Fabrication of Bonded Neodymium-Iron-Boron (NdFeB) Permanent Magnet through Warm Compaction

By

Sherrene Crystal Anak Basil

Dissertation submitted in partial fulfillment of
the requirements for the
Bachelor of Engineering (Hons)
(Mechanical Engineering)

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CERTIFICATION OF APPROVAL

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Approved by:

(Assoc.Prof.Dr. Patthi Hussain)
Project Supervisor

UNIVERSITI TEKNOLOGI PETRONAS
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December 2010

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified as reference and acknowledgements, and the original work contained herein have not been undertaken or done by unspecified sources or person.

SHERRENE CRYSTAL ANAK BASIL

ABSTRACT

Generally, bonded Neodymium-Iron-Boron (NdFeB) magnet is fabricated through compression bonding process using wet method which is more tedious and time consuming. The NdFeB melt spun ribbon powder is mixed together with polymeric binder in acetone solution and has to wait for the mixture to vaporize and become in paste form before being compressed in specified compression load. Then, the mixture will be cured in the oven for hours which is more time consuming. The suggested technique of warm compaction will overcome the above problem by speeding up the time of fabrication. Fabrication of bonded NdFeB permanent magnet through warm compaction is the other ways to improve fabrication time by mixing the polymeric binder with the NdFeB melt spun ribbon powder, and then follow by heating and compaction processes simultaneously. Thus, the time for curing the permanent magnet could be eliminated. The type of binder used in this study is phenolic. The study on warm compaction method are divided by two section which focus on the effect of polymer binder composition in bonded magnet and effect of warm compaction temperature on bonded magnet. The obtained results based on the magnetic properties measured by vibrating sample magnetometer (VSM) had reveal that the magnetic properties of bonded magnet of 5wt% phenolic heated at 170˚C is higher than the bonded magnet of 3.5wt% phenolic heated at 170˚C and the bonded magnet of 5wt% phenolic heated at 148˚C. From the obtained result, it is possible to have higher magnetic properties when the amount of polymer binder is more than the usually 2 – 3% mass portions as proven in this study. The portion of binder has greater influence on the magnetic properties compare to the warm compaction temperature where the sample magnet with 3.5wt% of phenolic heated at 170˚C has the lowest magnetic properties among the three samples.

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ABBREVIATION AND NOMENCLATURE

UTP	Universiti Teknologi PETRONAS
AMREC	Advanced Materials Research Centre
NdFeB	Neodymium Iron Boron
Sm – Co	Samarium – cobalt
H_c	Coercive Force
B_r	Remanent magnetic induction
M_s	Saturation magnetization
M_r	Remanent magnetization
BH_{max}	Maximum energy product
ρ	Density
SEM	Scanning Electron Microscope
VSM	Vibrating Sample Magnetometer
G	Gauss

CHAPTER 1

INTRODUCTION

1.1 Background of Study

The bonded magnet market has experienced the fastest growth of any permanent magnet industry especially after the discovery of Neodymium –iron- boron (NdFeB) magnets, one of rare earth permanent magnets [1]. According to K.H.J. Buschow, permanent magnet plays a role of increasing importance in modern society because they serve as vital components in numerous domestic and industrial devices [2]. In 1999, the bonded market throughout the world was about $875 million, of which about 42% were rare earth magnets and 52% ferrite [1]. Although bonded ferrite still dominates the market, bonded NdFeB magnets are becoming more and more important due to their superior magnetic properties (Hadjipanayis, 2003 and Ring, 2000) [1,3]. Bonded NdFeB magnets can be used in a wide range of applications. The emergence of large developing economies, growth of personal computer industry and the related technology and the government regulation for the efficiency in appliances and automobiles provide a tremendous growth opportunity for bonded NdFeB magnets. Both powder and magnet procedures need to constantly improve their products by introducing new powder grades or new manufacturing methods for the ever growing application opportunities (Ma et al, 2002) [4]. Most of the bonded NdFeB magnets are used in motor-related applications. Spindle motors of HDDs, CDs and DVDs account for 55% of the bonded NdFeB market (Ring, 2000) [3].

Bonded magnets are generally prepared by blending coercive powder with a binder or by encapsulating coercive powder in a binder, followed by compacting or molding the material to the final shape (Buschow, 1998) [2]. In this study, fabrication of bonded Neodymium-iron-boron permanent magnet through compression bonding uses magnetic powder blended with an epoxy that has been liquefied by dissolution in an organic solvent is time consuming because it takes time to wait for the mixture to dry before compacted into desired shape and finally, the compacted magnet is cured in an oven (Buschow, 1998)[2].

The suggested technique of warm compaction will overcome the above problem by speeding up the time of fabrication. Fabrication of bonded NdFeB permanent magnet through warm compaction is the other ways to improve fabrication time by mixing the polymeric binder with the NdFeB melt spun ribbon powder, and then follow by heating and compaction processes simultaneously. Thus, the time for curing the permanent magnet could be eliminated.

1.2 Problem Statement

Generally, bonded Neodymium-Iron-Boron (NdFeB) magnet is fabricated through compression bonding process using wet method which is more tedious and time consuming. The NdFeB melt spun ribbon powder is mixed together with polymeric binder in acetone solution and has to wait for the mixture to vaporize and become in paste form before being compressed in specified compression load. Then, the mixture will be cured in the oven for hours. One of the ways to overcome the production time is by using warm compaction method where the magnetic powder does not required to be mixed with polymeric binder in acetone solution and a curing process may not be needed. Although the warm compaction method is saving more production time, it is necessary to determine the magnetic properties of the bonded magnet.

1.3 Objective

The main objective of this project is to determine the magnetic properties of warm compaction bonded NdFeB permanent magnet with improving fabrication time and less procedure.

1.4 Scope of Study

The scope of study will be focusing on the effect of polymer binder composition in bonded magnet and the effect of warm compaction temperature on bonded magnet. The optimum polymeric binder composition in bonded magnet for warm compaction, mechanical and magnetic properties will be determined. In warm compaction method, compression and heating processes are done simultaneously compare with wet method which has to be cured in oven for hours after compaction. Phenolic would be used as the binder and then the mechanical and magnetic properties of warm compaction bonded NdFeB magnet would be analyzed by using optical microscope, Scanning Electron Microscopy and Vibrating Sample Magnetometer.

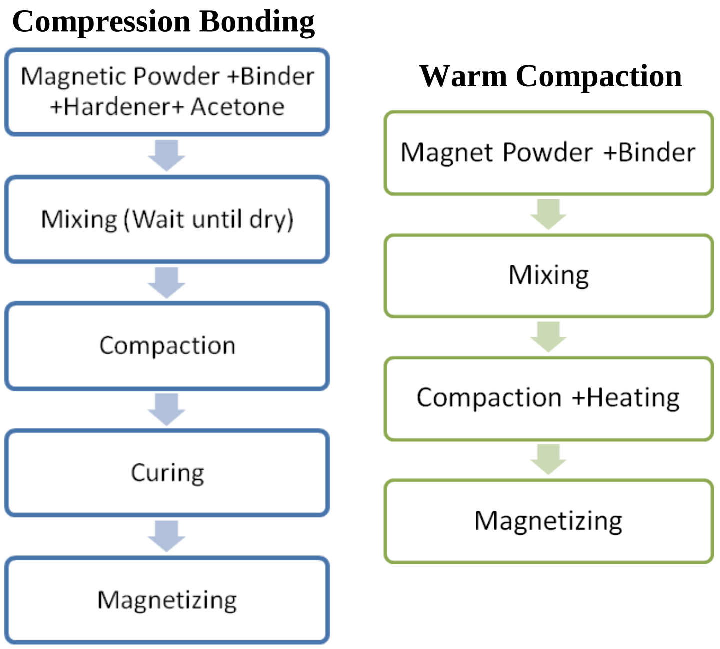


Figure 1.1: The Comparison Procedure between Compression Bonding and Warm Compaction Method.

CHAPTER 2

LITERATURE REVIEW

2.1 Permanent Magnet

A permanent magnet is made from a material that is magnetized and creates its own persistent magnetic field [5]. The four major families of permanent magnet are Neodymium – iron – boron (NdFeB), Samarium – cobalt (Sm – Co), Alnico and Hard Ferrite (Ceramic). Permanent magnetic materials are characterized by a broad magnetic hysteresis loop of high coercive force H_c and a high remanent magnetic induction B_r. Permanent magnetic materials are hard to demagnetize once magnetized. The demagnetizing curve for a permanent magnetic magnet is referred as the second quadrant of its hysteresis loop and can be used for comparing the strengths of permanent magnets [6].

The performance of a magnet is usually specified by its maximum energy product. The BH_{max} value is defined as the maximum when forming the product of the flux density B and the corresponding opposing field H for each point of the B-H curve in the second quadrant. The maximum energy product can be used to specify the quality of a permanent magnet material [2].

2.2 Neodymium-Iron-Boron

Neodymium – iron – boron magnet is one type of rare earth alloy that has two atoms of Neodymium (Nd), 14 atoms of Iron (Fe) and one atom of Boron (B). The chemical composition is $Nd_2Fe_{14}B$ but commonly abbreviated as NdFeB [7].

According to Croat , Nd-Fe-B powder is known as *melt spinning* or *rapid quenching.* An ingot of the required $Nd_2Fe_{14}B$ alloy is melted and forced under argon pressure through a small nozzle onto the surface of a water-cooled rotating metal wheel, producing a thin alloy ribbon [8].

In 1984, hard NdFeB magnetic materials with BH_{max} products as high as 300 kJ/m^3 (45 MGOe) were discovered [2]. Today, NdFeB are the strongest type of permanent magnet of its excellent magnetic properties [9]. NdFeB magnets can be formed by both pressing and sintering the powder or by bonding with plastic binders. NdFeB magnets are available in a number of different grades that span a wide range of properties and application requirements [10].

The application of NdFeB is limited by temperature due to its irreversible loss and moderately high reversible temperature coefficient of B_r and H_{ci}. The maximum application temperature is up to 200 °C for high coercivity grades [11].

2.2.1 Magnetic Properties of Magnets

Neodymium magnets have higher remanence, higher coercivity and energy product, but often have lower Curie temperature [9]. The high coercivity and energy product of NdFeB are resulted from the difficulty of nucleating reverse magnet domains that usually nucleate at the grain boundaries of the matrix grains. The intergranular nonferromagnetic Nd-rich phase forces the $Nd_2Fe_{14}B$ matrix grains to nucleate their reverse domains in order to reverse the magnetization of the material [6].

Shown in Table 2.1 is the Survey of several types of magnets and their room temperature characteristics and Curie temperatures by K.H.J. Buschow [2]

Table 2.1: Survey of several types of magnets and their room temperature characteristics and Curie temperatures [2]

Type of Magnet	T_c (°C)	$(BH)_{max}$ (Kj m^{-3})	B_r (T)	Db_r/Dt (%/deg)	${}_JH_c$ (kAm^{-1})
Sr-ferrite	450	7 – 37	0.20 – 0.44	-0.2	14-300 30-
Alcino	700 – 860	10 – 88	0.6 – 1.4	-0.02	275
Fe-Cr-Co		10 – 66	1.0 – 1.6	-0.03	26 – 51
$SmCo_5$	720	120 – 200	0.8 – 1.05	-0.04	600 – 2000
$Sm(Co,Fe,Cu,Zr)_7$	800	150 – 240	0.95 – 1.15	-0.03	450 – 1300
Nd-Fe-B	310	200 – 350	1.0 – 1.3	-0.13	750 – 1500

2.3 Bonded Neodymium-Iron Boron

Generally, bonded magnets are made from compacted high coercivity powders that are held together by non-magnetic binders such as epoxy, nylon and polyamides at an appropriate mixing ration in a mixer (Hadjipanayis, 2003)[1]. Based on the review articles of Croat on page 223, bonded NdFeB magnets are widely used in the application of computer peripherals, consumer electronics, office automation, automotive and other small appliances due to their superior intrinsic magnetic properties [2].

