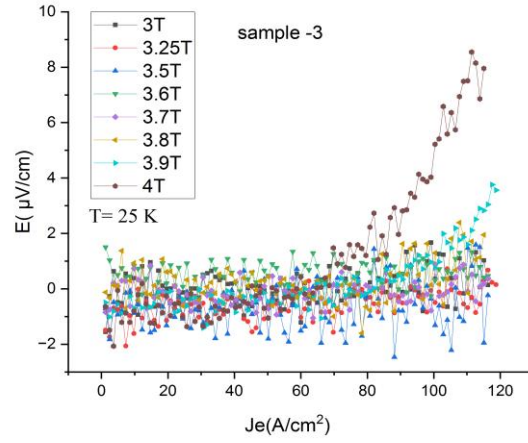


Figure 3.4. The E vs. J_e curves obtained for S_3 after heat treatment process under various MFs at 25 K.

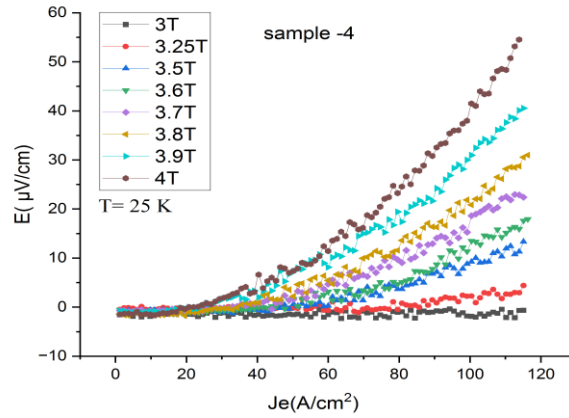


Figure 3.5. The E vs. J_e curves obtained for S_4 after heat treatment process under various MFs at 25 K.

Figure 3.6, Figure 3.7, and Figure 3.8 displayed the (E vs J_e) comparison curves for the samples labeled as S_1 , S_2 , S_3 and S_4 . These samples underwent a heat treatment process at a set temperature of 680°C and were subsequently subjected to MFs of 3.5, 3.8 and 4 Tesla respectively, at 25K. A careful analysis of these curves reveals consistent trends across the three figures. It is evident that sample S_3 consistently exhibits the highest performance, while sample S_4 consistently demonstrates the least desirable characteristics within each curve. All the samples were affected by the MF, but the extent of their impact varied and differed among them.

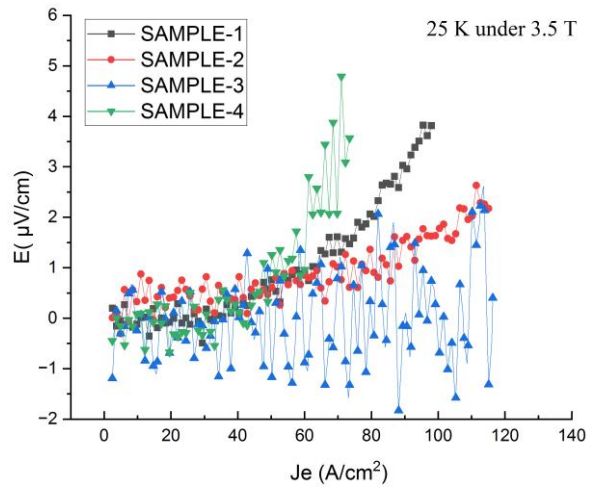


Figure 3.6. The E vs. J_e curves of S_1 , S_2 , S_3 , and S_4 after heat treatment process under 3.5 Tesla at 25 K.

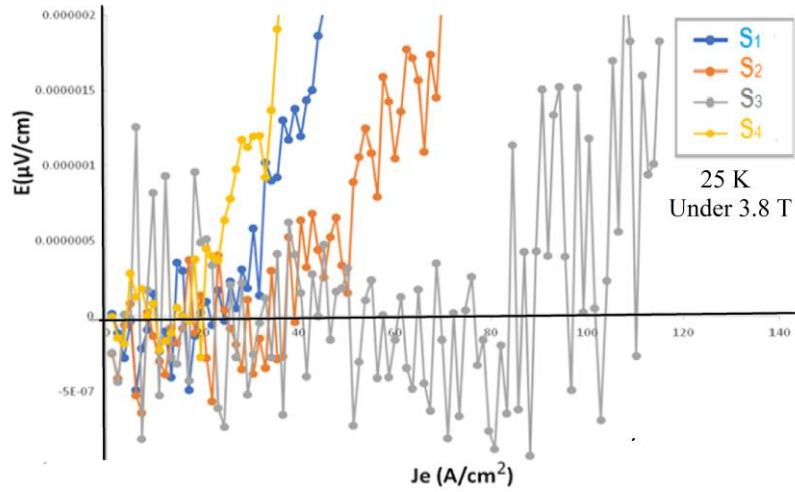


Figure 3.7. The E vs. J_e curves of S_1 , S_2 , S_3 , and S_4 after heat treatment process under 3.8 Tesla at 25 K.

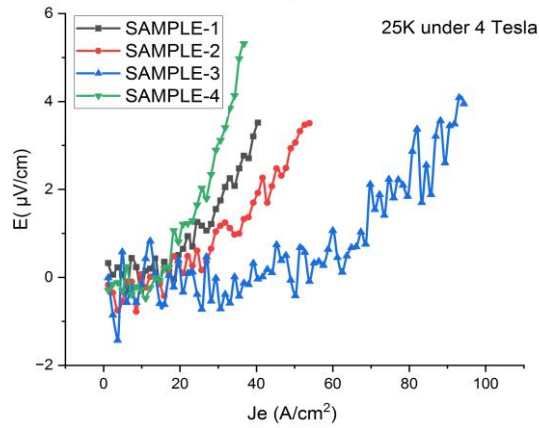


Figure 3.8. The E vs. J_e curves obtained of S_1 , S_2 , S_3 , and S_4 after heat treatment process under 4 Tesla at 25 K.

Table 3.1 shows significant performance disparities among the samples. Sample S_3 exhibits the best superconducting performance, while sample S_4 has the least desirable attributes. The I_c values quantify each sample's ability to carry electric current under different MF intensities. Table 3.2 shows J_{ce} values for the samples at 25K, along with their corresponding MF strengths. The main focus of this table is to illustrate how J_{ce} degrades as the MF strength increases. The data clearly indicate that as the MF grows stronger, the J_{ce} values decrease across all samples, reflecting reduced superconducting performance.

Table 3.1. The I_c in unit of (A) at 25K for heat treated samples.

Magnetic Field	S_1	S_2	$\uparrow S_3$	$\downarrow S_4$
3.5 T	0.51	0.88	0.93	0.40
3.8 T	0.35	0.56	0.72	0.28
4.0 T	0.23	0.39	0.57	0.19

Table 3.2. The J_{ce} in unit of (A/cm^2) at 25K for reacted wire samples.

Magnetic Field	S_1	S_2	$\uparrow S_3$	S_4
3.5 T	64.9	68.5	122.8	50.2
3.8 T	36.5	57.2	85.0	32.0
4.0 T	23.8	29.4	69.8	18.4

This trend emphasizes J_{ce} 's sensitivity to MF strength, highlighting the importance of precise control over this parameter to maintain optimal

superconducting properties. The group of heat-treated MgB_2/Fe samples demonstrated that Samples S_2 and S_3 , derived from shorter pieces of MgB_2 wire, exhibited the highest performance. In contrast, Samples S_1 and S_4 , taken from a longer segment of the same wire, yielded the lowest results. The short wire samples showed only minor differences between S_1 and S_2 , while S_3 and S_4 exhibited more pronounced performance variations. The E vs. J_{ce} curves, measured at 25 K under MFs ranging from 3 to 4 Tesla, illustrated how different magnetic strengths influenced superconducting behavior. Performance declined with increasing MF strength, with optimal results observed around 3 Tesla. Additionally, the J_{ce} values indicated a degradation trend at higher MFs, highlighting the necessity for precise control over these parameters to maintain superconductivity. This also revealed that the shorter pieces taken from the main wire facilitated the formation of MgB_2 phases and resulted in significantly better superconducting properties compared to the longer piece.

3.3 The Measurements of Resistivity-Temperature (ρ - T)

3.3.1 Before Bending

DC resistivity measurements (ρ - T) for 6 MgB_2/Fe superconducting wire samples (1.02 mm diameter) were performed using the four-point method. A constant DC bias current of 50 to 100 mA was applied across a temperature range of 10 to 50 K in a closed-cycle He cryostat. Figure 3.9 shows the temperature-dependent resistivity curves, offering insights into the electrical behavior of the wires before bending.

A notable disparity is evident just above the transition region, as illustrated in Figure 3.9. Specifically, S_1 exhibits a resistivity approximately five times larger than that of S_5 . This discrepancy can be attributed to inaccuracy in voltage tap distance determinations due to the width of the soldered region. An additional factor that could contribute to the significant difference in resistivity between S_1 and S_5 is the location from which the samples were extracted along the main wire. It is possible that S_1 was taken from one end of the wire, while S_5 was obtained from the opposite end. When samples are taken from the ends of a wire, there can be variations in the material's properties due to factors such as processing. In contrast, samples taken from the middle portion of the wire tend to exhibit greater uniformity with minor differences. This could explain why the resistivity values

of samples extracted from the middle portion of the wire showed relatively similar behavior. It is important to consider the potential influence of sample location when analyzing the resistivity data. Variations in resistivity among samples taken from different sections of the wire can provide insights into the overall homogeneity and consistency of the superconducting material. By taking representative samples from various locations along the wire, a more comprehensive understanding of its properties can be achieved.

