Faculty of Natural Science and Technology

Non-destructive evaluation of steel plates containing different hardness using low-frequency magnetic fields

Internship report MAT3

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Material science department POLYTECH GRENOBLE

Main Volume
AND
Annex

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ACKNOWLEDGMENT

First of all, I wish to thank all the peoples who permitted me to live in this great experience.

I'd like to begin with Dr. CHENEVIER, director of research at CNRS (Grenoble) and Senior University Research Administrator at Okayama University. Without his help, this internship wouldn't have been possible. He really cares about making internships in Japan possible for foreign students. Conversely, he also allows Japanese students from Okayama University to experience studying abroad.

Indeed, he submitted me to Dr. KIWA, an Associate professor at Okayama University, who was my interlocutor while I was in France and the organiser of my internship. He really facilitated me all administrative formalities to officialize my internship, and introduced me to my internship tutor, Professor TSUKADA, who was my tutor during this internship.

I especially want to render thanks to Dr. SAKAI, an assistant professor at Okayama University. He was my main interlocutor during this internship and he guided me throughout my work. He was sincerely concerned about my comfort, and in spite of his tight schedule he spent a lot of time talking with me about my work as well as my experience in Japan.

I finally want to thank all laboratory professors and students, who were cordial and welcoming towards me and the other international student Tom, from Taiwan. They even organised two welcome parties for us, in traditional Japanese restaurants. A big thank you to students Kentaro, Tsubasa, Yuki and Tetsuro with whom we spent a great trip in Himeji, and who helped us to buy bus and train tickets, which is not an easy task for a foreigner in Japan.

ありがとう ございます!

(aligatô gozaimasu !)

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INTRODUCTION

Recently, a new method of hot press for steel plates has been developed, allowing us to create “non-hardened” and “hardened” regions at the desired position on a steel plate. Due to the difference in hardness of these durable and non-durable regions, this plate has the ability to dramatically reduce the fracture in the accident of collisions: this makes this type of material very interesting in the automotive sector, for the bodywork (example in figure 1). According to a study conducted by some companies such as GESTAMP, the use of these steel plates with different levels of hardness could reduce the weight of the body work by 20%. While keeping users safe is a case of accident, this technology allows to reduce the amount of steel used for car manufacturing, as well as fuel consumption (indeed, the weight of a car determines its consumption).

In order to put this new technology into practice, industrialists must have the means to ensure that hard and soft regions have been properly prepared at the desired position. However, the conventional hardness measurement method requires long inspection time and is difficult to apply in the case of an industrial production line. A reliable and fast non-destructive testing method is required for identifying hardened and non-hardened areas in a steel plate for the implementation of this method in industry.

In a laboratory of the Okayama University, in which my internship took place, the group of Professor TSUKADA discovered that it is possible to carry out this evaluation by a magnetic method, using a process derived from the Eddy Current Testing. They developed a measurement method and a prototype probe which gives good results. The main purpose of my work during this internship was to reduce the size of this prototype probe while keeping the same quality of signals.

I will first introduce the context of my internship and the background of the research, then I will explain the experimental procedure of this non-destructive evaluation, and finish with the results we could obtain and interpret them.

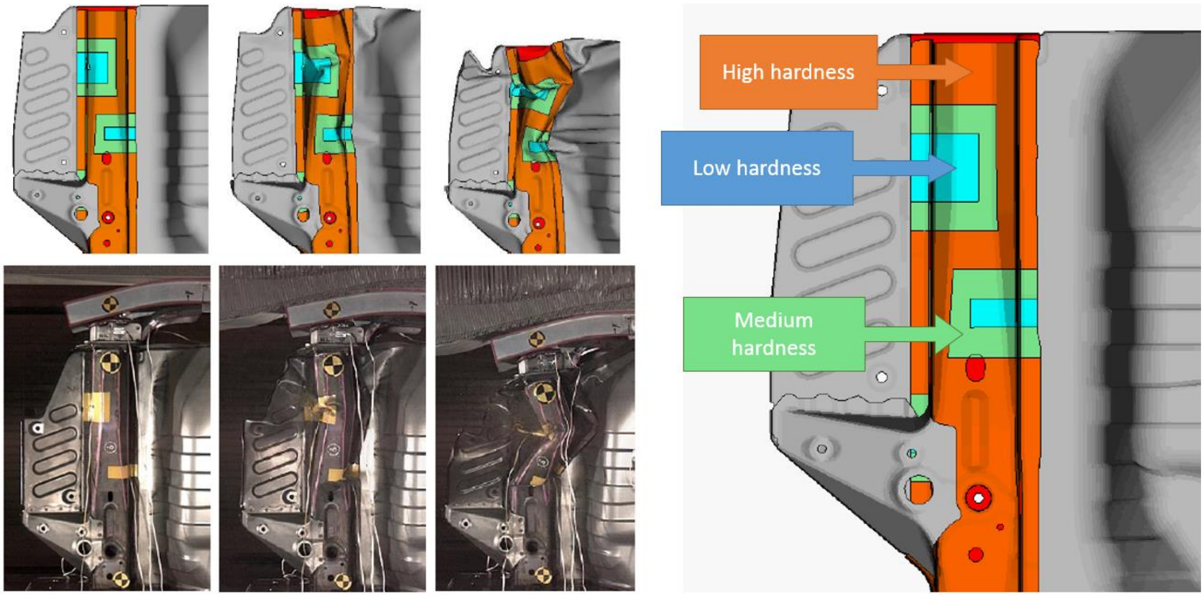


FIGURE 1: EXAMPLE OF UTILISATION OF A METAL PLATE WITH DIFFERENT LEVELS OF HARDNESS, FOR THE REAR FRAME OF A CAR

I. CONTEXT OF MY INTERNSHIP

At the end of my third year of study in material and science engineering at Polytech Grenoble (3rd year of a 5-year Master's degree), I performed a twelve-week internship in a laboratory of research at Okayama University from May 29, 2017 to August 21, 2017. I was working on the subject “Non-destructive evaluation using low-frequency magnetic field”, as a research assistant.

I had heard about this opportunity thanks to the International relations of Polytech Grenoble: I immediately got interested because I wanted to discover the working way in a laboratory and find out about NDE. I was also interested in Japanese culture and way of life.

1.1. Few Words about Okayama University

Okayama University is a national and public university in Japan founded in 1870 and located in the north of Okayama City. This university contains about 14,000 national and international students and about approximately 2,600 staff are engaged in educational and research activities, and university management.

Okayama University contains 4 campuses (Tsushima, Shikata, Misasa and Kurashiki) which are composed of 11 faculties:

- Faculty of Letters
- Faculty of Education
- Faculty of Law
- Faculty of Economics
- Faculty of Science
- Medical School
- Dental School
- Faculty of Pharmaceutical Sciences
- Faculty of Engineering
- Faculty of Environmental Science and Technology
- Faculty of Agriculture
- Matching Program Course