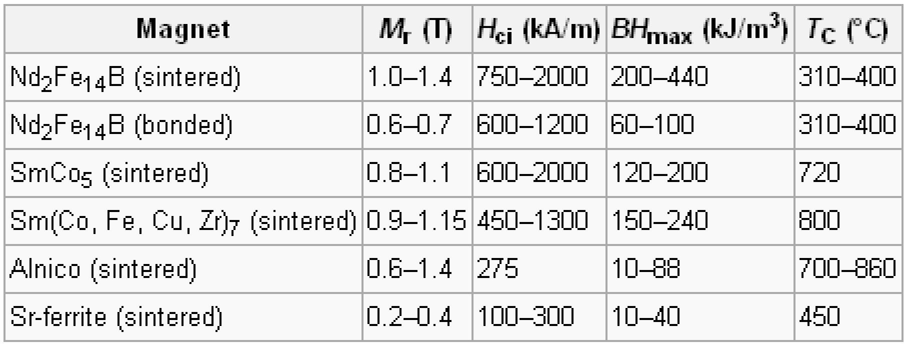
According to Peter Campbell, many of the fully dense permanent magnet materials, especially those that are sintered, are very hard and brittle, and machining them to their final shape is often tedious. This led to an interest in bonded magnets, which are made by consolidating a magnet powder with a powder matrix. While machining is easy, the production processes also frequently allow parts to be made directly to their final dimensions [8].

According to K.H.J Buschow, because of the presence of the binder the magnetic remanence is always lower than that of the fully dense magnetic material, as obtained for instance by sintering. There are, however, obvious advantages. The major advantage is that bonded magnets can be produced in net shape. Even fairly complicated shapes may be involved, as in injection molding. Another advantage is their superior mechanical properties [2].

Bonded NdFeB magnet has given the most important advantages including the cost effective net-shape manufacturing process, complex geometries can be produced, variety of selection on polymer binders which give the flexibility for production, meets the requirements of application, low weight and corrosion resistance [12, 13].

However, bonded NdFeB magnet has lower magnetic properties compared to sintered NdFeB magnet as shown in Table 2.2 below due to polymer dilution effect and limited maximum operating temperature because of the temperature characteristics of polymer binders [12].

Table 2.2: Magnetic performance between bonded NdFeB magnet and sintered magnets [9].



Magnet	M_r (T)	H_{ci} (kA/m)	BH_{max} (kJ/m^3)	T_C (°C)
$Nd_2Fe_{14}B$ (sintered)	1.0–1.4	750–2000	200–440	310–400
$Nd_2Fe_{14}B$ (bonded)	0.6–0.7	600–1200	60–100	310–400
$SmCo_5$ (sintered)	0.8–1.1	600–2000	120–200	720
$Sm(Co, Fe, Cu, Zr)_7$ (sintered)	0.9–1.15	450–1300	150–240	800
Alnico (sintered)	0.6–1.4	275	10–88	700–860
Sr-ferrite (sintered)	0.2–0.4	100–300	10–40	450

2.4 Manufacturing Method

K.H.J. Buschow had mentioned that bonded magnets are generally prepared by blending, coercive powder with a binder or by encapsulating coercive powder in a binder, followed by compacting or molding the material to the final shape. Depending on the binder, the magnets produced may be flexible or rigid [2]. There are four main manufacturing routes for bonded magnets:

2.4.1 Calendering

Calendering involves the processing of the material between rollers and leads to continuous strips of adjustable thickness and length. Magnetic loading can be up to 70% by volume [2].

2.4.2 Injection Molding

Injection molding involves forcing the heated mixture if magnetic powder and thermoplastic binder via tubes into a mold where it is allowed to cool and harden. Also in this case magnetic loading can become up to 70% [2].

2.4.3 Extrusion

Extrusion makes use of an orifice through which the compounded material is squeezed. During the extrusion process the orifice is heated and the profile is controlled as the compounded material cools. The magnetic loading can reach slightly higher values (up to 75% by volume) than calendering and injection molding [2].

2.4.4 Compression bonding

Compression bonding uses magnetic powder blended with an epoxy that has been liquefied by dissolution in an organic solvent. The latter is evaporated during the blending process, leaving the magnetic particles in an epoxy encapsulated state. After drying the coated powder is flowed into a conventional powder press and compacted into the desired shape. Finally, the compacted magnet is cured in an oven. Magnetic loadings up to 80% can be reached by this process [2]. However, due to the nature of pressing process, the basic shapes are limited [14].

Table 2.3: Comparison of the commonly used molding methods, polymer binders and basic physical characters and typical B_r and $(BH)_{max}$ of compression, injection, extrusion and calendering [4].

Molding Method	Polymer binder	Flexibility	B_r (mT)	$(BH)_{max}$ (kJ/m^3)	Typical fill ratio (vol %)	Allowable operation temperature (°C)	Remarks
Compression	Epoxy	Very rigid	620 - 720	45-85	70-85	180 or above	
Injection	Polymides 11 or 12 (Nylon)	Rigid	500 - 690	35-55	60-75	155	
Injection	Polyphenolyne sulfide (PPS)	Very rigid	420 - 600	27-48	51-65	180 or above	Brittle
Extrusion	Polyester	Flexible	500-630	40-55	50-70	150	Continuous magnets
Calendering	Ethylene copolymers (EAA/EEA), nitrile rubber, nordel or natsyn	Highly flexible	500-630	40-55	50-70	100	Flexible magnets or sheets magnets

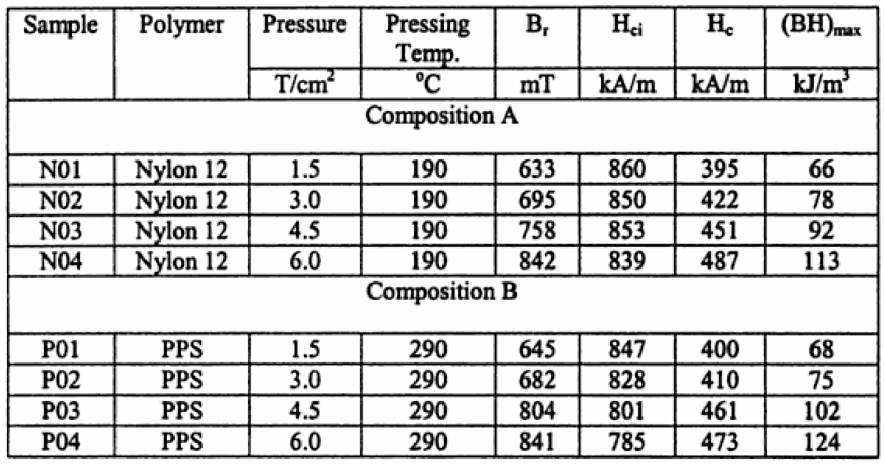
For this final year project, the study is more focused on compression bonding method as on the entire bonded magnet market, the bonded rare earth magnets accounted for about 42% of which 71. 5% are compression molded NdFeB magnets in 1999 [3, 12]. The study from Jinfang Liu et al was used an extruding machine to do compounding and hot compression molding can increase the density and magnetic properties of bonded rare earth magnets. However, there’s no high volume production using this process had been reported [3,12].

2.4.5 Hot compression Molding Process

In the study of process and magnetic properties of rare-earth bonded magnets by Jinfang Liu et al, a hot press was built at Electron Energy Corporation to do experiments on compression-molded magnets using thermoplastic and thermosetting resins. The hot press consists of a hydraulic press system, frames, a transverse magnetizing coil, a die with heaters, upper and lower punches, thermocouples, and a temperature controller [3, 12].

Accourding to Jinfang Liu et al, an extruder is used to make the compound consist with the composition of 96wt. % MQP-B, 0.2wt.% zinc stearate, 0.6wt. % antioxidant and 3.2wt. % Nylon 12. Then, the compound was granulated and fed into the die cavity. It was then compression molded under various pressures at 25, 120 and 210°C, respectively. It was found that hot compression molding of the composition at 210°C could produce samples with a density of 5.7 g/cm^3 using only 1 t/cm^2 pressure. By comparison, the pressing force would need to be at least 8 t/cm^2 if pressing at room temperature. The result shows that pressing at 120°C does not have a significant effect on density, because 120°C is below the melting point of Nylon 12. When the samples were pressed at 210°C, the nylon binder melted and flowed easily even under a low pressure. Below is the comparison of magnetic properties between NdFeB-Nylon 12 bonded magnet and NdFeB-Polyphenylene sulfide (PPS) bonded magnet [3,12].

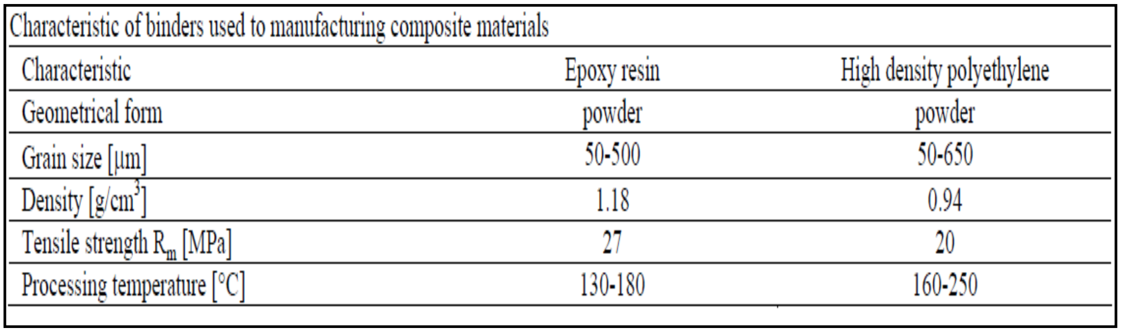
Table 2.4: Magnetic Properties of polymer bonded anisotropic NdFeB magnets by hot pressing [12]



Sample	Polymer	Pressure	Pressing Temp.	B_r	H_{ci}	H_c	$(BH)_{max}$
		T/cm^2	°C	mT	kA/m	kA/m	kJ/m^3
Composition A							
N01	Nylon 12	1.5	190	633	860	395	66
N02	Nylon 12	3.0	190	695	850	422	78
N03	Nylon 12	4.5	190	758	853	451	92
N04	Nylon 12	6.0	190	842	839	487	113
Composition B							
P01	PPS	1.5	290	645	847	400	68
P02	PPS	3.0	290	682	828	410	75
P03	PPS	4.5	290	804	801	461	102
P04	PPS	6.0	290	841	785	473	124

In the study of Manufacturing of hard magnetic composite materials Nd-Fe-B by M.Drak et al, the experiments were made with the polymer matrix magnetic composite materials reinforced with particles of the powdered rapid quenched NdFeB strip bonded with thermosetting epoxy resin (EP) and with the high density pressureless polyethylene (PEHD). The amount of polymer matrix was 2.5 wt%. Advanced composite materials were compacted by the one-sided uniaxial pressing. The cold pressing NdFeB-EP was pressed under the pressure 900Mpa at room temperature for 5 minutes and then being cured for 2 hours at 180°C after compacting. While for hot pressing NdFeB-PEHD was prepressed at room temperature under the pressure of 50Mpa for 1 minute and hot pressed for 3 minutes at 180°C under the pressure 350 Mpa. In Table 5 shows the characteristic of binder used to manufacturing composite materials between epoxy resin and high density polyethylene. The density of composite material NdFeB-PEHD is equal to 66.5% of theoretical density while for composite material NdFeB- EP is observed even higher value which is 75% of theoretical density. The density of composite materials depends on the pressing pressure, the higher the pressure the higher the ratio of density to theoretical density [15].

Table 2.5: Characteristic of binders used to manufacturing composite materials [15].



Characteristic of binders used to manufacturing composite materials

Characteristic	Epoxy resin	High density polyethylene
Geometrical form	powder	powder
Grain size [µm]	50-500	50-650
Density [g/cm^3]	1.18	0.94
Tensile strength R_m [MPa]	27	20
Processing temperature [°C]	130-180	160-250

2.5 Factors Affecting the Mechanical and Magnetic Properties of Bonded Magnet

2.5.1 Effect of Polymer Binder Composition in Bonded Magnet

According to M. Drak et al, the portion of the polymer matrix affects the mechanical and magnetic properties of the manufactured composite materials. The mechanical properties of the composite magnets depend mostly on the magnetic powder and binding agent types and on the technology employed. The portion of the polymer matrix affects the mechanical and magnetic properties of the manufactured composite materials. The mechanical properties increase along with the increasing portion of resin in the matrix but this increase has a negative effect on the magnetic properties. Usually the 2.5 – 3.0% mass portion is assumed [15,16].