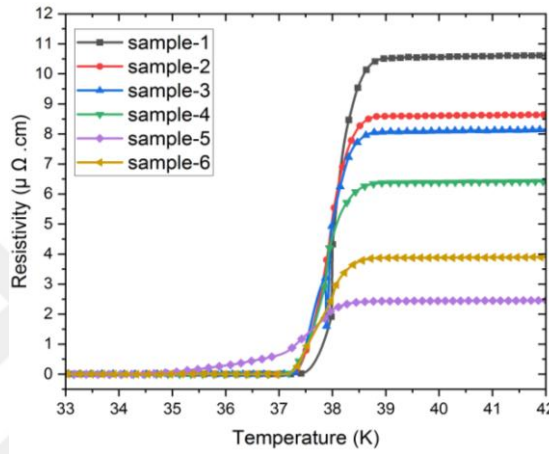


Figure 3.9. Temperature dependent resistivity (ρ - T) curves for 6 samples of MgB_2/Fe superconducting wires with $D = 1.02$ mm before bending.

3.3.2 After Bending

Figure 3.10 illustrates the temperature-dependent resistivity (ρ - T) curves obtained for the six samples of MgB_2/Fe superconducting wires, each with a diameter of 1.02 mm, after bending. The measurements and subsequent plotting of the (ρ - T) curves were conducted to investigate the impact of bending on the resistivity of the wires. By studying Figure 3.10, one can gain insights into the relationship between the bending and the resulting electrical behavior of the wires. Such information is crucial for optimizing the fabrication process and understanding the performance of the MgB_2/Fe superconducting wires in practical applications. Figure 3.10 clearly reveals a significant disparity in resistivity just above the T_c between S_4 and S_5 . Specifically, sample 4 exhibits a resistivity approximately seven times larger than that of sample 5. This observed distinction can be attributed to the variations in voltage distances resulting from differences in the total length and bending diameter when these samples underwent the

bending process. The measurements revealed that S_4 had a voltage distance of 6.83 mm and bending diameter of 100 mm. In contrast, S_5 had a voltage distance of 13.72 mm and bending diameter of 200 mm. The disparity in resistivity observed between S_4 and S_5 can be directly linked to the differences in voltage distances resulting from the variations in bending diameter. These variations impact the electrical conductivity and resistance of the samples, leading to the observed discrepancies in resistivity.

This information is crucial for understanding the underlying factors influencing the electrical behavior of the wires after bending and can contribute to optimizing the fabrication process and design considerations for future applications. Sampling from the ends of the wire often yields imprecise results compared to samples from the center. To ensure reliable outcomes, using a diverse sampling approach from multiple locations along the wire. This helps identify variations and trends in the wire's properties.

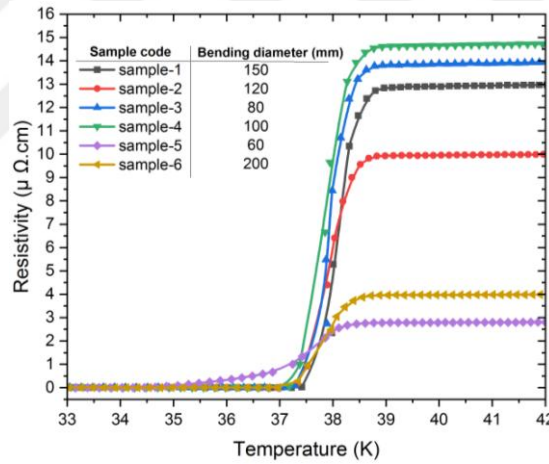


Figure 3.10. Temperature dependent resistivity (ρ - T) curves for 6 samples of MgB_2/Fe superconducting wires after bending.

3.4 The Examination of (E - J_e)

3.4.1 Before Bending

Figures 3.11 and 3.12 exhibit the (E vs J_e) curves obtained at 25K for the 6 wire samples under a MFs of 3.5 T and 3.8 T. These curves provide a comprehensive representation of the samples' performance in terms of their electric field characteristics. Consistent with the analysis of the I vs V curves, the

results confirm that samples S_1 and S_5 demonstrate superior performance while sample S_2 exhibits the least desirable behavior.

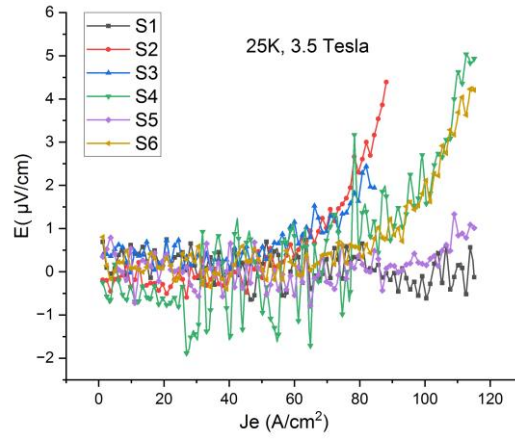


Figure 3.11. The E vs. J_e curves obtained for superconducting wires before bending under 3.5 Tesla at 25K.

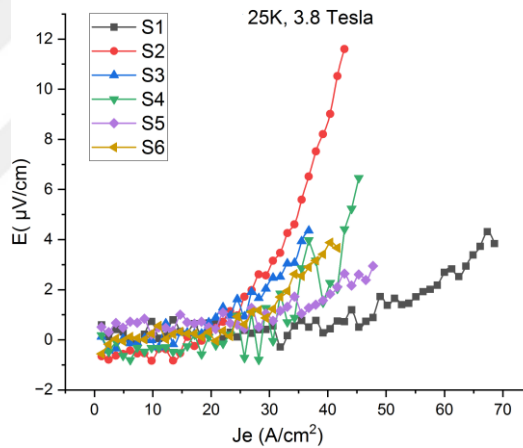


Figure 3.12. The E vs. J_e curves obtained for normal superconducting wires before bending under 3.8 Tesla, 25 K.

Table 3.3 provides quantitative data on the I_c values for the wire samples in their unbent state. This information serves as a valuable reference for further analysis and evaluation of the wire samples, enabling to identify the most suitable candidates for specific applications.

Table 3.4 presents the J_{ce} values, expressed in A/cm^2 , at 25K for the wire samples in their unbent state. This table presents quantitative data on the J_{ce} , highlighting the variations in performance among the different samples. The curves visually illustrate the distinct performance levels of the samples under the

applied MFs, with samples S_1 and S_5 displaying the best performance and sample S_2 exhibiting the least favorable behavior.

Table 3.3. The I_c in unit of (A) at 25K for wire samples before bending.

Magnetic Field	$\uparrow S_1$	$\downarrow S_2$	S_3	S_4	$\uparrow S_5$	S_6
3.5 T	0.97	0.50	0.54	0.59	0.83	0.77
3.8 T	0.36	0.20	0.23	0.31	0.38	0.25

Table 3.4. The J_{ce} in unit of (A/cm^2) at 25K for wire samples before bending.

Magnetic Field	$\uparrow S_1$	$\downarrow S_2$	S_3	S_4	S_5	S_6
3.5 T	120.8	63.5	66.3	80.2	108	83.0
3.8 T	44.0	20.2	22.3	26.9	31.8	26.9

3.4.2 After Bending

Figures 3.13 and 3.14 present the electric field versus current density (E vs J_e) curves obtained at 25K, offering insights into the behavior of the wire samples after the bending process. The analysis of these curves reveals that samples S_1 , S_2 , and S_4 exhibit the most favorable behavior, while samples S_3 , S_5 , and S_6 demonstrate the lowest performance. Table 3.5 and Table 3.6, offer quantitative data on present the I_c and J_{ce} values at 25K for the wire samples after the bending, allowing for a direct comparison of the samples' performance following bending.

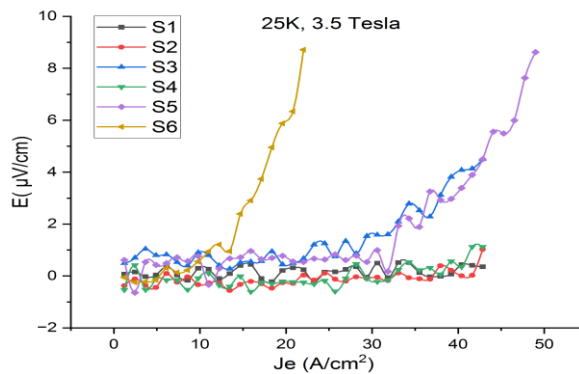


Figure 3.13. The E vs. J_e curves obtained for normal superconducting wires after bending under 3.5 Tesla . The total wire diameter is 1.02 mm.

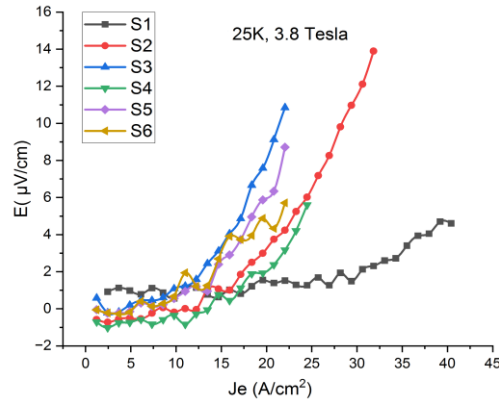


Figure 3.14. The E vs. J_e curves obtained for normal superconducting wires after bending at 3.8 Tesla.

Table 3.5. The I_c in unit of (A) at 25K for wire samples after bending.

Magnetic Field	$\uparrow S_1$	S_2	$\downarrow S_3$	S_4	S_5	S_6
3.5 T	0.62	0.37	0.24	0.36	0.29	0.42
3.8 T	0.19	0.18	0.08	0.14	0.12	0.17

Table 3.6. The J_{ce} in unit of (A/cm²) at 25K for wire samples after bending.