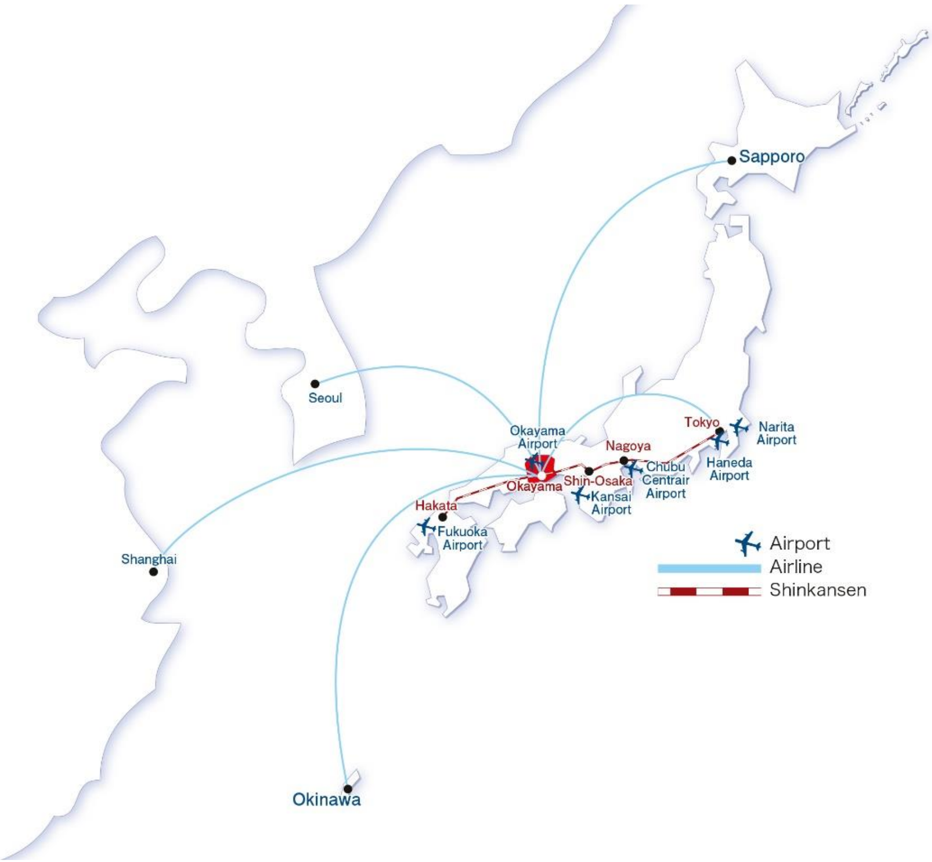


FIGURE 2: LOCATION OF OKAYAMA UNIVERSITY

I carried out my internship in the Graduate school of Natural Science and Technology which is located in the Tsushima campus.

FIGURE 3: MAP OF TSUSHIMA CAMPUS

1.2. Principle of Non-Destructive Evaluations

The objective of a non-destructive evaluation is to be able to control a sample without having to destroy it. NDEs are therefore a set of methods for characterising the integrity of structural parts and the condition of their materials without degrading them. These examinations can be carried out either during production, during use or in the context of maintenance: the piece may then be accepted or rejected according to the standards of the specifications.

Whatever the control technique used, the following five steps are identified:

1. The implementation of a physical process on the part → **excitation** (Electromagnetic wave, vibration, penetrating liquid, magnetic field ...)

2. The alteration of this process due to the anomaly contained in the part → **perturbation**

3. The **disclosure** of this perturbation by a suitable detector (Eye, sensor, imaging system ...)

4. The **conversion** of this variation into a form adapted to the processing of information

5. **Interpretation** of the information obtained.

Non-destructive testing therefore include a flow transmitter and a receiver or detector. According to the type of defaults tracked, the type of material of the piece, the required time and the cost of the control, a type of NDE is chosen among dozens of different methods. In our case, we do not use a NDE to detect a flaw, but to reveal irregularities of properties in a metal: the change of hardness due to the change of microstructure.

We can also reveal these irregularities using the traditional hardness testing: it consists of driving a penetrator, whose shapes and dimensions vary according to the type of test, in the metal to be tested. The load is constant and the surface or depth of the impression left in the material is measured: the impression will be all the more important as the material will be soft. The laboratory made a test of Vickers hardness on the steel plate that I used during my tests, in order to have a reference for the next experiments:

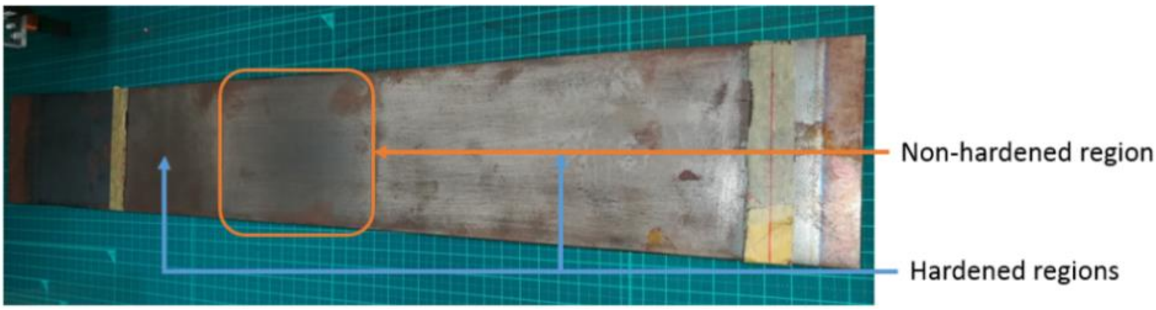


FIGURE 4: STEEL PLATE USED FOR EXPERIMENTS

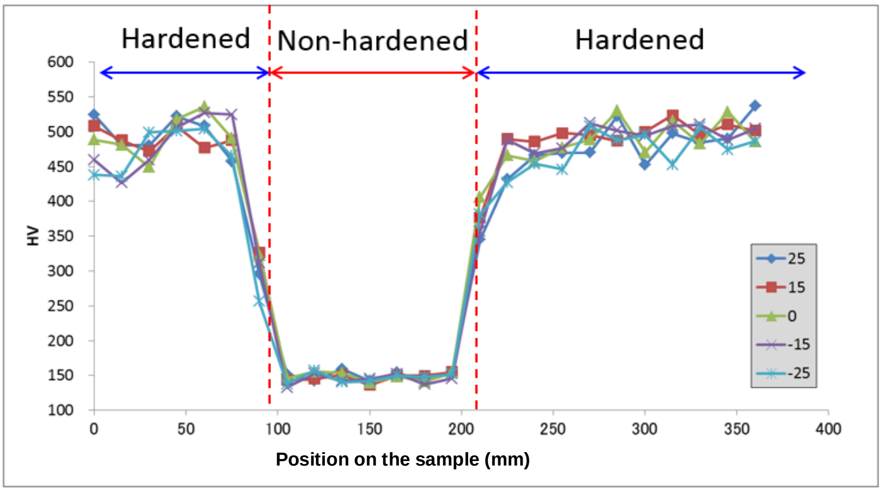


FIGURE 5: VICKERS HARDNESS OF THE STEEL PLATE IN FUNCTION OF THE POSITION (THE 5 CURVES REPRESENT THE 5 LINES OF MEASUREMENT)

II. BACKGROUND AND THEORY OF THE RESEARCH

2.1. Theory of our magnetic testing

As I mentioned in the introduction of this report, this conventional hardness control method is too long for a usage in industry and difficult to automatise. The laboratory is thus developing a magnetic method for this purpose, which should be easily automatised in industries. The principle of this magnetic method is based on the one of Eddy Current Testing:

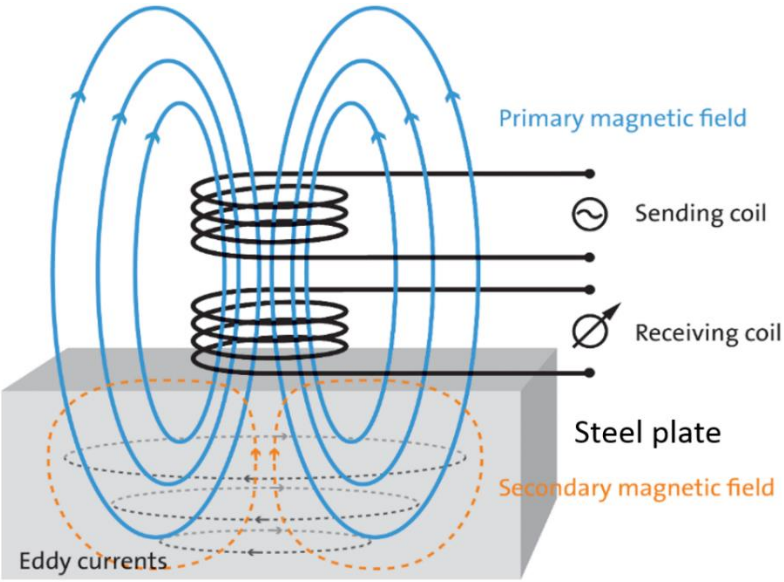


FIGURE 6: GENERAL EDDY CURRENT PRINCIPLE

1. An electric current is applied to sending coils
2. It emits an induced magnetic field thanks to Lenz's law
3. This primary magnetic field crosses the steel plate and creates induced currents (called Eddy currents)
4. These Eddy currents generate a secondary magnetic field
5. The secondary magnetic field is partially transformed in electric current by the receiving coil.

