Study of the Thermal Demagnetization Process of NdFeB Magnets

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Abstract

Currently, less than 1% of rare earth elements (REEs) are recycled due to the limitations of conventional recycling methods. Waste streams containing NdFeB magnets, such as household appliances, industrial motors, electric vehicle (EV) motors, and consumer electronics, are typically processed using traditional recycling techniques. These methods often involve shredding the material and applying separation techniques like magnetic and eddy current separation, which are designed to recover materials such as copper, iron, aluminum, plastic, and precious metals. However, they do not effectively recover REEs. Studies have shown that the ferrous fraction from typical recycling facilities for ferrous waste contains a REEs concentration which is too low to be economically viable for REE recovery.

This creates a pressing need of designing recycling processes able to valorize the REEs fraction. A critical step in these processes is the demagnetization of NdFeB magnets, without which their efficient separation from the waste stream would not be feasible. Demagnetization is necessary when processing waste through mechanical shredding and separation to prevent the strong magnetism of NdFeB magnets from causing operational issues. Issues such as the formation of “meatballs” (clusters of magnetic material) and magnets sticking to ferromagnetic parts of machinery are common when magnets remain magnetized. Moreover, demagnetization facilitates the separation of magnets from non-ferromagnetic fractions in the waste stream.

Demagnetization can be achieved using different techniques. One approach is hydrogen decrepitation, where hydrogen is absorbed by the NdFeB magnet, leading to brittle hydride formation that breaks down the magnet into a fine powder, which simultaneously induces demagnetization. Alternatively, thermal treatment can be used to raise the temperature of the magnets above their Curie temperature, at which point they lose their magnetic properties.

This study focused on the thermal demagnetization of NdFeB magnets contained within electric motors. Using an experimental design approach, we developed demagnetization curves that correlate the degree of demagnetization with key parameters such as temperature and treatment duration. The study also examined potential differences in demagnetization behavior when magnets were treated as part of an assembled motor versus individually. NdFeB magnets were subjected to varying temperatures and time intervals to generate these demagnetization curves, providing insights into the behavior of both individual magnets and those integrated within motor assemblies. Notably, it was observed that the average degree of demagnetization achieved varied depending on whether magnets were treated within the rotor or individually. This suggests that the assembly within the rotor affects the demagnetization response, resulting in a slower demagnetization process.

The experimental design (DOE) method enabled the development of a predictive model that estimates the degree of demagnetization based on time and temperature parameters. Results indicated that the coefficient for temperature (T) in the model consistently exerted a stronger influence on demagnetization than the coefficient for time (t), suggesting that temperature has a greater impact on demagnetization process.

1. Introduction

Currently, less than 1% of rare earth elements (REEs) are recycled (Jowitt et al., 2018), largely due to the limitations of conventional recycling processes. Waste containing NdFeB magnets, such as household appliance, industrial motors, electric motors of electric vehicles (EVs), consumer electronics, are typically treated using traditional recycling methods, which involve shredding the material and applying mechanical separation techniques such as magnetic separation and eddy current separation. These methods are primarily designed to recover materials like copper, iron, aluminum, plastic, and precious metals, but they do not effectively recover REEs. As demonstrated by Bandara et al., the ferrous fraction from a typical ferrous waste recycling plant contains around 100-200 ppm of neodymium (Nd), which is a concentration too low to be economically viable for recovery.

The challenge, therefore, is to design a recycling process specifically targeted at recovering the REEs fraction. A critical component of this process is the demagnetization of NdFeB magnets, without which their separation from the waste stream would not be feasible. Demagnetization is crucial for two main reasons: first, in processes where waste is dismantled to extract the magnets, demagnetization is required to allow for efficient separation; second, in cases where waste is processed through mechanical shredding and separation, demagnetization is essential to prevent the strong magnetism of NdFeB magnets from causing operational issues, such as the formation of "meatballs" (clusters of magnetic material) and the magnets sticking to ferromagnetic parts of the machinery. Furthermore, demagnetization allows the magnetic fraction to be separated from the ferrous fraction in the waste stream (Coelho et al., 2021).

Demagnetization can be achieved through different methods. One approach is hydrogen decrepitation (Walton et al., 2015) (Jönsson et al., 2020) which involves the absorption of hydrogen into the NdFeB magnet, leading to the formation of brittle hydrides that cause the magnet to break down into a fine powder. This process simultaneously induces demagnetization. Alternatively, thermal treatment can be used to raise the temperature of the magnets above their Curie temperature, at which point they lose their magnetic properties (K&J Magnetics., 2024).

In this study, we focused on the thermal demagnetization of NdFeB magnets contained within electric scooter motors. Using an experimental design approach, we generated demagnetization curves that correlate the degree of demagnetization with key parameters such as temperature and treatment time. Additionally, the study investigated whether there are differences in the demagnetization behavior of magnets when treated as part of the assembled motor versus when treated individually.

The findings of this study provide insights into optimizing the demagnetization process for efficient recycling of NdFeB magnets, ensuring that the REEs content can be effectively recovered and reused, supporting a more sustainable approach to the lifecycle of REEs in electric mobility and other industries.

2. Materials and instruments

The motors used for the demagnetization tests were sourced from end-of-life electric scooters from the same company (see Figure 1), making them identical in both structure and appearance.

Figure 1: The pictures shows the electric motor used for the study.

The magnets inside these motors all have identical dimensions: 3.3 cm in height, 1.2 cm in width, and 0.3 cm in depth, corresponding to a mass of approximately 9 grams (see Figure 2).

Figure 2: photo of a magnet that is inside the motors used for the study.

To measure the magnetic field generated by the permanent magnets in the electric scooter motors, a PCE-MFM 3000 Magnetic Field Meter (Gaussmeter) produced by PCE Americas Inc. was used (see Fig. 3).

Figure 3: The image shows the PCE-MFM 3000 Magnetic Field Meter (Gaussmeter) used to collect magnetic field values at various points.

The furnace used for thermal treatment is a ZE V.220 single-phase furnace (see Fig. 4).

Figure 4: The photograph shows the ZE V.220 single-phase furnace used for thermal treatments.

3 Experimental procedure

3.1 Motor Disassembly and Magnet Removal

The motors were first disassembled to access the magnets. The screws holding the two sections of the rotor were removed, and a puller was used to separate the rotor from the stator. Fig. 5 illustrates the process of rotor-stator separation using the puller.

Figure 5: picture showing the extraction step of stator from the rotor containing the magnets.

In Fig. 6, the main components of the disassembled motor are shown:

- **A**: Stator, which houses the copper windings.
- **B**: The upper aluminum half-shell of the rotor.
- **C**: The lower half-shell of the rotor, containing the NdFeB permanent magnet array.

Figure 6: a) Stator, which houses the copper windings b) upper aluminum half-shell of the rotor. c) The lower half-shell of the rotor, containing the NdFeB permanent magnet array.

Each motor contains 30 permanent magnets of identical size. To remove these magnets from the rotor, one was deliberately broken using a chisel. This allowed the rest of the magnets to be extracted one by one using a fine-tipped spatula.

3.2 Initial Magnetic Field Measurements

Magnetic field measurements were taken for each of the 29 remaining magnets (per motor) at five distinct points on both the north and south faces. This method was adopted due to the significant variation in magnetic field strength depending on the measurement location (stronger at the edges), and the susceptibility of different regions of the magnets to demagnetization post-thermal treatment.

The measurement points for each magnet are as follows:

- **C2**: 0.6 cm from the left side, 0.3 cm from the bottom.
- **C3**: 1 cm from the left side, 1.65 cm from the bottom.
- **C4**: 0.9 cm from the left side, 0.825 cm from the bottom.

- **S1**: 1 cm from the left side, 0.2 cm from the bottom.

Magnetic field measurements were taken on both the north and south faces of each magnet. In Fig. 7, one of the magnets used for the demagnetization tests is shown, with the measurement points highlighted in red on one face.

Figure 7: picture showing a magnet used for the demagnetization tests with the measurement points highlighted in red on one face.

3.3 Experimental methodologies for demagnetization tests

For the following tests, 10 motors were used, identified as motors A, B, C, D, E, F, G, H, I, and J.

Test 1

Motors A and B were disassembled, and the magnets were removed, numbered from 1 to 29 according to their position in the rotors. The initial magnetic field of each magnet was measured in every five points (C1, C2, C3, C4, S1) of the north and south face. The magnets were reassembled into two hybrid rotors, with magnets 1–14 from motor A combined with magnets 15–29 from motor B, and vice versa (see fig. 8). The purpose of creating hybrid motors was to test the variability in the behavior of magnets from different motors during demagnetization.

Figure 8: figure shows a hybrid motor composed of 14 magnets from motor A and 15 magnets from motor B.

Both rotors were subjected to thermal treatment at 200°C for 10 minutes. Rotor A was cooled in water, while rotor B was air-cooled. After cooling, the magnetic field of each magnet was measured again, and the degree of demagnetization was calculated. The magnets were placed back into the rotors and heated for an additional 25 minutes at 200°C. The cooling and measurement process was repeated. A final treatment of 25 minutes brought the total heating time to 60 minutes. The magnetic field was measured after each treatment to assess the effect of cooling methods on demagnetization.

Test 2

Magnets from motors C and D were removed and their initial magnetic fields were measured. The magnets were reassembled into a hybrid rotor, as in Test 1. This rotor underwent thermal treatment at 200°C, following the same time intervals: 10, 25, and 25 minutes. The rotor was air-cooled after each stage. The remaining magnets were treated individually, heated at the same temperature and time intervals, and cooled with the same methodology. This test aimed to compare the demagnetization behavior of magnets treated in bulk within the rotor versus those treated individually.

Test 3

A motor E was disassembled, and the magnets were numbered from 1 to 29. The initial magnetic field of magnets 1 to 14 was measured, and they were then treated individually, one at a time, at 250°C. The treatment consisted of three stages: 10 minutes initially, 25 minutes for the second stage, and another 25 minutes for the third, for a total of 60 minutes of thermal treatment, with air cooling between each step. After each thermal treatment, the magnetic field was measured, and the degree of demagnetization was calculated relative to the initial value.

Magnets 15 to 29 from motor E were combined with 15 magnets from another motor, F. The initial magnetic fields of the magnets from both motor E and motor F were measured. The 29 magnets were then placed in a rotor and thermally treated as a group at 250°C for 10 minutes in the first stage, 25 minutes in the second, and another 25 minutes in the third, for a total of 60 minutes of treatment. The magnets were allowed to air cool between stages. After each thermal treatment, the magnetic field was measured, and the degree of demagnetization was calculated relative to the initial value.

Finally, magnets 1 to 14 from motor F were combined with 15 magnets from a randomly selected motor and treated under the same experimental conditions as the first group, with the only difference being that the cooling was done in water.

The purpose of the test on motor E was to determine whether magnets assembled in a block within the rotor exhibit significantly different demagnetization behavior compared to individually treated magnets. The test on motor F aimed to assess whether the cooling method affects the degree of demagnetization.

Test 4

A motor G was disassembled, and the magnets were numbered from 1 to 29, with their initial magnetic fields measured. Half of the magnets from motor G were replaced with those from another randomly selected motor. The remaining magnets from motor G were placed in the rotor of the randomly chosen motor. The two resulting hybrid motors were treated at two different temperatures, 200°C and 250°C, respectively. The treatment durations were the same for both: 10 minutes for the first stage, 25 minutes for the second, and 25 minutes for the final stage, for a total of 60 minutes. After each thermal treatment, the magnetic fields were measured to study the behavior of the same type of magnets at different temperatures, as they all originated from the same initial motor.

Motor H was also disassembled, and the magnets were numbered from 1 to 29, with their initial magnetic fields measured. This motor was treated thermally at 300°C, following the same time intervals used for the previous motors, and the magnetic field was measured after each thermal treatment. At 300°C, it was observed that demagnetization was almost complete after just 10 minutes of treatment, making the differences in demagnetization between different motors negligible.

The purpose of the test was to observe how the degree of demagnetization behaves when motors are treated at different temperatures.

Test 5

The magnets from motor I were split into two groups, treated individually at 200°C and 250°C. The magnets from motor J were treated individually at 300°C. The purpose of the test was to study the demagnetization behavior of magnets when treated individually at different temperatures.

This experimental setup allowed for a detailed analysis of the thermal demagnetization behavior of NdFeB magnets under various conditions, focusing on the influence of cooling methods, treatment time, and temperature.

3.4 Calculation of Demagnetization Degree

The degree of demagnetization was calculated as the percentage loss of the initial magnetic field after thermal treatment using the following formula:

$$\Delta B\% = ((Bi - Bf)/Bi)) * 100$$

Where:

- **ΔB%** = Degree of demagnetization.
- **Bi** = Initial magnetic field, before thermal treatment.
- **Bf** = Final magnetic field, after thermal treatment.

3.5 Design of experiment (DOE)

To determine the contribution of time and temperature variables on the degree of demagnetization, the collected data were used to construct a Face-Centered Design (FCD) experimental model. This model was employed to determine the linear, quadratic, and interaction effects of the aforementioned variables on the degree of demagnetization. For each set of variables, 3 levels (-1, 0, +1) were chosen. Since time and temperature are on different scales of measurement, the variance in minutes is not the same as that in degrees. By using coded levels, it becomes possible to compare the two variables.

The mathematical model derived from the FCD experimental design takes the form of a linear sum of terms such as:

$$Y = B_0 + B_1X_1 + B_2X_2 + B_{11}X_1^2 + B_{22}X_2^2 + B_{12}X_1X_2$$

Where:

- Y = The calculated response, which is the degree of demagnetization obtained by varying the operational variables
- B_0 = Constant (intercept).
- B_1 = The linear coefficient for the variable X_1, which represents time.
- B_2 = The linear coefficient for the variable X_2, which represents temperature.
- B_{11} = The coefficient for the quadratic effect of the time variable.
- B_{22} = The coefficient for the quadratic effect of the temperature variable.

- B_{12} = The coefficient for the interaction effect between the time variable and the temperature variable.

