Compatibility of Materials with the Magnetic Resonance Environment - Experimental Analysis.

Márcio Antônio Sens

Universidade Federal Fluminense – marciosens@id.uff.br;

Abstract: A non-destructive and non-invasive experimental technique, by electrical measurements, was used to determine the magnetic susceptibility and the magnetic classification of metallic samples of materials used by the dental-medical-hospital sector. The results of these analyzes constitute the basis for the release and marketing license of materials for the magnetic resonance environment by ANVISA. It was detected that apparently identical metallic samples, of the same technical nomenclature, but of different origins, exhibit different magnetic properties. The results of the magnetic properties of a series of materials, called biometals, were compared with water, toner, and common aluminum alloys.

Keywords: AISI 304, AISI 316, aluminum, ANVISA, eddy current, electrical conductivity, implants, magnetic susceptibility, MRI, orthopedic, prosthesis, stainless steel, thermal conductivity, titanium.

1 INTRODUCTION

In the dental-medical-hospital sector, there is a constant search for new materials, called biomaterials, or biometals, which can reduce costs and increase the safety of patients and employees involved in treatments and/or exams. These materials are used as prostheses, or as non-active implants by medical specialties in orthodontics and orthopedics. Biometals are incorporated into animals and humans for a variety of orthodontic or orthopedic purposes. Stainless steel, titanium and alloy screws are routinely used to repair or correct structural trauma in the form of non-active implants.

However, these materials need to be evaluated for compatibility with the MRI environment, an increasingly common medical test. In such an environment, where magnetic fields can reach levels of up to four teslas, the translational attraction and torque related to the static magnetic field can pose risks to patients and individuals with implants or ferromagnetic devices. The relative risks are proportional to the force caused by the static magnetic field present, the force due to the spatial gradient, the mass of the implant, the shape of the implant, and the magnetic susceptibility of the material from which it is made.

Common non-ferrous metals in prostheses include: Titanium and its alloys; Aluminum; Brass; Copper; Bronze and Aluminum Alloy Bronze. The metal most used and compatible with the MRI system for medical use is titanium, as it is light and strong, has low electrical conductivity, low thermal conductivity, and is not magnetic. But it has one big drawback: titanium is expensive.

On the other hand, in magnetic resonance techniques, as well as in some methods of volumetric spectroscopy, pulsed magnetic fields are used, which can induce eddy currents in conductive parts immersed in magnetic fields. Such currents generate other unexpected magnetic fields, which can alter images and lead to false diagnoses. In addition, eddy currents can generate significant heating of the conductive parts of the prostheses during magnetic resonance imaging - MRI with pulsating fields. Thus, it is also important to know the conductive properties of materials, both electrical and thermal.

In Brazil, the approval of the commercialization of materials for application by the dental-medical-hospital sector is the responsibility of the National Health Surveillance Agency - ANVISA, which evaluates each case, through requests from interested parties or companies specialized in the subject, and the providing consistent technical information. The reasons why ANVISA made such demands were not investigated, nor if they follow any international regulations.

This work presents laboratory experimental results of the compatibility of some metallic alloys with the magnetic resonance environment and compares stainless steels and aluminum alloys, apparently of similar alloys, but with different magnetic susceptibilities. It has been observed that almost insignificant distinctions in the composition of metallic alloys can result in significant magnetic behavior.

For the experiments, cylindrical specimens of up to 12 mm in diameter and 5 mm in height, machined, without heat treatment, were used.

This publication will deal with an experimental technique to validate the experimental determinations of the physical quantity called magnetic susceptibility, allowing the classification in paramagnetic, diamagnetic, or ferromagnetic. The technique is fast and non-destructive, in addition to using very small samples, with a volume of around 250 mm³. Samples can be reevaluated multiple times to perform averages and display results.

2 ON THE PURPOSE AND APPLICATION OF MAGNETIC SUSCEPTIBILITY IN THE MEDICAL-HOSPITAL SECTOR

The lack of knowledge of the true magnetic and conductive characteristics of the materials used in prostheses and surgical instruments, the negligence of specific knowledge, or even the assumption that they are slightly paramagnetic, have led to the occurrence of accidents in the magnetic resonance rooms of centers for hospital exams. In this way, ANVISA has taken the necessary precautions before releasing the commercialization of these materials in Brazil, through the request of technical reports by accredited laboratories.

3 ABOUT THE REASONS THAT MOTIVATED THE RESEARCH

Efforts and studies to increase the reliability in the evaluation of magnetic properties; the conductive, electrical and thermal properties of the materials housed inside the human or animal body, in the form of passive implants, are fundamental when submitted to magnetic resonance imaging. Often, implants are installed without proof of transparency to electromagnetic fields. Often, patients receive these implants without knowing what was applied to them and, when asked if they have something in their body that could interfere with the images of medical exams, they have no answers, not even knowing if the biomaterials were metallic or not. These materials are usually lodged in the bone; in the dental arches and even in the ears.