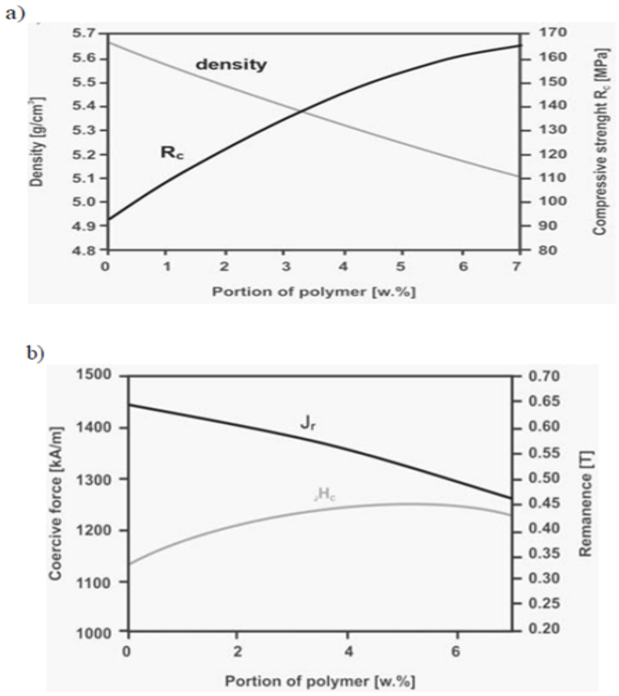


Figure 2.2: Influence of the portion of polymer matrix on: a) mechanical properties of composite materials, b)magnetic properties of composite materials [15,16]

According to Peter Campbell, the major drawback to bonded magnets is the reduction in their magnetic properties, relative to those that are 100% dense with magnetic material [8]. Hopstock says that the remanence, B_r, of a bonded magnet is reduced from that of its fully dense magnetic material [8].

According to Ishii et al, the resin-bonded type of magnets has a number of advantages over the sintered-type magnet, including a higher degree of dimensional accuracy even when made in a complicated shape, a higher degree of uniformity in quality and performance and a higher yield and a higher degree of machinability. However, resin-bonded type magnet has a relatively low density of magnetic material and its magnetic properties decrease in proportion to the amount of resin used as a binder. In order to obtain a resin bonded magnet of improved magnetic properties, it is necessary to minimize the amount of resin which is used to bind the magnetic powder containing the rare earth element. It is, however, also necessary ensure the high adhesive property, heat resistance and mechanical strength [17].

2.5.2 Effect on using wet binder on bonded magnet

According to Ishii et al, a thermosetting, thermoplastic or rubber-like resin has been used as a binder for making a resin bonded magnet. The thermoplastic and rubber-like resins are used mainly when magnets are made by injection or extrusion molding. The injection or extrusion molding, however, requires the use of large amount of resin that other molding does. The molded product has a low packing density of magnetic material and therefore, low magnetic properties. It has been considered that the requirements which have been stated can be satisfied by a magnet made by compression molding employing a thermosetting resin, particularly an epoxy resin. An epoxy resin is usually employed with a curing agent and exhibits excellent mechanical and adhesive properties. These properties have made epoxy resins useful to be used for making a resin bonded magnet. Many of the epoxy resins are, however, in the form of a liquid. When a liquid resin is used as a binder for magnetic powder, it forms secondary particles with powder, even if it is used only in a small quantity. The formation of secondary particles makes it difficult to satisfactorily supply a mixture of resin and powder into a mold for compression molding. The secondary particles are likely to form bridges in the mold, resulting in a lack of uniformity in pressure across the mold and thereby a lack of uniformity in quality of the molded products and a breakage of the mold [17].

Other than that, wet binder has influence the fabrication time for bonded magnet. According to P.Hussain et al, the magnets with diameter of 12mm and thickness of 4 mm were cured in an oven at about 150˚C for 1 hour [18]. Furthermore, according to Syahidatulmazidah Ismail , the sample of bonded NdFeB magnet was cured in an oven for 4 hours at 65˚C [24] and follow up with Muhammad Ikhbar Md Ismail, the sample of bonded NdFeB magnet in his study was cured in an oven for 1 hour at 150˚C [25].

2.5.3 Effect of compaction pressure on bonded magnet

M. Drak et al say that the density of composite materials depends on the pressing pressure, the higher the pressure the higher the ratio of density to theoretical density [15,16]. It is proven when the composite material Nd-Fe-B with the high density pressureless polyethylene (PEHD) being compressed under the pressure of 350 Mpa, the density is equal to 66.5% of theoretical density while for composite material Nd-Fe-B with epoxy resin under the pressure of 900 Mpa, the density is observed even higher value which is 75% of theoretical density [15].

In the study of fabrication of pressureless made polymer bonded NdFeB magnet and its magnetic and physical properties in comparison to compacted bonded magnet and ferrite magnet, P. Hussain et al had mentioned in the results that in compacted bonded magnet NdFeB, epoxy binders are well distributed among the particles of the powder while for pressureless bonded, the gaps in between the particles are narrower resulting in the pressureless bonded magnet has lower properties than the compacted bonded magnet. In the study, the properties of the pressureless bonded magnet were also compared with ferrite magnet, resulting that the fabricated pressureless bonded magnet has superior magnetic properties. Therefore, in the case of selecting magnetic materials having similar properties to ferrite magnet, pressureless bonded magnet could be considered for the materials selection [18].

Then in the study of further work on fabrication of pressureless made polymer bonded NdFeB magnet using epoxy resin toughened with reactive liquid natural rubber as the binding material by Patthi et al, the result shows that the magnetic properties of the pressureless bonded magnet NdFeB magnet using toughened epoxy resin as a binder exhibits superior magnetic and physical properties to that of its counterpart, the pressureless bonded NdFeB magnet using conventional epoxy resin binding material and to that of the ferrite magnet. Nevertheless, these properties are comparably lower to that of the compacted NdFeB permanent magnet [19].

Zhang et al had mentioned in the research of warm compaction technology on nylon bonded Nd-Fe-B magnets, the density of magnet increased with the increase of compaction pressure, which resulted in the increase of B_r, H_{cb} and $(BH)_{max}$ of magnet and the decrease of H_{cj} of magnet [20].

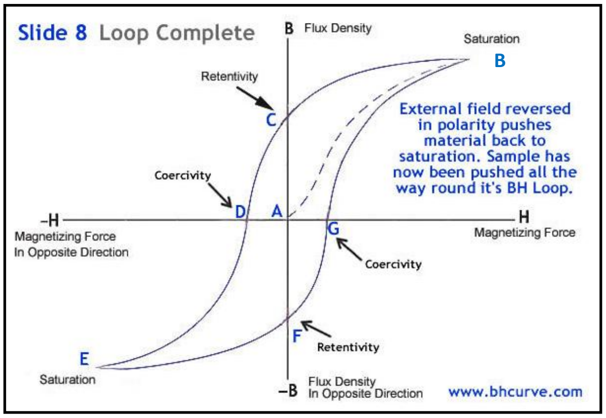
2.5.4 Effect of warm compaction temperature on bonded magnet

The temperature increased resulting in the enhancement of the density [21]. Wei et al have proved in their study that the increment of density is considered due to the decrease of the binder viscosity. When the binder viscosity decreases, the friction among the powders or between the powder and the mold is reduced. So the mixture and the binder is easily compressed and as a result, the density is improved [21].

According to Zhang et al, the density of the magnet increased a lot when the warm compaction temperature changed from 25ºC (room temperature) to 160ºC. The density increased a little when the warm compaction temperature changed from 160ºC to 190ºC. The density increased no more when the warm compaction temperature changed from 190ºC to 200ºC. Nylon is a kind of solid powder at room temperature. So the friction resistance at room temperature, which is among powders and between powders and die wall, are higher than those at warm temperature. With the increase of warm compaction temperature, nylon becomes softened and the friction resistance decrease, which makes the density of the sample increase. When the warm compaction temperature was above the melting point, the fluidity of nylon was very good. Hence, the densities of the magnets remained almost invariable when the warm compaction temperature changed from 190ºC to 200ºC [20].

Furthermore, Jinfang Liu et al had claimed that hot compression molding offers some advantages over the conventional compression molding process. Higher density can be achieved by hot compression molding due to the improved flow ability of the polymers. For bonded magnets using some of the thermosetting resins as binders, a separate curing process may not be needed [12].

2.6 Theory of Magnetism



External field reversed in polarity pushes material back to saturation. Sample has now been pushed all the way round it's BH Loop.

Figure 2.3: Hysteresis Loop or B-H Curve [16]

A hysteresis loop or known as B-H Curve is a closed curve obtained by plotting a graph of the magnetic induction of a ferromagnetic substance against the external magnetic field.The shape of the curve will describe the characteristic of the magnetic properties of the material and shows the ease to magnetize and the ability to retain magnetization [14].

The zero net magnetism at point A of a ferromagnetic sample is influenced by an external magnetic field. The externally applied field strength is increased until the sample material is saturated. As upon the influence of the external field is start to decrease until completely removed from point B, some residual magnetism remains in the sample which is referred as retentivity (point C). In order to bring the sample back to zero (point of coercivity) on the H axis, a reversal of the polarity of the external field is required. If the reversal applied field is still increased, the material will reach saturation induction which is in point E. When the reverse field is removed, the magnetic induction will return to the remanent induction as shown at point F. To complete the loop, a positive applied field would follow the FGA curve. The point C and D at the second quadrant of the B-H curve which referred as the demagnetizing curve displays the magnetic properties as the magnet performs work, thus the approximation of the magnetic output can be determined [6,22,23].

CHAPTER 3

METHODOLOGY

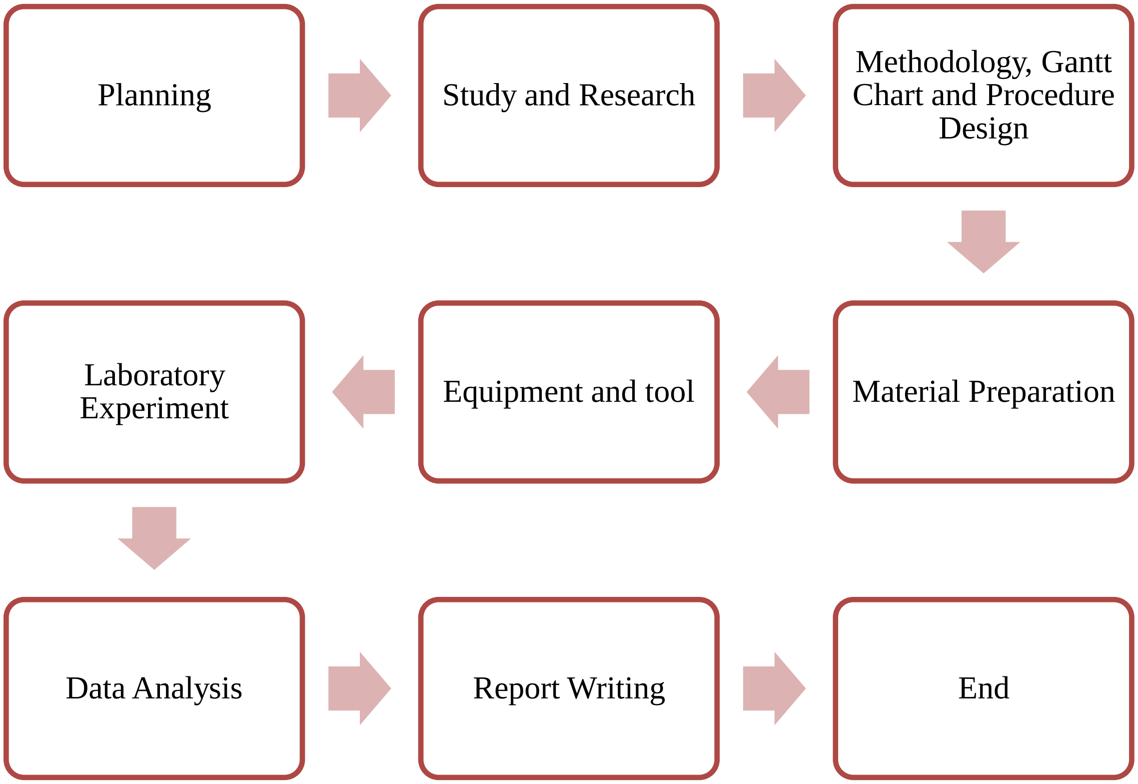


Figure 3.4: Final Year Project Process Flow

Figure 3.4 shows the final year project process flow for Fabrication-Neodymium-Iron (NdFeB) Permanent Magnet through Warm Compaction. The details were described more in the chapter onwards.