In a steel plate, if the hardness increases, the permeability decreases and the resistivity increases. It implies that the intensity of induced magnetic field will be higher in non-hardened areas than in hardened areas.

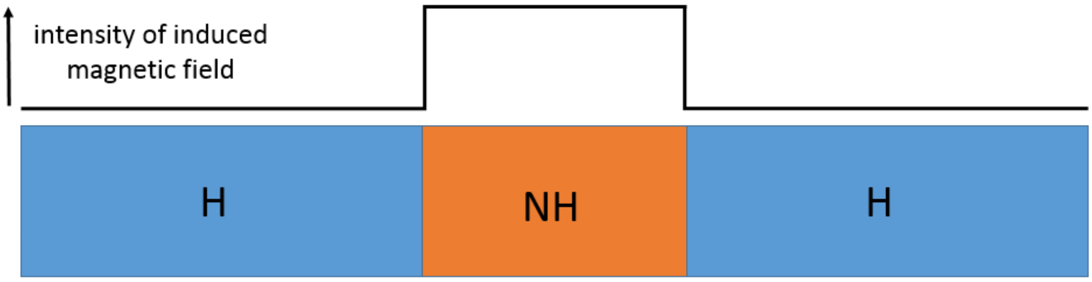


FIGURE 7: IDEAL SHAPE OF THE INTENSITY OF INDUCED MAGNETIC FIELD IN FUNCTION OF THE POSITION ON THE SAMPLE

To evaluate properly the steel plate used for automobile components, which is approximately 2 mm thick, we have to consider the skin depth effect: this electromagnetic phenomenon makes that alternating currents flows mostly near the outer surface of an electrical conductor, such as our steel plate. This effect becomes more and more apparent as the frequency increases, following this equation:

$$\delta = \frac{1}{\sqrt{\sigma \mu \pi f}}$$

with:

δ the **skin depth**
σ the **electrical conductivity** of the steel plate
μ the **magnetic permeability** of the steel plate
f the **frequency** of the magnetic field.

We can estimate the skin depth of the magnetic field inside the steel plate in function of the frequency, knowing the electrical conductivity and the magnetic permeability of hard and soft regions:

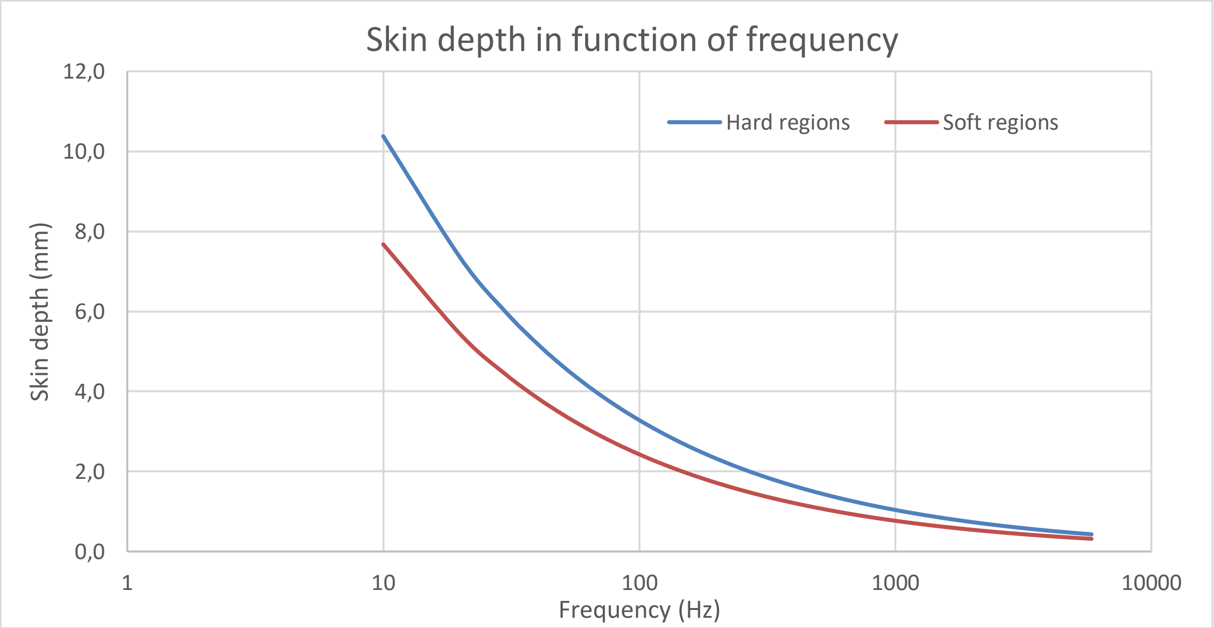


FIGURE 8: THEORETICAL SKIN DEPTH OF THE MAGNETIC FIELD THROUGH THE STEEL PLATE IN FUNCTION OF FREQUENCY

We will consequently work with a frequency of 100 Hz to be sure to analyse the whole thickness of the steel plate. The law of Lenz-Faraday allows us to express the electromotive force (emf) which appears at the terminals of the coil during the experiment, since it becomes a generator:

$$e = -\frac{d\Phi}{dt}$$

with :

- e the **electromotive force** at the terminals of the coil
- Φ the **magnetic field flux vector** through the coil.

As we are working with relatively low-frequency magnetic field (100 Hz), the output voltage (emf) of the receiving coil will have a low intensity, which will drastically reduce the sensitivity of our probe. Professor TSUKADA therefore had the idea to substitute the receiving coil by a small magnetic sensor, which sensitivity does not depend on the frequency of the magnetic field. In this study, we used magneto resistive (MR) sensor which has high sensitivity as low as 30 mT, because they are small, low-cost, highly sensitive and reliable.

2.2. Envisaged improvement: reduce the size of the probe.

Using the former measurement probe using a magnetic sensor (shown in figure 10), which was created before my arrival in the laboratory, we can already distinguish properly hard and soft regions on the steel plate:

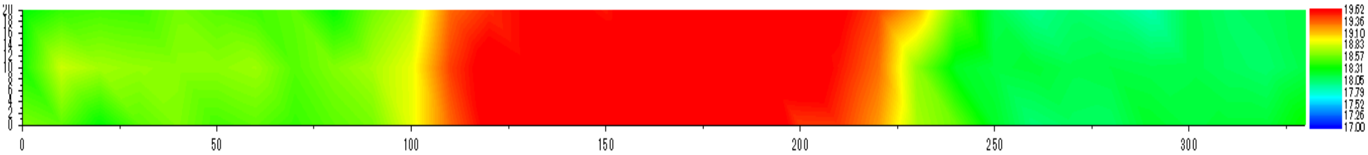


FIGURE 9: MAPPING OF THE INTENSITY OF INDUCED MAGNETIC FIELD USING THE PROBE N°1

By applying the measurement protocol explained later in this report with the first probe, we obtain this mapping (figure 9), showing the intensity of induced magnetic field in µTesla in function of the position, showed in millimetres. The red part shows a high intensity resulting from the non-hardened area of the plate. This result is totally in agreement with the Vickers test made on the sample (figure 5), which means that this probe is reliable.