The table 1 provides a detailed explanation of the variables X1 and X2, indicating what each variable represents. Additionally, it outlines the corresponding temperature and time values for each of the three levels: -1, 0, and 1.

Table 1: Definitions of variables X1 and X2, along with the corresponding temperature and time values at levels -1, 0, and 1.

Variables			Level		
#	Description	Unit	-1	0	+1
X_1	Time	minutes	10	35	60
X_2	Temperature	°C	200	250	300

The advantage of the experimental design is that, with the derived model, it is possible to predict the behavior of the degree of demagnetization by specifying the variables, time and temperature, in advance.

The total number of experiments (N) required for constructing the experimental design was calculated as follows:

$$N = 2^f + 2f + N_0$$

Where:

- f = Number of variables, which are time and temperature, thus equal to 2.
- N_0 = Number of replicates at the center point of the experimental design, which is 2.

Thus, the total number of experiments is 10.

4. Results and discussion

4.1 Test 1-influence of the cooling method at 200°C

The aim of this test was to determine whether the cooling method—instantaneous cooling in water versus slow cooling in air—significantly affects the degree of demagnetization measured after thermal treatment.

Table 2 presents the data on the degree of demagnetization of the magnets relative to the initial measured values after treatment at 200°C for 15, 35 and 60 minutes. Table A shows the degrees of demagnetization for the points located on the north face of the magnet, while Table B displays the degrees of demagnetization for the points on the south face. The columns labeled "water quenching" and "air cooling" represent the demagnetization values obtained using water and air as cooling mediums, respectively.

The aim of this test was to determine whether the cooling method—instantaneous cooling in water versus slow cooling in air—significantly affects the degree of demagnetization measured after thermal treatment.

Table 2: a) degrees of demagnetization after treatment at 200°C for the points located on the north face of the magnet b) degrees of demagnetization after treatment at 200°C for the points on the south face

a)

Time: 10 min															
	C1 N			**C2 N**			**S1 N**			**C3 N**			**C4 N**		
	Water	Air	Δ	Water	Air	Δ	Water	Air	Δ	Water	Air	Δ	Water	Air	Δ
Average ΔB%	68%	70%	-2%	59%	57%	2%	7%	11%	-4%	8%	13%	-5%	47%	48%	-1%
dev.st	4%	5%		3%	5%		5%	7%		6%	7%		4%	6%	
rsd%	5%	7%		5%	9%		77%	63%		74%	57%		9%	12%	
Median	68%	69%		59%	56%		6%	10%		5%	11%		46%	47%	
min	61%	63%		53%	50%		1%	1%		1%	4%		39%	36%	
max	74%	80%		67%	69%		20%	24%		22%	31%		54%	61%	
Time: 35 minutes															
	C1 N			**C2 N**			**S1 N**			**C3 N**			**C4 N**		
	Water	Air	Δ	Water	Air	Δ	Water	Air	Δ	Water	Air	Δ	Water	Air	Δ
Average ΔB%	92%	90%	2%	86%	82%	4%	60%	55%	5%	67%	61%	6%	84%	80%	4%
dev.st	1%	4%		2%	2%		5%	6%		4%	4%		2%	3%	
rsd%	2%	4%		3%	2%		9%	11%		6%	6%		2%	3%	
Median	92%	90%		86%	82%		61%	55%		68%	62%		84%	60%	
min	88%	85%		81%	78%		49%	36%		48%	51%		80%	75%	
max	95%	96%		90%	86%		69%	65%		74%	68%		88%	87%	
Time: 60 minutes															
	C1 N			**C2 N**			**S1 N**			**C3 N**			**C4 N**		
	Water	Air	Δ	Water	Air	Δ	Water	Air	Δ	Water	Air	Δ	Water	Air	Δ
Average ΔB%	92%	90%	2%	87%	84%	3%	65%	61%	4%	70%	66%	4%	86%	83%	3%
dev.st	2%	2%		2%	2%		4%	5%		4%	4%		1%	3%	
rsd%	2%	2%		2%	2%		6%	8%		5%	6%		1%	3%	
Median	92%	90%		87%	84%		65%	62%		71%	65%		86%	83%	
min	88%	86%		83%	81%		59%	46%		62%	56%		84%	77%	
max	95%	96%		92%	88%		74%	48%		77%	74%		89%	88%	

b)

Time: 10 min															
	C1 S			**C2 S**			**S1 S**			**C3 S**			**C4 S**		
	Water	Air	Δ	Water	Air	Δ	Water	Air	Δ	Water	Air	Δ	Water	Air	Δ
Average ΔB%	66%	70%	-4%	59%	57%	2%	8%	11%	-3%	12%	13%	-1%	46%	49%	-3%
dev.st	4%	4%		3%	5%		5%	6%		5%	7%		5%	6%	
rsd%	6%	6%		5%	9%		60%	57%		47%	54%		11%	11%	
Median	67%	69%		58%	56%		7%	11%		12%	13%		46%	48%	
min	59%	60%		52%	43%		2%	2%		3%	3%		35%	36%	
max	72%	77%		64%	68%		20%	25%		27%	34%		59%	60%	
Time: 35 minutes															
	C1 S			**C2 S**			**S1 S**			**C3 S**			**C4 S**		
	Water	Air	Δ	Water	Air	Δ	Water	Air	Δ	Water	Air	Δ	Water	Air	Δ
Average ΔB%	92%	89%	3%	85%	82%	3%	60%	54%	6%	66%	59%	7%	84%	80%	4%
dev.st	2%	2%		2%	2%		5%	5%		4%	9%		2%	2%	
rsd%	2%	2%		2%	2%		9%	9%		6%	15%		3%	3%	
Median	91%	89%		85%	82%		60%	54%		65%	61%		83%	79%	
min	88%	86%		82%	78%		38%	46%		56%	16%		79%	75%	
max	94%	95%		91%	85%		66%	63%		70%	69%		88%	86%	
Time: 60 minutes															
	C1 S			**C2 S**			**S1 S**			**C3 S**			**C4 S**		
	Water	Air	Δ	Water	Air	Δ	Water	Air	Δ	Water	Air	Δ	Water	Air	Δ
Average ΔB%	92%	90%	2%	87%	84%	3%	64%	60%	4%	69%	65%	4%	85%	83%	2%
dev.st	2%	2%		2%	2%		4%	4%		4%	3%		2%	2%	
rsd%	2%	2%		2%	2%		7%	6%		6%	5%		3%	3%	
Median	92%	90%		87%	83%		65%	61%		70%	65%		85%	83%	
min	88%	87%		83%	81%		51%	52%		58%	58%		81%	78%	
max	95%	95%		92%	87%		71%	66%		75%	72%		89%	88%	

Below is the legend for interpreting the table, which is consistent with the legend used for subsequent tests:

- Average ΔB%: Represents the average degree of demagnetization at the same point, calculated for all magnets.
- Dev. St.: Represents the standard deviation of the degree of demagnetization calculated for all values at the same point across all magnets.
- Rsd%: Represents the relative standard deviation, calculated as the ratio of the standard deviation to the average value.
- Median: Represents the median of the values.
- Min: Represents the minimum degree of demagnetization recorded at the same point across all magnets.
- Max: Represents the maximum degree of demagnetization recorded at the same point across all magnets.
- Δ: Indicates the difference in the degree of demagnetization between the two cooling methods used.

The results from the first demagnetization test revealed that, for each measurement point and regardless of the time considered, the average degree of demagnetization with air cooling or water quenching, along with the calculated standard deviation, overlap. Therefore, there is no significant difference between the two cooling methods used. Additionally, it was observed that, for both faces of the magnet, the final degree of demagnetization achieved at the thermal treatment temperature of 200°C is reached after just 35 minutes of treatment. In fact, the results after 60 minutes of treatment are the same (see Table 3).

Table 3:Average degree of demagnetization after 35 and 60 minutes of treatment at 200°C

Time: 35 minutes			
	C1 N		
	Water	Air	Δ
Average ΔB%	92%	90%	2%
dev.st	1%	4%	
rsd%	2%	4%	
Median	92%	90%	
min	88%	85%	
max	95%	96%	
Time: 60 minutes			
	C1 N		
	Water	Air	Δ
Average ΔB%	92%	90%	2%
dev.st	2%	2%	
rsd%	2%	2%	
Median	92%	90%	
min	88%	86%	
max	95%	96%	

It was also observed that the final degree of demagnetization at points near the edges (S1, C3, C4) or corners of the magnets is lower than that at points located in the center of the magnets (C1, C2) (see Table 4).

Table 4: Average degree of demagnetization after 60 minutes of treatment at the center of the magnet (C1N), at the edge (S1N), and near the side (C3N).

Time: 60 minutes									
	C1 N			S1 N			C3 N		
	Water	Air	Δ	Water	Air	Δ	Water	Air	Δ
Average ΔB%	92%	90%	2%	65%	61%	4%	70%	66%	4%
dev.st	2%	2%		4%	5%		4%	4%	
rsd%	2%	2%		6%	8%		5%	6%	
Median	92%	90%		65%	62%		71%	65%	
min	88%	86%		59%	46%		62%	56%	
max	95%	96%		74%	48%		77%	74%	

4.2 Test 2- difference between single magnets and magnets in assembly at 200°C

Table 5 presents the data on the degree of demagnetization of the magnets relative to the initial measurements. The treatment was conducted at 200°C for 15, 35 and 60 minutes. Table A shows the degrees of demagnetization for points located on the north face of the magnet, while Table B shows the degrees of demagnetization for points on the south face. Columns labeled "Single" report the average degree of demagnetization for the specified points on magnets treated and cooled individually. In contrast, columns labeled "Bulk" present the average degree of demagnetization for the specified points on magnets heated and cooled within the rotor.

The objective of this test is to determine whether magnets assembled in bulk within the rotor exhibit significantly different demagnetization behavior compared to magnets treated individually at a temperature of 200°C.

Table 5: a) degrees of demagnetization after treatment at 200°C for the points located on the north face of the magnet b) degrees of demagnetization after treatment at 200°C for the points on the south face

a)

Time: 10 minutes															
	C1 N			C2 N			S1 N			C3 N			C4 N		
	Single	Bulk	Δ	Single	Bulk	Δ	Single	Bulk	Δ	Single	Bulk	Δ	Single	Bulk	Δ
Average ΔB%	82%	53%	29%	81%	38%	43%	75%	7%	68%	78%	10%	68%	81%	25%	56%
dev.st	5%	15%		6%	21%		7%	7%		6%	9%		6%	18%	
rsd%	6%	28%		7%	54%		10%	91%		8%	97%		7%	74%	
Median	81%	44%		83%	30%		76%	5%		80%	4%		80%	16%	
min	73%	27%		71%	7%		63%	0%		68%	0%		71%	2%	
max	91%	76%		89%	65%		86%	23%		88%	30%		90%	49%	

Time: 35 minutes															
	C1 N			C2 N			S1 N			C3 N			C4 N		
	Single	Bulk	Δ	Single	Bulk	Δ	Single	Bulk	Δ	Single	Bulk	Δ	Single	Bulk	Δ
Average ΔB%	86%	87%	-1%	86%	78%	8%	81%	46%	35%	84%	55%	29%	86%	74%	12%
dev.st	4%	5%		4%	7%		5%	16%		5%	14%		4%	10%	
rsd%	5%	6%		5%	9%		6%	35%		5%	26%		5%	13%	
Median	85%	86%		86%	77%		82%	44%		84%	50%		85%	71%	
min	79%	79%		79%	67%		73%	19%		78%	31%		80%	60%	
max	93%	95%		91%	88%		89%	72%		90%	74%		92%	88%	

Time: 60 minutes															
	C1 N			C2 N			S1 N			C3 N			C4 N		
	Single	Bulk	Δ	Single	Bulk	Δ	Single	Bulk	Δ	Single	Bulk	Δ	Single	Bulk	Δ
Average ΔB%	88%	87%	1%	87%	80%	7%	83%	52%	31%	85%	59%	26%	87%	75%	12%
dev.st	4%	5%		4%	7%		5%	15%		5%	13%		4%	9%	
rsd%	5%	6%		5%	9%		6%	28%		5%	22%		5%	12%	
Median	86%	87%		87%	79%		84%	55%		85%	54%		86%	73%	
min	79%	79%		80%	68%		76%	26%		78%	38%		81%	62%	
max	93%	95%		92%	90%		90%	74%		92%	77%		93%	89%	

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b)

Time: 10 minutes															
	C1 S			C2 S			S1 S			C3 S			C4 S		
	Single	Bulk	Δ	Single	Bulk	Δ	Single	Bulk	Δ	Single	Bulk	Δ	Single	Bulk	Δ
Average ΔB%	81%	53%	28%	80%	38%	42%	73%	7%	66%	76%	9%	67%	79%	25%	54%
dev.st	5%	15%		6%	20%		7%	8%		7%	9%		6%	17%	
rsd%	7%	28%		7%	52%		9%	117%		9%	101%		8%	68%	
Median	79%	47%		80%	36%		72%	3%		74%	4%		78%	23%	
min	72%	32%		70%	6%		61%	0%		65%	0%		70%	1%	
max	90%	74%		88%	64%		84%	29%		87%	30%		88%	52%	
Time: 35 minutes															
	C1 S			C2 S			S1 S			C3 S			C4 S		
	Single	Bulk	Δ	Single	Bulk	Δ	Single	Bulk	Δ	Single	Bulk	Δ	Single	Bulk	Δ
Average ΔB%	85%	86%	-1%	84%	77%	7%	80%	44%	36%	82%	53%	29%	84%	73%	11%
dev.st	4%	6%		4%	7%		5%	15%		5%	13%		5%	10%	
rsd%	5%	6%		5%	10%		6%	33%		7%	24%		6%	13%	
Median	84%	87%		84%	78%		78%	41%		80%	49%		85%	75%	
min	77%	76%		78%	66%		71%	18%		73%	34%		75%	59%	
max	92%	94%		91%	87%		87%	68%		90%	72%		91%	68%	
Time: 60 minutes															
	C1 S			C2 S			S1 S			C3 S			C4 S		
	Single	Bulk	Δ	Single	Bulk	Δ	Single	Bulk	Δ	Single	Bulk	Δ	Single	Bulk	Δ
Average ΔB%	86%	86%	0%	85%	79%	6%	85%	50%	35%	84%	58%	26%	86%	75%	11%
dev.st	4%	6%		4%	8%		5%	14%		5%	13%		5%	10%	
rsd%	5%	7%		5%	10%		6%	28%		6%	22%		6%	13%	
Median	85%	87%		85%	79%		81%	49%		81%	54%		85%	77%	
min	78%	76%		79%	69%		73%	26%		75%	40%		75%	60%	
max	92%	96%		91%	89%		89%	73%		91%	77%		91%	89%	

Based on the results from this test, it was observed that, as in previous cases, demagnetization occurs to a greater extent at the center of the magnets when treated within the rotor, while it is less pronounced near the edges or sides of the magnets (see Table 6).