3.1 Planning

The planning preparation on the project work had been conducted on the early week after confirmation of project title by the Mechanical Engineering Department Coordinator. The work plans for Final Year Project I and Final Year Project II were discussed with the supervisor so that all the activities involved in this project could be complete within the timeframe.

3.2 Study and Research

The study and research related on the project work were obtained from online articles, magnet supplier official websites, journals and other related books. The focus on the research were on the Neodymium –iron- boron magnet background, the magnetic and physical properties of the magnet, type of manufacturing of the bonded magnet, advantages and disadvantages of bonded magnet and effect of polymer binder compositions, wet binder, compaction pressure and warm compaction temperature.

3.3 Methodology, Gantt chart and Experimental Procedure Design

By referring to Figure 3.4, Methodology, Gantt chart and experimental procedure are designed after browsing information on related topics. The Gantt chart of this project can be referred to Appendix A and B.

3.4 Material Preparation

Warm compacted bonded NdFeB magnets were fabricated using melt-spun ribbon NdFeB magnetic powder and mixed with polymeric binder. Phenolic used as the polymeric binder and later the mechanical and magnetic properties are examined.

3.5 Equipment and Tools

The required equipments for the warm compression method is automatic mounting machine while for analyzing the bonded NdFeB magnet magnetic properties are optical microscope, vibrating sample magnetometer (VSM) and scanning electron microscope (SEM).

- Automatic Mounting Machine is the tool for the warm compaction method where the mixture of NdFeB melt spun ribbon and polymeric binder are placed in the mounting press and being compress in heat and high pressure.
- Optical Microscope is used to study the micro structural properties of the materials.
- Scanning Electron Microscope (SEM) is one of electron microscope that images the sample surface by scanning it with a high-energy beam of electrons in a raster scan pattern. In analyzing the magnetic properties, SEM is used to examine the cross sectional microstructures of the samples/ specimens [12].
- Vibrating Sample Magnetometer (VSM) is a type of scientific instrument that measures magnetic properties. A sample is placed inside a uniform magnetic field to magnetize the sample. The sample is then physically vibrated sinusoidally, typically through the use of a piezoelectric material [13]. The magnetic moment of the sample is detected by pickup coils near the vibrating sample in an adjustable applied magnetic field. The basic requirements on using

VSM are the sample weight and density must be known [25]. The VSM is located at AMREC, SIRIM, Kulim Kedah.

- Balancer is used to measure the weight of the powders and also the sample magnet. The density of bonded magnet sample can be obtained by measuring the diameter, thickness and weight of the bonded magnet sample. The procedure in calculate the density can be refer in Appendix C.

3.6 Experimental Procedure

i. Effect of Polymer Binder Composition in Bonded Magnet

1. The NdFeB and phenolic were weight as below and mixed together until homogeneous mixture was achieved.

Table 3.6: Details on the Sample of Bonded Magnet

Powder	NdFeB		Powder	
No	Wt %	Weight (g)	Wt %	Weight (g)
1	98.0	9.80	2.0	0.20
2	97.5	9.75	2.5	0.25
3	97.0	9.70	3.0	0.30
4	96.5	9.65	3.5	0.35
5	96.0	9.60	4.0	0.40
6	95.5	9.55	4.5	0.45
7	95.0	9.50	5.0	0.50
8	90.0	9.00	10.0	1.00
9	80.0	8.00	20.0	2.00
10	70.0	7.00	30.0	3.00
11	65.0	6.50	35.0	3.50

2. The mixture was then compressed using automatic mounting machine. The compression load was 28MPa and simultaneously, heat was applied at 170°C (350°F) for 10 minutes.
3. The dimension and weight of each sample was measured to calculate the density of the samples.

ii. Effect of warm compaction temperature on bonded magnet

1. The NdFeB and phenolic were weight as below and mixed together until homogeneous mixture was achieved.

Table 3.7: Detail on the Sample of Bonded Magnet

NdFeB		Powder	
Wt %	Weight (g)	Wt %	Weight (g)
95.0	9.50	5.0	0.50

2. The mixture was then compressed using automatic mounting machine. The compression load was 28 MPa and simultaneously, heat was applied at 148°C (300°F) for 10 minutes.
3. The dimension and weight of each sample was measured to calculate the density of the samples.
4. Repeat Step 1-3 and apply heat at 170°C (350°F).

3.7 Data Analysis

In this project, there were 3 types of analysis which was getting the density, bonded magnet sample microstructure and finally the magnetic properties testing. The details of the laboratory equipment used for every testing are as below:

Table 3.8: Details on the laboratory equipment used for the data analysis

Data Analysis	**Laboratory Equipment**	**Location**
Density	Balancer	UTP
Bonded Magnet Sample Microstructure	Optical Microscope	UTP
	Scanning Electron Microscope	UTP
Magnetic Properties Analysis	Vibrating Sample Magnetometer	AMREC, SIRIM

3.7.1 Density

The thickness, diameter and weight of every sample were taken in order to get its density under the experiment of effect of polymer binder composition in bonded magnet and effect of warm compaction temperature on bonded magnet

3.7.2 Bonded Magnet Sample Microstructure

The bonded magnet sample microstructure analysis was carried out at Universiti Teknologi PETRONAS using the optical microstructure and scanning electron microscope.

For scanning electron microscope, four samples including melt spun ribbon neodymium-iron-boron powder are taken out in order to analyze its microstructure.

Below are the details of the three samples of bonded magnet.

Table 3.9: Detail on the parameters used for every sample

Sample Name	Sample Detail	
	NdFeB: Phenolic Ratio	Temperature (˚C)
Sample A	95:5	170
Sample B	96.5:3.5	170
Sample C	95:5	148

3.7.3 Magnetic Properties Analysis

The samples magnetic properties analysis consist of Sample A, B and C were carried out at Advanced Materials Research Centre (AMREC) in Kulim, Kedah. The sample was magnetized at applied magnetic field up to 26 kOe.

CHAPTER 4

RESULT AND DISCUSSION

4. DATA ANALYSIS

Manufacturing of composite materials by warm compaction method with polymer materials is a simple and not costly method taking into consideration low cost of polymer material and simplicity of their manufacturing [15]. This chapter will discuss about the results achieved from the magnetic properties analysis done on the warm compaction NdFeB-Phenolic bonded magnet samples.

4.1 Densities of magnets

In order to get analyze the magnetic property of NdFeB-Phenolic bonded magnet, the density of each magnet were determined and every magnet microstructure were obtained by using optical microscope and scanning electron microscope.

4.1.1 Density on the effect of polymer binder composition in bonded magnet

The density of magnets has an important influence on the property of the magnet especially in determine the value of magnetic induction, B_r and maximum energy product, BH_{max}. In order to get the density of phenolic-NdFeB bonded magnet, the thickness, diameter and the weight of every sample had to be measured, and then calculate them by using the equation in Appendix C. The raw data on density for

NdFeB-Phenolic bonded magnet are shown in Table 4.10(a) and 4.10(b) in Appendix D.

The density of sample has an important influence on the property of the magnet. The higher the density of sample, the better the property of the magnet was.

Based on Figure 4.5, the densities of the samples are decreasing with the increasing on portion of phenolic. Theoretically, the density of bonded magnet will decrease with the increasing on portion of polymer at fixed compression load.

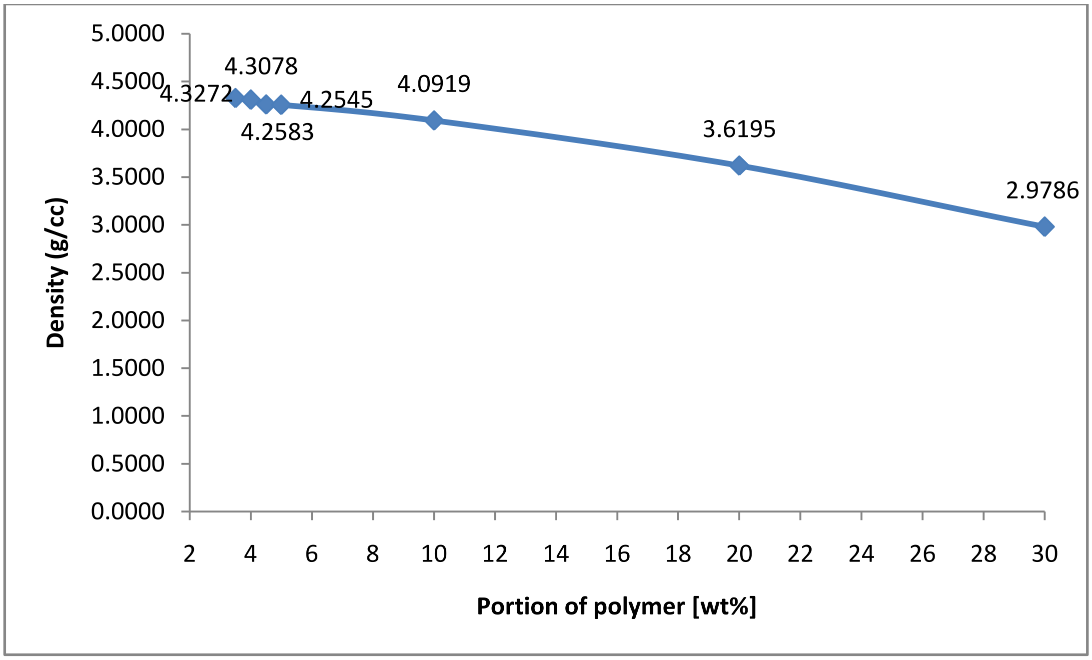


Figure 4.5: Density of bonded NdFeB versus portion of polymer

4.1.2 Density on the effect of warm compaction temperature on bonded magnet

Heated and compacted at 148°C, the density recorded was 4.2399 g/cc and for bonded magnet heated at 170˚C, the density recorded was 4.2545 g/cc. The density of the magnet increased about 0.343% when the warm compaction temperature changed from 148°C to 170°C. With the increased of warm compaction temperature, the friction resistances at room temperature, which are among powders and between powders and between powders and die wall become decreasing as the phenolic become softened which makes the density of the sample increase. It can be concluded that the fluidity of phenolic is very good at 170°C compared to the warm compaction temperature of 148°C, however, further evidence cannot be given due to the restriction of this experimental condition and further studies are still needed to clarify this hypothesis.

The expected result can be referred on the result obtain by Zhang et al from their study entitled the *Research of warm compaction technology on nylon bonded Nd-Fe-B magnets* [20]

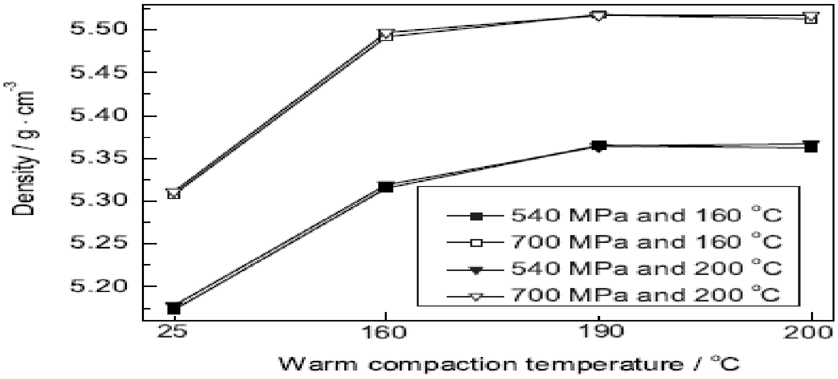


Figure 4.6: Influence of warm compaction temperature, compaction pressure (540 and 700 MPa) and thermosetting temperature (160 and 200˚C) on the densities of magnets [20].

The coupled magnetic powders were mixed uniformly with nylon11 powder and then were compressed to cubic samples at different pressure. Then, the samples were thermoformed for two hours at different thermosetting temperatures.

4.2 Metallography Analysis

Scanning Electron Microscopy (SEM) was used to examine the surfaces and gain insight into the cross section of warm compaction bonded NdFeB magnets. The melt spun ribbon NdFeB powder was observed under the SEM at the magnification of 50x and 500x and these are depicted in Figure 4.7 and Figure 4.8. The micrograph shows that the melt spun ribbon NdFeB powder having particle size of approximately 200µm.