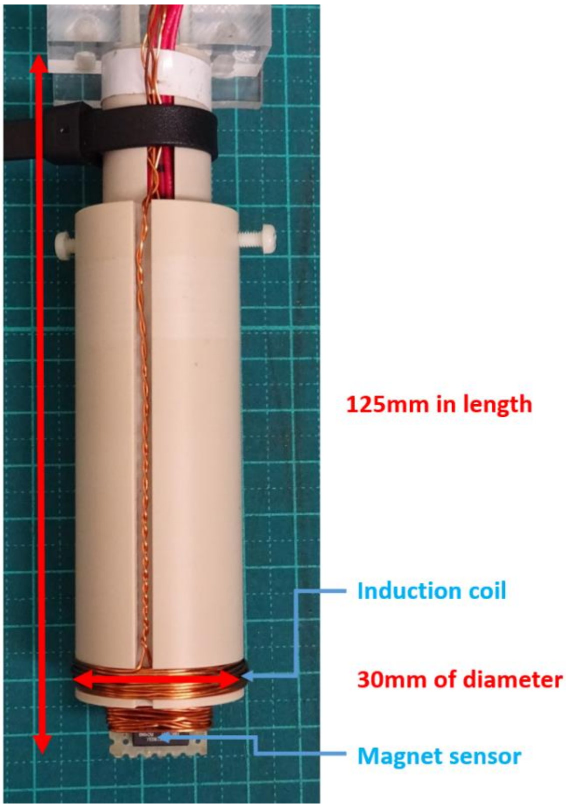


FIGURE 10: PROBE N°1

However, this probe is relatively big for use in industry. Considering the measurement of automobile components, there are many kinds of shapes for components and the size of the probe should be reduced.

For example, an automobile industry uses this kind of components:

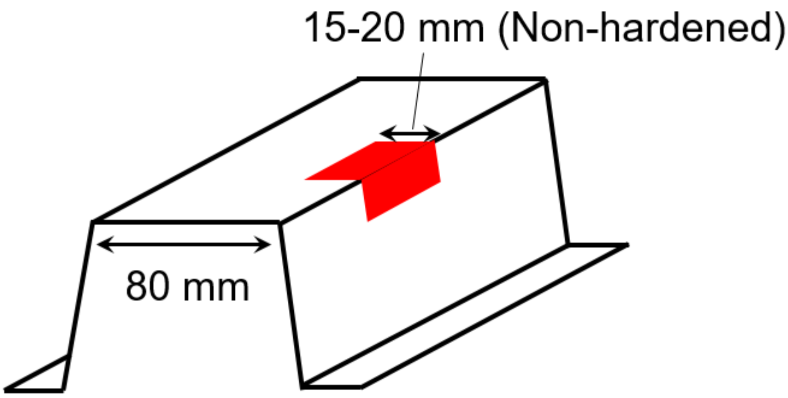


FIGURE 11: EXAMPLE OF SHAPE OF COMPONENTS TO ANALYSE

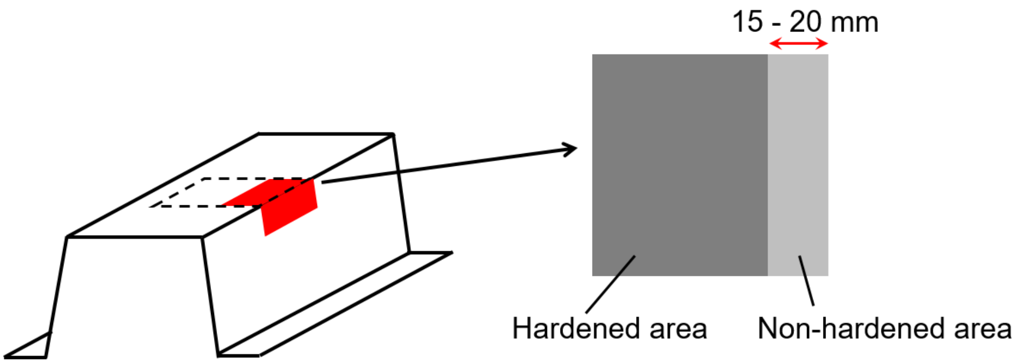


FIGURE 12: ACTUAL COMPONENTS FOR AUTOMOBILES, MADE BY BENDING A STEEL PLATE WITH DIFFERENT LEVELS OF HARDNESS

To properly evaluate this component, we need to have a spatial resolution below 15 mm. In order to respond as best as possible to industry demands, the main purpose of my work during this internship is to reduce the size of the probe.

A simulation model has been made to investigate the effect of coil size on the magnetic field distribution generated from this sample, displayed in ANNEXE 1 (pages 16 to 17).

III. EXPERIMENTAL TECHNIQUES

3.1. Equipment used

FIGURE 13: XYZ STAGE AND LASER

To carry out the measurement, we create the alternative current with a low frequency generator: we chose 100 Hz and 1V peak-to-peak. We also use DC generators to operate the magnetic sensor. An oscilloscope can be used to check the output of the magnetic sensor (detected magnetic field). The current flows the induction coil of the probe which is fixed on a XYZ stage.

A laser displacement sensor is fixed on the probe: when activated, it will be used to determine the operation amount of a motor fixed on the Z axis to maintain a constant and predefined distance between the probe and the sample. Before starting the analysis, we reset the magnet sensor by sending pulsed current to align its magnetic domains.

The output voltage which will be emitted by this magnetic sensor will have a small intensity and has to be optimised: we will use a lock-in amplifier. It has many advantages: it detects very small AC signals by extracting a signal of known frequency, amplifies it until 10^9, delete most part of noises and it is able to measure the variation of a phase of the alternative signal.

3.2. Safety Rules

- We use relatively high currents (about 0.3 A) to produce intense magnetic fields. It is necessary to check the connections when circuits are switched on and not to disconnect them while circuits are switched on.
- The metal samples to be tested are rough and sharp, therefore the use of protective gloves when handling them is recommended.

3.3. Measurement protocol of the control

To evaluate the positions of hardened and non-hardened regions of a steel plate, we start by fixing the probe on the motorised platform. Then, we chose the number of measurement points and lines, as well as the distance interval between each point. We set these settings on the interface of the motorised platform and on the computer, using the software LabVIEW. Then, we set up all generators according to chosen experimental conditions, and adjust the liftoff of the probe if we want to use the laser for Z-axis correction. After resetting the magnet sensor and check the calibration of the lock-in amplifier, we can finally start the analysis.

Using Excel, we obtain the graph of the output signal of magnetic sensors, in mV. Then we convert this signal into µT using the documentation of the magnetic sensor, to get the intensity of the induced magnetic field in function of the position on the sample (an example in figure 14).