Table 6: Average degrees of demagnetization at points C1N, S1N, and C3N for magnets treated within the rotor for 60 minutes at 200°C

	C1 N	S1 N	C3 N
	Bulk	Bulk	Bulk
Average ΔB%	87%	52%	59%
dev.st	5%	15%	13%
rsd%	6%	28%	22%
Median	87%	55%	54%
min	79%	26%	38%
max	95%	74%	77%

A significant difference was observed in the average degree of demagnetization between magnets treated within the rotor and those treated individually at points S1 and C3, both on the north and south sides, which represent the areas near the edges and sides of the magnets (see Table 7).

Table 7: Average degree of demagnetization at points S1N and C3N for magnets treated individually and those treated within the rotor after 60 minutes at 200°C.

	C1 N			S1 N			C3 N		
	Single	Bulk	Δ	Single	Bulk	Δ	Single	Bulk	Δ
Average ΔB%	88%	87%	1%	83%	52%	31%	85%	59%	26%
dev.st	4%	5%		5%	15%		5%	13%	
rsd%	5%	6%		6%	28%		5%	22%	
Median	86%	87%		84%	55%		85%	54%	
min	79%	79%		76%	26%		78%	38%	
max	93%	95%		90%	74%		92%	77%	

While this difference in the average degree of demagnetization after 10 minutes of treatment could be attributed to the unequal heating rates, due to the difference in mass between the individual magnets and the entire rotor, the same discrepancy persists even after 60 minutes of treatment. It can therefore be concluded that demagnetization is more effective when the magnets are treated individually.

4.3 Test 3- difference between single magnets and magnets in assembly at 250°C

Table 8 presents the data on the degree of demagnetization of the magnets after treatment at 250°C for 15, 35 and 60 minutes. Table A shows the demagnetization levels for points located on the north face of the magnet, while Table B provides the values for points on the south face. In the columns labeled "single" the average demagnetization values for the specified points on magnets treated and cooled individually are reported. The columns labeled "air" display the average demagnetization values for magnets treated and air-cooled within the rotor, while the columns labeled " water" show the average demagnetization values for magnets treated in bulk and cooled in water.

The purpose of this test is to determine whether magnets assembled in bulk within the rotor exhibit a significantly different demagnetization behavior compared to magnets treated individually at a temperature of 250°C, and to assess whether the cooling method—either rapid cooling in water or slow cooling in air—has a notable impact on the measured degree of demagnetization after thermal treatment.

Table 8: a) degrees of demagnetization after treatment at 250°C for the points located on the north face of the magnet b) degrees of demagnetization after treatment at 250°C for the points on the south face

a)

Time: 10 minutes															
	C1 N			**C2 N**			**S1 N**			**C3 N**			**C4 N**		
	Single	Air	Water	Single	Air	Water	Single	Air	Water	Single	Air	Water	Single	Air	Water
Average ΔB%	97%	88%	90%	97%	80%	83%	96%	48%	55%	96%	56%	62%	97%	75%	79%
dev.st	1%	3%	2%	1%	4%	2%	1%	9%	6%	1%	9%	5%	1%	5%	2%
rsd%	1%	3%	2%	1%	6%	3%	1%	18%	11%	1%	16%	9%	1%	6%	3%
Median	97%	88%	90%	97%	81%	84%	95%	49%	56%	96%	55%	63%	97%	76%	79%
min	95%	75%	87%	95%	59%	79%	92%	14%	44%	95%	19%	53%	95%	55%	74%
max	98%	92%	93%	99%	85%	86%	98%	58%	64%	98%	68%	70%	98%	80%	82%
Time: 35 minutes															
	C1 N			**C2 N**			**S1 N**			**C3 N**			**C4 N**		
	Single	Air	Water	Single	Air	Water	Single	Air	Water	Single	Air	Water	Single	Air	Water
Average ΔB%	100%	98%	98%	100%	97%	97%	100%	95%	94%	100%	96%	95%	100%	97%	96%
dev.st	0%	1%	0%	0%	2%	1%	0%	3%	1%	0%	3%	1%	0%	1%	1%
rsd%	0%	1%	0%	0%	2%	1%	0%	3%	1%	0%	3%	1%	0%	1%	1%
Median	100%	99%	98%	100%	97%	97%	100%	95%	94%	100%	96%	95%	100%	97%	96%
min	99%	95%	97%	99%	89%	96%	98%	82%	91%	99%	82%	94%	99%	91%	95%
max	100%	99%	99%	100%	98%	98%	100%	97%	95%	100%	98%	96%	100%	99%	98%
Time: 60 minutes															
	C1 N			**C2 N**			**S1 N**			**C3 N**			**C4 N**		
	Single	Air	Water	Single	Air	Water	Single	Air	Water	Single	Air	Water	Single	Air	Water
Average ΔB%	100%	98%	98%	100%	97%	97%	100%	95%	95%	100%	96%	96%	100%	98%	97%
dev.st	0%	1%	0%	0%	1%	0%	0%	3%	1%	0%	3%	1%	0%	1%	1%
rsd%	0%	1%	0%	0%	1%	0%	0%	3%	1%	0%	3%	1%	0%	1%	1%
Median	100%	99%	98%	100%	98%	97%	100%	96%	95%	100%	97%	96%	100%	98%	97%
min	100%	95%	97%	100%	91%	97%	100%	83%	94%	100%	83%	95%	100%	92%	97%
max	100%	100%	99%	100%	98%	98%	100%	97%	96%	100%	98%	97%	100%	99%	98%

b)

Time: 10 minutes															
	C1 S			C2 S			S1 S			C3 S			C4 S		
	Single	Air	Water	Single	Air	Water	Single	Air	Water	Single	Air	Water	Single	Air	Water
ge ΔB%	96%	87%	89%	96%	79%	82%	95%	47%	56%	96%	51%	62%	96%	73%	79%
dev.st	1%	4%	2%	1%	4%	2%	1%	7%	5%	1%	6%	4%	1%	6%	3%
rsd%	1%	5%	2%	1%	6%	2%	1%	14%	10%	1%	11%	6%	1%	8%	3%
Median	96%	88%	89%	96%	79%	82%	95%	47%	58%	94%	52%	61%	96%	74%	80%
min	94%	70%	86%	94%	59%	78%	92%	22%	45%	94%	31%	53%	95%	50%	74%
max	97%	95%	92%	98%	83%	86%	97%	58%	62%	97%	60%	68%	97%	83%	83%
Time: 35 minutes															
	C1 S			C2 S			S1 S			C3 S			C4 S		
	Single	Air	Water	Single	Air	Water	Single	Air	Water	Single	Air	Water	Single	Air	Water
ge ΔB%	99%	98%	98%	99%	96%	96%	99%	94%	93%	99%	95%	95%	99%	97%	96%
dev.st	0%	1%	0%	0%	2%	1%	1%	3%	1%	0%	2%	0%	0%	2%	0%
rsd%	0%	1%	0%	0%	2%	1%	1%	3%	1%	0%	2%	0%	0%	2%	1%
Median	99%	98%	98%	100%	97%	96%	99%	95%	93%	99%	95%	95%	99%	97%	96%
min	99%	93%	97%	98%	88%	95%	98%	82%	89%	99%	86%	94%	99%	89%	95%
max	100%	99%	99%	100%	98%	97%	100%	97%	94%	100%	97%	96%	100%	98%	97%
Time: 60 minutes															
	C1 S			C2 S			S1 S			C3 S			C4 S		
	Single	Air	Water	Single	Air	Water	Single	Air	Water	Single	Air	Water	Single	Air	Water
ge ΔB%	100%	98%	98%	100%	97%	97%	100%	95%	95%	100%	95%	96%	100%	97%	97%
dev.st	0%	1%	0%	0%	1%	0%	0%	3%	1%	0%	2%	1%	0%	1%	0%
rsd%	0%	1%	0%	0%	1%	0%	0%	3%	1%	0%	2%	1%	0%	2%	0%
Median	100%	98%	98%	100%	97%	97%	100%	95%	95%	100%	96%	96%	100%	97%	97%
min	100%	93%	97%	100%	90%	96%	100%	83%	93%	100%	87%	94%	100%	90%	97%
max	100%	100%	99%	100%	98%	98%	100%	100%	96%	100%	97%	97%	100%	98%	98%

The results from this test showed that the magnets treated individually, at the same temperature, reached complete demagnetization at all points after 60 minutes of treatment (see Table 9).

Table 9: Average degree of demagnetization after 60 minutes of treatment at 250°C for individually treated magnets

	Single	Single	Single	Single	Single	Single	Single	Single	Single	Single
Average ΔB%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
dev.st	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
rsd%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Median	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
min	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
max	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

However, magnets treated within the rotor showed different behavior, as they never reached complete demagnetization (see Table 10).

Table 10: Average degree of demagnetization after 60 minutes of treatment at 250°C for magnets treated individually, and those treated within the rotor, cooled in water or air-cooled.

	C1 N			C2 N			S1 N			C3 N			C4 N		
	Single	Air	Water	Single	Air	Water	Single	Air	Water	Single	Air	Water	Single	Air	Water
Average ΔB%	100%	98%	98%	100%	97%	97%	100%	95%	95%	100%	96%	96%	100%	98%	97%
dev.st	0%	1%	0%	0%	1%	0%	0%	3%	1%	0%	3%	1%	0%	1%	1%
rsd%	0%	1%	0%	0%	1%	0%	0%	3%	1%	0%	3%	1%	0%	1%	1%
Median	100%	99%	98%	100%	98%	97%	100%	96%	95%	100%	97%	96%	100%	98%	97%
min	100%	95%	97%	100%	91%	97%	100%	83%	94%	100%	83%	95%	100%	92%	97%
max	100%	100%	99%	100%	98%	98%	100%	97%	96%	100%	98%	97%	100%	99%	98%

Additionally, the results for magnets treated within the rotor using different cooling techniques are not significantly different. In fact, the average degree of demagnetization between air cooling and water cooling, combined with the calculated standard deviation, overlaps (see Table 11).

Table 11: Average degree of demagnetization after 60 minutes of treatment at 250°C for magnets cooled in water or air-cooled

	C1N		C2N		S1N		C3N		C4N	
	Air	Water	Air	Water	Air	Water	Air	Water	Air	Water
Average ΔB%	98%	98%	97%	97%	95%	95%	96%	96%	98%	97%
dev.st	1%	0%	1%	0%	3%	1%	3%	1%	1%	1%
rsd%	1%	0%	1%	0%	3%	1%	3%	1%	1%	1%
Median	99%	98%	98%	97%	96%	95%	97%	96%	98%	97%
min	95%	97%	91%	97%	83%	94%	83%	95%	92%	97%
max	100%	99%	98%	98%	97%	96%	98%	97%	99%	98%

4.4 Test 4- DOE applied to magnets in assembly

Table 12 presents the demagnetization data for the magnets treated within the rotor, compared to their initial measured values. Table A shows the demagnetization levels for points located on the north face of the magnet, while Table B shows the demagnetization levels for points on the south face. The three columns in each table display the demagnetization levels at treatment temperatures of 200°C, 250°C, and 300°C, for durations of 15, 35, and 60 minutes for each temperature.

The aim of this test is to construct a demagnetization response surface using a DOE approach, to better understand the influence of time and temperature when magnets are thermally treated inside the rotor.