Determining the magnitude called magnetic susceptibility of a small sample of material, just 250 mm³, is not a simple or elementary task. On the contrary, such a task is quite complex, and sophisticated instruments are needed, with highly qualified operators. However, the emergence of new electrical measurement instruments, simple to handle and low cost, has currently facilitated such studies and research, using previously unused alternative techniques.

One of these instruments is the impedance analyzer[8], whose inductance measurement range is between L: 0000.001 nH to 99.99999 H ± 0.05%, with IEEE-488.2 Interface, which can be connected directly to a PC, to record sequences of readings directly into Excel spreadsheets.

The present study is also an alert to the authorities that control the commercialization of dental, medical, and hospital materials, as well as to prosthesis designers, so that they become aware of the risks and that the experimental verification of the physical properties of the materials is within reach. Negligence can thus be avoided to mitigate the possibilities of future losses.

4 FUNDAMENTAL CONCEPTS

Magnetic measurements are indispensable in characterizing the magnetic properties of materials used for many modern applications and lead to advances in physics, medicine, and materials science[3].

If a material is placed inside a conductive coil and an electric current is applied through it, a magnetic field will appear in the coil, whose induction B can be defined by:

$$B = \mu_o \cdot [H + M][T]$$, where: Equation (1)

μ_0 = Air or vacuum permeability, [H/m];
H = Intensity of applied magnetic field, [A/m];
M= Magnetization due to material, [A/m];
B = Resultant magnetic induction, [T], [teslas].

$$\mu_x = \frac{B}{H} = \frac{\mu_o \cdot [H + M]}{H}$$, where: Equation (2)

μ_x = Permeability of the material immersed in the magnetic field, [H/m].

$$\mu_x = \frac{B}{H} = \frac{\mu_o \cdot [H + M]}{H} = \mu_o \cdot \left[1 + \frac{M}{H}\right]$$ Equation (3)

$$\mu_x = \frac{B}{H} = \mu_o \cdot \left[1 + \frac{M}{H}\right] = \mu_o \cdot [1 + \chi]$$, where: Equation (4)

χ = Magnetic susceptibility of the material immersed in the magnetic field of the coil, [Dimensionless].

Thus, the magnetic susceptibility is a coefficient of proportionality between the intensity of the magnetic field applied to a material and its magnetization. In general, this property is defined for non-ferromagnetic materials, as in ferromagnetic materials this quantity would be very high and non-linear, but strongly dependent on the intensity of the applied field.

With the availability of high-resolution automatic inductance measurement instruments with an IEEE-488.2 interface, the magnitude of the magnetic susceptibility of weakly paramagnetic or diamagnetic materials has also become possible through alternative techniques to previous magnetometers [4] and balance systems [1]. This is because, a conducting coil, air core, or X material core, has inductance as follows:

$$L_o = \mu_o \cdot \left[\frac{N^2 \cdot A_o}{\ell_o}\right] \Rightarrow L_x = \mu_x \cdot \left[\frac{N^2 \cdot A_x}{\ell_x}\right]$$, where: Equation (5)

$\mu_0 = 4 \cdot \pi \cdot 10^{-7}[H/m]$
N = number of coil turns;
A_0 and A_x = the core area, in [m²];
ℓ_0 and ℓ_x = the core length, in [m], and
L_0 and L_x = inductance of the set, in [H].

$$If \left[\frac{N^2 \cdot A_x}{\ell_x}\right] = \left[\frac{N^2 \cdot A_o}{\ell_o}\right] \Rightarrow \frac{L_x}{L_o} = \frac{\mu_x}{\mu_o}$$ Equation (6)

$$\frac{L_x}{L_o} = [1 + \chi_m] \Rightarrow \chi_m = \left[\frac{L_x - L_o}{L_o}\right]$$ Equation (7)

If two identical pairs of mutual inductor coils are used, one with a sample core and the other with an air core, and the secondary windings are connected in series in two different ways, additive and subtractive, as shown in **Figure 1**, and in **Figure 2**, then,

