Real Time In-Situ Monitoring of Metallurgical Phenomena with Laser Ultrasonics

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Abstract. The laser based ultrasonic technology allows assessing checking and measuring the properties of several materials without contact and in harsh conditions (high temperature, high speed…). In Arcelor Research, we integrated a laser-based ultrasonic equipment to an annealing simulation pilot in order to monitor in real time and in-situ the evolution of the microstructure of steel samples during thermal cycles. The digitalisation of ultrasonic signal at 1 Ghz combined with specific signal processing allow determining steel grade microstructure with great precision in particular: Phase transformation, recrystallisation temperature and recrystallised fraction,.. Moreover, a growth of austenitic grain size can be monitored in real time. The robustness, the reliability and the simplicity of this approach have been proved through many trials and a correlation with classical methods (metallographic examination, modelling,…)

This equipment appears as a new tool, which should ease the work of the metallurgists by measuring automatically grain size or evaluating the temperature of phase transformation and thus improve the knowledge of the properties of new steels.

Introduction

Compared to traditional ultrasonic techniques, laser-based ultrasonic technique has the advantage that the instrumentation is remote from the materials which makes its application flexible and suitable for both ambient, elevated temperatures [1-3] and on-line measurements. Therefore, this technology is very well adapted for steel manufacturing. In this paper, we present some examples of micro structural assessment obtained on a steel sample during thermal cycles.

1-Laser-based Ultrasonic principle

Ultrasonic waves are generated by a laser pulse that heats the metal surface very rapidly. This localised heating induces thermal expansion and/or ablation, which generates elastic waves that starts to propagate along the surfaces and through the sample. A second continuous laser is used in connection to an interferometer to pick-up the ultrasonic waves. All vibration modes are generated simultaneously with a very wide range of frequencies. Certain modes and/or frequencies may be selected by a suitable choice of test geometry and frequency response of the receiver [4-5].

2-Description of experimental device

2-1 Laser Generated Ultrasound device

This device (Figure 1) has been designed by ARCELOR RESEARCH to be used for a wide range of possibilities. Each part of the device is independent to make the entire system very flexible with respect to geometric and physical aspects. Pulsed laser for the generation and continuous laser for the detection are infrared lasers. The CFP (CONFOCAL FABRY-PEROT) interferometer has a frequency bandwidth between 2 and 150 MHz. Its sensitivity allows measuring vibrations of 1 pm in amplitude. Optics are used both for focussing and for positioning the laser beams. It is possible to make measurements on the same side or on the opposite side of the sample. A data acquisition card triggered by generation laser records the signal of the ultrasonic wave with a rate up to 1 GHz.