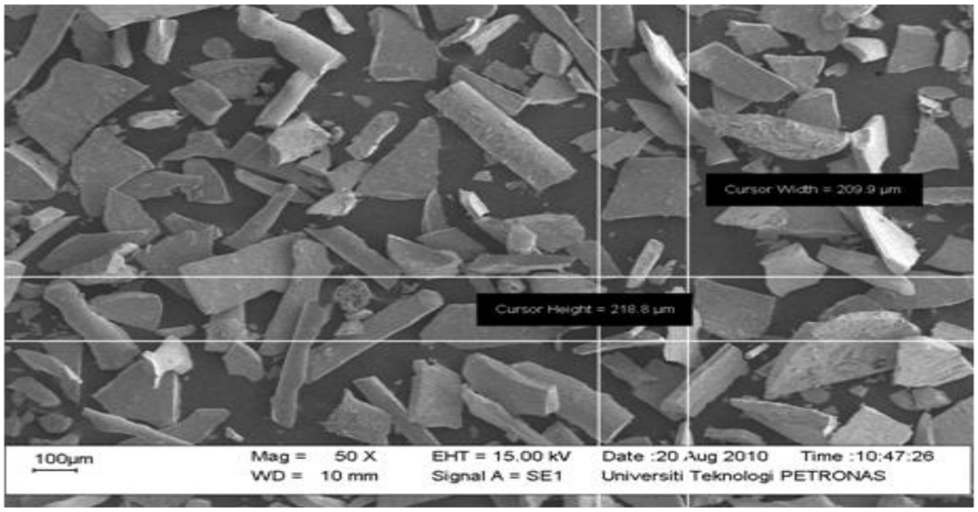


Figure 4.7: SEM image of melt spun ribbon NdFeB at Magnification of 50 X

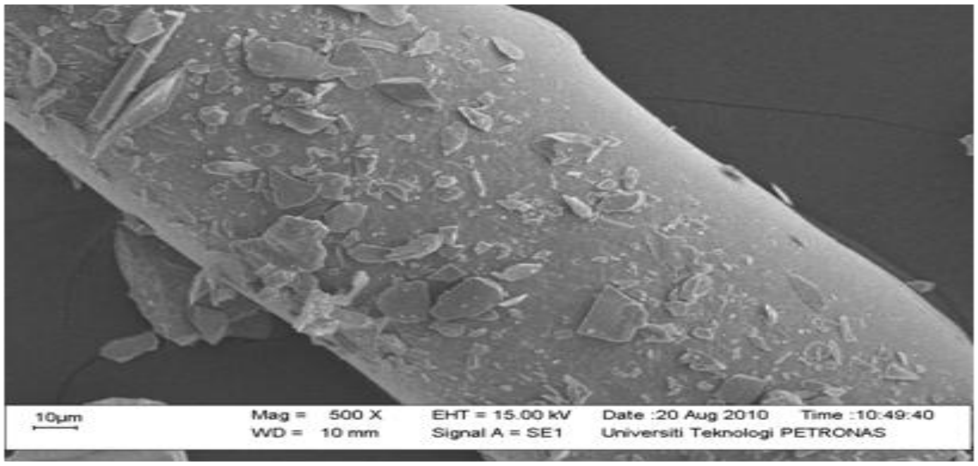
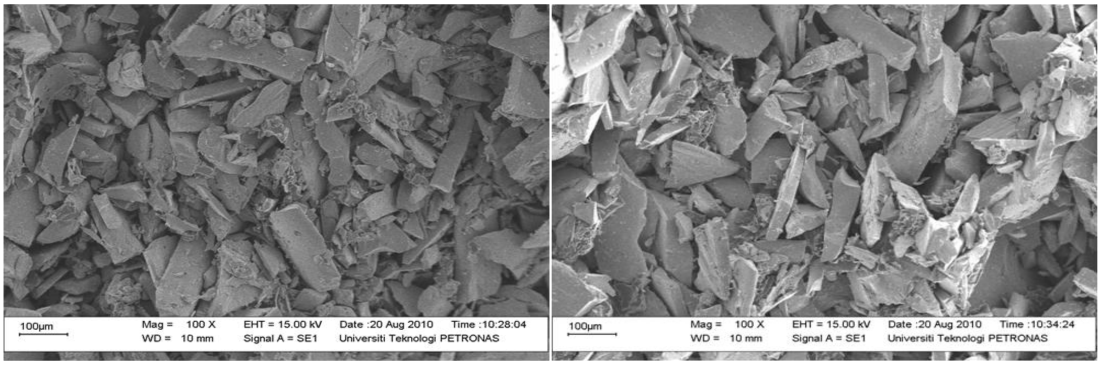


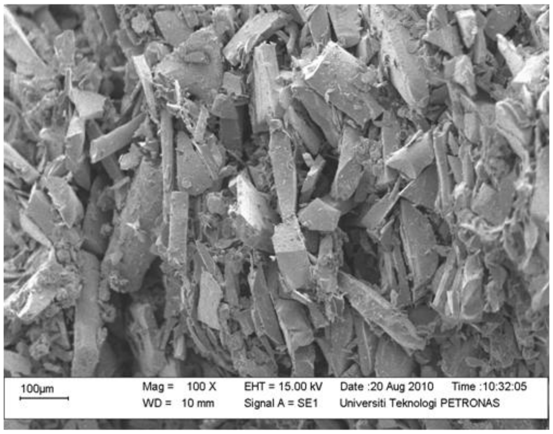
Figure 4.8: SEM image of melt spun ribbon NdFeB at Magnification of 500X

Figure 4.9 shows the image on the cross section of bonded NdFeB magnet generated by the SEM using the magnification of 100x on three samples which were warm compacted bonded magnet heated at 170˚C with the portion of phenolic at 3.5 wt% and 5 wt% and also for the sample heated at 148˚C with the portion of phenolic at 5 wt%. As can be seen from Figure 4.9(a), (b) and (c), pores exist in the images. This might happened due to the uneven stress distribution during compression as well as heat-shock where the heating were done simultaneously with the compaction.



(a) 5 wt% of phenolic heated at 170°C

(b) 3.5 wt% of phenolic heated at 170˚C

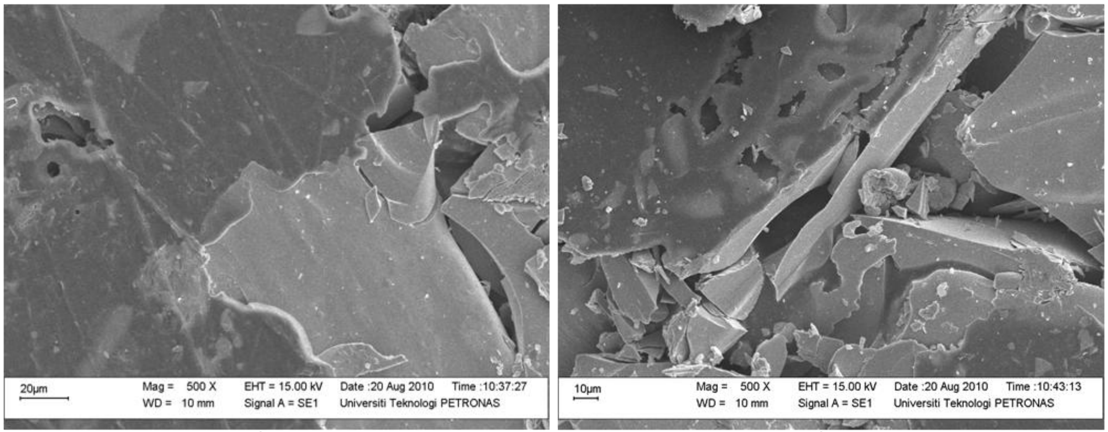


(c) 5 wt% of phenolic heated at 148°C

Figure 4.9: SEM image of cross section of bonded NdFeB magnet

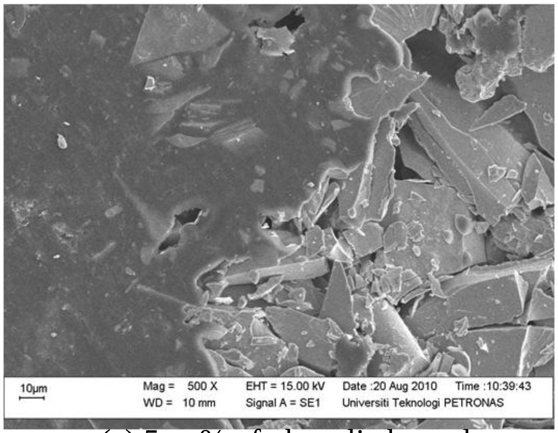
Figure 4.10 shows the image on the surface of bonded NdFeB magnet generated by the SEM using the magnification of 500x on three samples which were warm compacted bonded magnet heated at 170˚C with the portion of phenolic at 3.5 wt% and 5 wt% and also for the sample heated at 148˚C with the portion of phenolic at 5 wt%.

Based on the Figure 4.10(a), (b) and (c), few crannies can be seen. This can be result of debonding occuring between the phenolic and NdFeB powder, as the powders are not firmly bonded. Furthermore, the surface distribution are not even might be due to the mixture of phenolic and NdFeB powder are not well-achieved.



(a) 5 wt% of phenolic heated at 170°C

(b) 3.5 wt% of phenolic heated at 170˚C



(c) 5 wt% of phenolic heated at 148°C

Figure 4.10: SEM image of surface of bonded NdFeB magnet

The presence of elements in the sample magnet cannot be revealed using SEM with EDAX because of the technical problem. However, it still can be assumed that neodymium, iron and boron appear in the melt spun ribbon magnet.

4.3 Magnetic Properties

The hysteresis loop measurements were done at AMREC, Sirim at Kulim, Kedah for three samples which were warm compacted bonded magnet heated at 170˚C with the portion of phenolic at 3.5 wt% and 5 wt% and also for the sample heated at 148˚C with the portion of phenolic at 5 wt%. These results were calculated from the values obtained from the hysteresis loops of magnetic field perpendicular to the surface of the samples, measured by a Vibrating Sample Magnetometer (VSM) and these are shown in Figure 4.11, 4.12 and 4.13. A summary of the magnetic properties are given in Table 4.12.

Figure 4.11 below shows the hysteresis loop for three samples of warm compacted bonded magnet. The warm compacted bonded magnet heated at 170˚C with 5 wt% of phenolic can achieve coercivity, H_c of 8.25 kOe; a saturation magnetization, M_s of 93.97 emu/g; a remnant magnetization, M_r of 63.13 emu/g and a BH_{max} of 2.1 MGOe. The warm compacted bonded magnet heated at 170˚C with 3.5 wt% of phenolic can achieve coercivity, H_c of 7.74 kOe; a saturation magnetization, M_s of 72.94 emu/g; a remnant magnetization, M_r of 46.81 emu/g and a BH_{max} of 1.24 MGOe. The warm compacted bonded magnet heated at 148˚C with 5 wt% of phenolic can achieve coercivity, H_c of 8.11 kOe; a saturation magnetization, M_s of 83.68 emu/g; a remnant magnetization, M_r of 55.32 emu/g and a BH_{max} of 1.61 MGOe.

From the hysteresis loop, it is clear that the warm compaction bonded magnet with 5 wt% of phenolic heated at 170˚C has better magnetic properties compare to the sample heated at 170˚C with 3.5 wt% of phenolic. From the result achieved, we can say that the bonded magnet not necessarily will have better magnetic properties by having lesser portion of polymer as what we can refer to the statement of Ishii et al mentioning that in order to obtain a resin bonded magnet of improved magnetic properties, it is necessary to minimize the amount of resin which is used to bind the magnetic powder containing the rare earth element [17]. The bonded magnet with 5wt% of phenolic exhibits better magnetic properties because of the occurrence of the low portion of pores which is confirmed by examinations on the scanning electron microscope. Furthermore, based on the study by Drak et al, the portion of polymer affects the mechanical properties and magnetic properties of the manufactured composite materials [15]. According to Figure 2.2, the density of bonded magnet is decreasing as the portion of polymer increase. However, for the magnetic properties, the coercive force is increasing when the portion of polymer increase until it reaches approximately about 5 wt% of polymer before it starts to decrease.

