Supplementary Information

Strain-driven magnetostructural kinetics revealed in Heusler alloys

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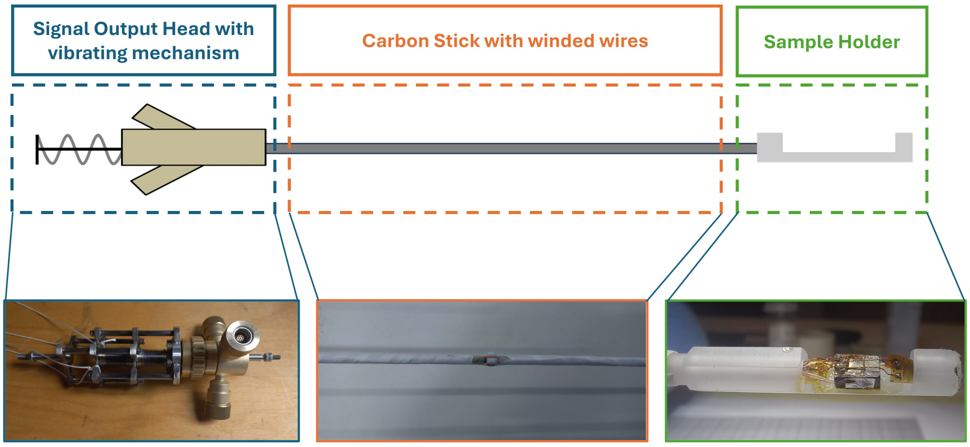
Supplementary Contents

Contents

Supplementary Methods

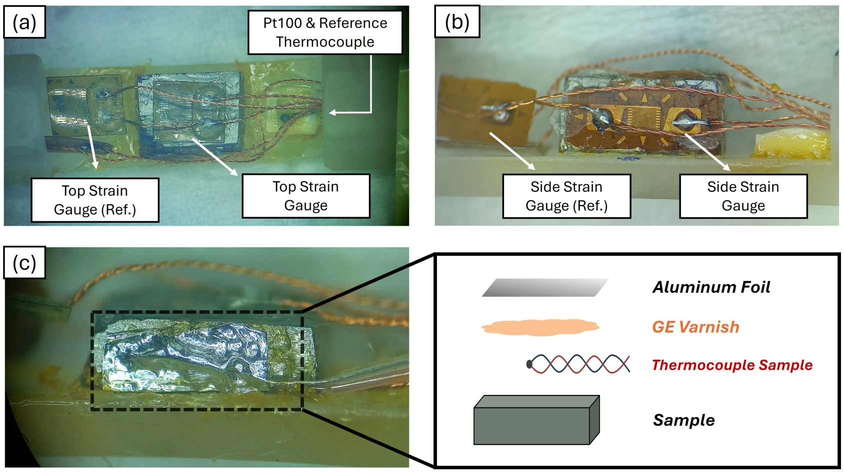
Custom-designed simultaneous measuring probe

For the simultaneous measurements of magnetization, strain, and sample temperature change, a custom-built probe was designed and build. Figure 1 shows a schematic representation of the whole probe, along with images of each of its constituent sections.



Supplementary Fig. 1: Schematic representation of the custom-designed simultaneous measuring probe, divided into its 3 main sections: (1) Signal output; (2) Carbon Stick, and (3) Sample holder.

To accommodate the sample and the sensors used for the simultaneous measurement, a sample holder was designed with a cut-off edge, where the sample was placed. The sample holder is presented in detail in Figures 2 (a), (b) and (c).