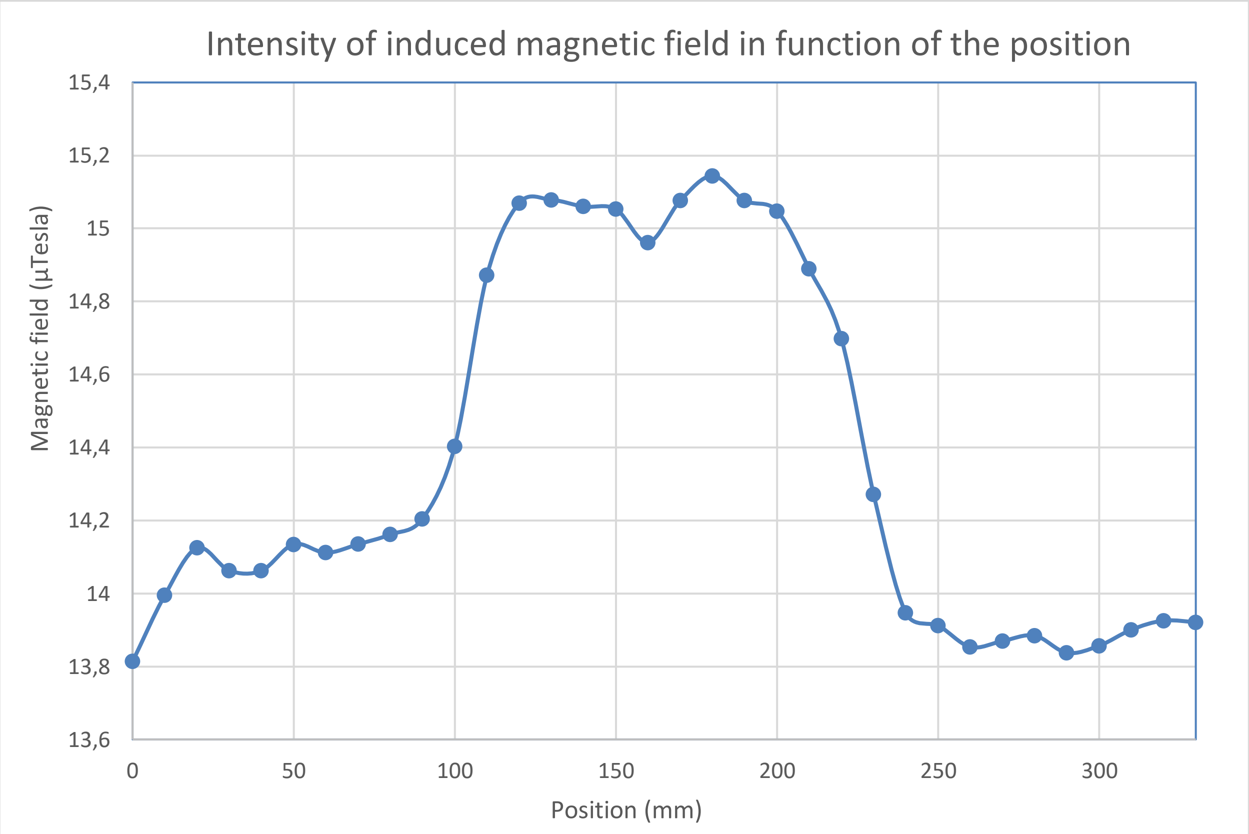


FIGURE 14: GRAPH OF THE INTENSITY OF INDUCED MAGNETIC FIELD IN FUNCTION OF THE POSITION, USING THE PROBE N°1

If we analysed several lines on the sample, we can use the software Origin to have the mapping of the induced magnetic field as previously shown in figure 9.

IV. RESULTS AND INTERPRETATIONS

4.1. New probes created

During the internship, we prepared 2 new probes, which are smaller than the former probe n°1:

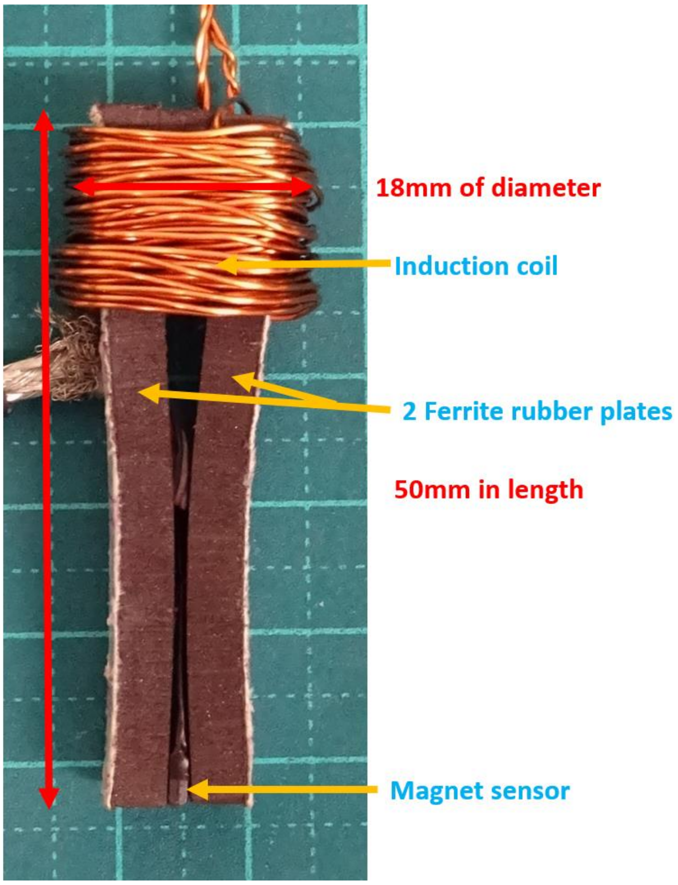


FIGURE 15: PROBE N°2

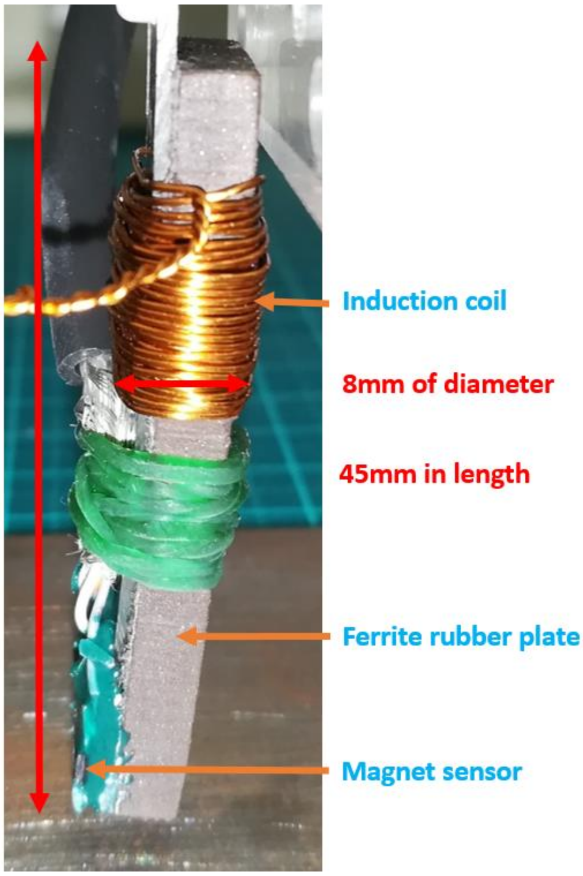


FIGURE 16: PROBE N°3

These two probes are smaller than the probe n°1 in diameter and in length, especially for the probe n°3. These probes use a rubber ferrite with an induction coil: the magnet sensor is sandwiched between two layers of a rubber plate for the probe n°2, and only one ferrite plate for the probe n°3.