Table 12: a) degrees of demagnetization after treatment at 200°C, 250°C, 300°C for durations of 15, 35, and 60 minutes for each temperature for the points located on the north face of the magnet b) degrees of demagnetization after treatment at 200°C, 250°C, 300°.

a)

Time: 10 minutes

	C1 N			C2 N			S1 N			C3 N			C4 N		
	200°C	250°C	300°C	200°C	250°C	300°C	200°C	250°C	300°C	200°C	250°C	300°C	200°C	250°C	300°C
Average ΔB%	70%	89%	98%	55%	82%	93%	12%	51%	86%	14%	57%	90%	41%	77%	96%
dev.st	3%	1%	1%	5%	1%	1%	11%	4%	4%	5%	3%	3%	6%	2%	2%
rsd%	5%	2%	1%	8%	1%	1%	93%	9%	4%	33%	6%	3%	13%	3%	2%
Median	70%	89%	98%	55%	82%	93%	10%	51%	86%	14%	58%	90%	42%	76%	97%
min	64%	86%	96%	46%	80%	89%	2%	42%	79%	7%	51%	84%	30%	74%	91%
max	75%	91%	100%	64%	84%	95%	46%	60%	91%	23%	62%	96%	48%	82%	99%

Time: 35 minutes

	C1 N			C2 N			S1 N			C3 N			C4 N		
	200°C	250°C	300°C	200°C	250°C	300°C	200°C	250°C	300°C	200°C	250°C	300°C	200°C	250°C	300°C
Average ΔB%	91%	100%	100%	84%	99%	100%	53%	99%	100%	64%	99%	100%	79%	100%	100%
dev.st	1%	0%	0%	2%	0%	0%	6%	0%	0%	3%	0%	0%	2%	0%	0%
rsd%	1%	0%	0%	2%	0%	0%	12%	0%	0%	5%	0%	0%	3%	0%	0%
Median	91%	99%	100%	84%	100%	100%	54%	99%	100%	65%	99%	100%	80%	100%	100%
min	89%	99%	100%	81%	99%	100%	34%	99%	100%	56%	99%	100%	75%	100%	100%
max	93%	100%	100%	87%	100%	100%	62%	99%	100%	67%	100%	100%	83%	100%	100%

Time: 60 minutes

	C1 N			C2 N			S1 N			C3 N			C4 N		
	200°C	250°C	300°C	200°C	250°C	300°C	200°C	250°C	300°C	200°C	250°C	300°C	200°C	250°C	300°C
Average ΔB%	93%	100%	100%	86%	100%	100%	61%	100%	100%	69%	100%	100%	83%	100%	100%
dev.st	2%	0%	0%	2%	0%	0%	5%	0%	0%	6%	0%	0%	2%	0%	0%
rsd%	2%	0%	0%	2%	0%	0%	8%	0%	0%	8%	0%	0%	3%	0%	0%
Median	93%	100%	100%	86%	100%	100%	62%	100%	100%	69%	100%	100%	83%	100%	100%
min	90%	100%	100%	82%	100%	100%	48%	100%	100%	60%	100%	100%	77%	100%	100%
max	100%	100%	100%	88%	100%	100%	66%	100%	100%	85%	100%	100%	86%	100%	100%

https://doi.org/10.26434/chemrxiv-2024-k6rkk **ORCID:** https://orcid.org/0009-0001-4652-2483

b)

Time: 10 minutes															
	C1 S			C2 S			S1 S			C3 S			C4 S		
	200°C	250°C	300°C	200°C	250°C	300°C	200°C	250°C	300°C	200°C	250°C	300°C	200°C	250°C	300°C
Average ΔB%	69%	88%	98%	50%	81%	93%	11%	53%	85%	13%	58%	90%	40%	77%	96%
dev.st	3%	2%	1%	15%	1%	1%	11%	3%	3%	5%	3%	2%	3%	1%	2%
rsd%	5%	2%	1%	29%	2%	1%	105%	7%	4%	41%	6%	3%	8%	1%	2%
Median	69%	88%	98%	54%	81%	93%	8%	52%	86%	13%	58%	90%	40%	77%	96%
min	65%	84%	95%	0%	79%	89%	2%	45%	77%	3%	51%	86%	33%	76%	93%
max	76%	91%	100%	61%	83%	95%	47%	59%	90%	22%	63%	95%	44%	79%	99%
Time: 35 minutes															
	C1 S			C2 S			S1 S			C3 S			C4 S		
	200°C	250°C	300°C	200°C	250°C	300°C	200°C	250°C	300°C	200°C	250°C	300°C	200°C	250°C	300°C
Average ΔB%	91%	99%	100%	83%	99%	100%	52%	99%	100%	60%	99%	100%	79%	99%	100%
dev.st	2%	0%	0%	1%	0%	0%	4%	0%	0%	2%	0%	0%	2%	0%	0%
rsd%	2%	0%	0%	2%	0%	0%	7%	0%	0%	4%	0%	0%	3%	0%	0%
Median	90%	100%	100%	82%	99%	100%	52%	99%	100%	60%	99%	100%	79%	99%	100%
min	89%	99%	100%	81%	99%	100%	47%	98%	100%	55%	98%	100%	77%	99%	100%
max	94%	100%	100%	85%	100%	100%	59%	99%	100%	64%	100%	100%	84%	100%	100%
Time: 60 minutes															
	C1 S			C2 S			S1 S			C3 S			C4 S		
	200°C	250°C	300°C	200°C	250°C	300°C	200°C	250°C	300°C	200°C	250°C	300°C	200°C	250°C	300°C
Average ΔB%	92%	100%	100%	85%	100%	100%	60%	100%	100%	66%	100%	100%	82%	100%	100%
dev.st	1%	0%	0%	1%	0%	0%	2%	0%	0%	2%	0%	0%	2%	0%	0%
rsd%	1%	0%	0%	1%	0%	0%	4%	0%	0%	3%	0%	0%	2%	0%	0%
Median	92%	100%	100%	85%	100%	100%	60%	100%	100%	66%	100%	100%	82%	100%	100%
min	90%	100%	100%	83%	100%	100%	55%	100%	100%	63%	100%	100%	80%	100%	100%
max	95%	100%	100%	87%	100%	100%	63%	100%	100%	70%	100%	100%	86%	100%	100%

The results from treating the permanent magnets at three different temperatures reveal that after 35 minutes at temperatures above 250°C, the magnets achieve nearly complete demagnetization at every measurement point. In contrast, at 200°C, the demagnetization remains incomplete even after 60 minutes of treatment (see Table 13).

Table 13: Average demagnetization degree after 60 minutes of treatment at 200°C and 35 minutes of treatment at 250°C.

	C1 N		C2 N		S1 N		C3 N		C4 N	
	200°C	250°C	200°C	250°C	200°C	250°C	200°C	250°C	200°C	250°C
Average ΔB%	93%	100%	86%	99%	61%	99%	69%	99%	83%	100%
dev.st	2%	0%	2%	0%	5%	0%	6%	0%	2%	0%
rsd%	2%	0%	2%	0%	8%	0%	8%	0%	3%	0%
Median	93%	99%	86%	100%	62%	99%	69%	99%	83%	100%
min	90%	99%	82%	99%	48%	99%	60%	99%	77%	100%
max	100%	100%	88%	100%	66%	99%	85%	100%	86%	100%

Using this dataset, an experimental design was created to develop a mathematical model that relates the degree of demagnetization to the variables of time, temperature, and their interaction. The resulting mathematical model can be used to predict the theoretically obtainable degree of demagnetization by specifying the values of the time and temperature variables in advance.

Below are a series of graphs (Figures 9-14), generated using the "CAT" software (Leardi et al.), illustrating the relationship between the degree of demagnetization and the variables of time and temperature. Fig. 9-10-11 displays the response curves for the average degree of demagnetization, compared to the mean measured, respectively, at point C1N, C1S and S1N on the magnets, as a function of time and temperature variables. Fig.12-13-14 show the three-dimensional graph from which the two-dimensional cross-section depicted in Figure 9-10-11, respectively, is derived. The data used for constructing the experimental design were based on the average degree of demagnetization measured at three points on the magnets: C1N and C1S, representing the central points of the north and south faces of the magnets, respectively, and S1N, chosen to observe the demagnetization behavior at a point located at the edge of the magnets. The demagnetization trends for the remaining points are consistent with the trends observed at these three selected points.

By fixing a temperature corresponding to one of the three levels in the experimental design and intersecting one of the blue curves on the graph, it is possible to determine the time required to achieve the average degree of demagnetization indicated by the respective curve.

The experimental design reveals that there is indeed an interaction between time and temperature on the degree of demagnetization, as evidenced by the non-linear relationship observed between the two variables.

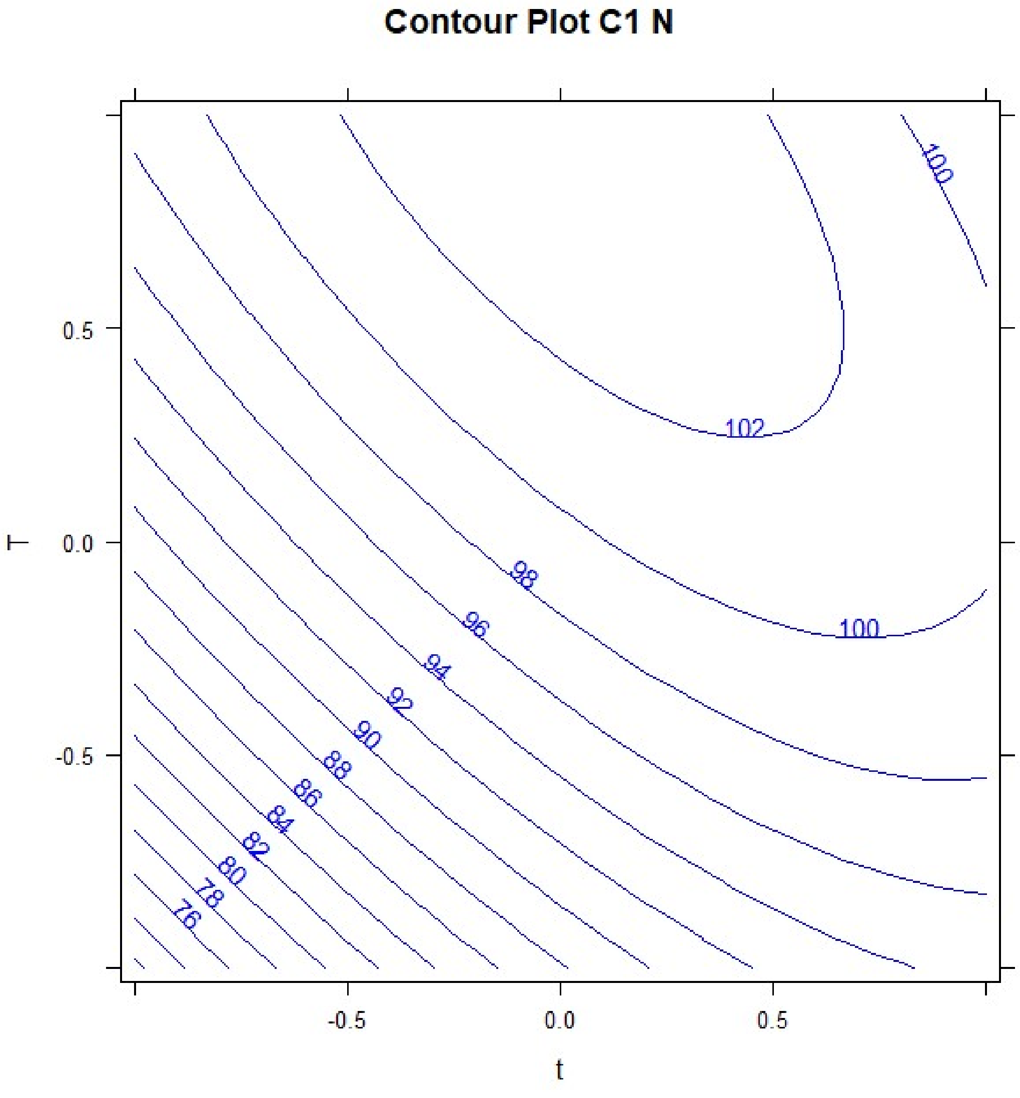

Figure 9: The graph displays the response curves for the average degree of demagnetization, compared to the mean measured at point C1N on the magnets, as a function of time and temperature variables.

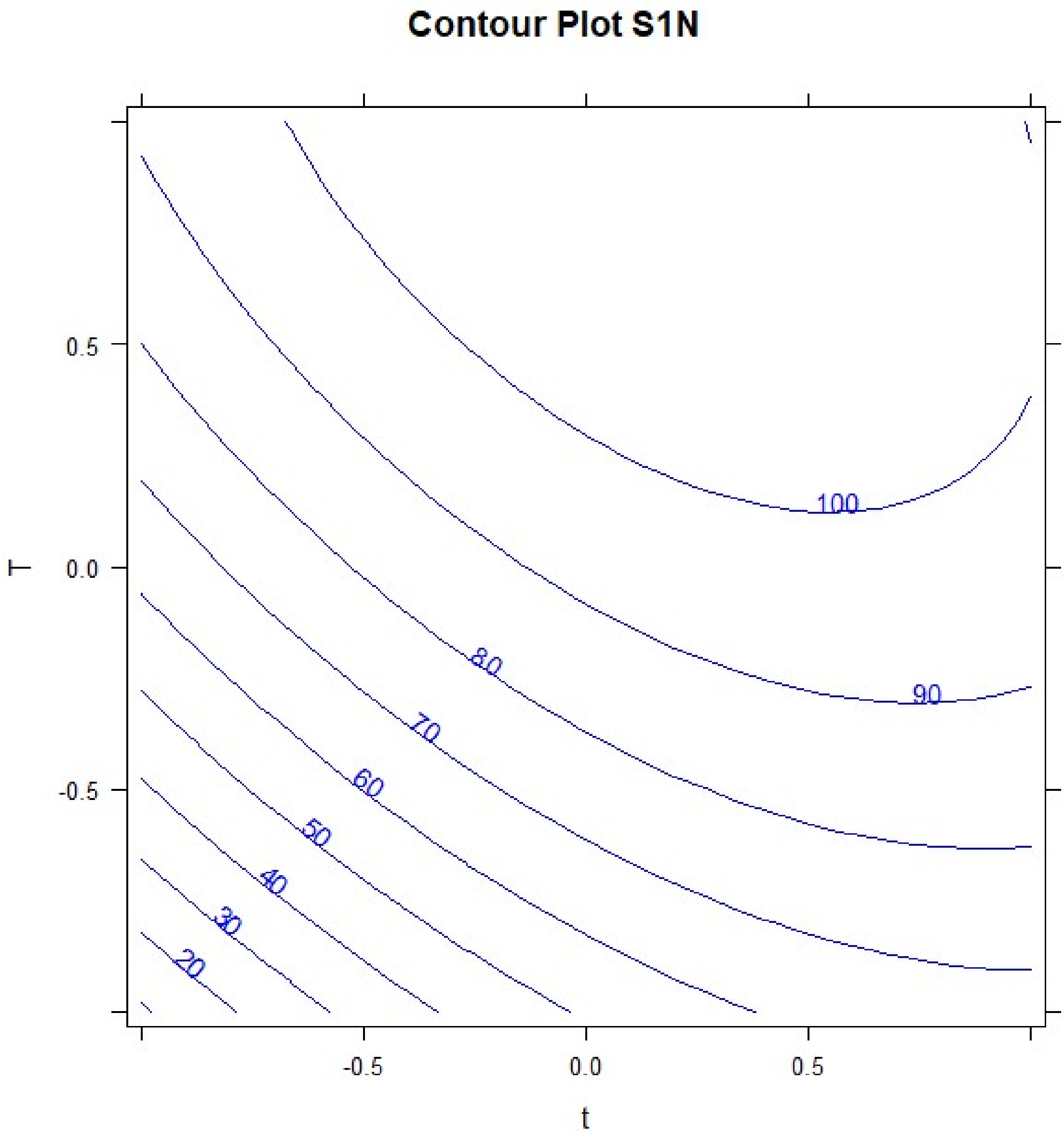

Figure 10: The graph displays the response curves of the average degree of magnetization, relative to the average measured at the S1N point of the magnets, in relation to the time and temperature variables.