Magnetic Field	$\uparrow S_1$	S_2	$\downarrow S_3$	S_4	S_5	S_6
3.5 T	85.0	42.8	28.2	41.4	33.0	17.2
3.8 T	18.5	13.72	9.80	17.2	12.24	13.5

3.5 Degradation Ratio

Table 3.7 and Table 3.8 provide a comparison of the I_c values between samples before and after the bending process, considering various diameters. Additionally, these tables present the I_c degradation ratio under MFs of 3.5 Tesla and 3.8 Tesla. Based on the analysis of these tables, it is evident that all samples were affected by the bending process. However, it is worth noting that the degradation ratios varied significantly among the different samples. Sample S_2 exhibited the lowest degradation ratio, with approximately 26% under 3.5 Tesla and 10% under 3.8 Tesla. This indicates a substantial reduction in the I_c values due to the bending process. On the other hand, sample S_5 displayed the highest degradation ratio, with approximately 84% under 3.5 Tesla and 69% under 3.8 Tesla. This suggests that this particular sample experienced a relatively smaller reduction in its I_c values compared to the other samples.

Table 3.7. I_c comparison between before/after bending and I_c degradation ratio under 3.5 Tesla.

Sample Code	S ₁	S ₂	S ₃	S ₄	S ₅	S ₆
Critical current before bending (Amp)	0.97	0.50	0.54	0.59	0.83	0.77
Bending diameter (mm)	150	120	80	100	60	200
Critical current after bending (Amp)	0.62	0.37	0.24	0.36	0.13	0.42
Conserved critical current ratio	64%	74%	44%	61%	16%	55%
Critical current degradation ratio	36%	26%↓	56%	39%	84%↑	45%

Table 3.8. I_c comparison between before/after bending and I_c degradation ratio under 3.8 Tesla.

Sample Code	S ₁	S ₂	S ₃	S ₄	S ₅	S ₆
Critical current before bending (Amp)	0.36	0.20	0.23	0.31	0.38	0.25
Bending diameter (mm)	150	120	80	100	60	200
Critical current after bending (Amp)	0.19	0.18	0.08	0.14	0.12	0.17
Conserved critical current ratio	52%	90%	34%	45%	31%	64%
Critical current degradation ratio	48%	10%↓	66%	55%	69%↑	36%

Overall, the comparison of I_c values and degradation ratios presented in Table 3.7 and Table 3.8. Samples S₂, S₃, and S₄, which are not ideal, show less degradation as the bending diameter increases. The only exception is S₁, which was bent to a large diameter of 150 mm and retains similar J_c at 3.5 T and higher J_c at 3.8 T compared to its state before bending. While S₁ and S₅ are comparable before bending, S₁ experiences much less deterioration afterward due to its larger bending diameter. S₅, bent to a smaller diameter of 60 mm, suffers more from mechanical damage. This suggests that bending MgB₂/Fe wires to a larger diameter may reduce the negative impact of increased MFs on their I_c . Sample S₆, bent to a diameter of 200 mm, was the largest and should theoretically show the least degradation. However, we observed that there wasn't much difference in performance between the 150 mm and 200 mm diameters. This indicates that bending the wire to these larger diameters may have a similar effect on its I_c . Figure 3.15 presents the change degradation in I_c versus bending diameters, while

Figure 3.16 shows I_c versus bending diameters at 25 K under a 3.5 T MF. Figure 3.17 depicts I_c versus bending diameters at 25 K under a 3.8 T MF.

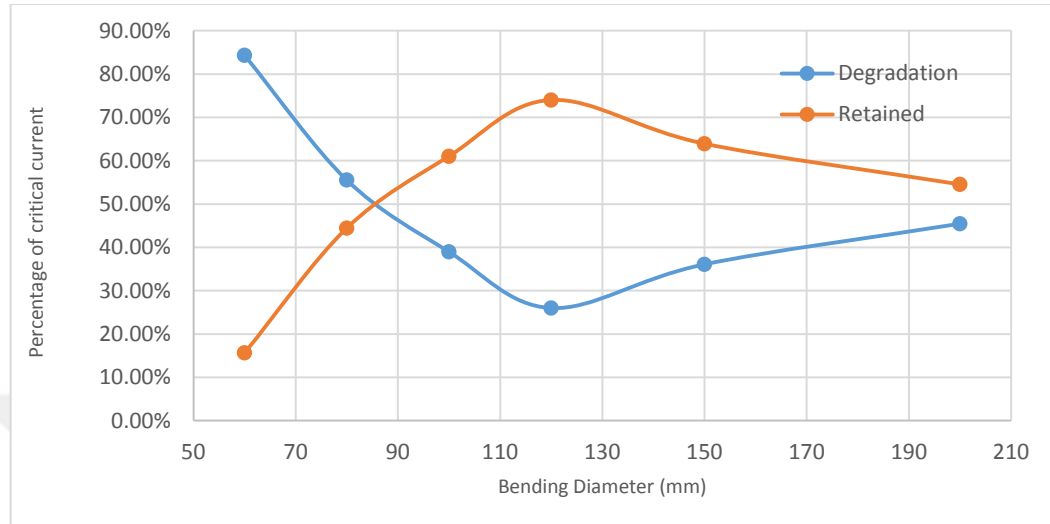


Figure 3.15. Presents the percentage of I_c versus bending diameters in (mm).

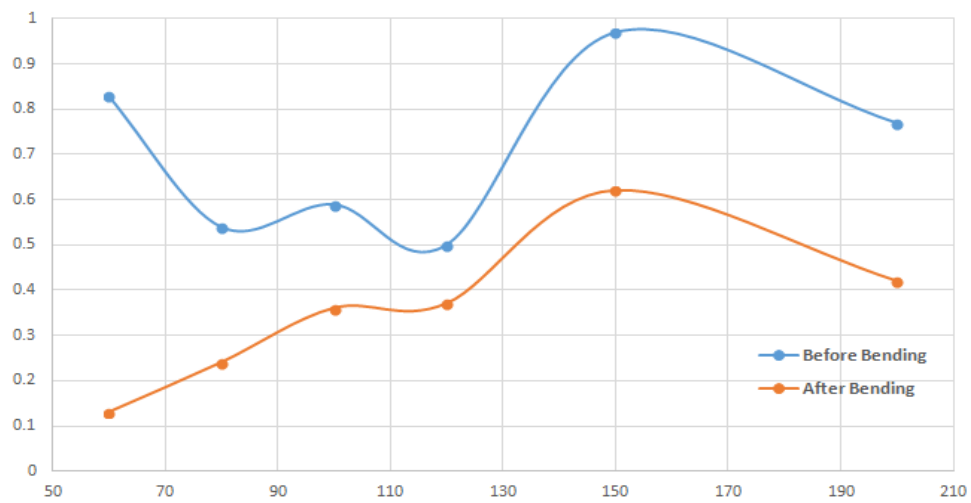


Figure 3.16. Critical current vs. bending diameters at 25 K under a 3.5 T MF.
Current is measured in (A), and diameters are in (mm).

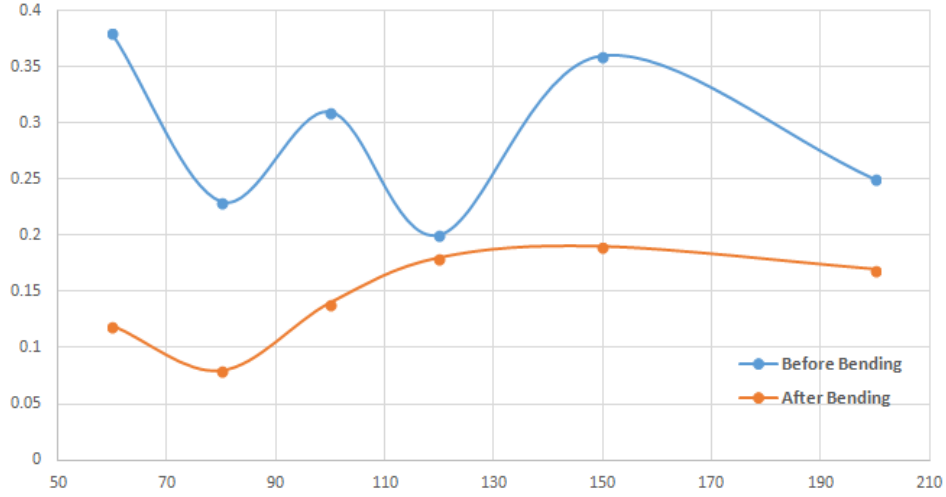


Figure 3.17. Critical current vs. bending diameters at 25 K under a 3.8 T MF. Current is measured in (A), and diameters are in (mm).

I_c values before and after bending reveals that all samples were impacted by the bending process, with notable variations in degradation ratios. S_2 showed the least degradation, approximately 26% under 3.5 Tesla and 10% under 3.8 Tesla, indicating minimal reduction in I_c . In contrast, S_5 faced the highest degradation at 84% under 3.5 Tesla and 69% under 3.8 Tesla, reflecting greater mechanical damage. Notably, samples S_2 , S_3 , and S_4 exhibited less degradation with increasing bending diameters, while S_1 maintained similar I_c values at 3.5 T and higher at 3.8 T after being bent to 150 mm. This suggests that larger bending diameters may mitigate the negative effects of MFs on I_c . However, the performance between samples S_6 (200 mm) and S_1 (150 mm) showed minimal differences, indicating that bending to larger diameters may yield similar effects on I_c .