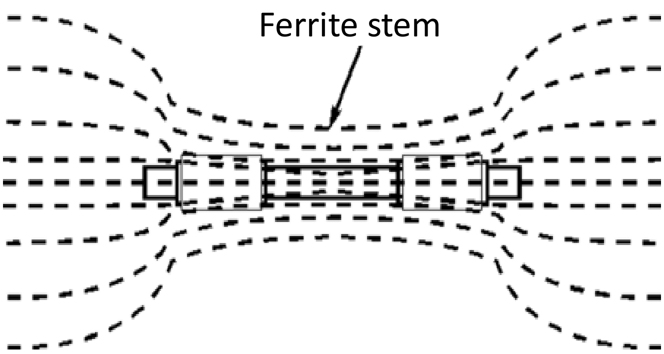


FIGURE 17: MAGNETIC FIELD LINES CLOSE TO A FERRITE STEM

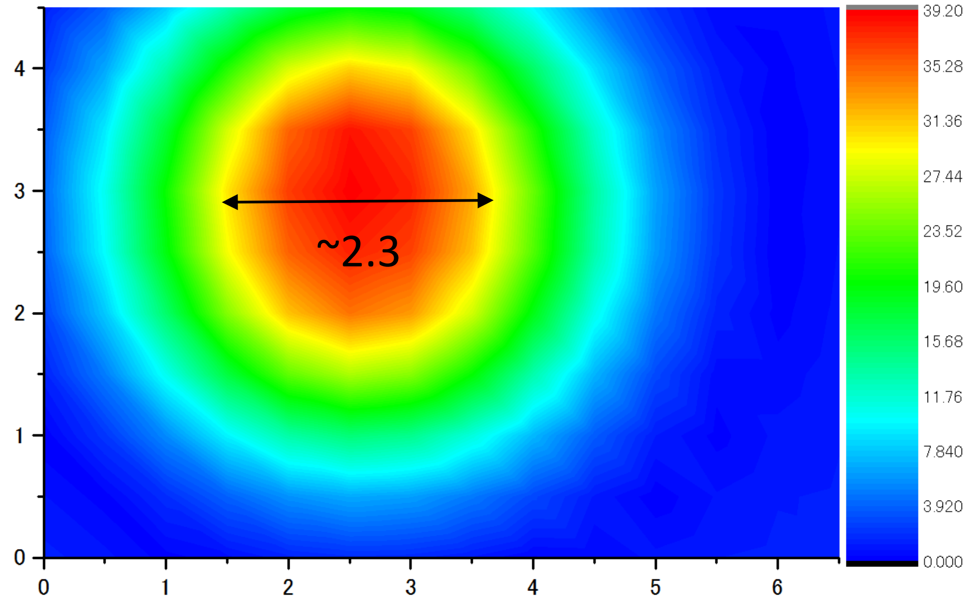
The interest of ferrite is its high permeability in weak fields (up to tens of thousands): the magnetic field is concentrated inside the ferrite, to reduce its potential.

The main drawback of ferrite is its poor mechanical properties: it is really hard and brittle. To overcome this lack of flexibility, we use a rubber containing ferrite.

Because of this, we can easily change the bottom shape of ferrite rubber which is close to the sample. This leads to reduce the probe size markedly.

4.2. Results of New Probes

To highlight the concentration of the magnetic field, we mapped the distribution of the magnetic field generated from each probe. To do this, we applied the same experimental protocol as for the measurement of a steel plate, but the one magnetic sensor was placed below the probe. We can then make the mapping of the distribution of the magnetic field for each probe, in µT:



We can see that the area of strong magnetic field in smaller for the probe 2 than for the probe 1, and even smaller for the probe 3. The unit of position is centimetres, and the unit of the magnetic field is μT.

FIGURE 18: MAGNETIC FIELD DISTRIBUTION OF THE PROBE N°1

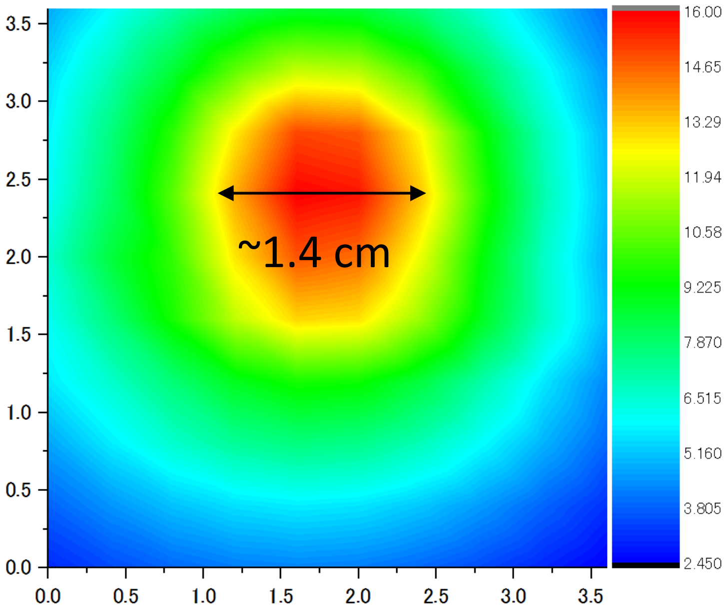


FIGURE 19: MAGNETIC FIELD DISTRIBUTION OF THE PROBE N°2

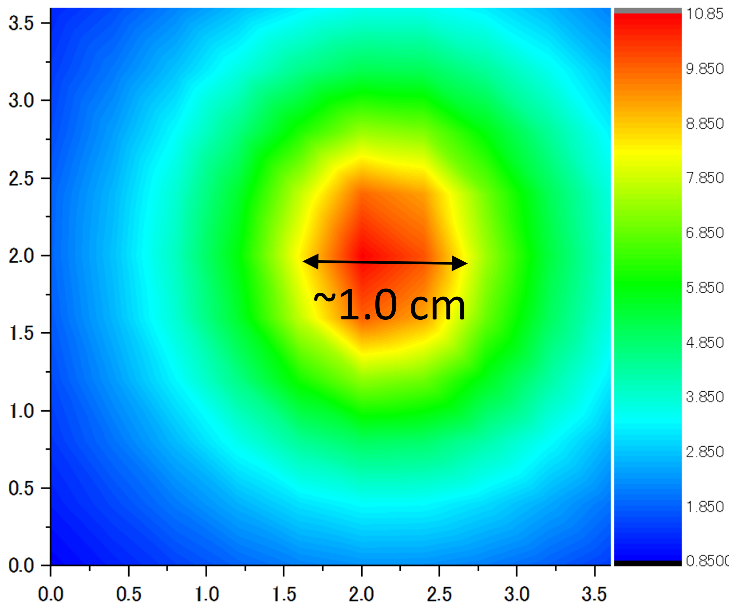


FIGURE 20: MAGNETIC FIELD DISTRIBUTION OF THE PROBE N°3

The next step was to evaluate the hardness of the steel plate with the new probes. We then applied the measurement protocol, with an input current of 100 Hz and 0.1A, without liftoff: the Z-axis correction was removed, and for each measurement point the probe touched the sample.

The measurement was done with 3 lines of 34 points, with an interval of 1 cm between each point and each line, and the intensity is given in µT. We can compare all probes:

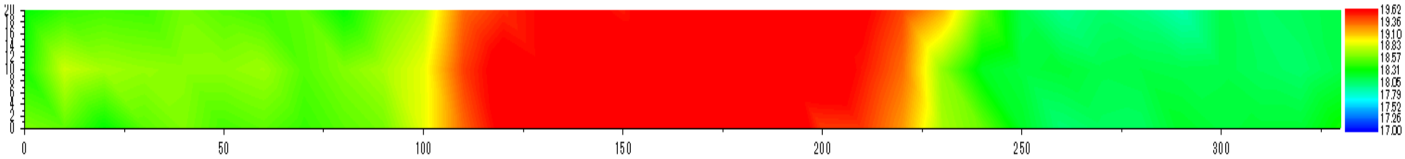


FIGURE 21: MAPPING OF THE INTENSITY OF INDUCED MAGNETIC FIELD USING THE PROBE N°1

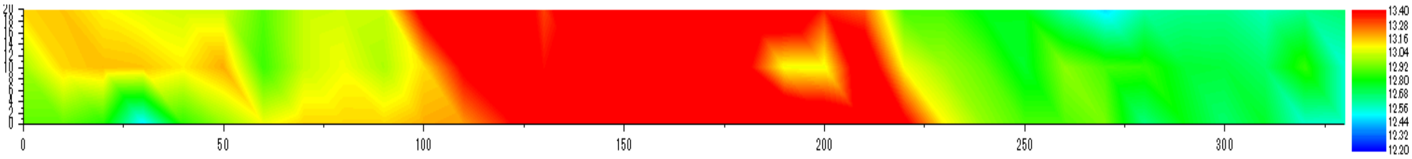


FIGURE 22: MAPPING OF THE INTENSITY OF INDUCED MAGNETIC FIELD USING THE PROBE N°2

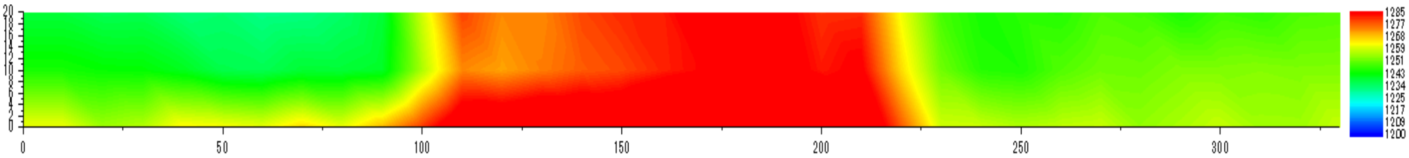


FIGURE 23: MAPPING OF THE INTENSITY OF INDUCED MAGNETIC FIELD USING THE PROBE N°3

4.3. Interpretation

As shown in Fig. 18, 19, 20, we can see that the reduction of the coil diameter and the use of ferrite was efficient, to reduce the area of applied magnetic field.