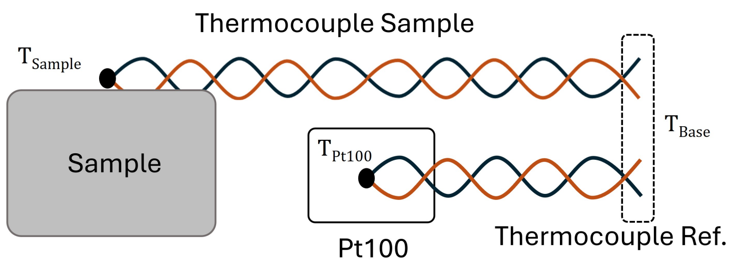
Supplementary Fig. 2: Final assembly of the sample in the sample holder shown in three different perspectives (a) Top view showing the Pt100 and reference thermocouple along with strain gauges (sample and reference) on top of the sample (b) Left side view showing the strain gauges (sample and reference) on the side of the sample (c) Right side of the sample where the thermocouple of the sample is placed. A schematic representation on the right shows the thermocouple assembly process.

Strain was measured at two locations on the sample using Vishay Micro-Measurements linear strain gauges. A strain gauge (model C5K-06-S5145-350) was placed on the top surface of the sample, which is referred to as the ”top strain”, seen in Figure 2 (a). On one of the samples’ sides, a strain gauge (model SK-09-031DE-350) was installed, whose measurement is referred to as the ”side strain”, seen in Figure 2 (b). To account for external influences on the strain gauge reading, a ”two-strain gauge” configuration was employed. In this configuration, one strain gauge is glued to the sample, while the other sits free in the sample holder. To further account for the field-induced signal in the wires, the so-called ”parasitic current”, a twisted wire pair was used for all gauges, comprising two 50 μm copper wires. Both gauges were glued with M-Bond 610 bond from Vishay Micro Measurements.

Figure 2 (c) shows the left side of the sample, where a 75 μm type-K thermocouple was placed. The thermocouple was placed directly on the surface of the sample, before being covered with GEVarnish and covered with a small aluminum foil, as schematized in Figure 2 (c).

Sample Temperature calculation

Given the limited amount of space on the sample holder region and other operational constraints such as having to accommodate wires along the carbon stick and the constant vibration of the whole probe, the following thermocouple measuring scheme was implemented, as seen in Figure 3.



Supplementary Fig. 3: Thermocouple wiring scheme used to determine the temperature change of the sample, ΔT_{Sample}. Image not to scale.

In this configuration, two 75 μm type-K thermocouples are used. One thermocouple, called ”Thermocouple Sample”, is placed on the sample where its tip is considered to be at a temperature T_{Sample}. The other ”Thermocouple Ref.” is placed on top of the Pt100 temperature sensor, and we considered its tip to be at the same temperature as the Pt100 sensor, T_{Pt100}. Both thermocouples are soldered to a section of the soldering pads region, which is considered to be at an unknown temperature T_{Base}. The voltage reading for each thermocouple will depend on the temperature on its tip and end section, and will follow the relations described in equations 1 and 2. In these equations, f is a calibration curve for a type-K thermocouple that translates a temperature into a voltage reading in the thermocouple.

$$V_{Sample} = f(T_{Sample}) - f(T_{Base}) \tag{1}$$

$$V_{Ref} = f(T_{Pt100}) - f(T_{Base}) \quad (2)$$

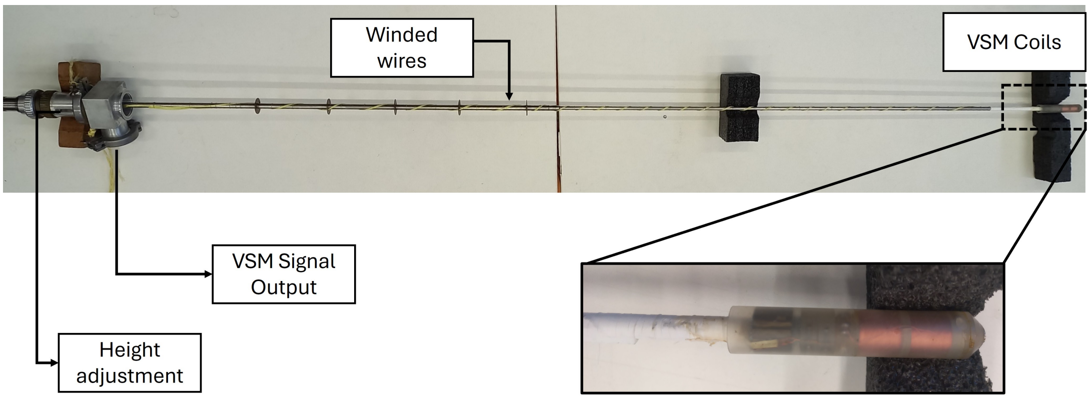
Considering that $f(T_{Base})$ is the same for both cases, the sample temperature is then calculated as shown in equation 3, where f^{-1} is a calibration curve for a type-K thermocouple that translates the voltage reading in the thermocouples into a temperature.