The results achieved by this article has the similarity with this study as the portion of polymer increase, the density of bonded magnet decreasing and the coercive force is higher for 5 wt% of phenolic compare to 3.5 wt% of phenolic heated at 170˚C

Under the effect of warm compaction temperature, the warm compaction bonded magnet with 5 wt% of phenolic heated at 170˚C has better magnetic properties compare to the warm compacted bonded magnet with 5 wt% of phenolic heated at 148˚C. The BH_{max} of bonded magnet heated at 170˚C is 23.8 % higher compare to bonded magnet heated at 148˚C. The warm compaction temperature has given the positive influence on the magnetic properties of bonded magnet and it can be concluded that the fluidity of phenolic at 170˚C is very good compared to the warm compaction temperature at 148˚C.

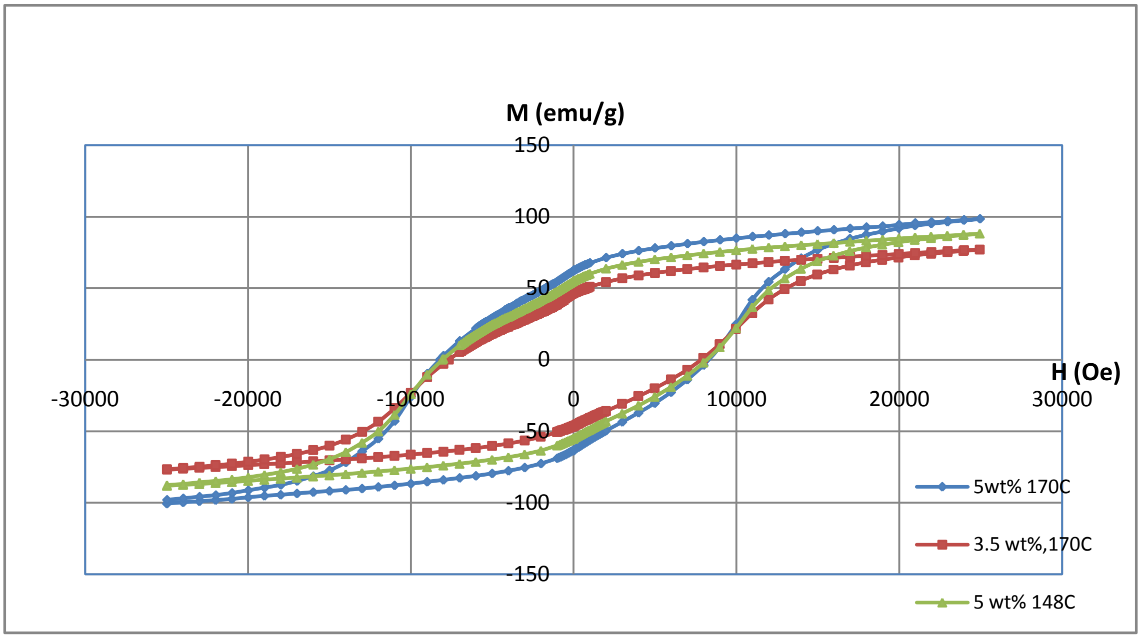


Figure 4.11: Hysteresis Loop for warm compacted magnet heated at 170˚C with the portion of phenolic at 3.5 wt% and 5 wt% and warm compacted magnet heated at 148˚C with the portion of phenolic at 5 wt%.

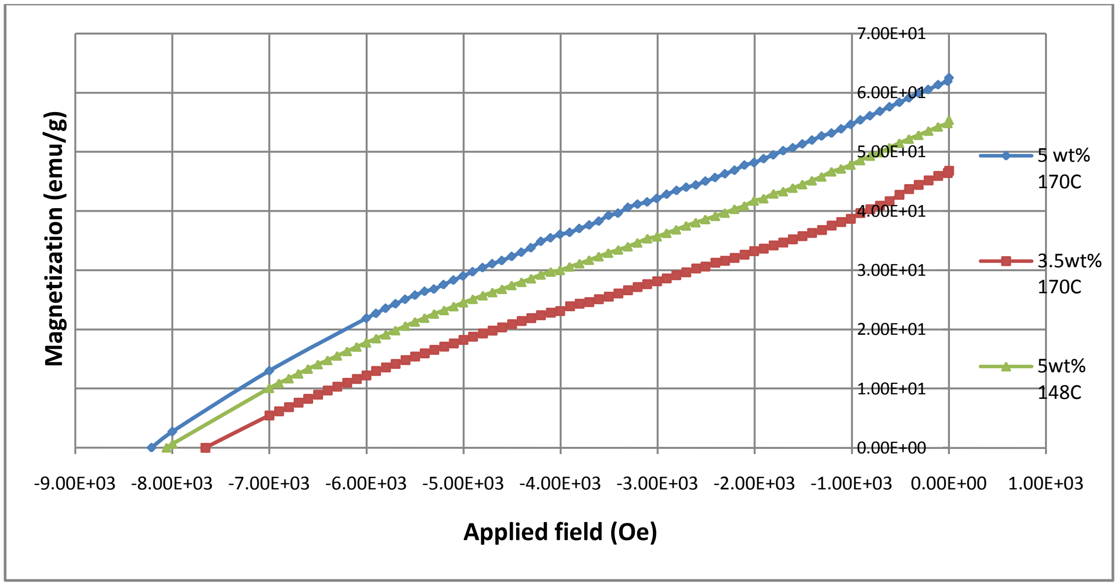


Figure 4.12: Demagnetization curve for warm compacted magnet heated at 170˚C with the portion of phenolic at 3.5 wt% and 5 wt% and warm compacted magnet heated at 148˚C with the portion of phenolic at 5 wt%.

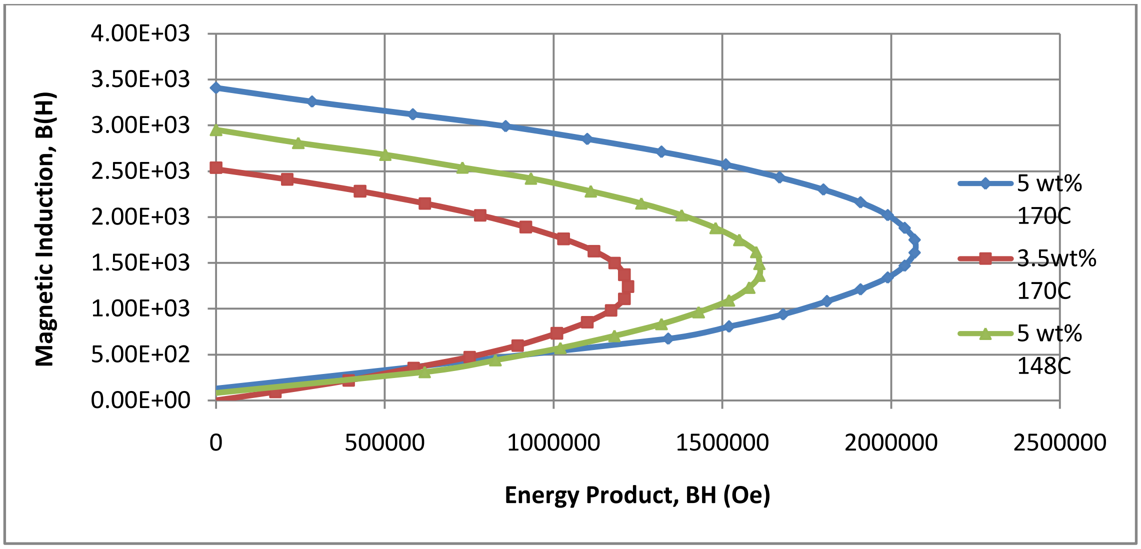


Figure 4.13: Energy Product against Magnetic Induction for warm compacted magnet heated at 170˚C with the portion of phenolic at 3.5 wt% and 5 wt% and warm compacted magnet heated at 148˚C with the portion of phenolic at 5 wt%.

Table 4.12: Magnetic Properties of the samples used in this work; H_c = coercive field, M_s= saturation magnetization, M_r= remanent magnetization, BH_{max}= maximum energy product, ρ= density

Material	H_c (kOe)	M_s (emu/g)	M_r (emu/g)	BH_{max} (MGOe)	ρ (g/cm^3)
NdFeB 5wt% 170°C	8.25	93.97	63.13	2.1	4.26
NdFeB 5wt% 148°C	8.11	83.68	55.32	1.61	4.24
NdFeB 3.5wt% 170°C	7.74	72.94	46.81	1.24	4.32

4.4 Comparison of magnet properties between compacted bonded magnet, warm compacted magnet and ferrite magnet.

Hussain et al have studied the properties of compacted bonded magnet and ferrite magnet [18, 19]. Among their studies, the best properties of magnet are shown in Table 4.13.

Table 4.13: Comparison of magnet properties between compacted NdFeb bonded magnet, warm compacted magnet and ferrite magnet.

Material	Binder: magnet ratio	H_c (kOe)	M_s (emu/g)	M_r (emu/g)	ρ (g/cm^3)
Compacted NdFeB Bonded Magnet	5:95	8.25	108.2	70.62	6.12
Warm compacted NdFeB Bonded magnet (Sample A)	5:95	8.25	93.97	63.13	4.26
Ferrite Magnet	-	1.851	69.49	35.69	5.27

In this article, the powder/epoxy/hardener mixtures were compressed by using a hand press machine under the pressure of 430 MPa and the binder content of compacted NdFeB bonded magnet was 5wt%. The properties of the compacted bonded magnet were also compared with ferrite magnet. Therefore, ferrite magnet from a motor was analyzed to obtain its magnetic and physical properties. Compare to warm compacted bonded magnet, the binder content was similar and the compaction pressure for warm compaction was about 28 MPa. These factors resulted in all of the magnetic properties of compacted bonded magnet being better compared to warm compacted bonded magnet. However, warm compacted bonded magnet has superior magnetic properties when comparing to ferrite magnet. The warm compaction bonded magnet could be a relevant option to be chosen for the manufacture of magnetic parts and to be used in many fields when the requirements of magnetic properties were higher compare to ferrite and the geometries of products were simple.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

From this study, the density of bonded magnet decreased with the increasing on portion of polymer at fixed compression load and thus, might be given the negative effect to the magnetic properties. However, it is the other way around when it comes to the magnetic analysis using VSM, where it was found that the magnet using phenolic binder at 5 wt% heated at 170°C has higher magnetic properties compare to the sample magnet with 3.5 wt% of phenolic heated at 170˚C. From the obtained result, it is possible to have higher magnetic properties when the amount of polymer binder is more than the usually 2 – 3% mass portions as proven in the study. Under the effect of warm compaction temperature with constant weight percentage of phenolic in bonded magnet, the density analysis shows that the density of bonded magnet increased with the increasing on warm compaction temperature and produce better magnetic properties where the sample magnet with 5 wt% of phenolic heated at 170˚C has higher magnetic properties compare to sample magnet with 5 wt% of phenolic heated at 148˚C. By referring on the hysteresis loop on the three samples, the portion of binder has greater influence on the magnetic properties compare to the warm compaction temperature where the sample magnet with 3.5wt% of phenolic heated at 170˚C has the lowest magnetic properties among the three samples.

Based on this study, the bonded magnet by warm compaction method has lower magnetic properties compare to bonded magnet by compression bonding. However, bonded magnet by warm compaction method has better magnetic properties compare to ferrite magnet from a motor. The warm compaction bonded magnet could be a relevant option to be chosen for the manufacture of magnetic parts and to be used in many fields when the requirements of magnetic properties were higher compare to ferrite and the geometries of products were simple.

If we are concerning about time processing, warm compaction method using dry polymer binder is recommended as the process is simpler when compared to compaction bonding method using wet binder since it not consumed so much time in this fabrication. Furthermore, as being mention before, the warm compacted bonded NdFeB magnet has superior magnetic properties compared to the ferrite magnet. As being mention by M. Drak et al, manufacturing of composite materials by warm compaction method with polymer materials is a simple and not costly method taking into consideration low cost of polymer material and simplicity of their manufacturing.

5.2 Recommendation

The bonded magnet market has experienced the fastest growth of any permanent magnet industry especially after the discovery of Neodymium –iron- boron (NdFeB) magnets, one of rare earth permanent magnets [1]. Therefore, in the modern and permanently developed world, there is the need to find new method which contributed to better properties and simultaneously with lower costs. There is no doubt when the researches try to find new materials or to improve currently known ones by changing their composition, structure and properties of the technology of their manufacturing [15].