3.6 Conduction Cooling System - Monitoring Test Analysis

The challenges encountered during the cooling process within the cryostat chamber was observed. The extended duration and limited efficacy of the cooling system, despite the incorporation of LN_2 , demonstrate the complexity involved in achieving optimal cooling conditions. These observations prompt further investigation and potential optimization of the cooling system to overcome the encountered limitations and enhance the overall performance of the cryogenic setup. Figure 3.18 elucidates the temperature-time profiles characterizing the cooling process within the cryostat chamber across three separated periods,

utilizing two different Helium compressors. The initial test conducted on February 26, 2024, successfully achieved the desired up to 30K temperature threshold using the CRYOvn/Delta compressor. However, during the subsequent test on April 18, 2024, the compressor encountered a critical failure, accompanied by smoke emission and oil leakage, rendering it inoperable. Subsequently, on April 22, 2024, the F-70/Sumitomo CRYO compressor was employed, initially demonstrating enhanced efficiency in cooling. However, after 398 minutes, the compressor experienced a partial cessation, resulting in the temperature stabilizing at approximately 68K. To counteract this limitation, the addition of LN₂ was implemented to further reduce the temperature. Consequently, a decrease in temperature was observed, reaching approximately 52K. In light of these findings, it is crucial to know that the measured temperatures presented in Figure 3.18 may not accurately represent the actual temperatures within the cryostat chamber. This discrepancy can be attributed to the improper positioning of the silicon diode, which failed to establish adequate contact with the cold surface. As a result, the temperature measurements obtained from the diode were not representative of the true temperature dynamics. The cooling process encountered several challenges, hindering the achievement of temperatures below 30K. Moreover, the measured temperatures displayed in Figure 3.18 should be interpreted with caution due to the limitations associated with the position of the silicon diode. These insights underscore the importance of experimental setup and accurate temperature measurement techniques when investigating cryogenic systems.

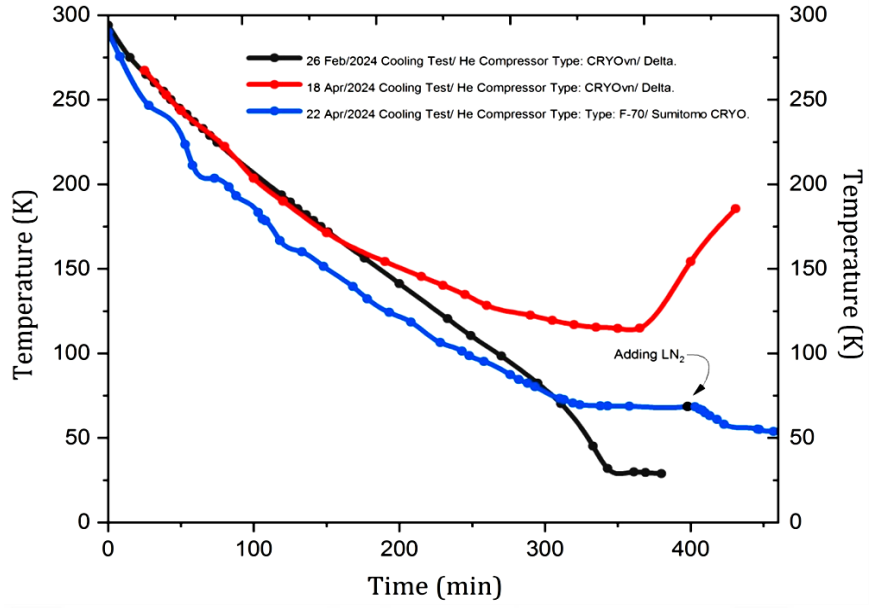


Figure 3.18. (Temperature Vs. Time) curves, cooling process performance inside the cryostat chamber in three different periods by using two different He compressors.

3.7 Non-insulated MgB_2/Fe Coils Tests

The cryostat has a cylindrical chamber with a diameter of 50 cm and a height of 60 cm and a steel flange on its top. Sealing is ensured with a circular cross-section gasket on the contact surface. The flange has all the elements of the cryogenic cooling system connected to it Figure 3.19(a). A large copper plate, connected to the underside of the steel top flange with GFRP rods, is in thermal contact with the liquid nitrogen vessel. This plate serves both as a structural element for attachments and a radiation shield, minimizing heat transfer from the room-temperature flange into the cryogenic environment. The inner surfaces of the liquid nitrogen vessel are covered with MLI to further reduce radiative heat transfer. High-current cables are insulated by Kapton tape and wound around the liquid nitrogen vessel to keep them cool Figure 3.19(b). Two GFRP lamellae with low thermal conductivity, each supporting two parallel REBCO tapes, form a thermal break between the sample and cryostat terminals.

Braided ETP copper cables transfer the test current from top flange to the warmer (77 K) end of the REBCO tape apparatuses. The temperature sensor (CX 1010) is mounted on bottom side of the solenoid coil and silicon diode (DT-670) is mounted on top of the nested coil as seen in Figure 3.19(c)-(d). The conduction

cooling of a six-layer nested coil down to 50 K was achieved in about 15 hours. To achieve lower temperatures, liquid nitrogen was added to the liquid nitrogen vessel after the high vacuum level of 8×10^{-6} mbar in a cryostat chamber is achieved. At temperature of 32.3 K, a transport current of 3 A increased the temperature of the coil former about 0.5 K and then the current was turned off and the system was allowed for cooling. At 29.5 K, when the transport current is increased to 11 A, 0.4 K rise in temperature was recorded.

As shown in Figure 3.20, a linear behavior in the Hall voltage was observed with the increase of the current applied to the coil, but it was also observed that the six-layer nested coil produced a very low MF. This indicates that the temperature of the windings is above or very close to the T_c and that most of the superconducting windings were not capable to transport currents. In other words, since there was no insulation between the turns, the current flowed largely in the longitudinal direction through the iron sheath materials rather than following the solenoidal superconducting path. On the other hand, it was noticed that no quenching was observed in the windings of the nested coil when a high current of 70 A at 26.6 K was applied for a few seconds. The current sharing at the ends of the layers and the ability of the non-insulated contact points between the windings to pass large currents indicate that the nested coils provide self-quench protection even under conduction cooling. The single layer NI solenoid coil was first cooled down to 55 K, and then liquid nitrogen was added for lower temperatures. MF at the centre of the small coil was measured as a function of the applied current at 29 K and the current was varied manually using a DC source with maximum output current of 200 A.

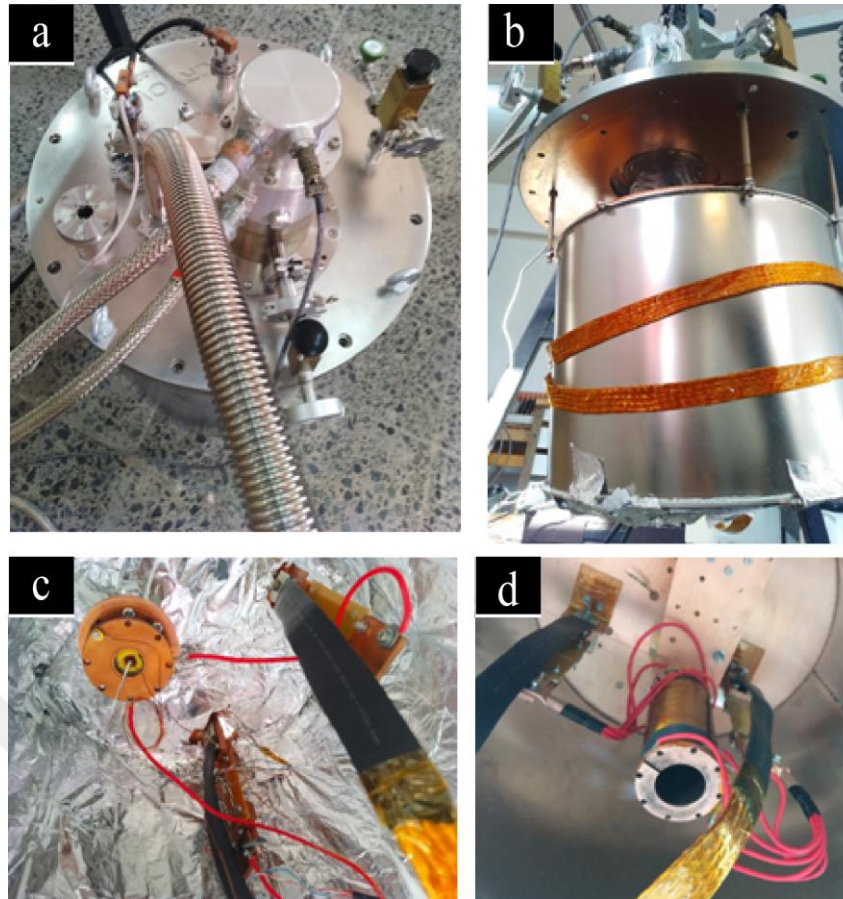


Figure 3.19. (a) The cryostat chamber, evacuated using a turbomolecular vacuum pump, (b) liquid nitrogen vessel and high current cables, (c) – (d) Set-up for cryogenic testing of MgB_2 coils.

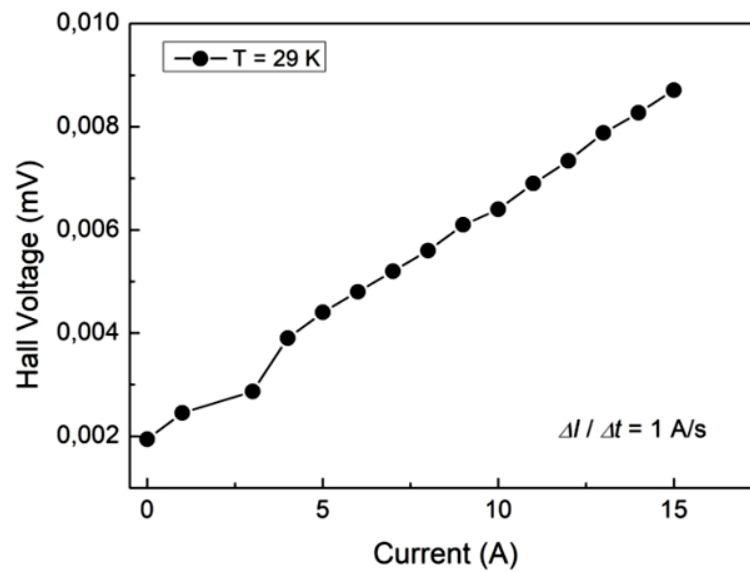


Figure 3.20. Hall voltage vs. Transport current curve obtained for the six- layer NI nested coil. The current ramping rate is $\Delta I / \Delta t = 1 \text{ A/s}$.