$$T_{Sample} = f^{-1}(V_{Sample} - V_{Ref} + f(T_{Pt100})) \quad (3)$$

It is important to mention that two assumptions were made when using this configuration: (1) the tip of the ”Thermocouple Ref.” is at the same temperature as the Pt100; (2) the ends of both thermocouples are at the same temperature T_{Base}. Although these considerations are reasonable to be made, they can produce a discrepancy in the calculated T_{Sample} value. However, we do not consider this ΔT_{Sample} value to be an exact temperature of the sample but rather an estimation of the change in the sample temperature observed in the measurements. Furthermore, given the scope of the manuscript, we are more interested in the time at which a variation is starting to be detected in the sample temperature and relate this change to the kinetics of the sample rather than measure a precise variation of this temperature. For this purpose, a specially designed adiabatic temperature measurement setup should be considered.

Full measuring setup

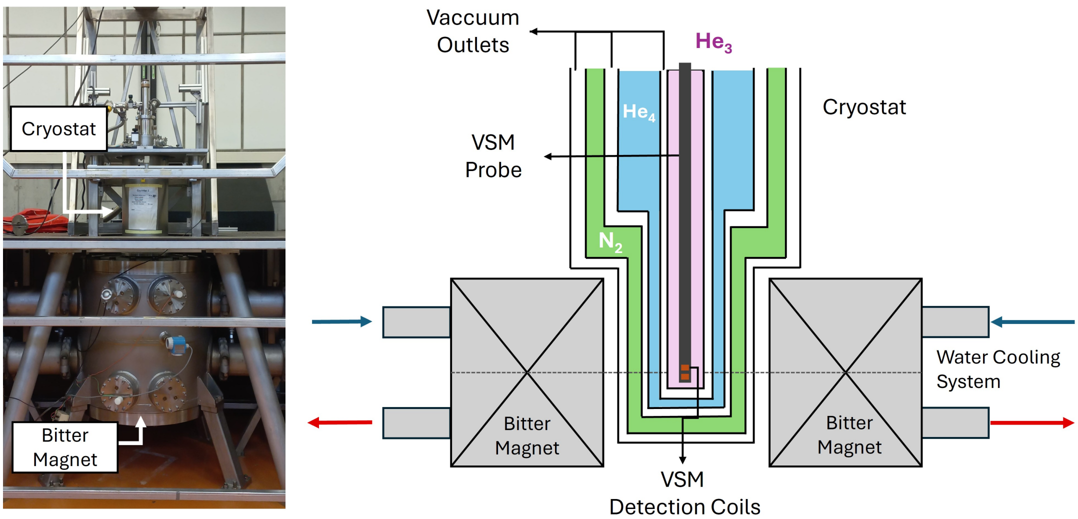
To measure magnetization, the custom-designed probe is placed inside a VSM probe used in the HFML facilities to measure magnetization, as depicted in Figure 4.