It is important if further studies on warm compaction method can be done in order to prove that this method could generate much better magnetic properties in the future. In this study, the pressure used for fabrication is about 28 MPa, which is considered low pressure when compared to the compression bonding method. The author would like to recommend that for future work, the technology of warm compaction with polymer does not need the preheating up to the polymer processing temperature but needs higher pressure to consolidate the powders [15].

Other than that, different types of binder could be used in the future work in order to clarify which dry binder suits more for warm compaction method and thus, improving the bonding between the magnetic powders. Besides that, due to the limitation of temperature set up for automatic mounting machine, the densities for sample magnet could only be tested for two different temperatures, thus cannot clarify more on the influence of warm compaction temperature on the densities of magnets. Hopefully, another machine could be used for the purposes of temperature variation in the fabrication of warm compaction bonded magnet.

Furthermore, different types of NdFeB powder could be used such as NdFeB spherical powder and with different particle size. From this recommendation, better results could be achieved and the method of warm compaction can be proven to become the next main fabrication method for NdFeB bonded magnet.

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APPENDIX A

	Milestone for Final Year Project I															
No.	Detail/Week	1	2	3	4	5	6	7		8	9	10	11	12	13	13	14
1	**Selection of Project Topic**	🟦	🟦						**MID SEMESTER BREAK**								
	- Meeting with Project Supervisor	🟩	🟩														
	-Study and Research	🟩	🟩														
2	**Preliminary Research Work**		🟦	🟦	🟦												
	Literature Reviev		🟩	🟩	🟩												
	Methodology			🟩	🟩												
3	**Submission of Preliminary Report**				🟩 ▲												
4	**Project Work**					🟦	🟦	🟦			▲						
	Availability of Equipment & Material Required						🟩	🟩									
	Continue Literature Review					🟩	🟩	🟩									
	Methodology Analysis					🟩	🟩	🟩									
5	Submission of Progress Report									🟩 ▲							
6	**Seminar** (Compulsary)									🟩 ▲							
7	**Project Work Continues**									🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
	Warm Compaction Process									🟩	🟩	🟩	🟩	🟩	🟩		
	Data Gathering & Analysis									🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
8	**Submission of Interim Report Final Draft**																🟩 ▲
9	**Oral Presentation**									During study week							

Legend:

Symbol	Description
▲	Suggested Milestone
🟦	Suggested process milestone
🟩	Process completed

APPENDIX B

	Milestone for Final Year Project II															
No.	Detail/Week	1	2	3	4	5	6		7	8	9	10	11	12	13	14
1	**Project Work Continues**	🟦	🟦	🟦				**MID SEMESTER BREAK**								
	Warm Compaction Process	🟩	🟩	🟩												
2	**Submission of progress report 1**				🟩▲											
3	**Project work continues**				🟦	🟦	🟦									
	Warm Compaction Process				🟩	🟩	🟩									
	Metallography Analysis (Image collection + EDAX analysis)				🟩											
4	**Submission of progress report 2**									🟩▲						
5	**Seminar** (Compulsary)									▲		🟩				
6	**Project work continues**								🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
	- Magnetic Properties Analysis										🟩					
	-Result and Findings -Data gathering & discussion								🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
7	**Poster exhibition**												🟩▲			
8	**Submission of Dissertation Final Draft**															🟩▲
9	**Oral Presentation**								During study week							
10	**Submission of Dissertation (hard bound)**								7 days after oral presentation							

Legend:

Symbol	Description
▲	Suggested Milestone
🟦	Suggested process milestone
🟩	Process completed

APPENDIX C

A. Determination of Density and Volume Calculation

I. Density, $\boldsymbol{\rho = \frac{m}{V}}$

II. Volume, $\boldsymbol{V = \pi r^2 \mathrm{h}}$

Where,

m=mass

V=Volume

r = radius

h = thickness

B. Weight percentage, wt%

$$f_{w} = \frac{M_f}{M_f + M_m}$$

Where,

f_w= the weight fraction

M_f = mass of plymer binder

M_m = mass of magnet powder

Then , **wt% = f_w x 100%**

C. Theoretical Density Calculation

$$\rho_{mix} = \frac{m_{NdFeB} + m_{binder}}{V_T}$$

where;

$$m_{Nd} = \rho_{Nd} \times V_T \;;$$

$$m_{binder} = \rho_{binder} \times V_T$$

D. Ratio of experimental density to theoretical density (%) = $\left. Density\ of\ bonded\ NdFeB\ magnet \middle/ Theoretical\ Density \right.$

APPENDIX D

Table 4.10a*:* Density on polymer portion from 10 until 35 wt%

Binder wt%	Sample No.	Diameter (cm)	Thickness (cm)	Volume (cm3)	Weight (g)	density (g/cm3)	sample density (g/cm3)	Average Density (g/cm3)
35	1	2.540	0.729	3.69	9.9980	2.7066	2.7066	2.6995
		2.540	0.729	3.69	9.9980	2.7066		
		2.540	0.729	3.69	9.9980	2.7066		
	2	2.540	0.727	3.68	9.9180	2.6924	2.6924	
		2.540	0.727	3.68	9.9180	2.6924		
		2.540	0.727	3.68	9.9190	2.6926		
30	1	2.540	0.665	3.37	9.9630	2.9567	2.9567	2.9786
		2.540	0.665	3.37	9.9630	2.9567		
		2.540	0.665	3.37	9.9630	2.9567		
	2	2.540	0.652	3.30	9.9130	3.0005	3.0004	
		2.540	0.652	3.30	9.9120	3.0002		
		2.540	0.652	3.30	9.9130	3.0005		
20	1	2.540	0.547	2.77	9.9820	3.6014	3.6014	3.6195
		2.540	0.547	2.77	9.9820	3.6014		
		2.540	0.547	2.77	9.9820	3.6014		
	2	2.540	0.536	2.72	9.8790	3.6374	3.6375	
		2.540	0.536	2.72	9.8790	3.6374		
		2.540	0.536	2.72	9.8800	3.6378		
10	1	2.540	0.460	2.33	9.9360	4.2628	4.2628	4.0919
		2.540	0.460	2.33	9.9360	4.2628		
		2.540	0.460	2.33	9.9360	4.2628		
	2	2.540	0.498	2.52	9.8940	3.9209	3.9209	
		2.540	0.498	2.52	9.8940	3.9209		
		2.540	0.498	2.52	9.8940	3.9209		

Table 4.10b**:** Density on polymer portion from 3.5 until 5 wt%

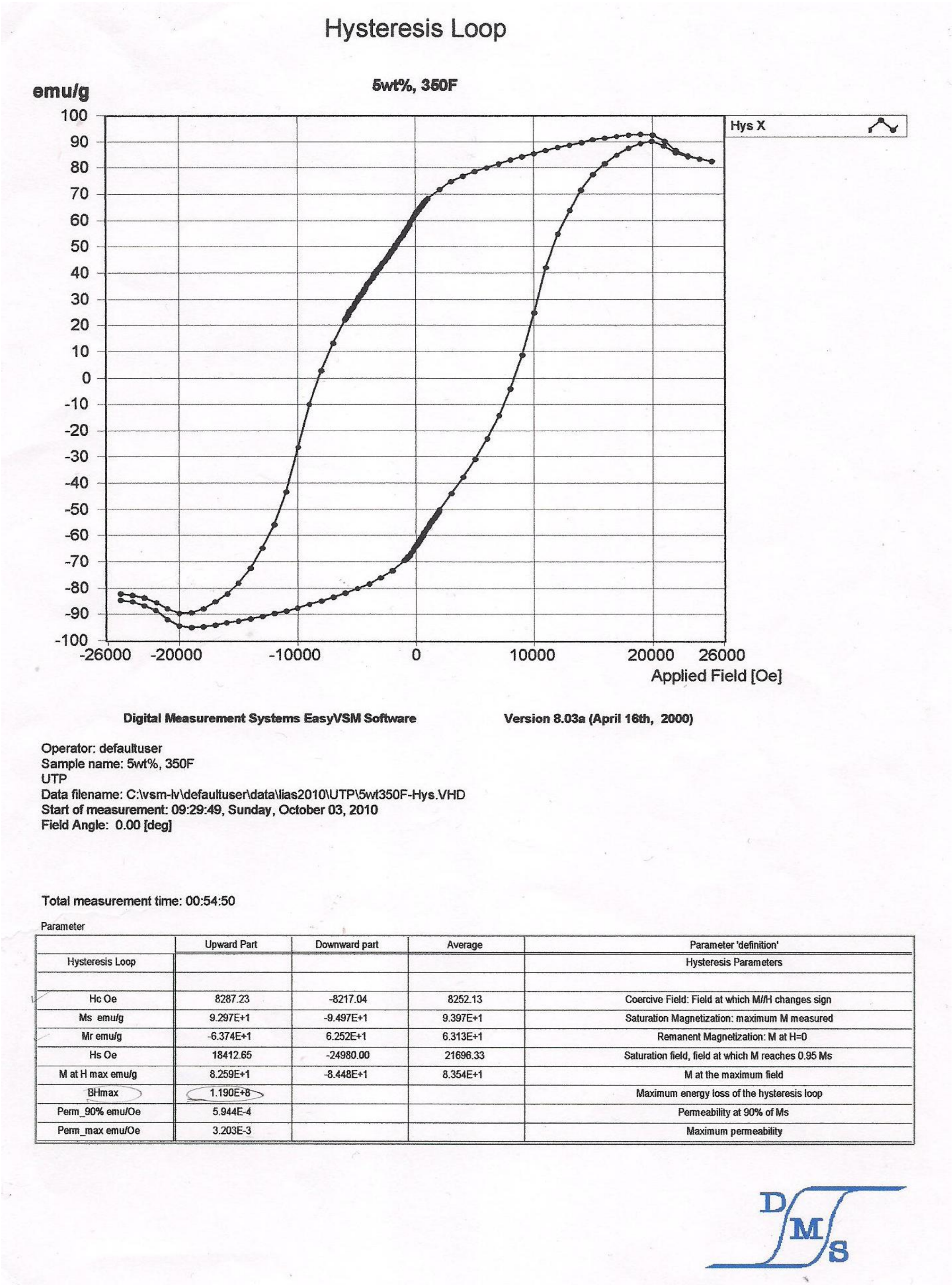
Binder wt%	Sample No.	Diameter (cm)	Thickness (cm)	Volume (cm3)	Weight (g)	Density (g/cm3)	Sample density (g/cm3)	Average Density (g/cm3)
5	1	2.540	0.462	2.34	9.9320	4.2427	4.2428	4.2545
		2.540	0.462	2.34	9.9330	4.2431		
		2.540	0.462	2.34	9.9320	4.2427		
	2	2.54	0.461	2.34	9.9690	4.2677	4.2663	
		2.54	0.461	2.34	9.9690	4.2677		
		2.54	0.461	2.34	9.9590	4.2634		
4.5	1	2.540	0.460	2.33	9.9890	4.2856	4.2571	4.2583
		2.540	0.460	2.33	9.8900	4.2431		
		2.540	0.460	2.33	9.8890	4.2427		
	2	2.540	0.463	2.35	9.9890	4.2578	4.2594	
		2.540	0.462	2.34	9.9790	4.2627		
		2.540	0.463	2.35	9.9890	4.2578		
4	1	2.540	0.452	2.29	9.9310	4.3361	4.3335	4.3078
		2.540	0.452	2.29	9.9350	4.3378		
		2.540	0.452	2.29	9.9090	4.3265		
	2	2.540	0.460	2.33	9.9810	4.2821	4.2821	
		2.540	0.460	2.33	9.9810	4.2821		
		2.540	0.460	2.33	9.9810	4.2821		
3.5	1	2.540	0.450	2.28	9.8810	4.3334	4.3233	4.3272
		2.540	0.450	2.28	9.8780	4.3321		
		2.540	0.453	2.30	9.8800	4.3043		
	2	2.540	0.452	2.29	9.8890	4.3177	4.3311	
		2.540	0.452	2.29	9.9240	4.3330		
		2.540	0.451	2.29	9.9240	4.3426		

APPENDIX E

Table 4.11**:** Density of bonded NdFeB of 5wt% on the effect of warm compaction temperature