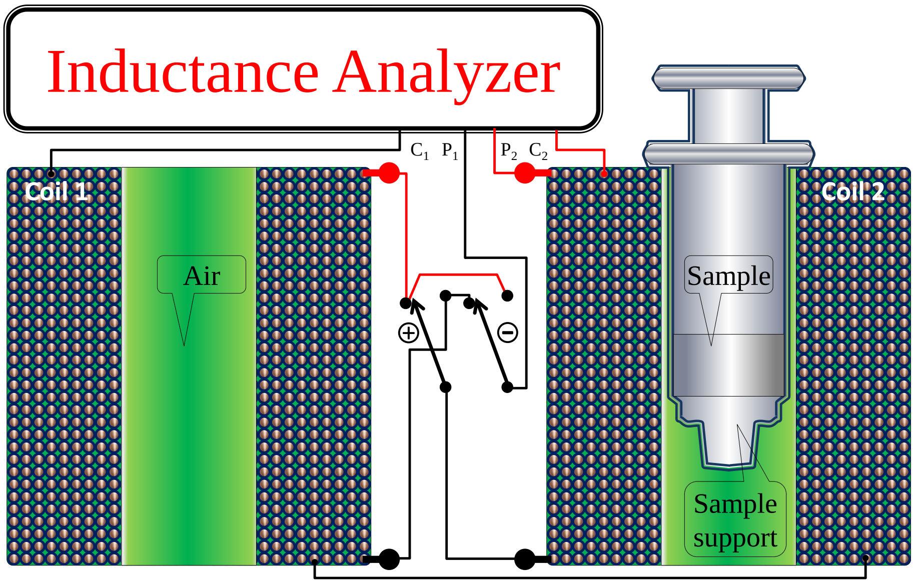


Figure 1 – Experimental Setup with Sample Housing inside the Mutual Inductor

$$A = L_x - L_o$$

$$B = L_x + L_o$$

$$A = L_x - L_o \Rightarrow B = L_x + L_o$$, then

$$\chi_m = \left[\frac{A}{B-A}\right] \cdot 2\,x\,100[\%]\,or\left[\frac{A}{B-A}\right] \cdot 2\,x\,10^6\,[ppm]$$, where Equation (8)

χ_m = Magnetic susceptibility of the material sample immersed in the magnetic field of the coil 2.

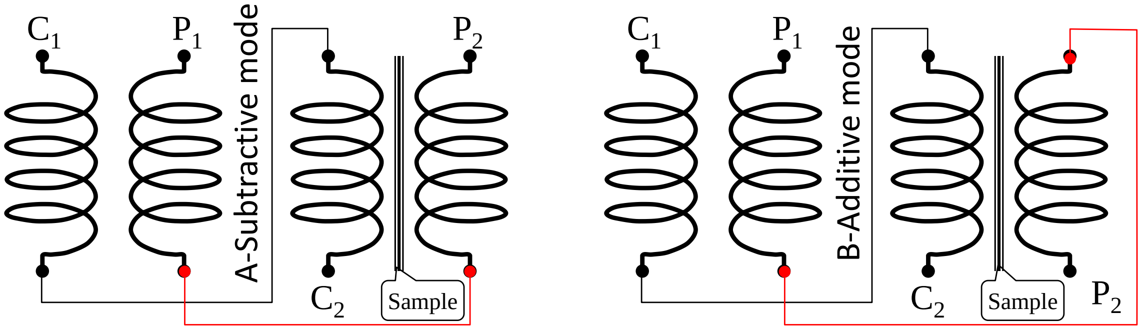


Figure 2 – Experimental Electrical Diagram with the Sample inside the Mutual Inductor

5 LITERATURE SURVEY

A biomaterial is understood to mean any synthetic material that is used to replace or restore body tissue function and is continuously or intermittently in contact with body fluids [9]. This definition is a bit restrictive, because it excludes materials used for devices such as surgical or dental instruments.

Although these instruments are exposed to body fluids, they do not replace or increase the function of human tissue. It should be noted, however, this material is extremely used for surgical instruments, particularly stainless steels and may be exposed to high magnetic field environments in MRI scanners [2].

Austenitic stainless steels are not ferromagnetic, in general, they harden easily and corrosion resistance is acquired by the presence of a surface film. Ferromagnetic alloys should not be used on the human body as they can become detached in a strong magnetic field. Ferrite should not be present in implants, not only from the point of view of its resistance to corrosion, but also because it is ferromagnetic. MRI should not be applied to an individual with any type of ferromagnetic material in their body and, if possible, should be avoided for any patient who has a metallic implant. Two possible problems can arise: the heating of the metal and the distortion of position produced by the metal even though it is not magnetic [2].