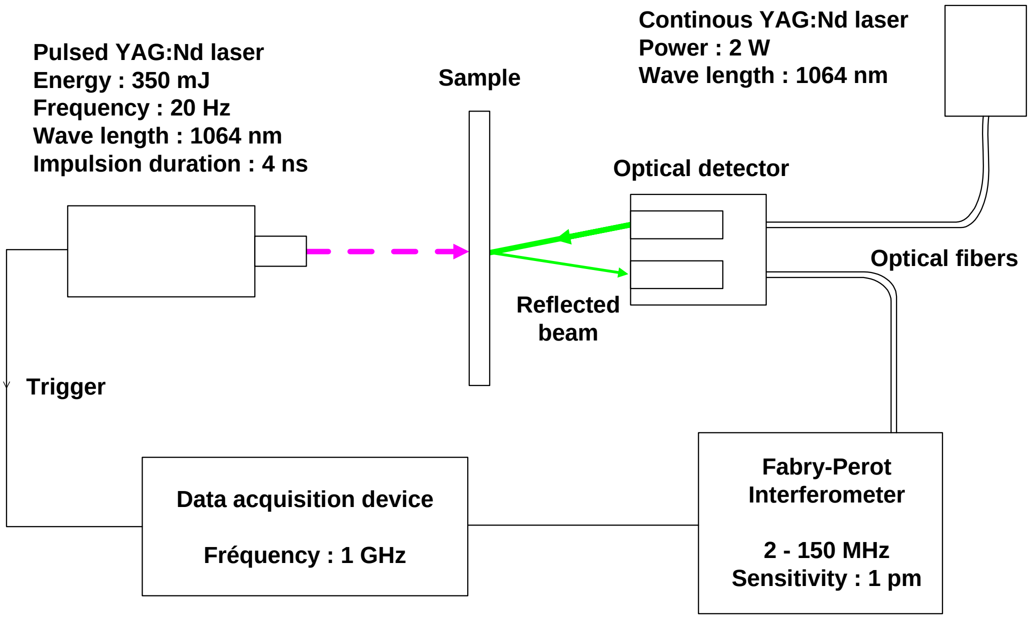


Figure 1 : Overview of the laser-based ultrasonic system at ARCELOR RESEARCH

2-2 Continuous annealing pilot

Figure 2 shows a view of the furnace (or continuous annealing pilot) and the laser system. This furnace reproduces the industrial annealing conditions. The heating device is based on Joule effect and the temperature measurement is made using a pyrometer. The sample and the electrodes are confined in a metal box with glass windows, in order to control gas atmosphere, while allowing access of the infrared laser beams to the sample’s surface. The two lasers of the system can be installed for emission and reception on the same side of the sample or on the opposite side. The results presented in this paper have been obtained with this second configuration.

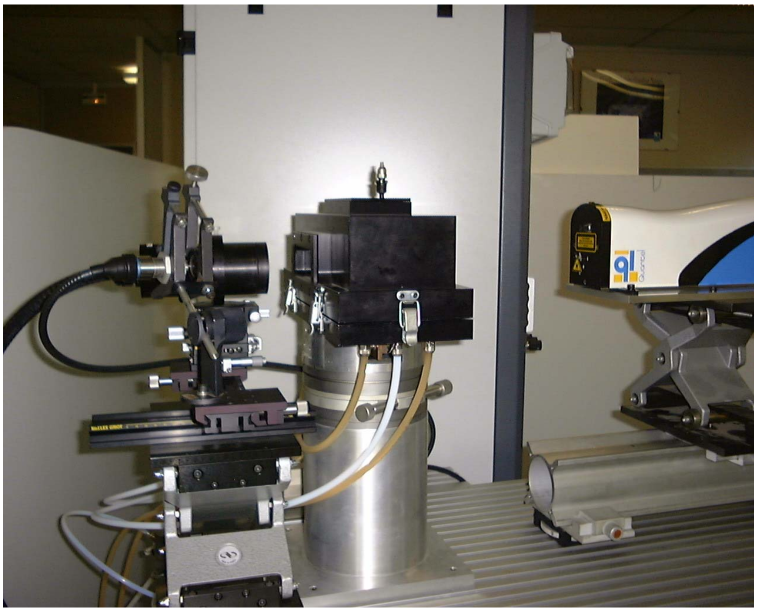


Figure 2 : Laser-based Ultrasonic equipment installed with the annealing pilot

3- Experimental results

3-1 Determination of phase transformation transformation and recrystallisation temperature

Figure 3 shows a typical example of time between two ultrasonic surface echoes obtained during dynamic heating trials. It allows outlining easily, in real time, phase transformation and recrystallisation temperature. These two phenomena generate a modification of ultrasonic velocity trend.