Temp (°C)	Sample No.	Diameter (cm)	Thickness (cm)	Volume (cm3)	Weight (g)	Density (g/cm3)	Sample density (g/cm3)	Average Density (g/cm3)
148	1	2.540	0.460	2.33	9.8470	4.2246	4.2246	4.2399
		2.540	0.460	2.33	9.8470	4.2246		
		2.540	0.460	2.33	9.8470	4.2246		
	2	2.540	0.458	2.32	9.8680	4.2521	4.2552	
		2.540	0.458	2.32	9.8680	4.2521		
		2.540	0.457	2.32	9.8680	4.2614		
170	1	2.540	0.462	2.34	9.9320	4.2427	4.2428	4.2545
		2.540	0.462	2.34	9.9330	4.2431		
		2.540	0.462	2.34	9.9320	4.2427		
	2	2.540	0.461	2.34	9.9690	4.2677	4.2663	
		2.540	0.461	2.34	9.9690	4.2677		
		2.540	0.461	2.34	9.9590	4.2634		

APPENDIX F



Digital Measurement Systems EasyVSM Software **Version 8.03a (April 16th, 2000)**

Operator: defaultuser
Sample name: 5wt%, 350F
UTP
Data filename: C:\vsm-lv\defaultuser\data\lias2010\UTP\5wt350F-Hys.VHD
Start of measurement: 09:29:49, Sunday, October 03, 2010
Field Angle: 0.00 [deg]

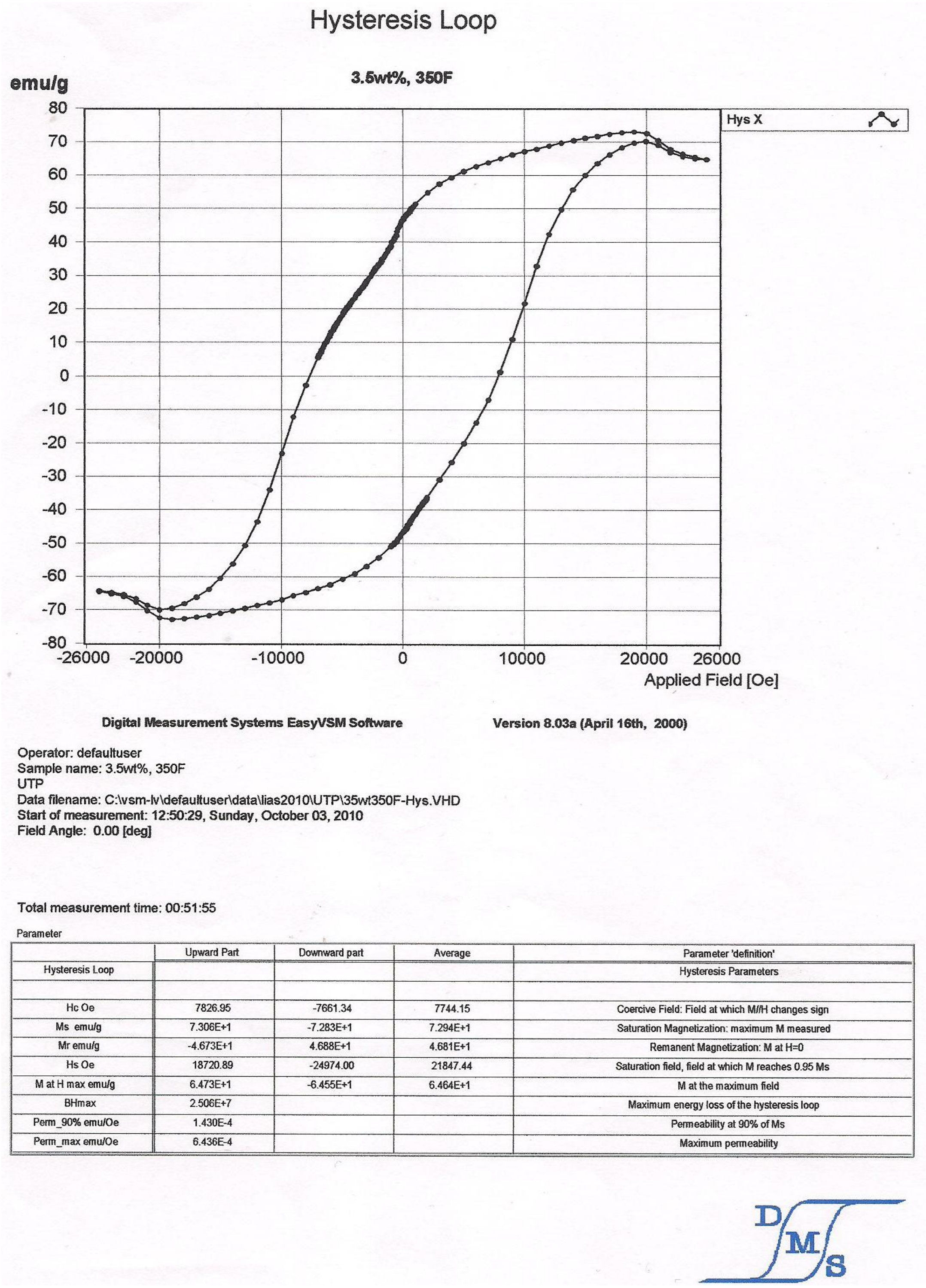
Total measurement time: 00:54:50

Parameter

	Upward Part	Downward part	Average	Parameter 'definition'
Hysteresis Loop				Hysteresis Parameters
Hc Oe	8287.23	-8217.04	8252.13	Coercive Field: Field at which M//H changes sign
Ms emu/g	9.297E+1	-9.497E+1	9.397E+1	Saturation Magnetization: maximum M measured
Mr emu/g	-6.374E+1	6.252E+1	6.313E+1	Remanent Magnetization: M at H=0
Hs Oe	18412.65	-24980.00	21696.33	Saturation field, field at which M reaches 0.95 Ms
M at H max emu/g	8.259E+1	-8.448E+1	8.354E+1	M at the maximum field
BHmax	1.190E+8			Maximum energy loss of the hysteresis loop
Perm_90% emu/Oe	5.944E-4			Permeability at 90% of Ms
Perm_max emu/Oe	3.203E-3			Maximum permeability

Figure 4.14: Hysteresis Loop for Sample A

APPENDIX G


Hysteresis Loop

3.5wt%, 350F

Digital Measurement Systems EasyVSM Software **Version 8.03a (April 16th, 2000)**

Operator: defaultuser
Sample name: 3.5wt%, 350F
UTP
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Start of measurement: 12:50:29, Sunday, October 03, 2010
Field Angle: 0.00 [deg]

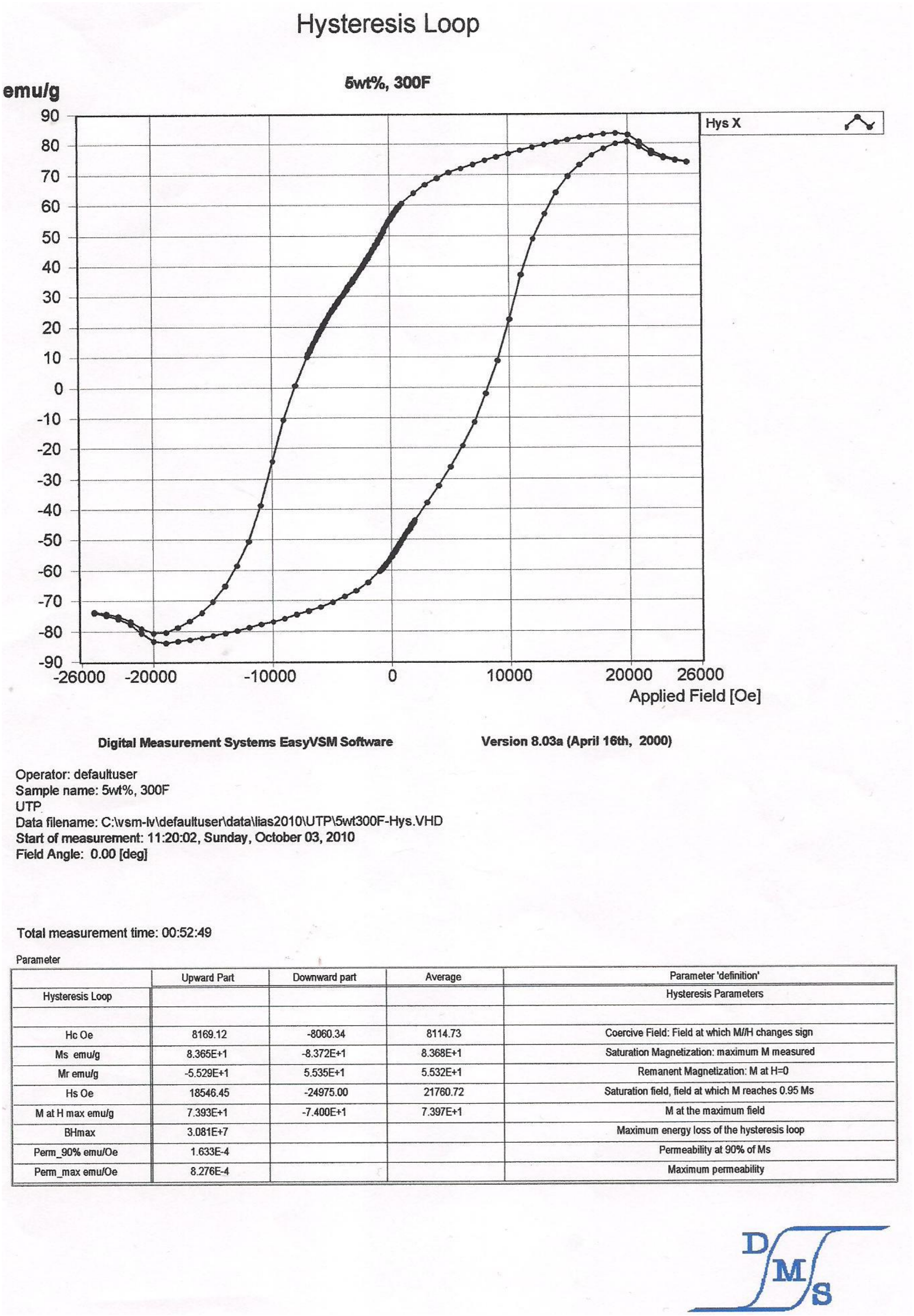
Total measurement time: 00:51:55

Parameter

	Upward Part	Downward part	Average	Parameter 'definition'
Hysteresis Loop				Hysteresis Parameters
Hc Oe	7826.95	-7661.34	7744.15	Coercive Field: Field at which M//H changes sign
Ms emu/g	7.306E+1	-7.283E+1	7.294E+1	Saturation Magnetization: maximum M measured
Mr emu/g	-4.673E+1	4.688E+1	4.681E+1	Remanent Magnetization: M at H=0
Hs Oe	18720.89	-24974.00	21847.44	Saturation field, field at which M reaches 0.95 Ms
M at H max emu/g	6.473E+1	-6.455E+1	6.464E+1	M at the maximum field
BHmax	2.506E+7			Maximum energy loss of the hysteresis loop
Perm_90% emu/Oe	1.430E-4			Permeability at 90% of Ms
Perm_max emu/Oe	6.436E-4			Maximum permeability

Figure 4.15: Hysteresis Loop for Sample B

APPENDIX H



Digital Measurement Systems EasyVSM Software

Version 8.03a (April 16th, 2000)

Operator: defaultuser
Sample name: 5wt%, 300F
UTP
Data filename: C:\vsm-lv\defaultuser\data\lias2010\UTP\5wt300F-Hys.VHD
Start of measurement: 11:20:02, Sunday, October 03, 2010
Field Angle: 0.00 [deg]

Total measurement time: 00:52:49

Parameter

	Upward Part	Downward part	Average	Parameter 'definition'
Hysteresis Loop				Hysteresis Parameters
Hc Oe	8169.12	-8060.34	8114.73	Coercive Field: Field at which M//H changes sign
Ms emu/g	8.365E+1	-8.372E+1	8.368E+1	Saturation Magnetization: maximum M measured
Mr emu/g	-5.529E+1	5.535E+1	5.532E+1	Remanent Magnetization: M at H=0
Hs Oe	18546.45	-24975.00	21760.72	Saturation field, field at which M reaches 0.95 Ms
M at H max emu/g	7.393E+1	-7.400E+1	7.397E+1	M at the maximum field
BHmax	3.081E+7			Maximum energy loss of the hysteresis loop
Perm_90% emu/Oe	1.633E-4			Permeability at 90% of Ms
Perm_max emu/Oe	8.276E-4			Maximum permeability

Figure 4.16: Hysteresis Loop for Sample C