Study of Magnetization Processes in Steel

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Abstract: Ferromagnetic materials are characterized for having high magnetization and for their non-linear and non-reversible nature. This work shows a study of hysteresis loops in steel to identify different ferromagnetic magnetization mechanisms. Some hysteresis loops have been studied in different zones of the principal loop. A magnetometer was used to measure the magnetization changes and a DC power supply to give current to a coil to create a magnetic field. Having the results, we defined a degree of irreversibility for each loop and plotted it against the different parameters of our experiment.

I. THEORICAL BACKGROUND

Ferromagnetic materials are characterized for having a large spontaneous magnetization (M_S) and for having magnetic moment even without an applied magnetic field. Besides, their magnetization has a non-linear and non-reversible behaviour and it is represented as a hysteresis loop. This behaviour is due to a strong molecular field [1], being the one which points spins divided in small volumes called ferromagnetic domains. In a magnet, the magnetic field lines must close themselves. However, this requires a certain energy. In order to minimize this energy, the system breaks itself into domains, separating by domain walls.

Energy Contributions

There is a wide variety of domain configurations which depends on several contributions. These contributions are exchange energy, magnetostatics energy, anisotropic energy and magnetostriction energy [2].

The exchange energy shows the interaction among the non-paired electrons' spins. This interaction orientates the spins and its energy depends on the interatomic distance. The exchange energy is positive in ferromagnetic materials since spins are aligned in the same direction between them, and it is negative in antiferromagnetic materials since spins are orientated in opposite directions among them.

The magnetostatics energy is the one related with the applied magnetic field. A magnetised sample will generate a stray field outside and a demagnetizing field (H_D) inside which opposites magnetization. The magnetostatics energy depends on the applied magnetic field and it is also reduced if the sample breaks into more domains.

The magnetostriction energy shows the effect of magnetization as a mechanic alteration in the sample's crystal structure. This mechanic alteration can affect magnetic permeability.

The anisotropic energy shows the energy it takes to rotate spins from an easy axis to a difficult axis. It is known spins tend to orientate themselves throughout certain axis, so a high energy is needed to rotate spins which are not throughout that axis, called easy axis. The anisotropic energy is defined as:

$$E_{ani} = \int_0^{Ms} \mu \left(H_{diff} - H_{easy}\right) dM \ (1),$$

where H_{diff} and H_{easy} are the applied magnetic fields in difficult and easy axis, respectively. Anisotropy means having different properties in different directions and it depends on the type of material. The more impurities or hardpoints a sample has, the more anisotropic it is. Crystal anisotropy becomes an obstacle to spins and domain rotations. It is more difficult to align spins at the same direction as the applied field in anisotropic materials with high anisotropy.

These are the different contributions when it comes to break our system into domains.

Domains

The ferromagnetic domains are separated from each other by domain walls. There are two types of walls according to its magnetostatics energy: Bloch walls and Néel walls. Since Bloch walls is more present in bulk materials and Néel walls in thin films, we will focus in the first one. In Bloch walls, spins are rotating progressively until reverse 180º as it is observed at **fig.1**. It is because two domains separated by the wall have different exchange energies. Therefore, the system must have more energy than exchange energy to be able to reverse its domains. Nevertheless, this energy is large, so the system divides itself into domains to minimize the energy to orientate spins. It is less energetic to rotate several domains gradually than inverse only one monodomain. The more domains we have, the less energy we need to achieve spin inversion. However, it does not only depend on exchange energy but also on anisotropy. As it was explained in former paragraphs, a higher energy is needed to rotate spins which are not throughout the easy axis. Therefore, walls formation also depends on anisotropy and it affects their width. Systems with low anisotropy are not divided in many domains which are separated by wide walls while anisotropic systems are divided in multiple domains separated by thin walls.

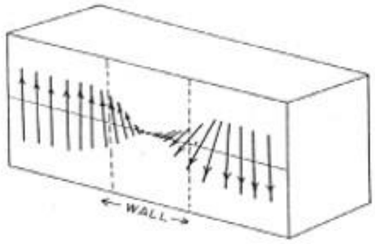

Fig.1: Spins inversion between domains separated by a Bloch wall.[3]

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According to the anisotropy, there are two types of ferromagnetic materials, hard materials and soft materials. Hard materials have a huge amount of impurities and hardpoints therefore they are very anisotropic while soft materials are not. Since hard materials have a huge amount of impurities, it is more difficult to orientate spins, so the system breaks up into domains, so hard materials have more domains with thin walls and soft materials have less domains with wide walls.