As seen in Figure 3.21, currents greater than 10.8 A could not be applied from the current source to the coil. The I_c value for a single layer NI solenoid coil was considered to be around 10.8 A, because above this current value, a sudden increase in the resistance occurs as shown in Figure 3.21(b). However, the I - V curve also reveals a non-linear behavior above 5 A, with the coil also exhibiting signs of heating beyond this threshold. The assessment of the coil's I_c was not based on a specific criterion, as there was no voltage tap connections on the coil. Instead, the evaluation was performed solely using the potential readings from the constant current source. The linear variation of the measured Hall probe voltage with current shown in Figure 3.21(c) indicates that the coil is operational and generating MF with the expected magnitude. However, since these coils undergo a "Wind & React" process and wire I_c degradation is unlikely. Instead, it is suggested that the root of the problem (heating above 5 A) lies in insufficient temperature uniformity upon cooling, which may hinder the coil's performance and contribute to the observed low self-field current. It is important to note that the resistance referred to Figure 3.21 is the total resistance of the circuit, which includes the internal resistance of the current source.

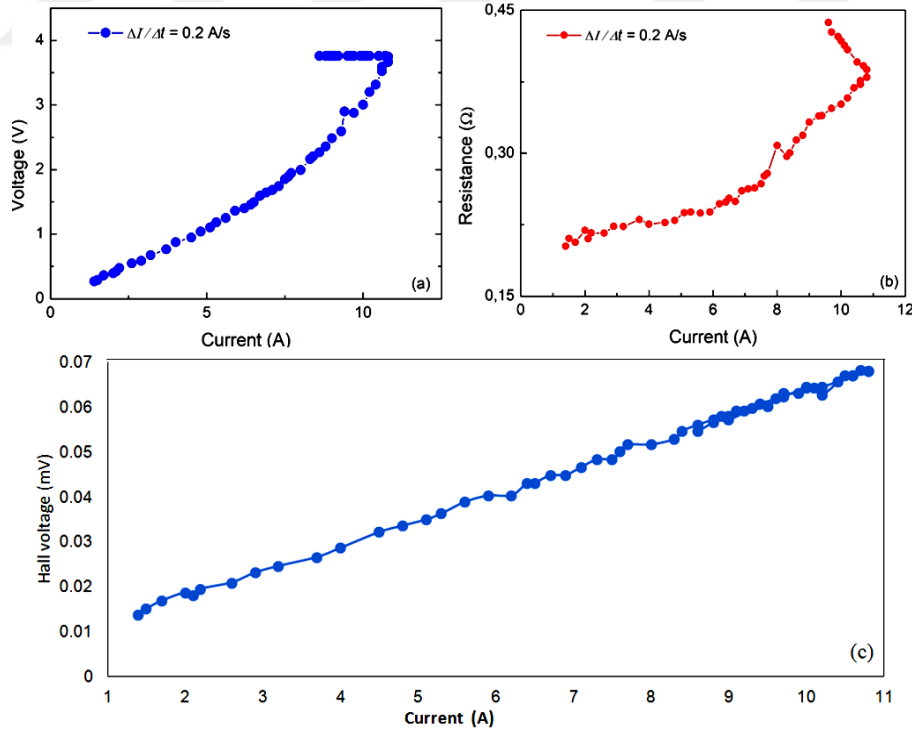


Figure 3.21. (a) Current-voltage, (b) current-resistance curves obtained from the single layer NI solenoid coil and (c) the Hall probe voltage as a function of the transport current passing through the NIC1 coil at around 29 K.

The Hall voltage – current curves in Figure 3.22 were obtained for current ramping rates of approximately 0.3 A/s, 0.45 A/s, and 7.5 A/s. The linear variation of the measured Hall voltage (HGCA-3020 Cryogenic Hall sensor) with applied current shows that the coil is operational and generating a MF. It is observed that when the current ramping rate increases, high currents can be applied to the coil in a short time and the generated MF is proportionally increases. When the applied current exceeds the I_c value, heat is generated, and the dissipation of the generated heat causes an increase in the temperature of the windings and thus a decrease in the current carrying capacity of the windings. Applying the current at a slow ramp rate allows the generated heat to dissipate, which results in high resistance at low applied currents. When 22.3 A is passed through the solenoid coil (20 mm in length and 17 turns), the calculated MF at the centre is about 23.8 mT. According to the Hall sensor datasheet, 0.239 mV corresponds to a MF of 30 mT. Therefore, 0.178 mV measured in the experiments (Figure 3.22) for 22.3A shows that a MF is approximately 22.3 mT at the centre of the NI solenoid coil. This result showed that the NI MgB₂ solenoid coil was cooled below T_c by conduction cooling and solenoidal currents were maintained.

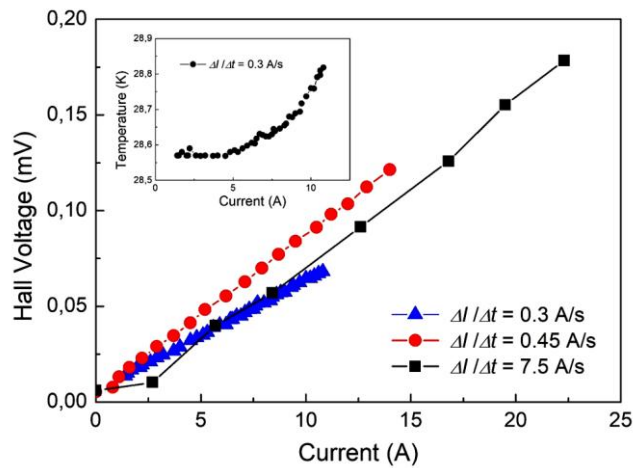


Figure 3.22. Hall voltage as a function of the transport current passing through the single layer NI solenoid coil. The inset shows the temperature change for $\Delta I/\Delta t = 0.3$ A/s.

To facilitate current transfer to the MgB₂ coils during cryogenic testing, a REBCO current lead assembly was integrated into the cryostat. This assembly consists of REBCO superconducting tapes, renowned for their high current-

carrying capacity and mechanical durability, connected to an ETP copper plate beneath the upper flange. This plate, in contact with the liquid nitrogen jacket, provided sufficient cooling of the REBCO leads enabling them to carry high currents. However, the braided ETP copper cables used to connect the upper flange to the REBCO assembly, while in contact with a 77 K liquid nitrogen vessel, still transfer some heat to the measurement area. This highlights the need for careful thermal management in high-current cryogenic systems to minimize heat transfer and maintain optimal operating temperatures. The large dimensions of a six-layer NI nested coil posed a challenge for effective cooling, particularly in the upper layers.

3.8 MgB₂ Superconductors in Wastewater Treatment

Despite its inherent advantages, the application of MgB₂ in WWT systems faces hurdles and challenges that underscore untapped potential rather than insurmountable limitations:

1. Cryogenic Operational Efficiency:

MgB₂'s 10–20 K operational window offers a practical advantage over traditional LTS, as cryocoolers for this range are increasingly efficient and modular. Optimizing thermal budgets and parasitic heat loads could further enhance energy efficiency, positioning MgB₂ as a cost-competitive solution for specialized applications.

2. Material Innovation:

While MgB₂'s brittleness complicates large-scale deployment, its simple composition and low raw material costs enable rapid prototyping of composite architectures (e.g., SiC-doped wires) to improve mechanical resilience. Advances in grain boundary engineering are also poised to boost flux pinning, enhancing J_c at higher MFs.

3. Magnetic Separation Superiority:

MgB₂-based HGMS systems hold unique promise for removing paramagnetic contaminants (e.g., heavy metals, microplastics) with precision. Its T_c advantage over LTS allows stronger MFs at lower cooling costs, enabling targeted pollutant removal in industrial effluents where regulatory compliance justifies investment.

4. Economic and Hybrid Potential:

MgB₂'s low production costs and compatibility with hybrid systems (e.g., integration with electrochemical reactors or membrane filtration) could offset cryogenic expenses. Pilot-scale trials focusing on lifecycle cost analyses are critical to demonstrating its long-term viability for niche WW applications.



4. DISCUSSION

MgB₂/Fe is a promising and economically viable superconductor, and our study focused on enhancing the strength and flexibility of MgB₂/Fe wires through various fabrication techniques. We employed groove rolling, wire drawing, and electro-thermal heat treatment to produce elongated monocoil wires using the PIT method. The initial powder mixture, composed of amorphous boron and magnesium, was ground and mixed for three hours before being loaded into cleaned iron tubes, achieving a density of 1.53 g/cm³. After sealing the tubes with aluminum foil, we reduced the 12 mm diameter tube to approximately 1 mm through groove rolling and cold drawing. This process resulted in wire elongation to about 180 meters, ensuring the desired dimensions and structural properties of the MgB₂/Fe superconducting wires. To prevent fractures during the diameter reduction process, we applied a heat treatment at 650 °C. Prior to this, we conducted a thorough analysis of heat distribution in a four-meter convection furnace, recording temperatures every five minutes to ensure accuracy. The calibrated thermometer revealed distinct temperature differences due to the furnace's insulation, which informed our process. The wire was drawn through the furnace at a rate of 2.5 cm/min and 750 °C, with heat treatment initiated after approximately 50% diameter reduction. This approach minimized the risk of distortions or fractures, while the use of dies helped maintain structural integrity and ensure reliable fabrication outcomes.