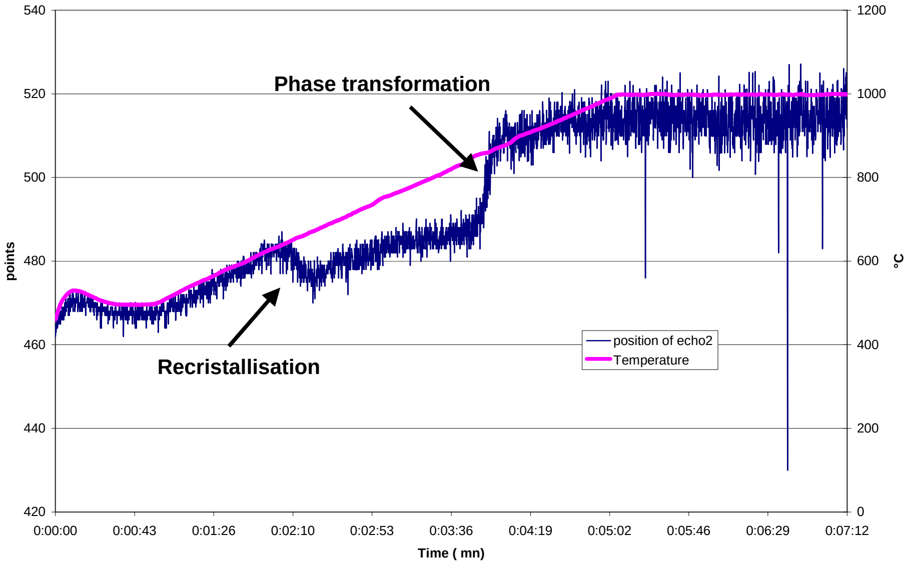


Figure 3: Classical evolution of time between two ultrasonic echoes during a thermal cycle

Figure 4 shows similar results obtained respectively with IF steel and low carbon steel grades.

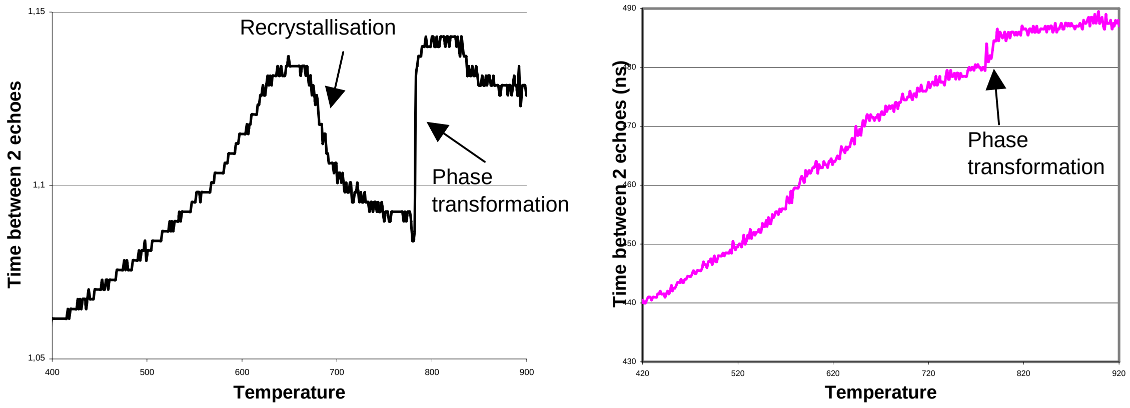


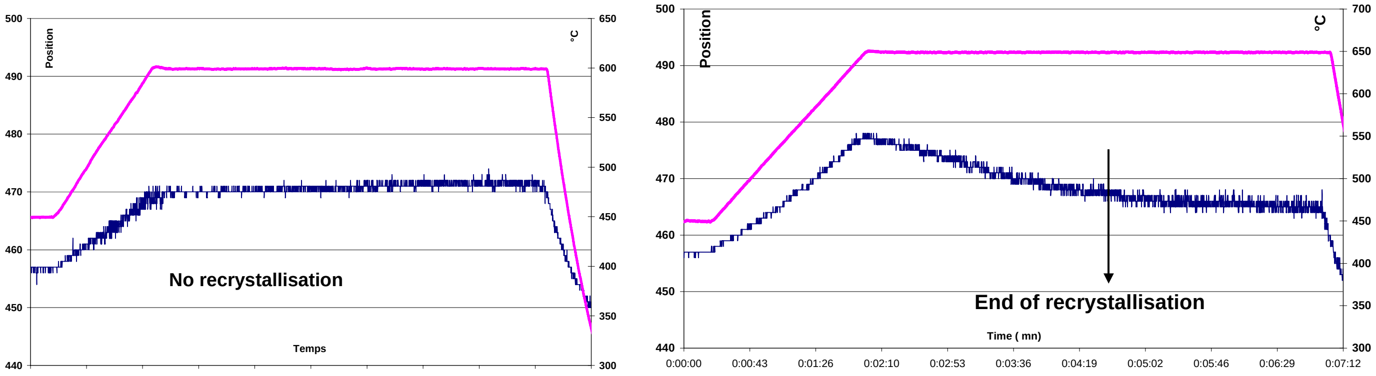
Figure 4. Time between 2 echoes recorded in Arcelor Research during annealing for different steel types showing recrystallisation and transformation from ferrite to austenite
(a) IF steel with 0.003C (b) LC steel with 0.014C