Hysteresis Loops

At the beginning of the introduction we claimed that in ferromagnetic materials, magnetization have a non-linear and non-reversible response to magnetic field. As a result of this, a hysteresis loop is obtained, showing the magnetization evolution against the applied magnetic field.

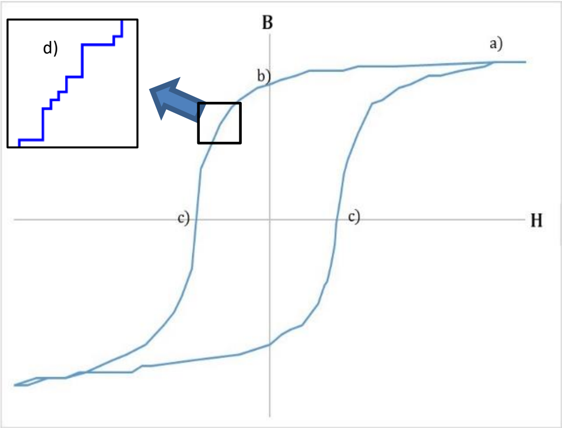

Fig.2: Schematic representation of hysteresis loop. Three different zones are observed: saturation zone (a), remanence zone (b) and coercivity field (c). The square in (d) shows Barkhausen sequences.

In **fig.2**, a representation of hysteresis loop is observed. Three different regions are shown. Firstly, the saturation zone **(a)**. If we applied a magnetic field, H, magnetization will increase until it reaches a constant value called Spontaneous Magnetization, M_S. In saturation zone, all domains are aligned with the same orientation as the applied magnetic field. Secondly, the remanence zone **(b).** Decreasing H, it is observed that magnetization does not returns to the same way as it increased but there is a discrepancy. When there is no magnetic field applied, the sample has a certain magnetization called remanence magnetization, M_r. In remanence, most domains are still orientated in the same direction as in **(a),** but a small portion of them have different orientations. The portion of domains with different orientation can be estimated as the difference among M_S and M_r. For example, if $M_r = 0.8M_S$, the 80% of the domains will be aligned with H while the remaining 20% will have a different orientation. Eventually, the coercivity field **(c).** Decreasing H even more, the loop reaches H axis. It is observed that in this zone, magnetization is zero at this value of H known as coercivity field, H_C. In H_C, most domains have different orientations so that the sum of their magnetic moments is zero.

Nevertheless, Hysteresis loops are not continuous. In **fig.2**, it is noticed some discrete jumps called Barkhausen sequences **(d)**. Barkhausen sequences are due to discrete and irreversible changes in domains [4].

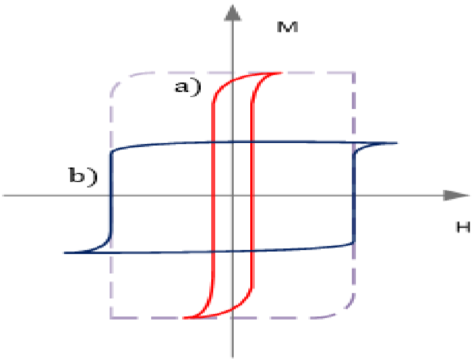

Fig.3: Schematic representation of hysteresis loop for soft materials (a) and hard materials (b). Soft materials have lows coercivities while hard materials have high coercivities [5].

Hysteresis loops are different for hard materials and for soft materials. The properties for each type are observed in **fig.3.** It is shown that hard materials have wider loops than soft materials, since they have a higher coercivity field. As it was explained in **section 2**, hard materials are more anisotropic because of they have a bigger amount of impurities and hard points. Impurities affect to the cycle's reversibility and make it more difficult to reach saturation and as a result, the cycle becomes more irreversible.