We assessed the bending strain tolerance of the MgB₂/Fe wires to determine the maximum diameters suitable for coil fabrication without performance loss. Using a custom bending test probe, we focused on the fabrication and transport properties of monofilament wires. Six samples from the elongated MgB₂/Fe wire were analyzed to identify the optimal diameter. Following the production of MgB₂/Fe samples, sectioned the 6 samples into 25 mm for cryostat testing. We measured of these samples in their unbent state were conducted at 25 K and MFs of 3.5, 3.8, and 4 Tesla, evaluating resistivity-temperature (ρ - T) and current-voltage (E - J_e) characteristics. Before bending, we observed a significant disparity in resistivity, with S_1 exhibiting about five times higher resistivity than S_5 , which we attributed to differences in voltage distance and possibly extraction locations. At 25 K, I_c measurements indicated S_1 was the

best performer, while S_2 was the least effective among the six samples. The electric field versus current density (E vs J_e) curves at 3.5 and 3.8 Tesla confirmed that Samples S_1 and S_5 outperformed the others, particularly S_2 , which demonstrated the least favorable behavior. These results underscored the distinct performance levels under varying MFs. After bending, we tested the same 6 samples at diameters of (200 mm, 150 mm, 120 mm, 100 mm, 80 mm, and 60 mm) to determine the optimal bending diameter and assess the impact on superconducting properties. A notable resistivity disparity was observed between S_4 and S_5 , with S_4 showing about seven times higher resistivity due to variations in voltage distances related to total length and bending diameter. The E vs J_e curves at 25 K confirmed these findings, with S_1 , S_2 , and S_4 demonstrating the most favorable behavior, while S_3 , S_5 , and S_6 showed the least desirable performance. Additionally, J_{ce} values at 25 K allowed for direct comparisons of sample capabilities, highlighting S_1 , S_2 , and S_4 as superior performers while S_3 , S_5 , and S_6 lagged behind. Post-bending analysis revealed that even at a diameter of 200 mm, transport current decreased by about 45%. Lower deterioration rates were observed for diameters of 80 mm, 100 mm, and 120 mm due to their initial low current capacities.

In our experiments with heat-treated MgB_2/Fe samples, shorter wire pieces (S_2 and S_3) showed superior performance compared to longer pieces (S_1 and S_4). The E vs. J_{ce} curves at 25 K indicated that performance decreased with increasing MFs, with optimal results around 3 Tesla. Additionally, J_{ce} values revealed a degradation trend at higher fields, emphasizing the need for precise control to maintain superconductivity. The shorter wire segments also facilitated better phase formation of MgB_2 , enhancing their superconducting properties. During the production of MgB_2/Fe wire, several issues can arise during the mechanical deformation stages. Among these issues, one of the most common problems is the weakening of the sheath material, leading to breakage during cold drawing at weak points. Therefore, in addition to wire drawing, processes such as cylindrical die rolling and drawing were also employed. Rapid successive cylindrical rolling operations can lead to excessive overheating in the composite sample due to deformation. This pressure and heat may cause the (Mg+2B) powder mixture inside the metal tube to ignite explosively, resulting in cracks in the tube. Additionally, irregular mechanical deformation might create cracks in the metal

sheath, allowing the powder mixture to escape and ignite upon contact with atmospheric oxygen. However, the magnesium powder particles are not small enough to trigger such a flash, and they do not refine sufficiently during the early stages of wire production, making this second scenario unlikely. To prevent issues that arise before the first intermediate heat treatment, the rolling steps should be performed slowly, or alternatively, denser powder or tablet filling should be used; applying cold drawing between cylindrical rolling processes with circular dies also helps mitigate these problems.

According to the conduction-cooling system, the cryostat chamber consists of a single-wall chromium steel casing with an upper flange secured to the lower chamber. It features a cylindrical liquid nitrogen jacket for circulating the test volume, with vacuum and measurement connections made through the upper flange using feed-throughs. To improve cooling efficiency, the inner walls of the liquid nitrogen tank were insulated with MLI. An ETP copper plate, equipped with holes for securing coils, is mounted on the cold head. High DC current sources power both the samples and the Hall probe, with voltage measured. Current flows through insulated, vacuum-rated entry ports using ETP copper rods, and materials chosen for the current terminals minimize Joule heating to reduce the load on the cooling head. Braided ETP copper tapes transmit current to the REBCO apparatus and contact the 77 K liquid nitrogen reservoir, although some heat transfer occurs.

In wind-and-react coils, the insulation layer also undergoes thermal processing at high temperatures with the coil, which reduces its resistance to mechanical effects. Since the insulating layer beneath the wire remains intact at the interfaces where the windings contact the insulated ETP copper former, no short circuits occur between the windings and the coil. The REBCO current transfer apparatuses were connected to an ETP copper plate beneath the upper flange, enabling cooling. The 6-layer bitter-type solenoid coil created using the wind-and-react method carried significant currents during cryogenic measurement tests. Each end of the coil has a total of 12 wire leads, with each lead connected to the REBCO current transfer apparatus on the sample side using flexible copper wires. If the REBCO apparatuses were not sufficiently cooled, burning would be inevitable at currents above a few amperes. The copper plate beneath the upper flange is in contact with the liquid nitrogen jacket, which facilitates cooling.

REBCO superconductors were utilized to ensure efficient current transfer to the superconducting coil, primarily due to their high in-field current-carrying capacity and mechanical durability. These second-generation REBCO tapes have a T_c of approximately 90 K. Since the superconducting MgB_2 coils will be cooled to around 15 K to 20 K, the REBCO superconductor can effectively transfer high currents to the MgB_2 windings without generating heat. Current connections from the upper flange of the cryostat facilitate the flow of current through an electrically insulated, vacuum-rated entry port using an ETP copper rod. The materials chosen for the current terminals exhibit low thermal conductivity, preventing Joule heating under high current conditions, which helps reduce the load on the cryogenic cooling head and enables operation at lower temperatures. Additionally, braided ETP copper tapes transmit current from the upper flange to the REBCO current transfer apparatus while remaining in contact with a liquid nitrogen reservoir cooled to 77 K. However, it is important to note that, despite this contact, the braided ETP copper tapes still conduct some heat transfer.

In I_c tests conducted with high currents at low temperatures, the total resistance of the circuit within the cryostat should not exceed the milliohm level; the total voltage of 4.186 V across the circuit when a current of 72.2 A is flowing indicates that the total resistance of the circuit is 58 m Ω . The total resistance of the circuit, excluding the source resistance, was determined to be 70 m Ω at room temperature and 50 m Ω at 29 K. This can only be achieved with superconducting current leads. Superconducting current leads are typically made from high-temperature superconductors like Bi-2223, which can carry resistance-free current at 77 K, and due to their low thermal conductivity, they transfer limited heat.

The large dimensions of the 6-layer bitter-type coil negatively impacted the cooling process. Insufficient cooling in the upper layers affected current circulation in the windings, resulting in measured MFs that were below expectations. Nevertheless, a Hall probe voltage measured increased linearly with the current flowing through the coil. The linear relationship between the measured Hall probe voltage and the current was observed much more clearly in a single-layer coil. In the test of a multilayer normal solenoid coil, the Hall probe shifted outside the coil, preventing field measurement. When the current exceeded 33 amperes, characteristic signs of sudden current quenching, such as the wire bursting and melting due to high heat during breakage, were observed.

Otherwise, heavy metals are major freshwater and industrial activities pollutants, posing serious health risks due to their toxicity and persistence. According to conventional methods for heavy metals removal/ reduce in WWT, researchers have explored various methods for removing heavy metals from WW. Traditional approaches include electrochemical treatments like EC, EF, and ED. Other techniques involve physicochemical processes such as chemical precipitation and ion exchange, along with adsorption using materials like activated carbon and wood sawdust. Although electrochemical treatments have historically been overlooked due to high electricity costs. Numerous studies examined traditional methods like membrane filtration, ion exchange, chemical precipitation, and adsorption. While EC, EF, and ED offer promising solutions for WWT, each method has inherent disadvantages that can impact their effectiveness and adoption. EC faces significant challenges related to reactor design and electrode reliability. These issues can hinder the process's efficiency and scalability, making it less attractive for widespread use. Additionally, the operational costs associated with EC can be high due to energy consumption and the need for regular maintenance of sacrificial electrodes. Furthermore, although EC is effective in removing small colloidal particles, it may struggle with highly soluble pollutants, limiting its applicability in certain WW scenarios. EF, while adaptable and effective for removing heavy metals, also has its limitations. Its efficiency can diminish in very low concentration scenarios, requiring specific conditions to achieve optimal performance. This need for careful optimization can complicate the implementation of EF in practical applications. Moreover, the integration of EF into existing systems may necessitate additional infrastructure, which can be a barrier for some facilities. ED, although cost-effective and selective for heavy metal recovery, is primarily limited to specific applications. This restriction could reduce its utility in broader WWT contexts. Additionally, ED requires stringent control of operating conditions, such as voltage and pH, to maintain optimal performance. This complexity can pose operational challenges and necessitate advanced monitoring and control systems, making it less accessible for some treatment facilities (Hunsom et al., 2005; Montgomery & Elimelech, 2007; Hahladakis et al., 2013; Azimi et al., 2017).

The applications of MFs in water purification, coagulation and sedimentation of colloidal particles, and WWT, emphasizing their potential benefits and limitations while calling for further research in this area. MFs have shown effectiveness in separation processes by influencing the characteristics of contaminants, thereby enhancing purification efficiency when combined with other techniques. Various magnetic technologies utilize permanent magnets or high-gradient magnetic separation (HGMS) in methods, each affecting system performance differently. However, the mechanisms behind these applications are not fully understood, leading to conflicting theories in the literature (Kronenberg, 1985; Ambashta & Sillanpää, 2010; Nur Syamimi et al., 2014).