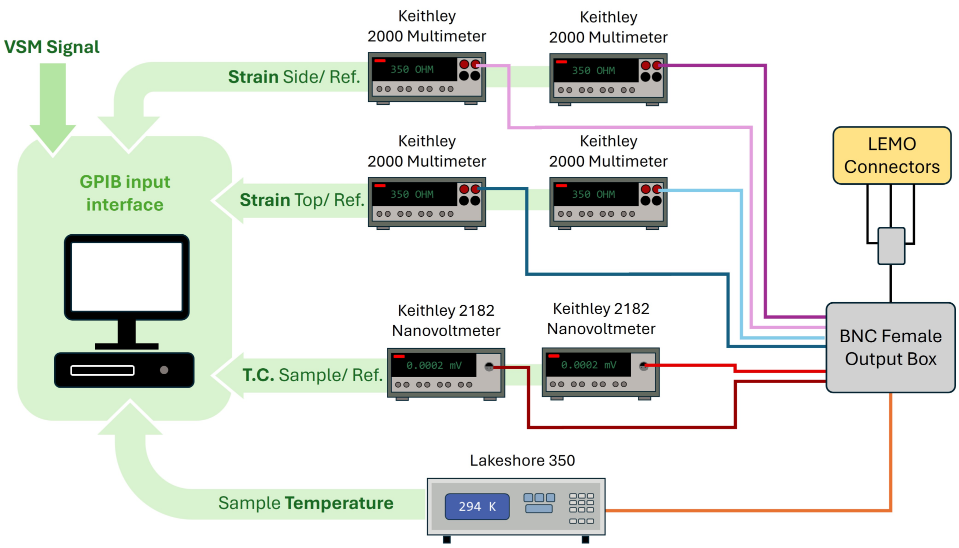
Supplementary Fig. 4: VSM measuring probe commonly used in the High Field Magnetic Laboratory facility to measure magnetization.

This probe is composed of VSM detection coils, placed at the end of the VSM probe, whose signal is then extracted by wires wound along a stick. On the top part of this probe, a LEMO connection signal output can be found along with a height adjustment screw. This adjustment is important to place the center of the VSM coils inside the center of the bitter magnet, where the magnetic field is maximum.

Both the custom-designed probe and the VSM probe are placed inside a Bitter magnet, which can generate magnetic fields up to 30 T with field sweep rates of 10 T/ min. Inside the bitter magnet, a flow cryostat can be found, which is used to control and set the temperature for the experiment. Figure 5 shows an image of the bitter magnet cell used, along with a schematic representation of the flow cryostat.



Supplementary Fig. 5: (left) Image of the bitter magnet cell used with a flow cryostat (right) Schematic representation of the flow cryostat used in the experiment.

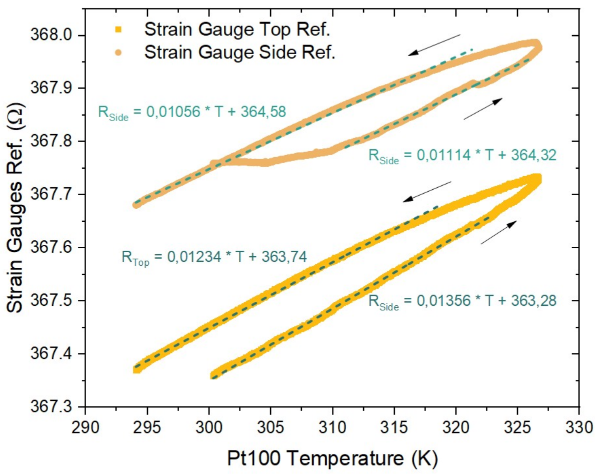


Supplementary Fig. 6: Scheme depicting the wiring configuration used to extract the signals coming from the sensors located in the sample holder. All signals are collected in a GPIB interface and recorded simultaneously in a Labview program.

Figure 6 schematizes the full data acquisition of the sensors placed in the sample holder and the VSM signal. Once both the custom-design probe and VSM probe are placed inside the magnet, the LEMO connectors' signal is extracted and brought to an output connection box, composed of 24 BNC female outputs. Each of these BNC outputs will correspond to a given signal coming from the sensors in the sample holder. These outputs are then connected to a given device to proceed with the data reading and collection. For strain gauges, all four sensors are connected to a Keitlhey 2000 Multimeter. The two thermocouples used are connected to a Keithley 2182 nanovoltmeter. Finally, the Pt100 sensor is plugged into a Lakeshore 350, where the calibration curve from resistance (Ω) to temperature (K) was uploaded. All of these signals are then extracted from a GPIB connection and plugged to a computer, where they are collected and saved in a Labview program at an acquisition rate of around 400 ms.