The mapping of probe n°1 and probe n°3 are quite similar and both good, while the mapping of the probe n°2 is a bit more unstable.

We can say that we achieved our objective: we obtained a result as well as with the former probe, with a new probe (n°3) which is approximately three times smaller in diameter and in length.

V. CONCLUSION

During this internship, I've had the opportunity to work in a research laboratory on a concrete problem, which is truly stimulating: the outline was improving a probe for non-destructive evaluation which will allow a significant optimisation of weight of vehicle body shells. The main objective of my work was attained: we have reduced the size of the probe by about three times, and we are able to acquire an accurate mapping of the steel plate hardness.

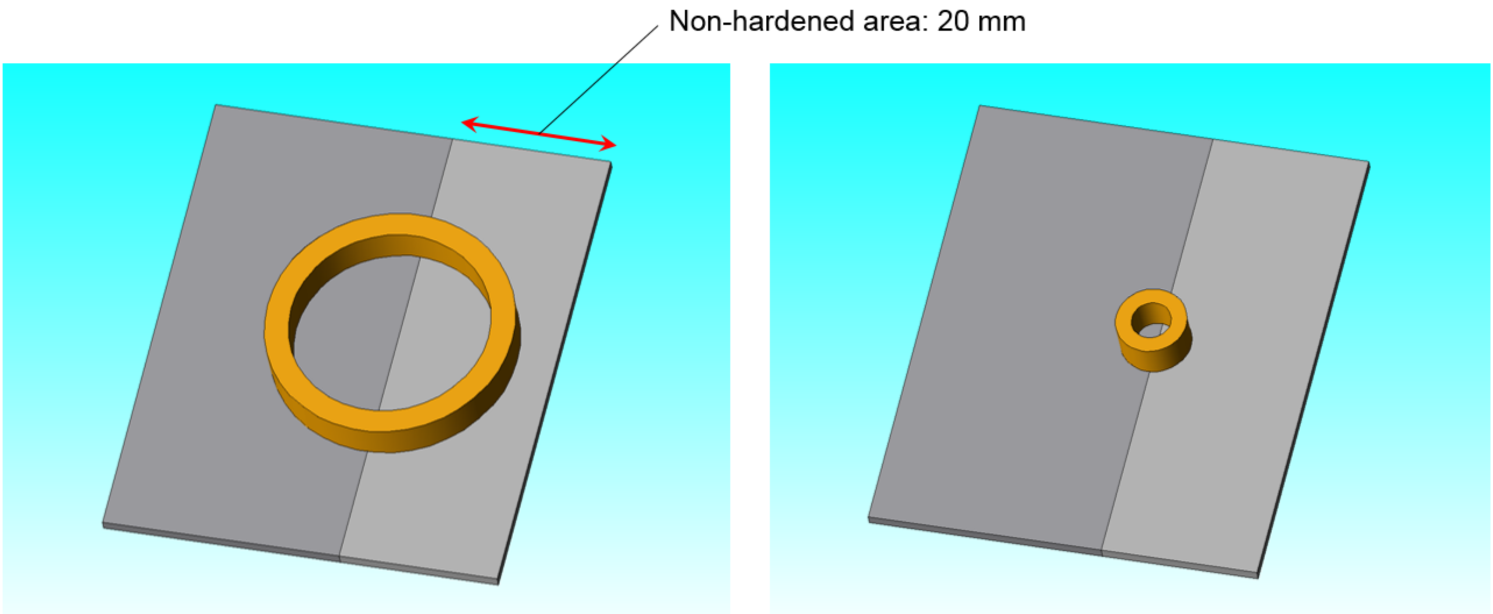
Naturally, there is still a lot of remaining work before the implantation of the method in industry. For instance, a probe that touches the metal precisely should be considered, because the magnetic field intensity is very sensitive to the spacing with the sample, the miniaturisation of the probe should be continued, possibly in considering new techniques, etc.

During my internship, my level of autonomy increased gradually: at the beginning I had to learn experimental protocols while experimenting with Professor SAKAI and student ITO, with the aim of being able to experiment all by myself thereafter. This requires good methodology and memory, since everything is written in Japanese on interfaces. I've had to deal with a lot of data, I've consequently improved my organisation of work and my ability to synthesise results. I was also initiated to LabVIEW and Origin, I improved my skill on Excel and had to read some scientific publications written by my professors in English: this requires a good focusing.

Writing this report was also challenging and rewarding: I accomplished a lot of different experience that I didn't mention in this report, but which took me a lot of time. For example, I studied the impact of the input current frequency, the impact of Z-axis correction or the impact of demagnetisation of the steel plate, on the resulting signal. Among all of these works, it has been interesting to focus the report on only one common thread: the reduction of the size of the probe.

In conclusion, this 3-month internship in Japan has really been a wonderful and enriching experience. I enjoyed experiencing the work in a scientific research laboratory. Working in a foreign country permits to learn different ways of working and thinking, and I benefited from my free time to travel in a lot of places: the cultural disorientation is really fulfilling and make us reconsider what we thought evident or taken for granted.

VI. ANNEXES



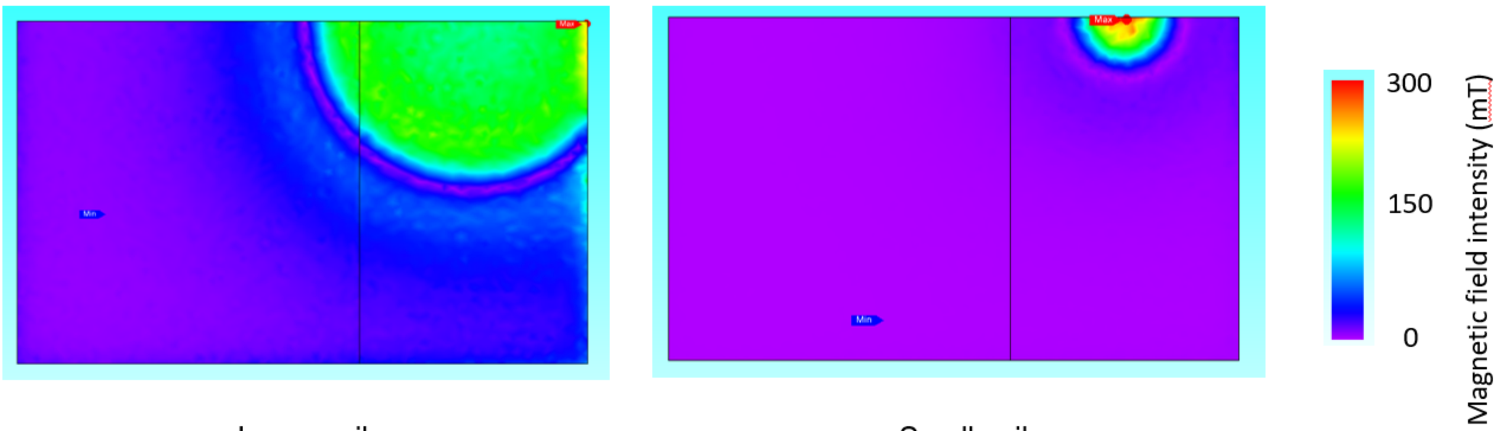
Coil diameter: 25 mm

Coil diameter: 5 mm

Magnetic field distribution generated from the sample

- Magnetic field was applied using each coil and the magnetic field generated from the eddy current inside the sample was calculated by finite element method (FEM).
  The software used is JMAG.
- The coils were moved at the interval of 5 mm.