3-2 Determination of the rate of recrystallisation

In the previous part, we showed that we can easily obtain qualitative information concerning the recrystallisation phenomenon. With laser based ultrasound, it is also possible to obtain quantitative information about recrystallisation phenomenon. An example performed with cold rolled IF steel grade is visualised on figure 4:

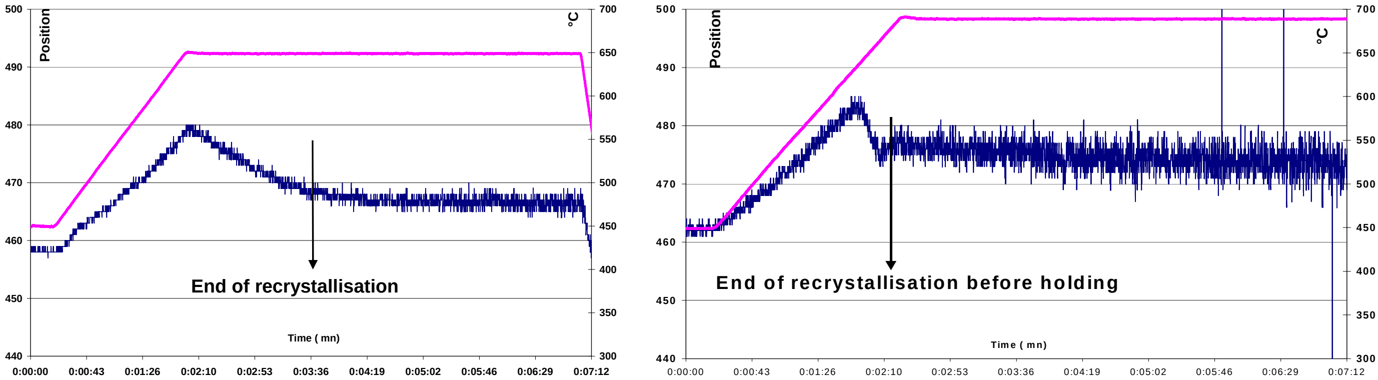
- Holding at 600°C: The parameter studied does not change during the trial. Recrystallisation has not yet begun. There is no change in the sample structure. Therefore, wave velocity stays constant.
- Holding at 650°C and 660°C: The parameter studied decreases; steel structure changes and ultrasonic wave velocity changes. When recrystallisation is finished, the parameter stabilizes.
- Holding at 690°C: The parameter studied stops varying before beginning of the holding; complete recrystallisation is achieved.

By analyzing these curves, it is possible to determine a value of recrystallisation rate. For this purpose, the ultrasonic velocity corresponding to the maximum could be a good criterion.



600°C Holding

650°C Holding



660°C Holding

690°C Holding

Figure 4: Displays of recrystallisation evolution for several holding temperatures. The pink line describes the thermal cycle, and the blue line displays the corresponding ultrasonic time-of-flight

3-3 Monitoring grain size growth

Another example of the potential of laser based ultrasonic technique is the possibility to measure austenitic grain growth in real time. This value is impossible to determine using any other method.

This experiment was performed with an epicentric configuration (ultrasound generation on one sample side, ultrasound detection in the other sample side). Figure 5 shows the evolution of corresponding spectrum as a function of time. This evolution corresponds to a growth of grain size characterised by an increase of ultrasonic attenuation due to grain growth..