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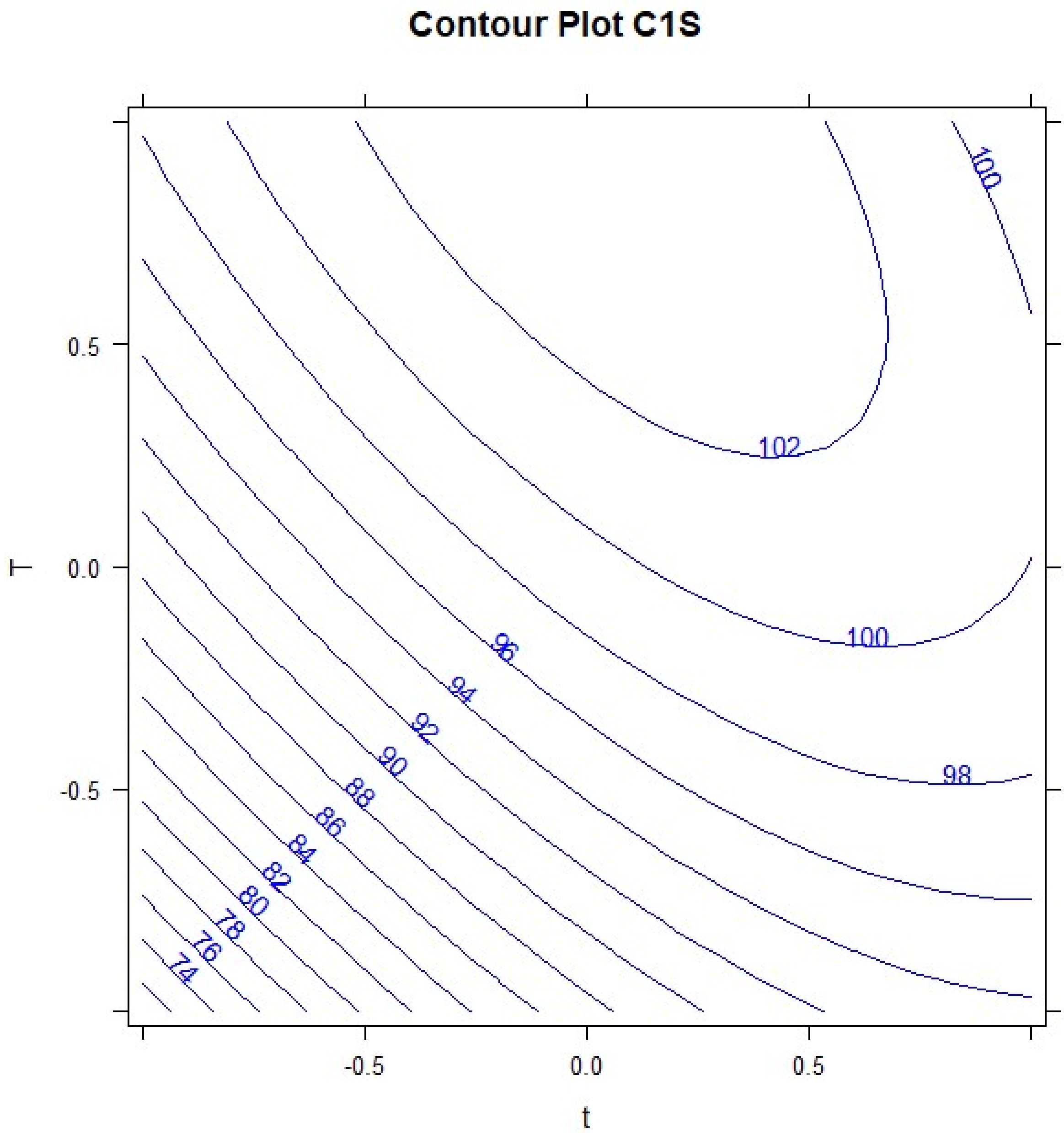

Figure 11: The graph shows the response curves of the average magnetization, relative to the average measured at the C1S point of the magnets, in relation to the variables of time and temperature.

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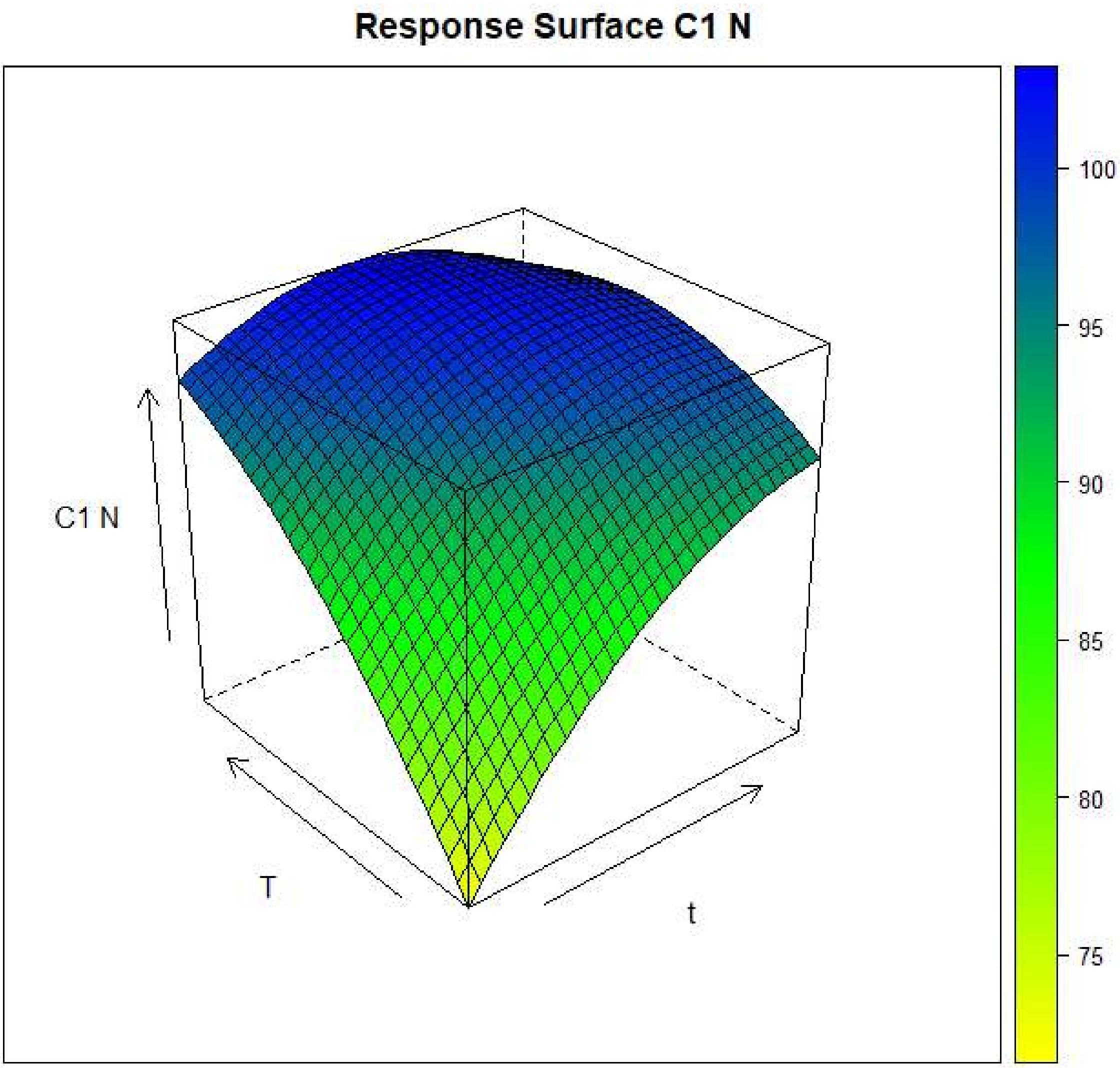

Figure 12: Three-dimensional graph from which the two-dimensional cross-section depicted in Figure 9 is derived.

.

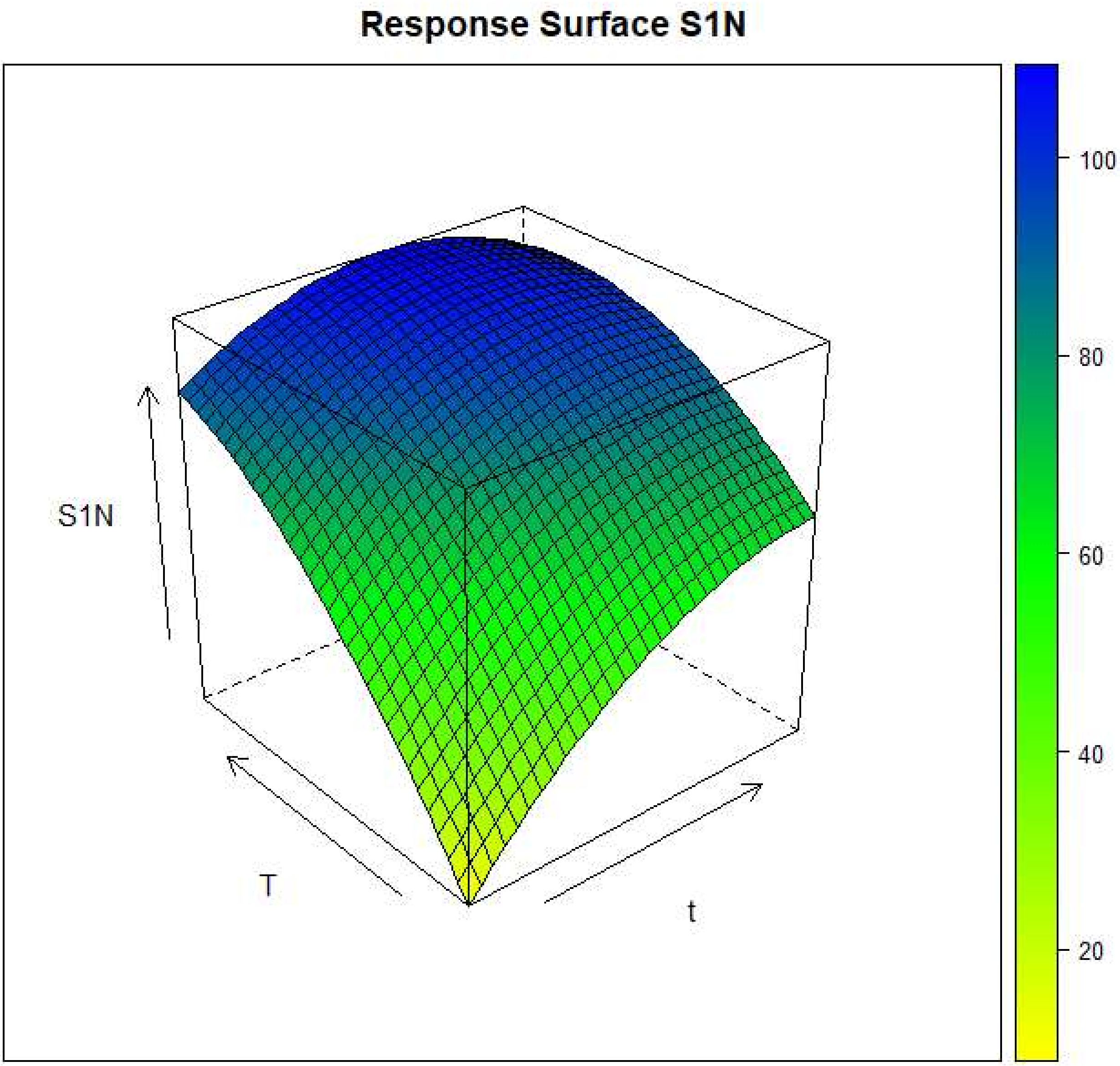

Figure 13: Three-dimensional graph from which the two-dimensional cross-section presented in Figure 10 is derived.

.