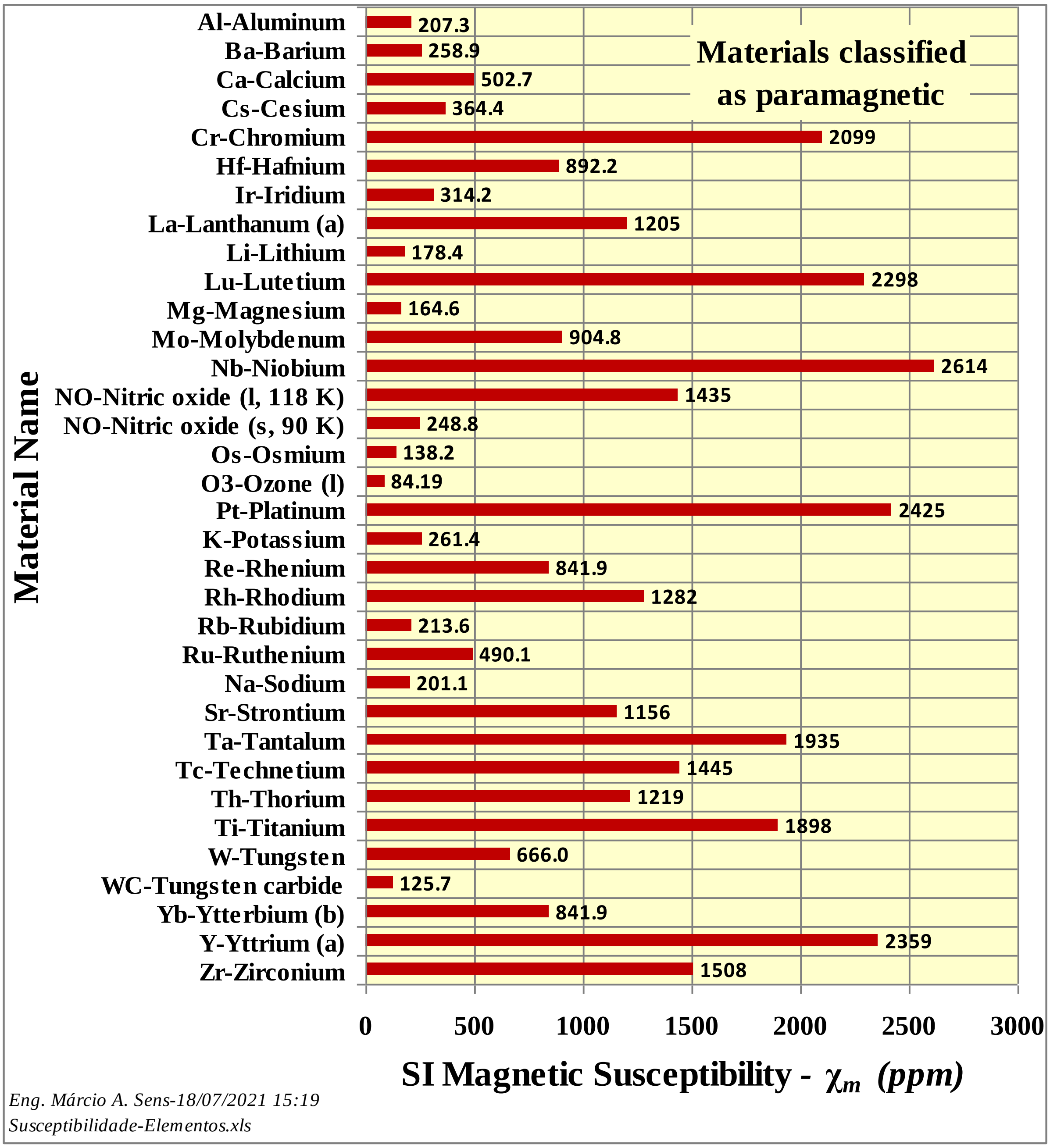
Standard procedures, adequately demonstrating experimental techniques for determining the magnetic susceptibility of small samples, were not found in the literature. But tables were found with results of magnetic susceptibility, in the CGS System [5], [6], [7] and [13], which were converted here to the International System of Units - SI, as shown in **Figure 3**, for the paramagnetic and similarly shown in **Figure 4** for diamagnetic materials. It should be noted, however, that bismuth, for having a much higher value in magnetic susceptibility, among the diamagnetic materials, had the graph bar cut off, so as not to leave the others too insignificant. It should also be noted that the unit of magnitude was expressed in ppm, not %.

These figures provide magnetic susceptibility values for the elements and inorganic compounds indicated, all values refer to nominal ambient temperature (285 to 300 K), unless otherwise indicated. When the physical state (s = solid, l = liquid, g = gas, aq = aqueous solution) is not given, the most common crystalline form is understood. An entry of “Iron” indicates a ferromagnetic substance.

Substances are arranged alphabetically by most common English name, not by chemical formula, except that compounds such as hydrides, oxides, and acids are grouped with the parent element. Water appears almost at the end of the list, as the name begins with the letter "W", in the English language.