The below mappings are the examples when the coils are the center of non-hardened area.

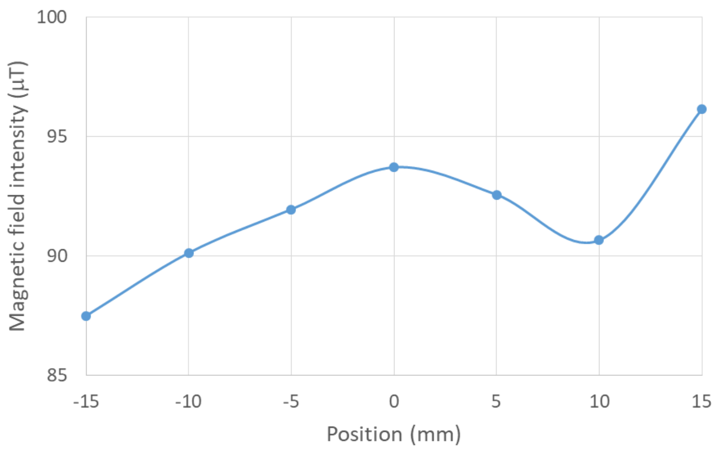


Large coil

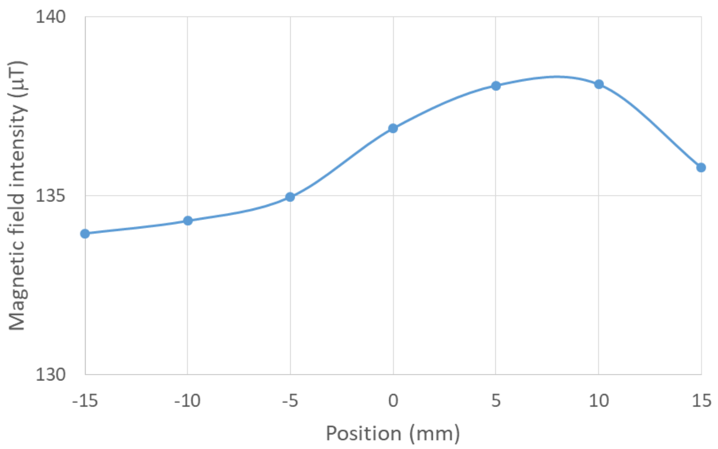
Small coil

ANNEXE 1: SIMULATION MODEL TO INVESTIGATE THE EFFECT OF COIL SIZE (PART 1)

Magnetic field at the center line of sample

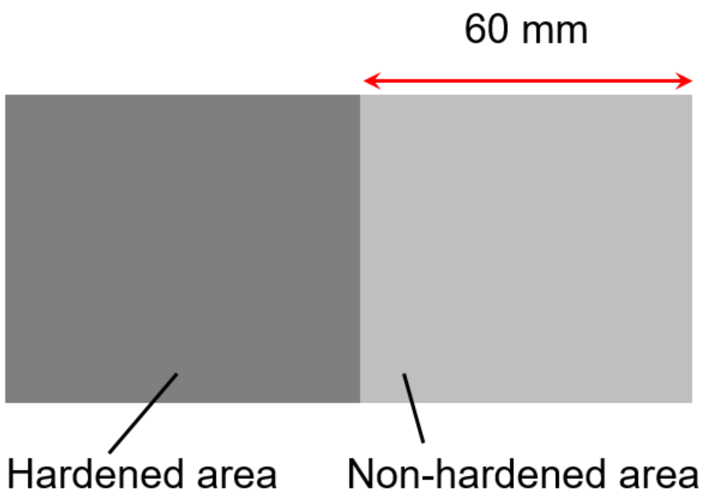


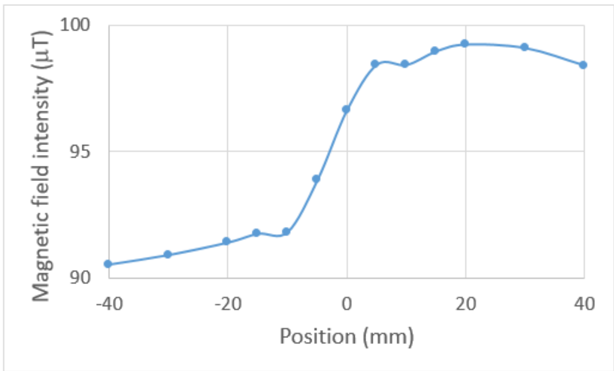
Large coil



Small coil

If the steel plate is enough long, the signal change is observed even if the large coil is used.





ANNEXE 1: SIMULATION MODEL TO INVESTIGATE THE EFFECT OF COIL SIZE (PART 2)

DOS DU RAPPORT

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Title: Non-destructive evaluation of steel plates containing different hardness using low-frequency magnetic fields

Résumé :
Récemment, une nouvelle méthode de presse à chaud est née et permet de créer des régions "durcies" et "non durcies" à la position souhaitée dans une plaque d'acier. La différence de dureté entre ces régions permet de réduire considérablement l'impact d'un choc, ce qui prédispose ces plaques d'acier à une utilisation dans les structures automobiles. Avant de les implanter dans l'industrie, une méthode de contrôle non destructif fiable et rapide est requise afin de contrôler la position des régions durcies et non durcies à l'intérieur des plaques d'acier. L'équipe du professeur TSUKADA, à l'université d'Okayama, a alors mis au point une méthode d'évaluation magnétique permettant cette évaluation : ils ont mis au point une sonde permettant de détecter fidèlement l'emplacement de ces régions. Ce rapport relate de mon stage en laboratoire au sein de cette équipe de recherche, travaillant sur l'amélioration de cette méthode de contrôle. Mon objectif est de créer une sonde plus petite que la sonde prototype afin d'augmenter sa résolution spatiale, pour permettre le contrôle de pièces industrielles comprenant des régions non durcies plus petites. Je présente dans un premier temps le contexte de mon stage et de la recherche, ainsi que les intérêts de réduire la taille de la sonde. J'explique ensuite la procédure expérimentale d'un contrôle de dureté d'une plaque d'acier. Puis, je présente les deux nouvelles probes créées et je finis par montrer et interpréter leurs résultats.

Summary :
Since recently, a new method of hot pressing makes it possible to create "hardened" and "non-hardened" regions at the desired position in a steel plate. The difference in hardness between these regions considerably reduces the impact in the event of a shock, which predisposes these steel plates to use in automobiles structures. Before implanting them in industries, a reliable and rapid non-destructive testing method is required to control the position of the hardened and non-hardened regions within the steel plate. Professor TSUKADA's team, from Okayama University, has developed a magnetic evaluation method which permits this evaluation: they developed a probe allowing an accurate localisation of these regions. This report recounts my internship in the laboratory within this research team, working on the improvement of this method of control. My goal is to create a probe smaller than the prototype probe to increase its spatial resolution, allowing the control of industrial components containing smaller hardened and soft regions. Firstly, I present the context of my internship and of the research, as well as the interests of reducing the size of the probe. Then, I explain the experimental procedure of the hardness control of a steel plate. Finally, I present the two new probes created and I end up by showing and interpreting their results.