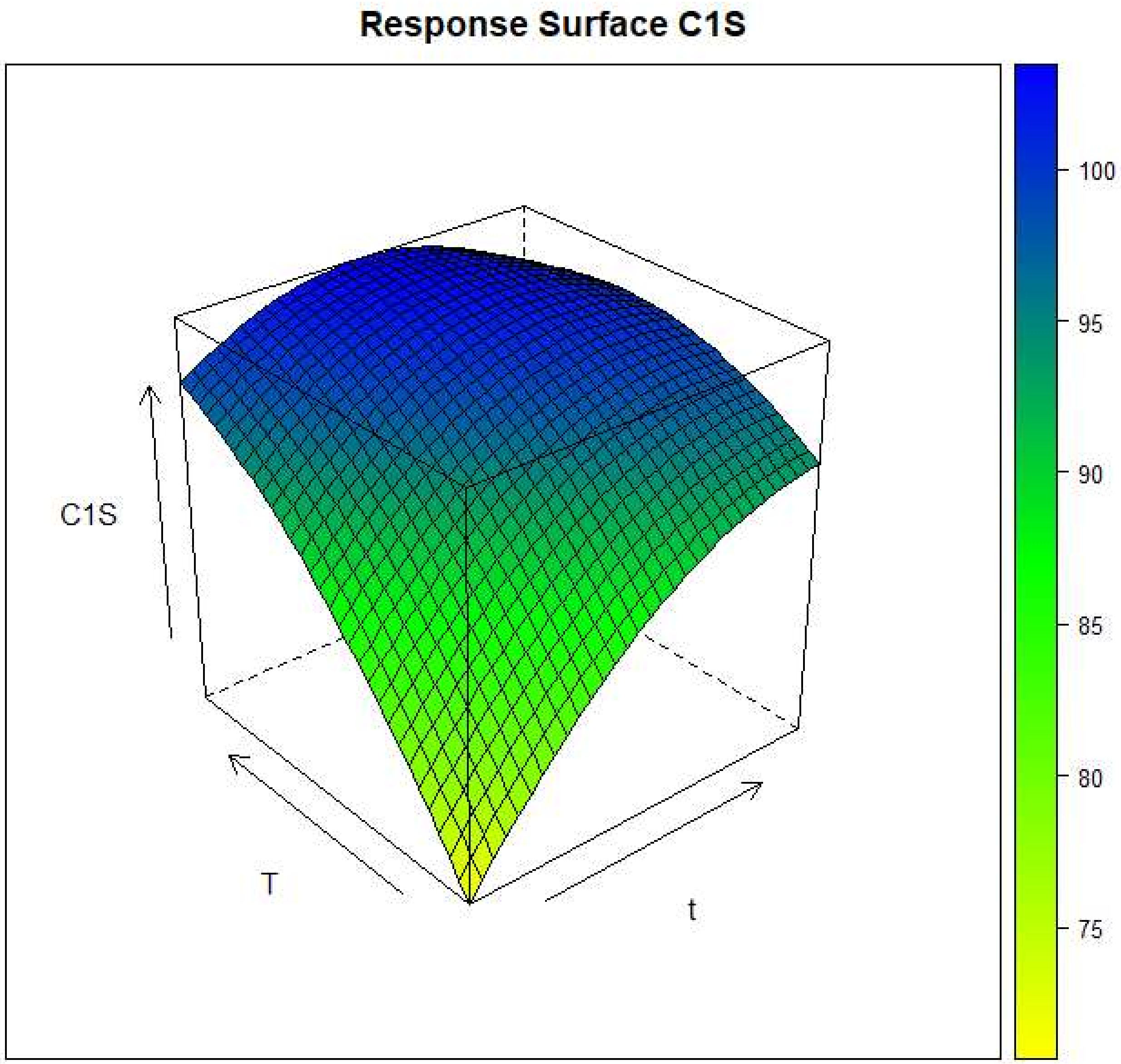

Figure 14: Three-dimensional graph from which the two-dimensional cross-section depicted in Figure 11 is derived.

In Fig. 12-13-14, the x-axis and y-axis represent time and temperature, respectively, with values increasing in the directions indicated by the arrows. The z-axis shows the average degree of demagnetization, which increases along the direction of its corresponding arrow. It is observed that the degree of demagnetization increases more significantly with rising temperature. This result is further emphasized by the coefficient related to the temperature variable (T) shown in Figure 15-16-17, which is greater than the coefficient related to the time variable (t).

In Fig.15-16-17, the values of the coefficients for the mathematical model obtained through the experimental design are shown for points C1N, S1N, and C1S, respectively. The "Maximum Leverage" value indicates the reliability of the mathematical model. A lower value of Maximum Leverage means that the model is more capable of accurately predicting the demagnetization outcome when the time and temperature variables are set in advance.

The following are the definitions of the parameters in the experimental model:

- b0: Represents the constant term of the mathematical model.
- t: Represents the coefficient for the linear effect of the time variable in the model.
- T: Represents the coefficient for the linear effect of the temperature variable in the model.
- t*T: Represents the coefficient for the linear interaction between the time and temperature variables in the model.
- t^2: Represents the coefficient for the quadratic effect of the time variable in the model.
- T^2: Represents the coefficient for the quadratic effect of the temperature variable in the model.

In Figure 15-16-17, the degrees of freedom and the standard deviation of the various coefficients are also shown. RMSECV (Root Mean Square Error of Cross-Validation) indicates the percentage error obtained in predicting the average degree of demagnetization.

```
[1] Maximum leverage
[1] 0.05717
[1]
[1] Coefficients
    b0       t       T     t*T     t^2     T^2
99.432   5.651   7.690  -5.786  -4.814  -3.913
[1]
[1] Degrees of freedom (regression)
[1] 123
[1]
[1] Std.dev. of coefficients:
    b0       t       T     t*T     t^2     T^2
0.4601  0.2555  0.2585  0.3166  0.4425  0.4376
...
[1] RMSECV
[1] 2.431
```

Figure 15: Coefficients of the mathematical model derived from the experimental design for the point C1N.

```
[1] Maximum leverage
[1] 0.05717
[1]
[1] Coefficients
    b0      t      T    t*T    t^2    T^2
 92.51  16.47  28.98 -12.29 -13.53 -12.47
[1]
[1] Degrees of freedom (regression)
[1] 123
[1]
[1] Std.dev. of coefficients:
    b0      t      T    t*T    t^2    T^2
1.5952 0.8856 0.8961 1.0975 1.5339 1.5172
---
 [1] RMSECV
 [1] 8.41
```

Figure 16: Coefficients from the mathematical model derived through the experimental design for the point S1N.

```
[1] Maximum leverage
[1] 0.05717
[1]
[1] Coefficients
    b0      t      T    t*T    t^2    T^2
99.331  5.791  8.048 -5.714 -5.163 -3.937
[1]
[1] Degrees of freedom (regression)
[1] 123
[1]
[1] Std.dev. of coefficients:
    b0      t      T    t*T    t^2    T^2
0.4612 0.2561 0.2591 0.3173 0.4435 0.4387
---
[1] RMSECV
[1] 2.434
```

Figure 17: coefficients from the mathematical model obtained through the experimental design for the point C1S.

4.5 Test 5- DOE applied to single magnets

The table 14 provides data on the degree of demagnetization for magnets treated individually, compared to their initial measured values. Table A presents the demagnetization degrees for points located on the north face of the magnets, while Table B shows the demagnetization degrees for points on the south face. The tables are organized into three columns, reflecting the degrees of demagnetization obtained at treatment temperatures of 200°C, 250°C, and 300°C, respectively. The purpose of this test is to plot a demagnetization curve using experimental design to understand the influence of time and temperature on magnets treated individually.

Table 14: a) degrees of demagnetization after treatment at 200°C, 250°C, 300°C for durations of 15, 35, and 60 minutes for each temeprature for the points located on the north face of the magnet b) degrees of demagnetization after treatment at 200°C, 250°C, 300°C.

a)

Time: 10 minutes															
	C1 N			C2 N			S1 N			C3 N			C4 N		
	200°C	250°C	300°C	200°C	250°C	300°C	200°C	250°C	300°C	200°C	250°C	300°C	200°C	250°C	300°C
Average ΔB%	85%	98%	100%	83%	98%	100%	77%	97%	100%	81%	97%	100%	83%	98%	100%
dev.st	1%	1%	0%	2%	1%	0%	3%	1%	0%	2%	1%	0%	1%	1%	0%
rsd%	2%	1%	0%	2%	1%	0%	4%	1%	0%	2%	1%	0%	2%	1%	0%
Median	86%	98%	100%	83%	98%	100%	77%	97%	100%	81%	97%	100%	84%	98%	100%
min	83%	96%	100%	80%	96%	100%	69%	95%	100%	78%	95%	100%	81%	96%	100%
max	87%	99%	100%	85%	99%	100%	80%	98%	100%	84%	98%	100%	85%	100%	100%
Time: 35 minutes															
	C1 N			C2 N			S1 N			C3 N			C4 N		
	200°C	250°C	300°C	200°C	250°C	300°C	200°C	250°C	300°C	200°C	250°C	300°C	200°C	250°C	300°C
Average ΔB%	90%	100%	100%	88%	100%	100%	84%	100%	100%	87%	100%	100%	89%	100%	100%
dev.st	1%	0%	0%	1%	0%	0%	2%	0%	0%	1%	0%	0%	1%	0%	0%
rsd%	1%	0%	0%	1%	0%	0%	2%	0%	0%	1%	0%	0%	1%	0%	0%
Median	90%	100%	100%	89%	100%	100%	85%	100%	100%	88%	100%	100%	89%	100%	100%
min	88%	99%	100%	86%	100%	100%	81%	100%	100%	85%	100%	100%	87%	100%	100%
max	92%	100%	100%	90%	100%	100%	87%	100%	100%	90%	100%	100%	90%	100%	100%
Time: 60 minutes															
	C1 N			C2 N			S1 N			C3 N			C4 N		
	200°C	250°C	300°C	200°C	250°C	300°C	200°C	250°C	300°C	200°C	250°C	300°C	200°C	250°C	300°C
Average ΔB%	91%	100%	100%	90%	100%	100%	86%	100%	100%	89%	100%	100%	90%	100%	100%
dev.st	1%	0%	0%	1%	0%	0%	2%	0%	0%	1%	0%	0%	1%	0%	0%
rsd%	1%	0%	0%	1%	0%	0%	2%	0%	0%	1%	0%	0%	1%	0%	0%
Median	91%	100%	100%	90%	100%	100%	86%	100%	100%	89%	100%	100%	90%	100%	100%
min	90%	100%	100%	87%	100%	100%	83%	100%	100%	88%	100%	100%	88%	100%	100%
max	92%	100%	100%	92%	100%	100%	90%	100%	100%	90%	100%	100%	92%	100%	100%

b)

Time: 10 minutes															
	C1 S			C2 S			S1 S			C3 S			C4 S		
	200°C	250°C	300°C	200°C	250°C	300°C	200°C	250°C	300°C	200°C	250°C	300°C	200°C	250°C	300°C
verage ΔB%	84%	98%	100%	82%	98%	100%	76%	97%	100%	80%	97%	100%	82%	98%	100%
dev.st	2%	1%	0%	2%	1%	0%	3%	1%	0%	3%	1%	0%	2%	1%	0%
rsd%	2%	1%	0%	2%	1%	0%	3%	1%	0%	4%	1%	0%	2%	1%	0%
Median	84%	98%	100%	82%	98%	100%	76%	97%	100%	80%	97%	100%	82%	98%	100%
min	81%	96%	100%	77%	96%	100%	71%	95%	100%	75%	95%	100%	80%	96%	100%
max	86%	100%	100%	85%	100%	100%	79%	99%	100%	86%	99%	100%	85%	100%	100%
Time: 35 minutes															
	C1 S			C2 S			S1 S			C3 S			C4 S		
	200°C	250°C	300°C	200°C	250°C	300°C	200°C	250°C	300°C	200°C	250°C	300°C	200°C	250°C	300°C
verage ΔB%	90%	100%	100%	88%	100%	100%	83%	100%	100%	87%	100%	100%	88%	100%	100%
dev.st	1%	0%	0%	2%	0%	0%	2%	0%	0%	1%	0%	0%	2%	0%	0%
rsd%	1%	0%	0%	2%	0%	0%	2%	0%	0%	1%	0%	0%	2%	0%	0%
Median	90%	100%	100%	88%	100%	100%	83%	100%	100%	86%	100%	100%	88%	100%	100%
min	89%	100%	100%	85%	100%	100%	81%	100%	100%	85%	100%	100%	85%	100%	100%
max	91%	100%	100%	90%	100%	100%	86%	100%	100%	89%	100%	100%	90%	100%	100%
Time: 60 minutes															
	C1 S			C2 S			S1 S			C3 S			C4 S		
	200°C	250°C	300°C	200°C	250°C	300°C	200°C	250°C	300°C	200°C	250°C	300°C	200°C	250°C	300°C
verage ΔB%	91%	100%	100%	89%	100%	100%	85%	100%	100%	88%	100%	100%	89%	100%	100%
dev.st	1%	0%	0%	1%	0%	0%	2%	0%	0%	1%	0%	0%	1%	0%	0%
rsd%	1%	0%	0%	1%	0%	0%	2%	0%	0%	1%	0%	0%	1%	0%	0%
Median	90%	100%	100%	89%	100%	100%	85%	100%	100%	88%	100%	100%	90%	100%	100%
min	89%	100%	100%	87%	100%	100%	83%	100%	100%	86%	100%	100%	87%	100%	100%
max	92%	100%	100%	91%	100%	100%	88%	100%	100%	89%	100%	100%	92%	100%	100%

The data collected from treating permanent magnets individually at 200°C, 250°C, and 300°C show that, compared to treating magnets within the rotor under the same operational conditions, the average degree of demagnetization after 10 minutes is consistently higher in all cases (see Table 15).

Table 15: Average degree of demagnetization after 10 minutes for magnets treated individually versus those treated within the rotor at different temperatures: 200°C, 250°C, and 300°C.

	Individually treated magnets			Magnets treated within the rotor		
	C1 N after 10 minutes					
	200°C	250°C	300°C	200°C	250°C	300°C
Average ΔB%	85%	98%	100%	70%	89%	98%
dev.st	1%	1%	0%	3%	1%	1%
rsd%	2%	1%	0%	5%	2%	1%
Median	86%	98%	100%	70%	89%	98%
min	83%	96%	100%	64%	86%	96%
max	87%	99%	100%	75%	91%	100%

Except for the treatment at 200°C, demagnetization is either complete or nearly complete for magnets treated individually after just 10 minutes of treatment (see Table 14). In all cases, the maximum achievable degree of demagnetization for the given temperature conditions is reached after 35 minutes of treatment (see Table 14).

As with Test 4, the results obtained were used to develop an experimental design aimed at creating a mathematical model that summarizes the findings and can predict the average degree of demagnetization based on predefined time and temperature variables. Using this experimental design, the graphs shown in Figures 18 through 23 were generated.

The figures 18-19-20 display the response curves for the average degree of demagnetization, compared to the mean measured, respectively, at point C1N, C1S and S1N on the magnets, as a function of time and temperature variables. The fig. 21-22-23 show the three-dimensional graph from which the two-dimensional cross-section depicted in Figure 18-19-20, respectively, is derived.

In Fig.24-25-26, the values of the coefficients for the mathematical model obtained through the experimental design are shown for points C1N, S1N, and C1S, respectively.