Strain gauge data analysis

For each set of measurements, special care with the strain gauge data analysis was taken into account. This analysis primarily consists of detecting external contributions such as temperature variations on the detected strain gauge signal. Before starting the kinetic protocols measurements, a temperature dependence was done, and the variation of the reference strain gauges was recorded, as shown in Figure 7.



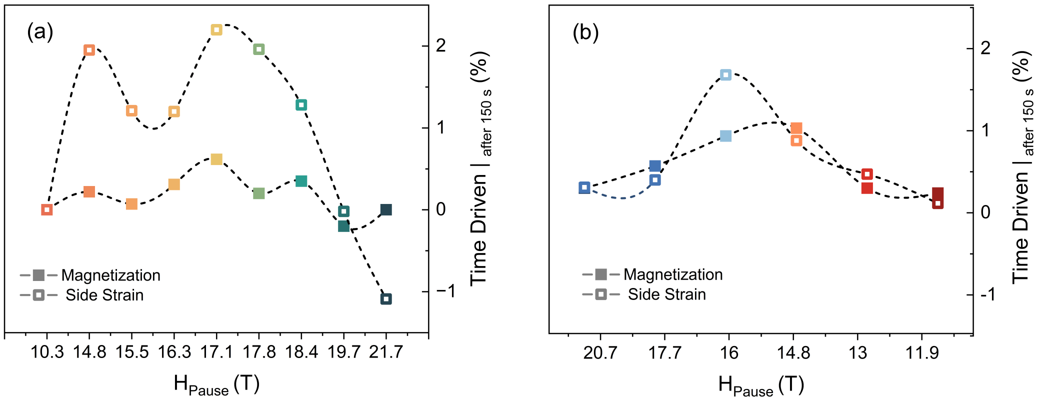
Supplementary Fig. 7: Top and side strain gauge measured values as a function of the temperature of the Pt100 sensor for a temperature range between 294 K up to 326 K. Arrows indicate the heating and cooling process. Linear fits were performed on each cooling/heating section of the data, whose result is presented next to the fit.

Throughout the entire set of experiments presented in the manuscript, the temperature of the experiment was kept rather constant, having obtained deviations from 0.2 K to 0.6 K. From the data shown in Figure 7, we estimated the strain variation associated with the thermal lag detected by the Pt100 sensor. The corrected strain signal was then converted to $\Delta L/L_0$ (%) using Equation 4.

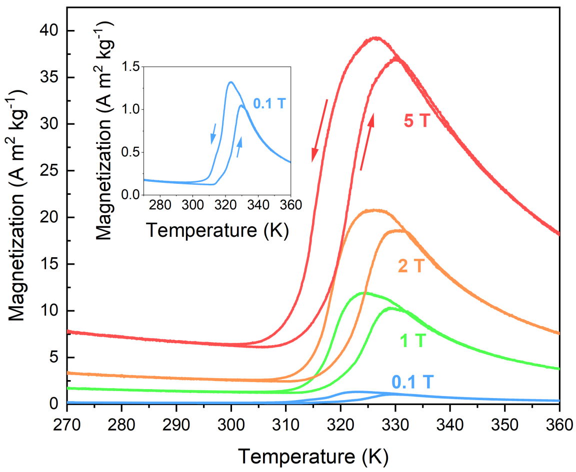
$$\left(\frac{R - R_0}{R}\right) * \frac{1}{G.F.} * 100 = \Delta L/L_0(\%) \tag{4}$$

Here, R (Ω) is the corrected resistance, R_0 (Ω) the initial resistance, and $G.F.$ (gauge factor), a constant specific to each strain gauge model.

Supplementary Data



Supplementary Fig. 8: Evolution of the magnetization and side strain fractions during the simultaneous measurements for (a) forward transition and (b) reverse transition from $t = 150$ s up to $t = 300$ s after the field is halted.



Supplementary Fig. 9: Temperature dependence of magnetization for different applied magnetic fields. The inset shows the magnetization curve measured at 0.1 T.