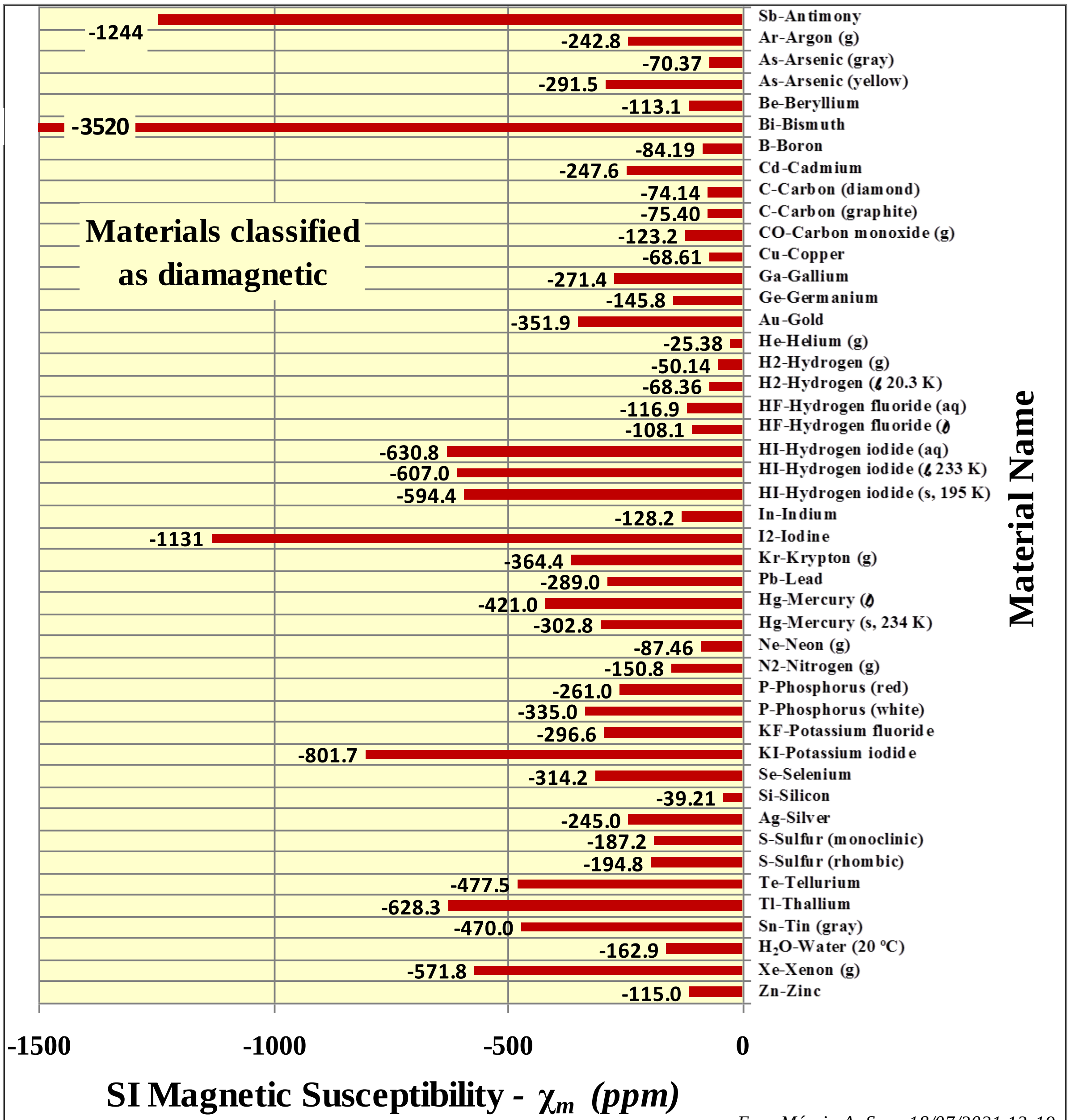
It should also be noted that the metallic elements are in pure form, not metallic alloys. Titanium, for example, is commercialized for human prostheses in the form of alloys, that is, added to other elements and, in this way, would have a distinct magnetic property.

It should also be taken into account that metallic materials, even in their pure state, that have been machined or molded, or beaten, can exhibit different magnetic properties. After such mechanical hardening, the materials can be annealed to relieve stress and return to their natural condition.



Eng. Márcio A. Sens-18/07/2021 15:19
Susceptibilidade-Elementos.xls

Figure 3 - Magnetic Susceptibility of Paramagnetic Materials [5], [6], [7] and [13].



Eng. Márcio A. Sens-18/07/2021 13:19
Susceptibilidade-Elementos.xls

Figure 4 - Magnetic Susceptibility of Diamagnetic Materials [5], [6], [7] and [13].

It is found in the literature, on the other hand, the use of magnetic property susceptibility as a factor for characterizing the concentration of magnetic nanoparticles in insulating mineral oil. The advantage, in this case, is that the sample will not be destroyed, altered or consumed, as would occur by analytical techniques. **Figure 5** reproduces and illustrates the application of magnetic susceptibility as a means of characterizing the concentration of magnetic particles in insulating mineral oil [10].