A strong magnetic gradient is particularly important for effective particle separation, especially when dealing with small volumes. Moreover, using a magnetic gradient in combination with an alternating field proves to be more effective than relying solely on a static field resulting in faster crystallization and improved descaling outcomes. Magnetic filtration removes suspended solids and starch by creating a magnetic gradient as a solution flows through coils magnetized by external permanent magnets. These magnets, arranged with alternating poles, generate an oscillating MF that enhances the gradient by concentrating flux lines. As the solution moves through the coils, charged particles are attracted and separated. The effectiveness of this process depends on the magnetic strength and the characteristics of the coil magnetization (Kronenberg, 1985; Iwasaka & Ueno, 1997; Franzreb & Holl, 2000).

However, the effects of magnetic memory on microorganisms differ from those on water molecules. While stronger magnetic memory can enhance particle aggregation, it doesn't have the same effect on bacteria. Instead, weak or strong magnetic memory may either promote or hinder bacterial growth, influencing the performance of systems like WWT. These effects arise from variations in magnetic susceptibility (Nur Syamimi et al., 2014). Moreover, magnetic treatment also aids in reducing scaling by encouraging homogeneous nucleation such as in CaCO_3 . However, careful exposure to the MF is vital when treating water with silica to ensure effective crystallization and minimize scaling. Various methods have been used to combat scaling, including electrochemical processes and chemical inhibitors, but these can pose health risks in drinking water systems (Alimi et al., 2009).

The effects of MFs on water purification processes that the exposure to a SMF of 0.4–0.6 T enhanced precipitation and improved sludge coagulation by reducing electrokinetic potential. This suggests that MFs can facilitate the aggregation of particles, potentially increasing the efficiency of WWT and observed that a much lower SMF of 0.0025 T decreased the conductivity of deionized water, indicating that MFs can affect ionic interactions within water. While studies highlighted the significance of hydrogen bonding in water, stating that its structural stability and viscosity are closely linked to these interactions, by demonstrating that exposure to SMFs ranging from 0 to 10 T could increase hydrogen bonds by up to 0.34%, which resulted in decreased self-diffusion coefficients and enhanced viscosity and stability of water. This finding suggests that MFs can promote water's structural integrity, potentially leading to improved purification outcomes. Furthermore, a 6 T MF can strengthen hydrogen bonds in both H₂O and D₂O, inhibiting thermal motion through the Lorentz force. This phenomenon, termed “enhanced-dynamic magnetic susceptibility,” indicates that strong MFs may significantly influence molecular interactions in water while MFs may weaken hydrogen bonds between water clusters, they can enhance bonding within the clusters, as indicated by a lower friction coefficient in magnetized water. MFs alter hydrogen bonding dynamics, thereby enhancing reactions such as improved adsorption. Collectively, these findings suggest that MFs can play a crucial role in optimizing water purification processes by modifying the molecular interactions and structural properties of water (Iwasaka & Ueno, 1998; Inaba et al., 2004; Krzemieniewski et al., 2004; Akopian & Aïrapetian, 2005; Holysz et al., 2007; Chang & Weng, 2008; Toledo et al., 2008; Cai et al., 2009; Y. Wang et al., 2013; J. Ma et al., 2018).

The impact of SMFs on the removal of heavy metals from WW, illustrating variations in removal efficiency based on the type of adsorbent and MF intensity. Notably, the use of zerovalent iron for copper ion (Cu²⁺) removal demonstrated a remarkable 88% increase in efficiency with an SMF intensity of less than 0.001 T. This suggests that even minimal MF exposure can significantly enhance the removal of specific heavy metal ions, making it an effective strategy for WWT. the application of zeolite and carbon modified with calcium and iron at an SMF of 0.086 T resulted in a total molar removal increase of only 10% to 20%

for cadmium (Cd^{2+}) and zinc (Zn^{2+}). This indicates that while SMFs can improve adsorption, the extent of enhancement may vary significantly depending on the materials used. Granular activated alumina showed a modest increase in removal efficiency for multiple heavy metals (Cu^{2+} , Pb^{2+} , Cd^{2+}) at an intensity of 0.118 T, with improvements ranging from 1.9% to 8.2%. This variability highlights the need for tailored approaches when selecting adsorbents and MF strengths. Na-rectorite and Ca-rectorite exhibited increases in adsorption capacity for zinc (Zn^{2+}) and copper (Cu^{2+}) at 0.32 T and 0.34 T, respectively, with increases of 10% and 12%. Conversely, vermiculite and halloysite, under similar conditions (0.518 T), showed a decrease in removal efficiency for copper and nickel (Cu^{2+} , Ni^{2+}), indicating that the effects of SMFs can be highly dependent on the specific adsorbents used. Ferric chloride demonstrated a notable improvement in the removal of arsenic (As^{5+}) with a removal efficiency increase ranging from 6% to 50% at an intensity of 0.35 T, suggesting that SMFs can enhance coagulation processes in certain contexts. Activated carbon displayed significant improvements in adsorption capacity for cadmium (Cd^{2+}) and zinc (Zn^{2+}) at 1 T, with increases of 63% and 15%, respectively, underscoring the potential of MFs in optimizing heavy metal removal.

Studies indicate that higher MF intensities can significantly improve the removal of organic compounds. For instance, a 30% increase in phenol removal at a MF intensity of 450 mT, a submerged filter system employing magnetically anisotropic tubular media with a high magnetization of 2100 Oe. This effectively treated sewage with a COD concentration of 200 mg/L, achieving an impressive removal efficiency of up to 94% within just 8 hours. The mixed effects of MFs on bacterial biodegradation are particularly noteworthy; different bacterial strains exhibit varying magnetic susceptibilities, which can lead to either enhancement or inhibition of their metabolic activities. The optimal MF intensity for promoting bacterial activity and biodegradation remains ambiguous. While some studies suggest that intensities ranging from 1 mT to 1 T can be beneficial, higher MF strengths may inhibit bacterial function, thus impacting overall treatment performance. This variability indicates that specific bacteria may thrive under different magnetic conditions, complicating the establishment of a one-size-fits-all approach. Research indicates that recirculation enhances removal performance

due to the magnetic memory effect, which improves particle interactions and solid-liquid separation. Conversely, biological WWT tends to be more effective with a single pass flow configuration. This suggests that the design and operational parameters of treatment systems must be carefully considered to optimize the benefits of MFs in conjunction with flow dynamics.

Superconducting systems offer several advantages over conventional activated sludge treatment, notably higher efficiency and reduced processing times. For optimal performance, a MF intensity greater than 0.7 T is essential, with recent developments demonstrating the capability to generate fields as high as 2.56 T using NbTi solenoid coils. One such design operates at 65 A, achieving a central field strength of 2.56 T. This system features a unique construction with multi-filamentary NbTi/Cu wires, which ensures stability and effective heat management. Additionally, a safety margin of 20% signifies a robust design that can withstand operational stresses. The successful operation at high currents, with a maximum temperature rise maintained below 70 K during quench incidents, further confirms the reliability and effectiveness of these superconducting systems. In the realm of sewage sludge management, a separate study investigated the effects of a 1.5 T SMF on methane production during anaerobic digestion. The findings indicated a 24% reduction in methane production, along with decreased concentrations of several ionic species, including NH_4^+ and NO_3^- . However, the application of the SMF also facilitated the precipitation of valuable nutrients such as struvite, suggesting a potential trade-off between methane yield and nutrient recovery. Moreover, the effectiveness of cryomagnetic separation for nonferrous waste has been demonstrated, utilizing a powerful 5 T MF to enhance metal extraction from industrial effluents. The automation of these systems offers significant environmental benefits, particularly in recovering valuable metals from WW streams. In a complementary approach, a separation efficiency of 82% for Cr was achieved in synthetic WW, along with a 55% reduction in molybdenum concentrations in real WW. Effective magnetic separation was maintained with a flow velocity of 7 L/min, although challenges related to pH stabilization in genuine WW were also noted.

The concentrations of heavy metals in WW after magnetic separation, highlighting the effectiveness of MFs separation via superconductors in reducing pollutant levels. Initially, the WW contained significant concentrations of several

heavy metals, including dissolved Cr at 0.13 mg/L and Mo at 9.8 mg/L. The total concentrations of Cr and molybdenum were reported as 0.25 mg/L and 9.8 mg/L, respectively. The presence of solid matter at 8.8 mg/L further indicates a complex mixture requiring effective treatment solutions. The results indicated varying concentrations of Cr and molybdenum based on the applied magnetic flux density. For Cr, concentrations remained consistent at 6 mg/L across magnetic flux densities of 0.7 T and 1.3 T, and decreased slightly to 5.5 mg/L at higher densities of 1.8 T, 2.4 T, and 3.0 T. This suggests that while the initial removal was effective, increasing the magnetic flux density did not lead to further significant reductions in Cr concentrations. In contrast, the concentrations of molybdenum after separation exhibited a more gradual decline with increasing magnetic flux density. At 1.0 T, the molybdenum concentration was recorded at 6.2 mg/L, decreasing to 5.5 mg/L at higher densities of 2.5 T and 3.0 T. This trend indicates that magnetic separation is effective for molybdenum removal, albeit with diminishing returns at higher flux densities. Over a year of operating a 300 m³/d EMS system, the process removed more than 80% of particulate organics and 60% of soluble organics in just 10 minutes, utilizing only 0.036 kWh/m³. This highlights the system's exceptional efficiency and cost-effectiveness in organic recovery, making it a promising solution for municipal WWT.