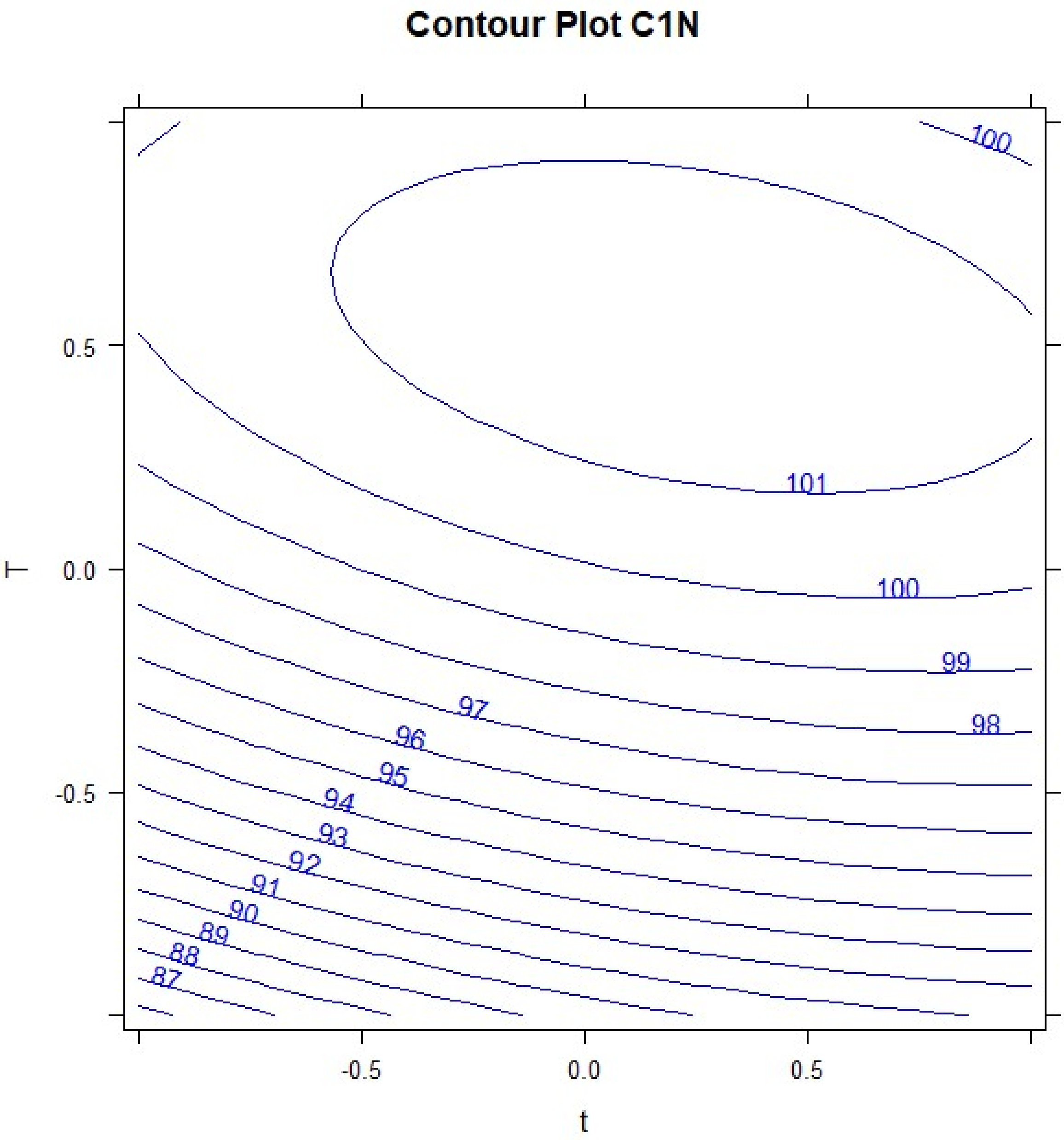

Figure 18: The graph displays the response curves of the average degree of demagnetization, compared to the average measured at point C1N on the magnets, in relation to the time and temperature variables.

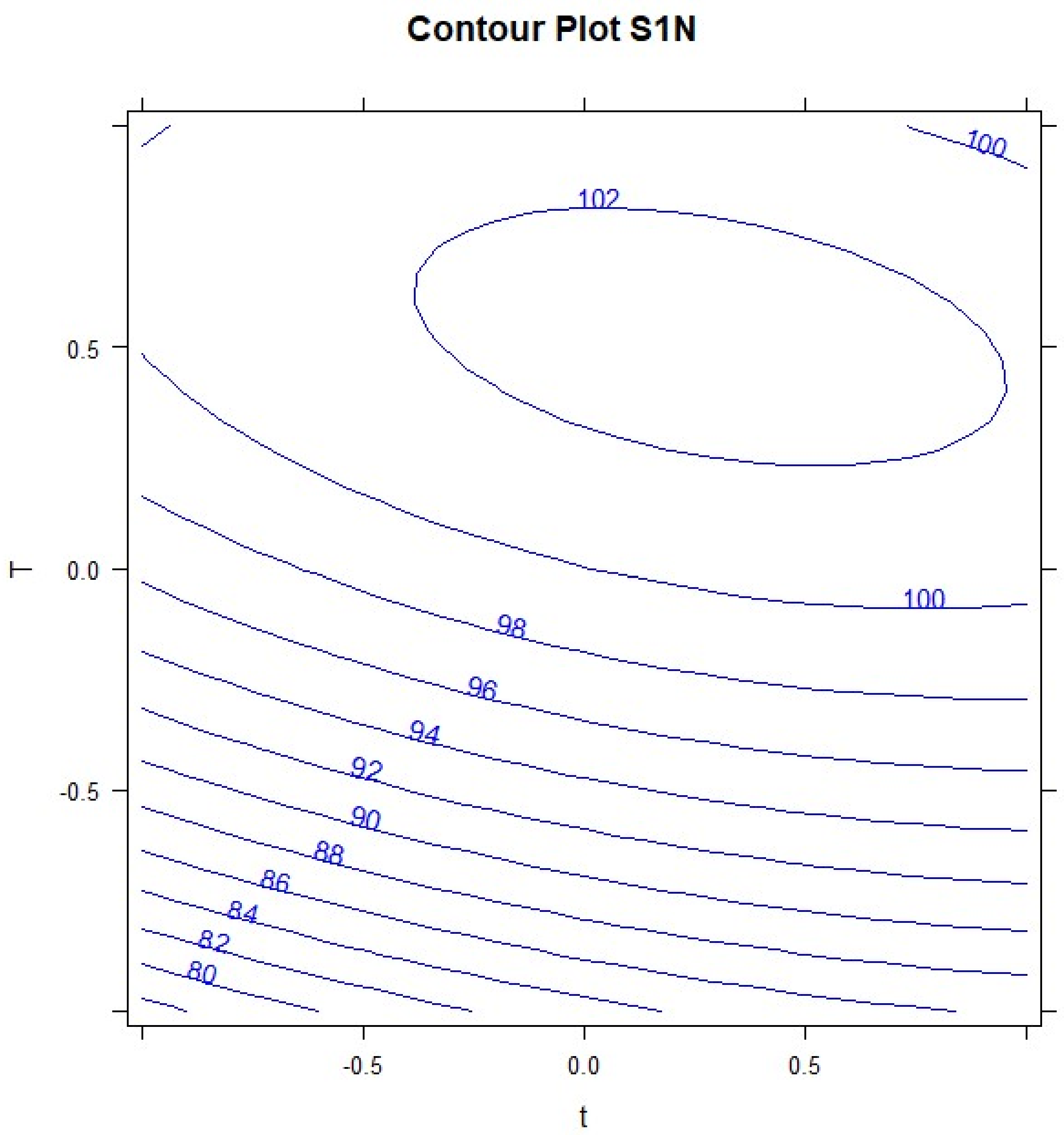

Figure 19: The graph shows the response curves of the average degree of demagnetization, compared to the average measured at point S1N on the magnets, in relation to the time and temperature variables.

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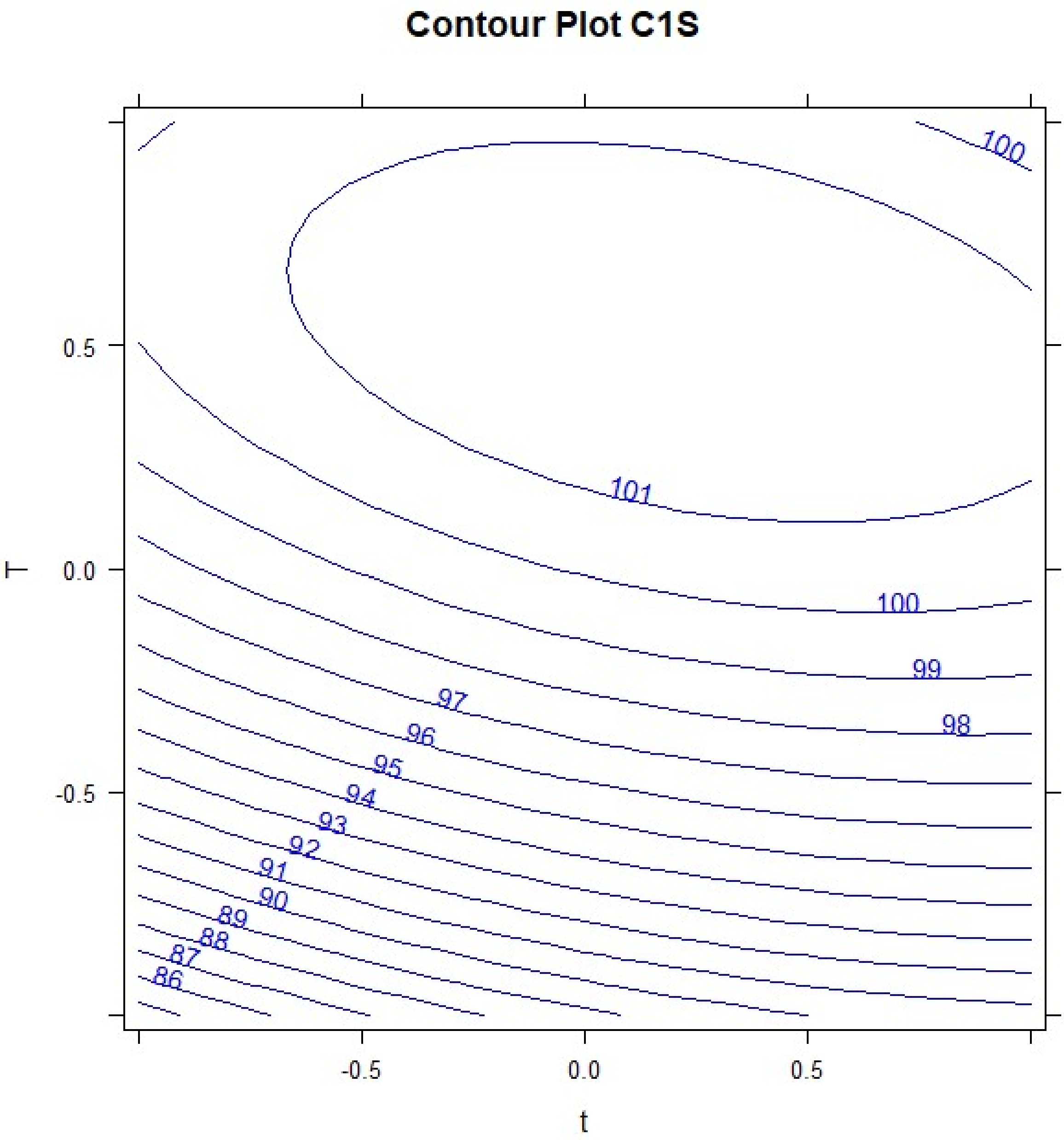

Figure 20: The graph shows the response curves of the average degree of demagnetization, compared to the average measured at point C1S on the magnets, in relation to the time and temperature variables

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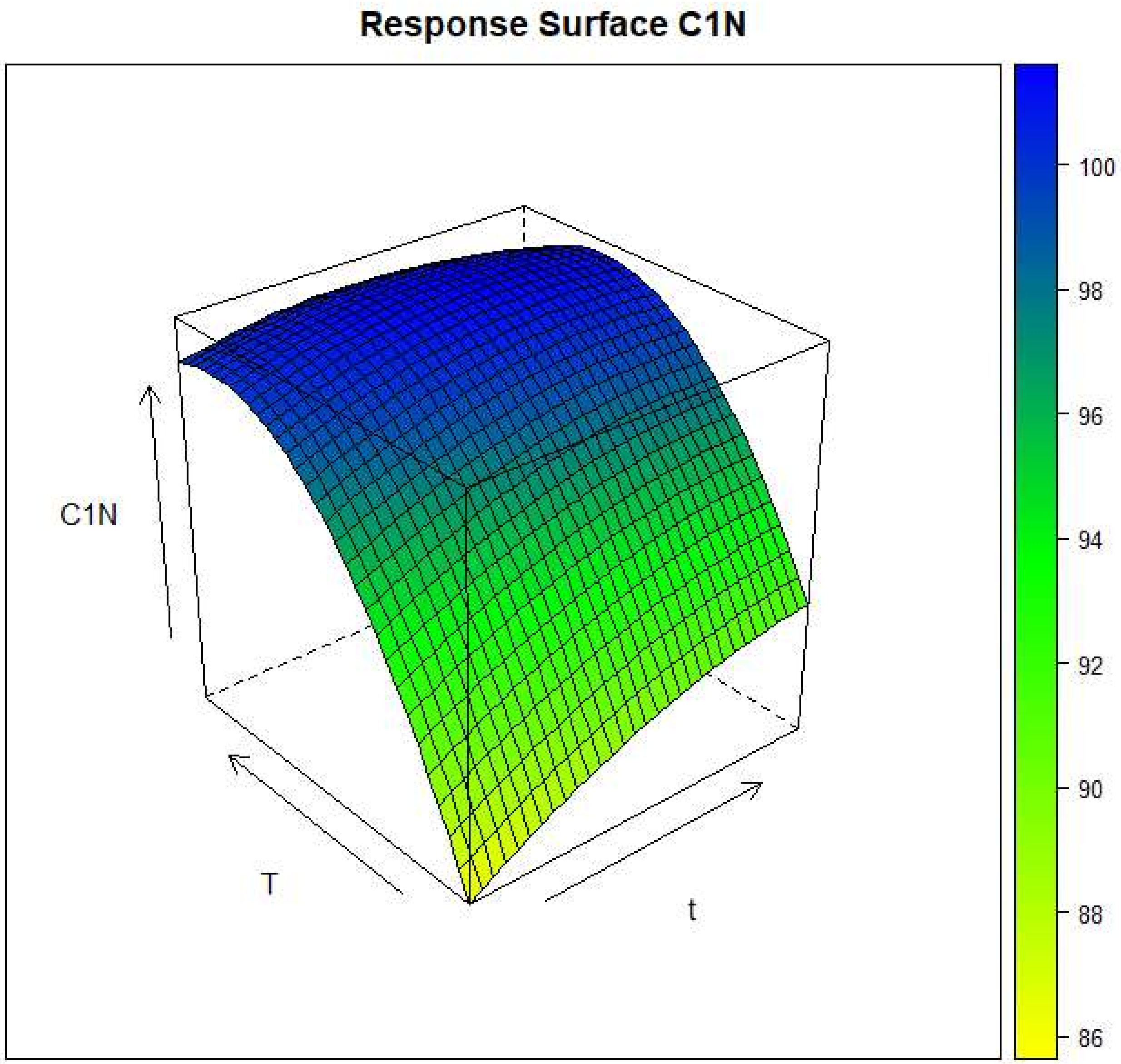