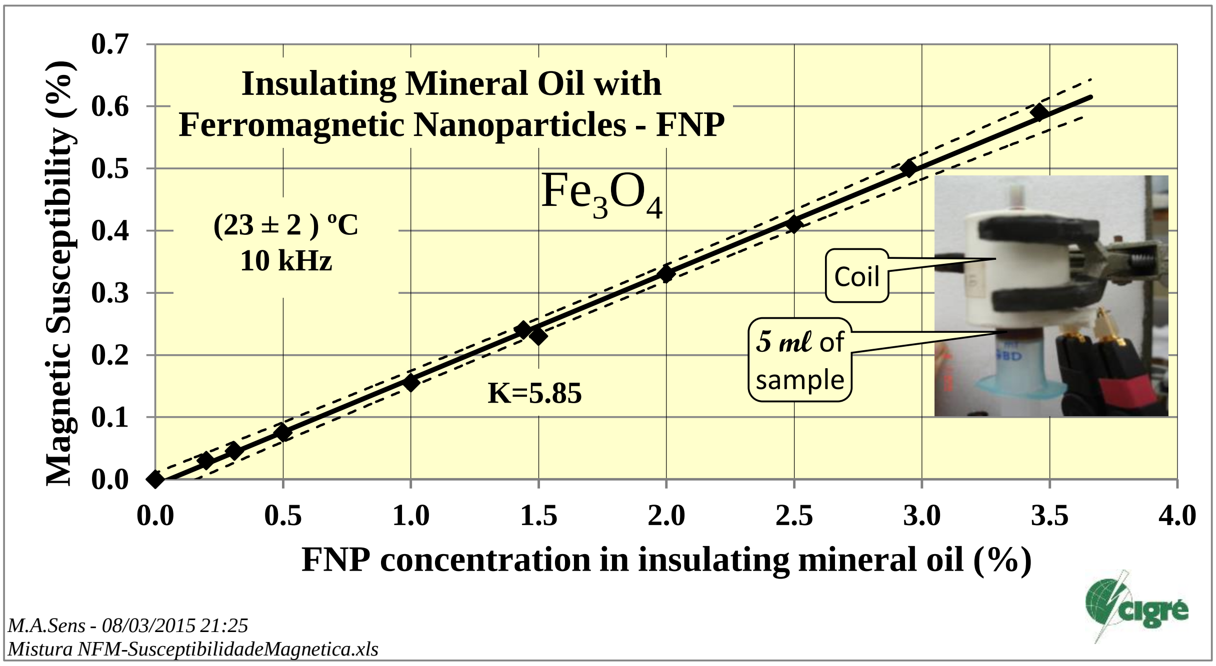


Figure 5 - Concentration of Magnetic Particles in Insulating Mineral Oil Through Magnetic Susceptibility [10].

6 OBJECT UNDER TEST AND RESULTS

The tested samples consisted of metallic cylinders, machined, not thermally treated, with 8 and 12 mm in diameter by 5 mm in height. All samples, solid, powdered, or liquid, of indicated volumes, were housed in injection syringes and inserted into the measurement solenoid described in **Figure 1**, page **4**.

The samples were provided by those interested in the analyses [12], [11], as required by the National Health Surveillance Agency - ANVISA, for the analysis of requests for authorization to market the products.

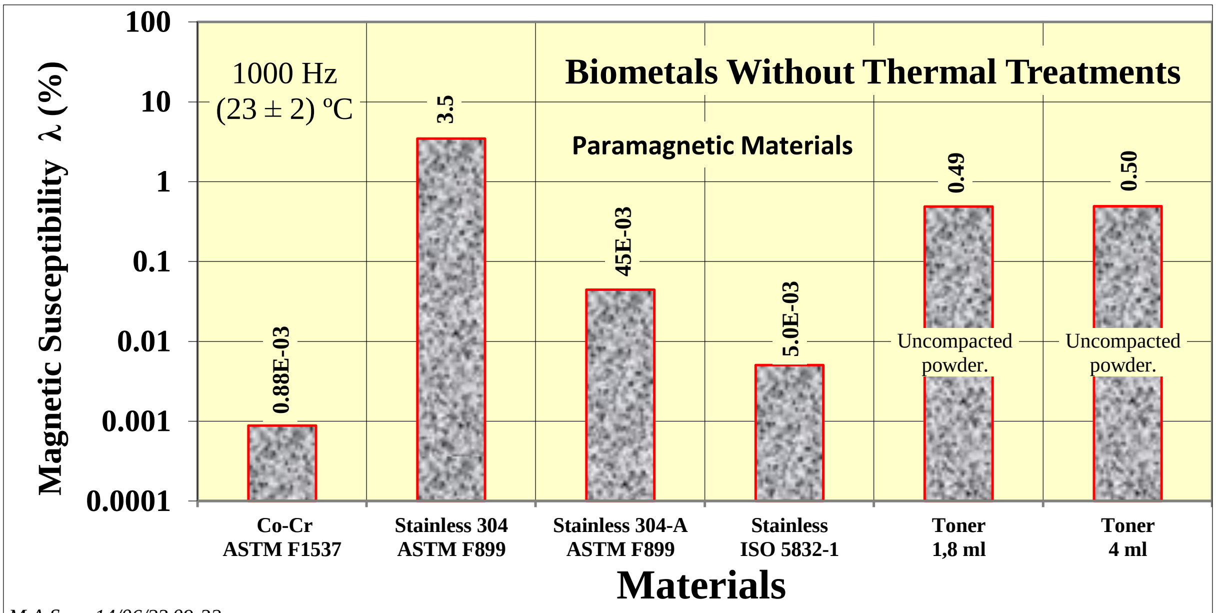
The properties of the evaluated biometal samples, including some reference materials such as toner and tap water, are shown in **Table 1**. In addition to the magnetic properties described here in detail, density; electrical conductivity, and thermal conductivity, whose analysis procedures are beyond the scope of this work.