Magnetization Processes

Domain configurations are the main reason of this irreversible behaviour and some magnetization processes act depending on the applied magnetic field. They are domain growth and domain rotation. On the one hand, the domain growth explains the domain movement. If we apply a small H, the domain wall starts to deform. The deformation is so small that it is still reversible. However, if we increase H, the deformation will increase as well, and the domain grows. If it continues growing, it will come across with impurities or hardpoints and it will become irreversible Barkhausen sequences are a result of this effect. On the other hand, we have the domain rotation. When the magnetic field is strong enough to grow and to move domains, they start to align themselves with H. The moment when all domains are aligned with the applied field, the magnetization achieves saturation. However, if we applied H to the opposite direction, the sample will not break into domains and it will behave as a monodomain and all spins rotate at the same time. This process is known as coherent rotation and it is reversible until the material breaks into domains and continue the loop.

II. EXPERIMENTAL DEVELOPMENT

The aim of this work is to identify the different magnetization mechanisms in hysteresis loops. Some hysteresis loops have been studied in different zones of the principal loop. The main sample used for the experiment was a steel bar, since steel is a hard material and it is appropriate to observe hysteresis loops and their properties. To measured hysteresis loops, we used a DC power supply to induce current to a coil in order to create a magnetic field, H. A coil's magnetic field is defined as $H = nI$ (2). Furthermore, we used a magnetometer to measure the magnetization, measuring its rotation. As a result, different hysteresis loops with different sizes, shown in **fig.4**, have been measured in different zones of

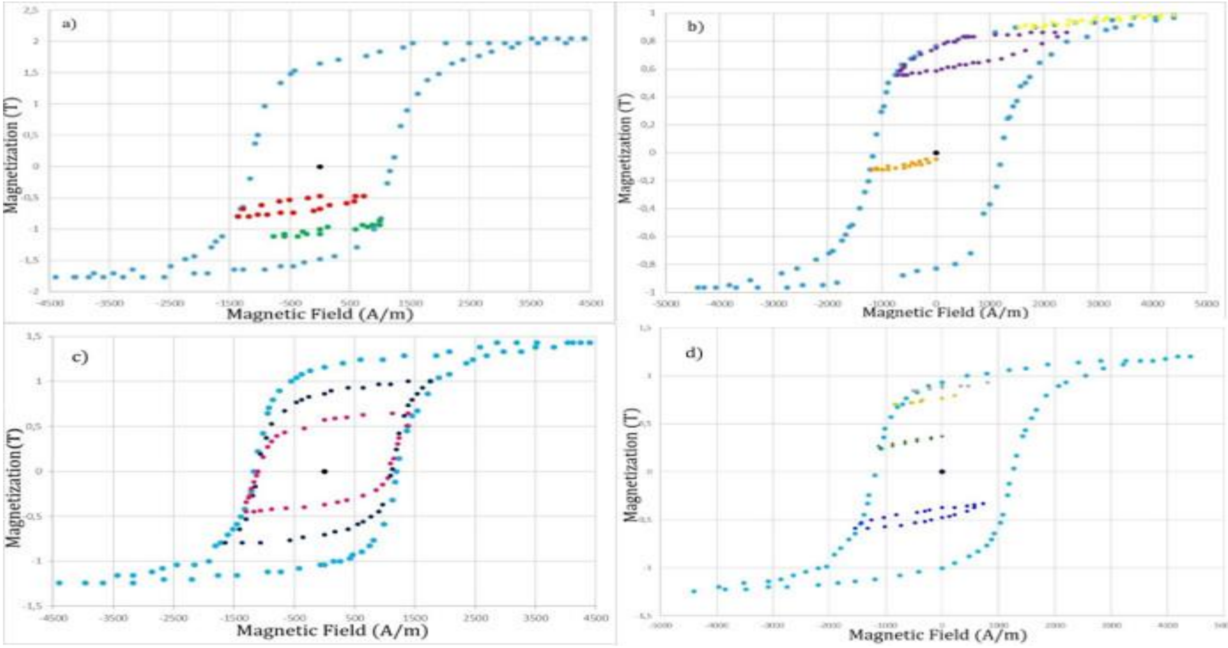

Fig. 4: Hysteresis loops of the steel sample obtained in different zones of the principal loop. Loops in (a) were studied equally wide but in different height. Loops in (b) were studied in "keys" positions as saturation, remanence and coercivity zone. Loops in (c) were studied around zero magnetization and magnetic field. Loops in (d) were studied rising the magnetic field progressively and in different zones.

the principal cycle. Notice that although the "magnetization" term is used, we are referring to the magnitude B. However, as ferromagnetic have a high magnetization, it is correct to claim $B \approx \mu_0 m M$ (3).