Figure 21: Three-dimensional graph from which the two-dimensional section shown in Figure 18 is derived

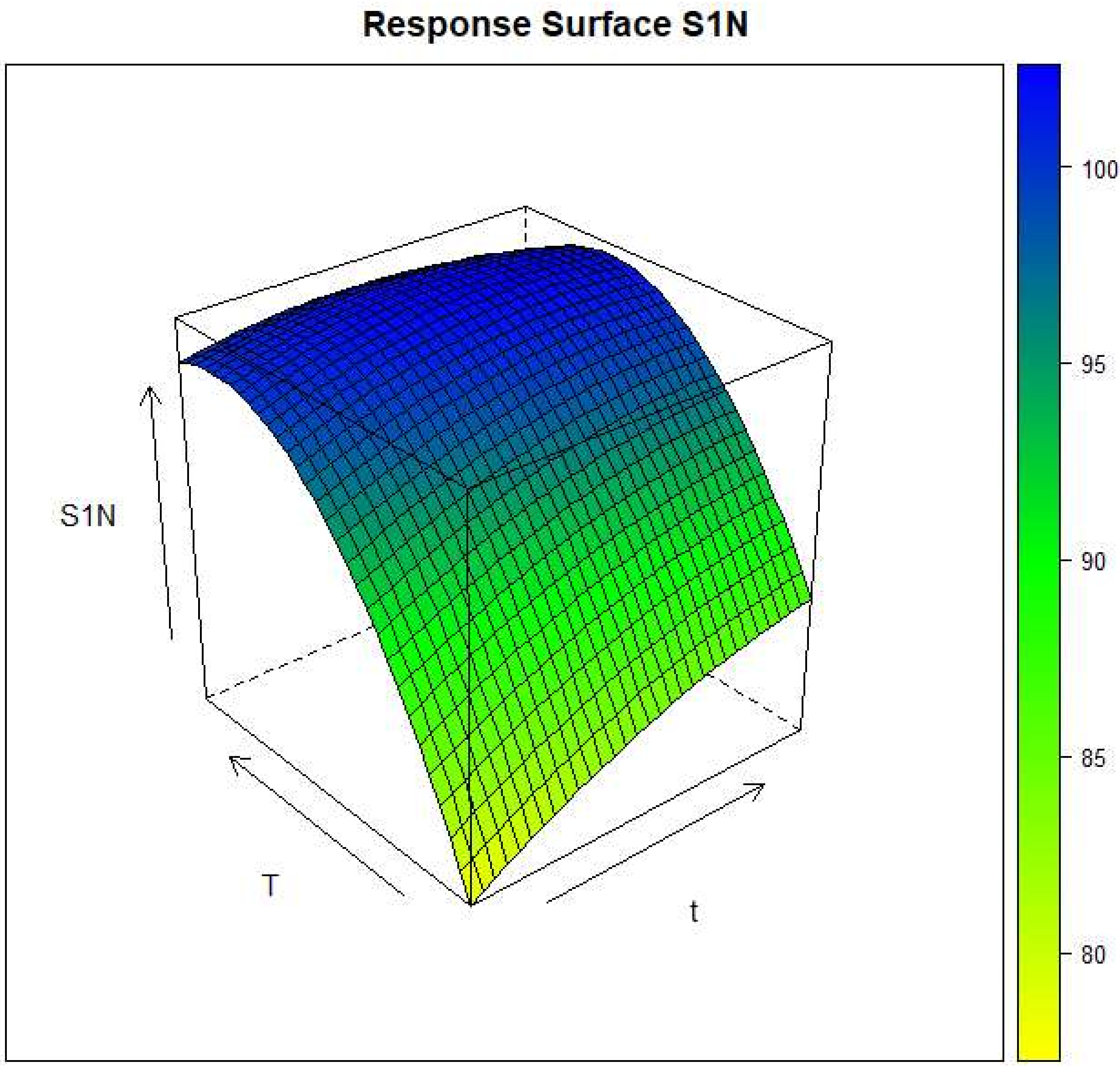

Figure 22: Three-dimensional graph from which the two-dimensional section shown in Figure 19 is derived

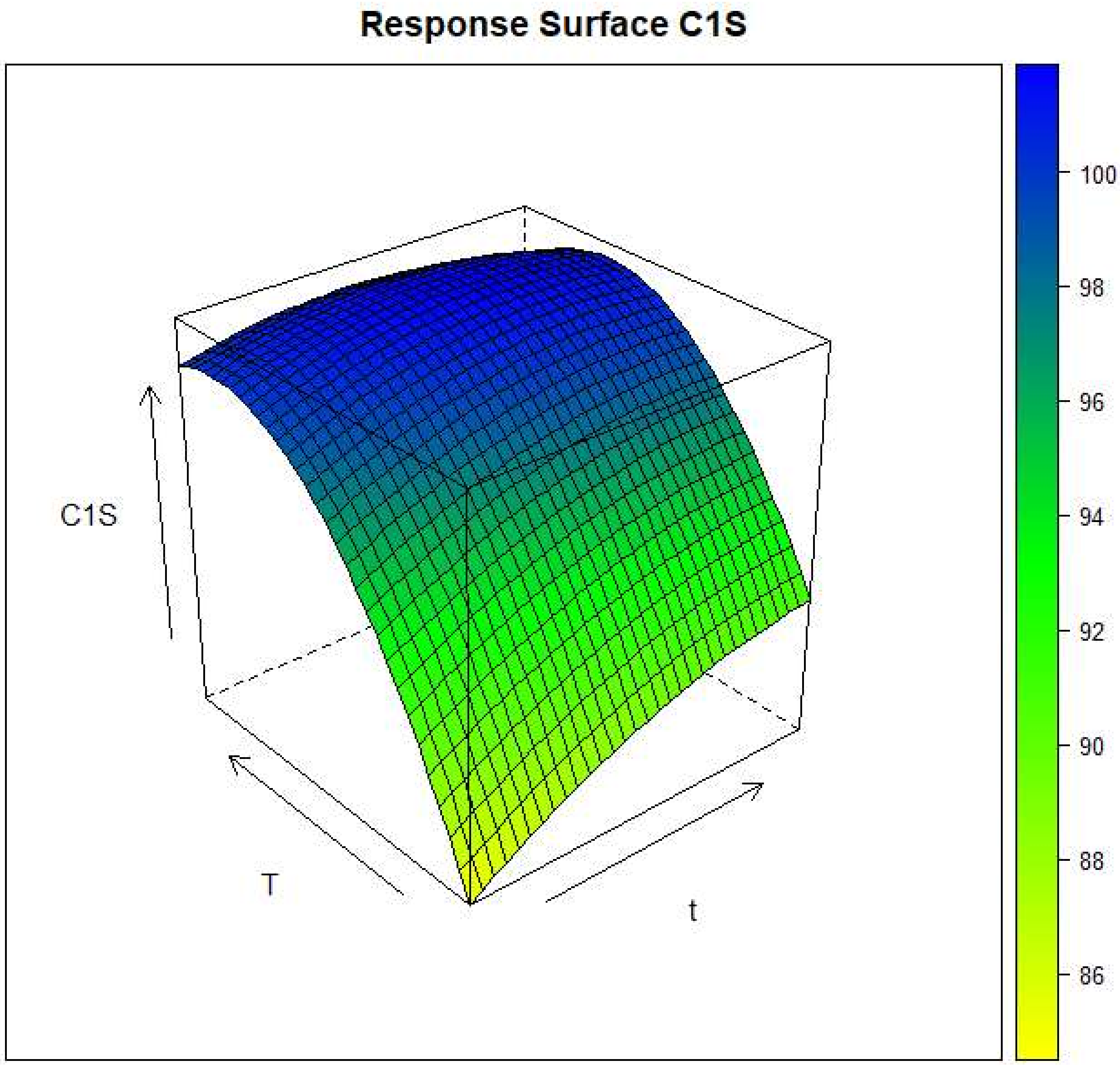

Figure 23: Three-dimensional graph from which the two-dimensional section shown in Figure 20 is derived.

```
[1] Maximum leverage
[1] 0.0575
[1]
[1] Coefficients
    b0      t      T    t*T    t^2    T^2
99.920  1.291  5.646 -1.446 -1.014 -4.874
[1]
[1] Degrees of freedom (regression)
[1] 121
[1]
[1] Std.dev. of coefficients:
     b0       t       T     t*T     t^2     T^2
0.16661 0.09188 0.09409 0.11386 0.16173 0.15809

[1] RMSECV
[1] 0.8736
```

Figure 24: The figure displays the values of the coefficients for the mathematical model derived from the experimental design for the point C1N.

```
[1] Maximum leverage
[1] 0.0575
[1]
[1] Coefficients
    b0      t      T    t*T    t^2    T^2
99.966  2.105  8.878 -2.411 -1.483 -7.832
[1]
[1] Degrees of freedom (regression)
[1] 121
[1]
[1] Std.dev. of coefficients:
    b0      t      T    t*T    t^2    T^2
0.2850 0.1572 0.1610 0.1948 0.2767 0.2705

[1] RMSECV
[1] 1.5
```

Figure 25: The figure displays the values of the coefficients for the mathematical model derived from the experimental design for the point S1N.

```
[1] Maximum leverage
[1] 0.0575
[1]
[1] Coefficients
     b0       t       T     t*T     t^2     T^2
100.103   1.430   6.024  -1.643  -1.188  -5.316
[1]
[1] Degrees of freedom (regression)
[1] 121
[1]
[1] Std.dev. of coefficients:
     b0       t       T     t*T     t^2     T^2
0.17894 0.09868 0.10106 0.12229 0.17370 0.16979

[1] RMSECV
[1] 0.9404
```

Figure 26: The figure displays the values of the coefficients for the mathematical model derived from the experimental design for the point C1S.

5 Conclusions

During this study, the thermal demagnetization behavior of NdFeB magnets was analyzed, both when treated individually and when assembled within the rotors of electric motors. The primary objective was to understand how different variables, including the cooling method, treatment duration, and temperature, influenced the degree of demagnetization.

A series of tests were conducted where magnets were removed from the rotors of various motors, their initial magnetic fields were measured, and they were subsequently subjected to thermal treatments at different temperatures and over progressively longer periods. Some magnets were treated individually, while others were tested in bulk within the rotors, allowing for a comparison of results and the evaluation of differences in demagnetization behavior under these operational conditions.

By using different cooling methods (water or air cooling), it was possible to determine whether the cooling method significantly affected the demagnetization behavior. Additionally, the tests at various temperatures allowed for the assessment of how the magnets' behavior changed with varying treatment temperatures, focusing on differences between magnets treated at 200°C, 250°C, and 300°C.

From the results obtained through various demagnetization tests, several conclusions have been drawn, as outlined below. Firstly, it was observed that the cooling method used to cool the magnets before measuring the magnetic field does not significantly affect the average degree of demagnetization achieved after thermal treatment. Given the measurement error, the results obtained with either cooling method overlap.

At each treatment temperature, there is a specific duration after which, even if the temperature is maintained constant, the average degree of demagnetization reaches a plateau or slows down significantly. If the temperature is sufficiently high, demagnetization becomes complete; otherwise, it remains relatively constant and below 100%.

It has been observed that the average degree of demagnetization varies depending on the measurement location, even when the temperature and treatment time are held constant. Magnets tend to reach the plateau more quickly at the center compared to the edges. The average degree of demagnetization at the edges is lower than at the center, indicating that the edges are more resistant to demagnetization.

Another notable finding is that the average degree of demagnetization achieved, when demagnetization is not complete, differs depending on whether the magnets are treated inside the rotor or individually. It appears that the manner in which the magnets are assembled within the rotor affects their response to demagnetization, causing the demagnetization process to be slower.

Through experimental design, a mathematical model has been developed to predict the average degree of demagnetization in relation to time and temperature variables, with an acceptable error margin of up to approximately 2%. This model accurately predicts outcomes within the range of time and temperature studied in the experiments.

At a 99.9% confidence interval, the coefficients obtained from the mathematical model are statistically significant. This indicates that not only do the linear terms for time and temperature significantly contribute to the degree of demagnetization, but the interaction between time and temperature and the quadratic terms also have significant effects. If this were not the case, the model could have been simplified by eliminating some of these terms.

The coefficients for time (t) and temperature (T) in the mathematical model show that the coefficient associated with temperature is consistently greater than that associated with time. This suggests that the effect of temperature on demagnetization is more influent than that of time.

6 References

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