Table 1 - Results Obtained for the Properties of the Evaluated Samples

Sample	Density	Electrical Conductivity (% IACS)	Thermal Conductivity [W/(m.K)]	Magnetic Susceptibility χ_m (%)	Magnetic Class
Co-Cr ASTM F1537	8.3288 ± 8.0E-3 (5 pts)	1.5185 ± 2.4E-3 (50 pts)	5.8799 ± 9.4E-3 (50 pts)	0.881E-3 ± 70E-6 (10 pts)	Paramagnetic
Aluminum ISO 209	2.6807 ± 4.1E-3 (2 pts)	49.454 ± 32E-3 (20 pts)	191.49 ± 0.13 (20 pts)	-2.2190 ± 3.7E-3 (50 pts)	Diamagnetic
Aluminum T6 6351	2.6873 ± 3.8E-3 (5 pts)	48.4870 ± 5.8E-3 (50 pts)	187.745 ± 22E-3 (50 pts)	-0.28093 ± 0.20E-3 (10 pts)	Diamagnetic
Stainless 304 ASTM F899	7.8249 ± 7.3E-3 (5 pts)	N/A	N/A	3.47674 ± 0.17E-3 (10 pts)	Paramagnetic
Stainless 304-A ASTM F899	7.8412 ± 8.4E-3 (5 pts)	1.6323 ± 7.3E-3 (50 pts)	6.320 ± 28E-3 (50 pts)	44.565E-3 ± 30E-6 (10 pts)	Paramagnetic
Stainless ISO 5832-1	7.875 ± 15E-3 (2 pts)	2.0546 ± 3.3E-3 (20 pts)	7.956 ± 13E-3 (20 pts)	5.04E-3 ± 0.60E-3 (50 pts)	Paramagnetic
Ti 6Aℓ 4V ASTM F136	4.3848 ± 1.7E-3 (5 pts)	0.70623 ± 0.35E-3 (50 pts)	2.7346 ± 1.3E-3 (50 pts)	-0.272E-3 ± 47E-6 (10 pts)	Diamagnetic
Ti 6Aℓ4V ISO 5832-3	4.3740 ± 8.5E-3 (10 pts)	0.9241 ± 2.0E-3 (100 pts)	3.5781 ± 7.7E-3 (100 pts)	-3.35E-3 ± 0.32E-3 (250 pts)	Diamagnetic
Titanium Grade 2 ASTM F67	4.4649 ± 8.3E-3 (5 pts)	3.1470 ± 7.2E-3 (50 pts)	12.185 ± 28E-3 (50 pts)	-1.976E-3 ± 68E-6 (10 pts)	Diamagnetic
Toner 1,8 ml	N/A	N/A	N/A	0.488833 ± 86E-6 (10 pts)	Paramagnetic
Toner 4 ml	N/A	N/A	N/A	0.49513 ± 0.75E-3 (25 pts)	Paramagnetic
Water 4 ml	N/A	N/A	N/A	-2.8E-3 ± 1.0E-3 (25 pts)	Diamagnetic
T(°C)	**23 ± 2**	**20**	**20**	**23 ± 2**	**23 ± 2**

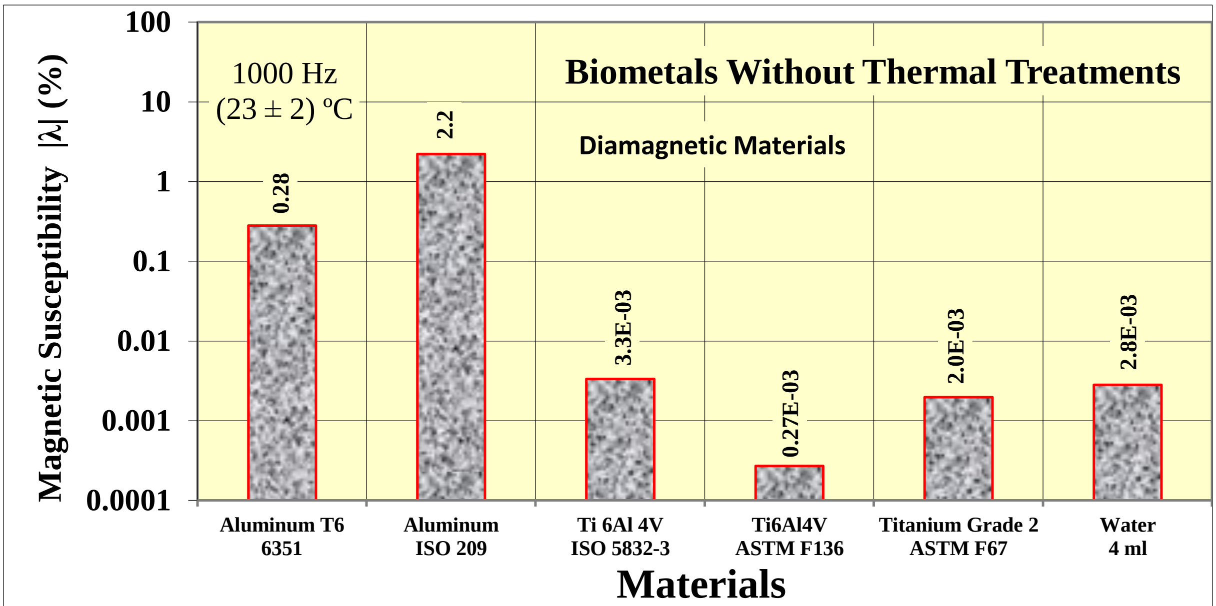
M.A.Sens-15/06/23 09:33-SciTec-Titanio-Ensaios-Semetro.xlsx-TestResults

The susceptibility results have been separated here by magnetic classification, for graphical illustration on logarithmic scales. **Figure 6** shows the magnetic susceptibility, initially, only of the paramagnetic materials. While **Figure 7** shows the same results for materials classified as diamagnetic, those are, with negative magnetic susceptibility, or lower than that of air.