In order to identify the magnetization mechanisms, we first identify how irreversible they are. We define a variable called **degree of irreversibility**. It is defined as the quotient between the cycle's area and the cycle's rectangle area:

$$G_i(\%) = \frac{Cycle's\ Area}{Cycle's\ Rectangle\ Area} = \frac{Cycle's\ Area}{Width \cdot Height}\ (4).$$

The Cycle's rectangle area is defined as the product among the cycle's width and height, as it is shown in **fig.5.** As it is observed in **fig.4**, hysteresis loops are different depending on the zone they are measured, the applied magnetic field and the magnetization evolution. As it is observed in **fig.5**, the applied magnetic field and the magnetization evolution correspond to the cycle's width and height, respectively. Therefore, the grade of irreversibility has been calculated for every loop and has been represented against the different parameters of our experiment. The cycle's in **fig.4** with very small areas as the yellow, grey and gold cycles, were supposed to have $G_i(\%) = 0$.

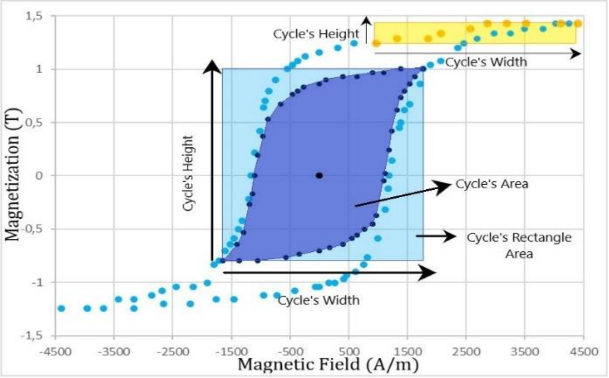

Fig.5: A schematic representation of hysteresis loops and the calculation of the degree of irreversibility. It shows to opposite examples, one very irreversible (blue) and one very reversible (yellow).

III. DATA PROCESSING

The degree of irreversibility, $G_i(\%)$, has been potted against the following variables: cycle's width, cycle's height, mean magnetization and mean magnetic field. The following figures represent three different variables at the same time being $G_i(\%)$ as one of them. Those figures were plotted in order to analyse better this non-reversible behaviour since hysteresis depends on many variables. It is observed that in the following figures, $G_i(\%)$ has been plotted as circles whose radius shows its value. The bigger is the circle, the higher is $G_i(\%)$. Each colour circle represents the same colour cycle in **fig.**4. Notice that yellow, grey and gold cycles have been plotted as small circles since they have no irreversibility.

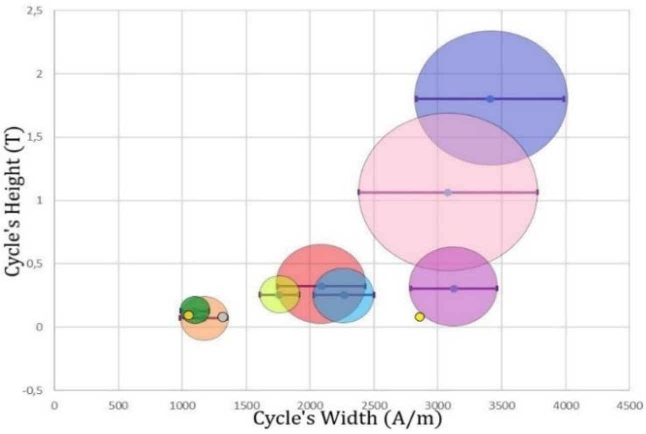

Fig.6: Degree of irreversibility of the cycles plotted against of the cycle width and cycle height. Notice that the most irreversible cycles are the wider and the higher ones.

In **fig.6**, $G_i(\%)$ has been plotted against the cycle width and height. On the one hand, it is shown that generally the lowest degrees of irreversibility correspond to the smallest cycles, the ones with small width and height. On the other side, the tallest and the widest ones are the most irreversible. That means, the higher is the applied magnetic field, the more the magnetization grows and the bigger the cycle is, therefore the more irreversible it becomes. However, there are a few exceptions such as the yellow cycle. It is observed that even though the yellow cycle is wide, the magnetization does not increase. This fact is because hysteresis not only depends on the applied field but also on the zone it is measured.