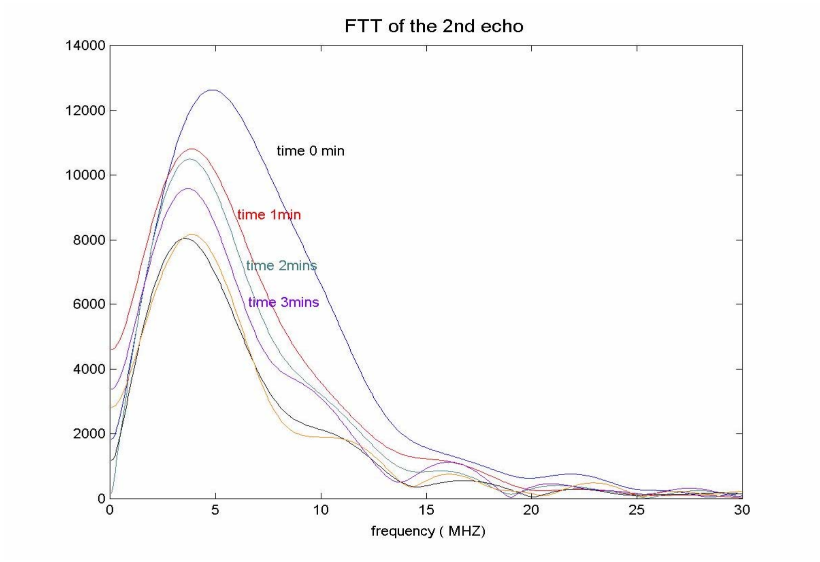


Figure 5 : Evolution of ultrasonic spectrum during an holding temperature at 1000°C **.**

Ultrasonic attenuation corresponds to the growth of grain size

Figure 6 presents the relation between the grain size and presents LUS parameter during holding time for 2 temperatures: 1000 and 1050°C. The LUS parameter (*Q=HF/LF*)(6) was calculated by using the LF range 1-7MHz and HF range 13-40MHz. A low value on the LUS parameter means that there is low HF content due to large grains. Therefore, a good reproducibility is observed.

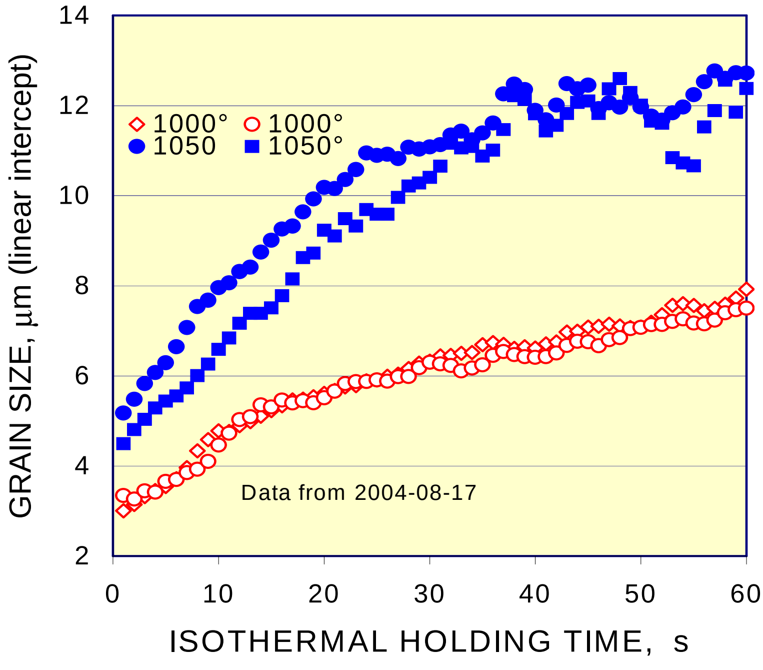


Figure 5: Grain size versus isothermal holding time for samples of 1mm stainless 316 [6]

4- Conclusions

The works presented in this paper show the potential of laser based ultrasonic as a tool to evaluate microstructural characteristics and metallurgical transformation of steel in real time during thermal cycle. Some parameters as the rate of recrystallisation, the evolution of grain size, can be determined immediately with a correct precision without destroying the sample.

Therefore, this technology can be use easily on product moving at high velocity (typically 600m/mn). Similar information concerning material microstructure could be obtained for example at the exit of hot-rolling mill, at the exit of continuous annealing,…The knowledge in real time of steel microstrucrure is very important in particular to increase the productivity while maintaining a constant quality.

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