M.A.Sens-14/06/23 09:32
SciTec-Titanio-Ensaios-Semetro.xlsx-Indutancias-Ingl

Figure 6 - Magnetic Susceptibility of Tested Paramagnetic Materials



M.A.Sens-14/06/23 12:11
SciTec-Titanio-Ensaios-Semetro.xlsx-Indutancias-Ingl

Figure 7 - Magnetic Susceptibility of Tested Diamagnetic Materials

7 INTERPRETATION OF RESULTS.

As shown in **Figure 6**, for the materials evaluated and classified as paramagnetic, the cobalt-chromium alloy resulted in lower magnetic susceptibility than the others. It should be noted that stainless steel 304, from different suppliers, resulted in a much greater magnetic susceptibility, one of which was approximately four thousand times greater than the cobalt-chromium alloy. It is also worth mentioning that a stainless steel 5832 alloy resulted in lower susceptibility than toner, used in laser printers and copiers.

On the other hand, among the materials tested and classified as diamagnetic, presented in modulus in **Figure 7**, to allow a logarithmic scale, it is observed that the aluminum alloy ISO 209 stood out, with greater susceptibility, in modulus. While titanium alloys, widely used in biomedicine, have been shown to be almost as diamagnetic as water, that is, such alloys are perfectly compatible with magnetic resonance environments.

8 CONCLUSIONS

It was concluded that the experimental technique, by electrical measurements, was completely satisfactory in determining the magnetic susceptibility of small samples, like 25 mm³ in volume.

The results show that two metallic alloys, with the same technical nomenclature, but with a slight difference in chemical composition, can exhibit a magnetic susceptibility of 78 times, one greater than the other.

It should be noted that titanium appears in the literature among paramagnetic, as seen in **Figure 3**, page **6**, but here, based on the results shown in **Figure 7**, page **10**, it turned out to be diamagnetic. It so happens that when the properties refer to titanium, it is a pure material and not in the form of alloys, such as those commercially available for use in medical prosthesis. Such alloys may be as low as 90 % titanium[11], [12].

Some of the tested materials exhibited, in tests, magnetic susceptibilities equivalent to those of water. Such materials can certainly be inserted into magnetic fields such as those found in MRI devices, without a doubt they are perfectly compatible with MRI environments.

9 REFERENCES

[1] Curie and Cheneveau, "Magnetic balance", J. de Physique, vol. 2, p. 796 (1903)

[2] J.R. Davis, editor, Handbook of Materials for Medical Devices - Overview of Biomaterials and Their Use in Medical Devices, p1-11 DOI: 10.1361/hmmd2003p001, www.asminternational.org.

[3] L Spinu, University of New Orleans, USA B C Dodrill, Lake Shore Cryotronics C Radu, Lake Shore Cryotronics, Magnetometry measurements, 2013.

[4] L Spinu, University of New Orleans, USA B C Dodrill, Lake Shore Cryotronics C Radu, Lake Shore Cryotronics, Magnetometry measurements, 2013.

[5] Landolt-Börnstein, Numerical Data and Functional Relationships in Science and Technology, New Series, II/16, Diamagnetic Susceptibility, Springer-Verlag, Heidelberg, 1986

[6] Landolt-Börnstein, Numerical Data and Functional Relationships in Science and Technology, New Series, III/19, Subvolumes a to i2, Magnetic Properties of Metals, Springer-Verlag, Heidelberg, 1986-1992.

[7] Landolt-Börnstein, Numerical Data and Functional Relationships in Science and Technology, New Series, II/2, II/8, II/10, II/11,and II/12a, Coordination and Organometallic Transition Metal Compounds, Springer-Verlag, Heidelberg, 1966-1984.

[8] QuadTech 7600, QuadTech 7600 Plus, 7600 Plus Precision LCR Meter Manual, 2014.

[9] R.G. Craig and J.M. Powers, Ed., Restorative Dental Materials, 11th ed., Mosby, Inc., 2002.

[10] Sens, M. A.; Assis Filho, Francisco de, e UETI, Edson Electromagnetic Characterization Of Magnetic Nanofluid", D1-05 - XVI ERIAC – Encontro Regional Ibero-americano da Cigré, Iguazú, Argentina, 17 a 21 de Mayo de 2015.

[11] Sens. Márcio Antônio; Relatório de Ensaio - DLF-2999/2020 – "Propriedades Elétrica, Térmica e Magnética de Biometais" - Traumec Tecnologia e Implantes Ortopédicos Importação e Exportação Ltda, 12 páginas, Rio de Janeiro, 2020.

[12] Sens. Márcio Antônio; Relatório de Ensaio - DLF-3268/2020 – " Propriedades Elétrica, Térmica e Magnética de Biometais" - Scitec Soluções em Ensaios de Materiais e Produtos Ltda., 11 páginas, Rio de Janeiro, 2020.

[13] Tables de Constantes et Données Numérique, Volume 7, Relaxation Paramagnetique, Masson, Paris, 1957.

Semetro-2023-Petropolis-Biometais-Rev05.docx
M.A.Sens-03/09/2023 22:03.