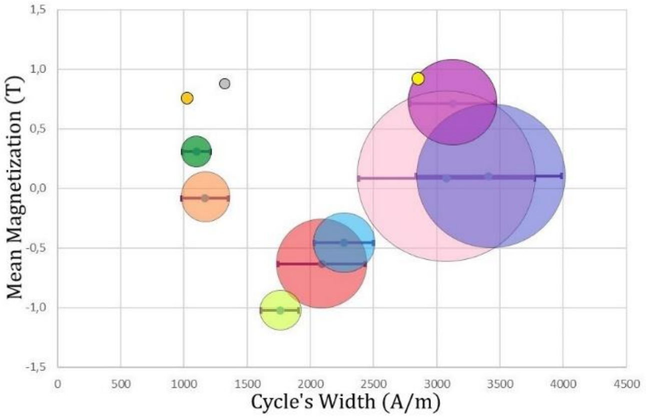

Fig.7: Degree of irreversibility of the cycles plotted against the width of the cycle and the mean magnetization of each cycle. It shows that the most irreversible cycles are the wider ones and located close to zero mean magnetization.

In order to observed hysteresis according different zones, the following figures have been plotted against the mean magnetization and the mean magnetic field. In **fig.7** and **fig.8**, the degree of Irreversibility is plotted against its mean magnetization for each cycle and its width and height, respectively. The mean magnetization is the value of the magnetization at the middle of the loop and it is used to locate the its vertical position in **fig.4**. In **fig.7**, it is clearly observed how irreversibility changes according its width and where it is in the vertical axis. It shows that the most irreversible cycles are the wider ones and those which are located close to zero mean magnetization. In **fig.8**, it is shown a similar observation but against the cycle's height instead of its width. It is clearly observed that the tallest loops, such as the pink one, are located close to zero mean magnetization and they have a higher degree of irreversibility.

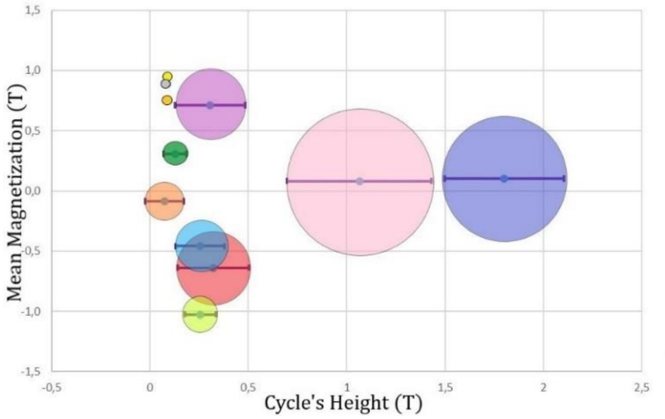

Fig.8: Degree of irreversibility of each cycle plotted against the height of the cycle and the mean magnetization of each cycle. It shows that the most irreversible cycles are the higher ones and located close to zero mean magnetization.

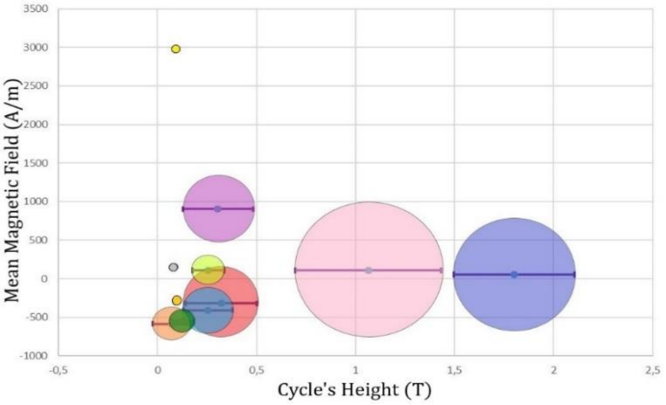

Fig.9: Degree of irreversibility of each cycle plotted against the height of the cycle and the mean magnetic field of each cycle. It shows that the most irreversible cycles are the higher ones and located close to zero mean magnetic field.

In **fig.9**, we have a similar figure to **fig.8** but against mean magnetic field. The mean magnetic field is the value of the applied magnetic field at the middle of the loop and it is used to locate its horizontal position **fig.4**. It shows a similar behaviour to the former figures since the cycles which shows a bigger change in magnetization are those which are located close to zero mean magnetic field.