HGMS is another prominent technique, utilizing a magnetically susceptible wire bed within an electromagnet to create significant MF gradients. The effectiveness of HGMS is influenced by factors such as particle size and magnetic properties. superconducting HGMS systems can achieve field strengths up to 6 T, making them particularly effective for removing pollutants like iron oxides. In contrast, HGMS utilizes magnetic forces to separate metals without the need for coagulants, offering an eco-friendly alternative. Studies indicate that the effectiveness of HGMS increases with the incorporation of ferromagnetic wires, enhancing the force exerted on particles achieved over 85% removal efficiency for ferrite precipitates in laboratory WW using HGMS, and the addition of cationic polyacrylamide improved arsenic removal by 15% during HGMS applications.

MgB₂ presents a promising alternative for superconducting applications due to its low production costs and the abundance of inexpensive raw materials. This versatility positions MgB₂ as a potential candidate for various applications, including in superconducting wires and tapes. However, its application in WWT

remains largely unexplored, with several significant challenges hindering large-scale implementation. One major consideration is the limited research focused on the use of MgB_2 in WWT. While its superconducting properties are well understood, practical applications in this field are scarce. The predominant superconducting materials currently used in scientific and medical applications are NbTi and Nb_3Sn , which have proven track records. Consequently, the technology surrounding MgB_2 requires further validation before it can be effectively implemented in WWT processes. Operationally, MgB_2 superconductors must function at very low temperatures, around 39 K, necessitating complex cryogenic systems that consume substantial energy. This requirement poses significant challenges for large-scale WWT, which typically involves chemical and biological processes that may not align with the operational needs of superconductors. Additionally, the mechanical strength and stability of MgB_2 under the harsh conditions commonly found in WW environments could further limit its applicability.

Despite its potential advantages, the economic feasibility of using MgB_2 in WWT is also a critical concern. Although MgB_2 is relatively cost-effective compared to other superconductors, the overall production costs can still be higher than conventional treatment methods. Therefore, the widespread adoption of MgB_2 in WW applications may be restricted to specific scenarios, such as the removal of heavy metals from hazardous industrial WW, which would require thorough research to establish its effectiveness. To make MgB_2 a viable option for WWT several steps must be taken. Targeted studies are needed to identify the specific heavy metals present in hazardous and industrial WW. Additionally, enhancing MgB_2 's properties through methods such as doping or composite creation will be crucial. Moreover, improving cooling systems and exploring hybrid approaches can help mitigate the energy demands of maintaining superconducting conditions. By integrating MgB_2 into a hybrid system with existing WWT facilities, it may be possible to leverage its superconducting properties to target specific pollutants effectively while minimizing disruption to other water constituents.

5. CONCLUSION

This study has successfully produced and fabricated elongated superconductor monocoil wires of MgB_2/Fe using the PIT method, with a focus on their superconducting properties. We systematically evaluated the electrical and mechanical characteristics of these wires under varying MFs. MgB_2 is not only economically viable but also easy to produce, making it an attractive option for superconducting applications. To ensure the wires' suitability for coil winding, we employed techniques such as groove rolling, wire drawing, and electro-thermal heat treatment to enhance strength and flexibility. We prepared a stoichiometric mixture of magnesium and boron powders, achieving a packing density of (1.3-1.5) g/cm^3 . The resulting billets underwent groove rolling, reducing the outer diameter to 0.81 mm, and we successfully produced wires up to 180 meters long. Our extensive measurements confirmed that we achieved appropriate bending diameters of up to 150 mm, allowing for winding onto non-insulated ETP copper formers. We fabricated both NI single-layer and multilayer MgB_2 coils and tested them in a conduction cooling system, ultimately reaching a temperature of 26.6 K, essential for attaining the superconducting state of the coils. To facilitate current transfer during cryogenic testing, we integrated a REBCO current lead assembly, which provided sufficient cooling through contact with a liquid nitrogen jacket. However, the braided ETP copper cables still introduced some heat into the measurement area, underscoring the need for careful thermal management in high-current cryogenic systems. While we faced challenges with cooling efficiency in the six-layer nested coils, the linear increase in Hall probe voltage with coil current confirmed the operating principles. This study suggests that additional cooling strategies, such as incorporating extra cold fingers, may be necessary for optimal performance. Future designs should prioritize efficient cooling to ensure uniform current distribution and maximize MF generation. Moreover, we recommend investigating self-quench protection for the MgB_2 coils.

Otherwise, this research highlights the potential of MgB_2 superconductors in WWT, addressing critical needs in the context of growing water scarcity. By

leveraging the unique properties of MgB_2 , we can enhance pollutant removal through magnetic separation techniques. We recommend further research into optimizing magnetic separation systems that utilize MgB_2 , focusing on coil geometry and cooling methods. Integrating MgB_2 coils into existing treatment facilities could significantly improve the removal of para-particles, reducing pollution levels in industrial wastewater. Continued investigation into the behavior of these particles in high MFs will be essential for refining these methods, ultimately contributing to more efficient WWT solutions and advancing global environmental goals.

Subsequently, here are some recommendations that could pave the way for future advancements based on this study:

- To address the challenges associated with MgB_2 wire production, it is essential to prioritize the integrity of the sheath material during mechanical deformation. The weakening of the sheath can result in breakage; therefore, employing techniques such as cleaned cylindrical die rolling is recommended to mitigate this risk. These methods can enhance the durability of the wires during fabrication.
- Overheating and ignition risks are significant concerns when rapidly rolling cylindrical wires. To prevent the potential ignition of the (Mg + 2B) powder, it is advisable to adopt slower rolling techniques or utilize denser powder mixtures. These adjustments can help maintain safe production temperatures.
- Cross-sectional shape irregularities often arise from using softer sheath materials. To minimize these irregularities, it is beneficial to use harder materials, such as iron or steel, which can provide better structural integrity during the wire-forming process. This change can lead to more consistent wire shapes and improved performance.
- For accurate I_c measurements, using pulsed test currents is essential. This approach allows for safe measurements without generating excess heat at superconducting transition points. Additionally, incorporating lock-in

amplifiers can ensure precise readings, enhancing the reliability of the testing process.

- The effects of bending stress should also be carefully evaluated. Circular bending can create extrinsic cracks in MgB_2/Fe wires, which may reduce the I_c . It is recommended that the safe bending diameter for coil winding exceed 200 mm to avoid such issues.
- For insulation layer development, the react-and-wind method is effective for applying insulation to ETP copper. However, it is important to select a heat-resistant material that adheres well to copper to ensure durability under operational conditions.
- In terms of cryogenic measurement setups, using a six-layer bitter-type coil with 12 wire leads connected to a REBCO apparatus has proven effective. However, it is critical to ensure adequate cooling, as insufficient cooling at high currents can lead to burnout.
- Current terminal design must also be optimized. Current terminals should enter the cryostat through insulated, vacuum-sealed ports to minimize heat transfer. While ETP copper bars provide some insulation, they still transfer heat, which can affect performance.
- Managing resistance constraints is vital during I_c tests. It is essential to keep circuit resistance below milliohms, which can be effectively achieved using high-temperature superconducting leads. This allows for reliable operation and better results.
- Cooling challenges have been noted with larger six-layer coils, which can hinder cooling efficiency and affect current circulation and MF measurements. The relationship between coil current and MF was clearer in single-layer coils, suggesting a need for improved cooling strategies in multilayer designs.

- During testing, signs of quenching, such as wire bursting and melting, were observed at currents exceeding 33 A. This indicates the importance of developing effective quench protection mechanisms for the MgB₂ coils.
- The six-layer bitter-type coil, constructed using the react-and-wind method, featured ceramic insulation capable of withstanding temperatures up to 670 °C. I_c tests highlighted the necessity for low thermal conductivity materials in current leads to maintain resistance below a milliohm, achievable only with superconducting leads.

To advance the integration of MgB₂ into WWT systems, the following strategic priorities are proposed:

- **Material Optimization:**

Refinement of doping strategies; such as the incorporation of TiB₂ nanoparticles or graphene, is critical to enhance the J_c and mechanical stability of MgB₂. These dopants improve flux-pinning mechanisms and grain boundary cohesion, enabling higher MF tolerance and durability in harsh operational environments.

- **Cryogenic System Innovation:**

Development of compact, high-efficiency cryocoolers with improved coefficients of performance is essential to minimize energy demands. Modular designs tailored for WWT infrastructure could reduce cooling costs while enabling scalable deployment in industrial or decentralized settings.

- **Interdisciplinary Synergy:**

Collaborative frameworks between materials scientists, cryogenic engineers, and environmental researchers are necessary to design MgB₂-enhanced hybrid reactors. Such systems could integrate superconducting magnetic separation with electrochemical oxidation processes, targeting recalcitrant organic pollutants (e.g., pharmaceuticals, dyes) with unprecedented energy efficiency.

Finally, future work should focus on characterizing bitter-type coils further to enhance cooling efficiency. Using flexible high-temperature superconducting current leads could minimize Joule heating, as current setups have limited operational temperatures to between 27 and 30 K. By addressing these challenges, we can significantly improve the performance and applicability of MgB_2 superconductors in various fields.

Investigating magnetic treatment methods could reveal new ways to enhance WWT processes, particularly in modifying water properties and improving pollutant removal. The advancement of MgB_2 superconductors presents a promising opportunity, but we must tackle existing challenges such as research limitations and the need for low operational temperatures. Future studies should delve into the types of pollutants found in wastewater and explore how to enhance the properties of MgB_2 . Additionally, developing hybrid treatment approaches and improving cryogenic systems could facilitate the integration of MgB_2 into existing WWT frameworks. By overcoming these challenges, we can harness the full potential of MgB_2 superconductors to improve water management and effectively remove hazardous heavy metals, ultimately contributing to a cleaner and more sustainable environment.

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