Taking the former figures into account, a better description of irreversibility has been exposed. Not only hysteresis depends on the applied field but also on where the cycle is located. At a first sight, it is observed that the widest cycles are the one which show the highest irreversibility. However, as it was said before, the yellow one was an exception. Although it was applied with a high field, its degree is approximately zero, since its magnetization does not increase so its area is nearly zero. Looking at the former figures, the yellow loop is located on the top of the principal cycle. Therefore, cycles which are located close to remanence zone and saturation zone are more reversible. In the **theorical background**, we talk about different magnetization mechanisms. In saturation and remanence zones, when a magnetic field with the opposite direction, H, is applied, the sample behaves as a monodomain and all spins start to align with H. This is a reversible mechanism, until H increases and then the sample breaks into domains.

To sum up, centred wide cycles are the most irreversible since the most irreversible magnetization mechanisms take place. Wide cycles, which are not centred, also have some irreversibility although is lower and the ones located close to saturation, are the most reversible. Besides, if the applied field is low and the location is close to saturation or remanence, the cycles' irreversibility will be nearly zero. Depending on what they are located, the mechanisms will be different as well as their domains configurations. Eventually, those domains configurations will be the responsible of the cycles' areas as well as their degree of irreversibility. It is clearly observed in

fig.10, where it is shown how $G_i(\%)$ increases according the cycle's areas and the cycle's rectangle areas. As the cycle's area axis is represented in logarithmic scale, the yellow, grey and gold cycles have not been represented in **fig.10**, since their cycle's area were approximate to zero.

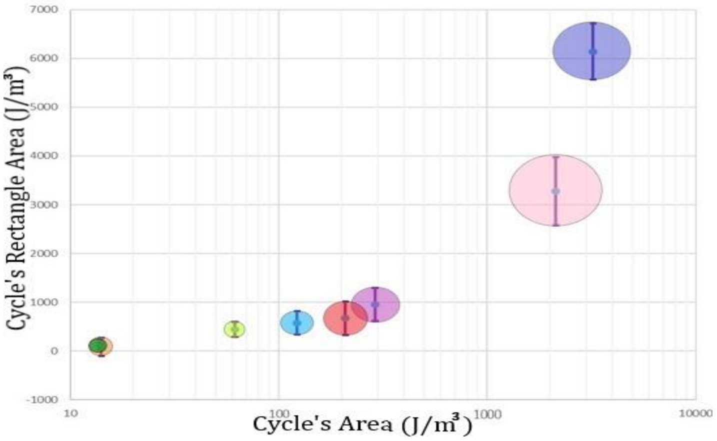

Fig.10: Degree of irreversibility of the cycles plotted against the cycle's area and the cycle's rectangle area. It shows how the grade increments according to the areas. The abscissa axis is represented in logarithmic scale.

The following tables show a summary for each cycle. Each table show the width, the main magnetic mechanism, and the degree of irreversibility for each cycle.

Loop	Width (A/m)	Main Magnetic Mechanism	Gi (%)
Red	2090	Irreversible Domain Growth	31
Green	1760	Reversible Domain Growth	14
Yellow	2860	Reversible Domain Rotation	≈0
Purple	3125	Irreversible Domain Growth and Rotation	30
Orange	1166	Reversible Domain Growth	12
Indigo	3410	Irreversible Domain Growth and Rotation	52
Pink	3080	Irreversible Domain Growth and Rotation	63
Grey	1320	Reversible Domain Growth	≈0
Gold	1034	Reversible Domain Growth	≈0
Dark Green	1100	Reversible Domain Growth	8
Blue	2266	Irreversible Domain Growth	25

Table 1: A table representing the width, the main magnetic mechanism and the degree of irreversibility for each cycle in **fig. 4.**

IV. CONCLUSIONS

A description of hysteresis in ferromagnetic materials has been exposed. Hysteresis loops not only depends on the applied magnetic field but also on the zone it is placed. There are different mechanisms in different zones and the sample achieves different domains configurations. Eventually, these domains are the responsible of the cycles' sizes and their irreversibility, being the biggest ones the most irreversible and those who are centred.

V. ACKNOWLEDGMENTS

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