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FMR studies of cobalt-based amorphous ribbons; effect of the temperature

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Abstract. — The aim of this study is to point out the magnetic behaviour of cobalt-based amorphous conductors from ferromagnetic resonance measurements. From our data, linewidth $\Delta H$, position $H_0$ and amplitude $(\Delta r/\Gamma)_{max}$ of the resonance peak and values of the flattening factor $K$, we determine the $g$-factor (or Landé factor), the damping parameter $\lambda$, the transverse relaxation time $T_2$ as well as the maximum variations $\Delta \mu_M^\prime$, $\Delta \mu_M^\prime\prime$ and $\Delta \mu_M^\prime\prime$ of the relative magnetic permeability $\mu = \mu - j \mu^\prime$. Then we determine the role played by the temperature.

1. Introduction.
Because of the skin effect, amorphous metals more than a few $\mu$m thick are opaque to microwave radiations, thus their FMR studies have to be led by reflection so that the data, recorded as a function of an applied magnetic field, show the variations of amplitude and phase of their reflection factor $r = r e^{i\phi}$. From these variations, we can obtain the magnetic behaviour of our materials at 9 GHz: the $g$-factor, the damping parameter $\lambda$, the transverse relaxation time $T_2$ and the maximum variations $\Delta \mu_M^\prime$, $\Delta \mu_M^\prime\prime$ and $\Delta \mu_M^\prime\prime$ of the complex permeability $\mu = \mu^\prime - j \mu^\prime\prime$ with a calculation we previously set out [1]. Then we consider the effect of the temperature, at 298 K and 77 K, on these magnetic terms.

2. Experimental details.
Our experiments were carried out by using an X-band three-wave interferometer which has led to transmission investigations on other materials [2, 3]. We modified this apparatus to work by reflection, inserting a circulator and a rectangular-to-circular wave guide transition in order to turn the amorphous sample around its axis and to have a symmetric demagnetizing factor. The sample fills up the whole section of the circular guide and is put on a support (see Fig. 1).
Because liquid oxygen is paramagnetic and may produce an error in our measurements, the investigations, led at 77 K, forced us to take some precautions: a stream of dry nitrogen gas circulates through the wave guide so that any trace of oxygen and steam be eliminated (see Fig. 1). Using a heat resistance, we check that we obtain the thermal equilibrium after about ten minutes.

3. Samples.

The samples (Vitrovac, Vacuumschmelze, Germany) which are investigated are discs 30 μm thick and 24.75 mm in diameter cut out from amorphous ribbons. The ribbons are obtained following the Planar Flow Casting process (PFC) [4].

Because of the PFC process, the samples present two non-identical surfaces: the bright surface (BS) is the free one during the process and the matt one (MS) is the surface in contact with the wheel during the process.

The samples are of two kinds:

6 030 : \( \text{Co}_{70}(\text{FeMo})_2\text{Mn}_3(\text{Bsi})_{23} \)

6 025 Z : \( \text{Co}_{68}\text{Fe}_4\text{Mo}_2\text{B}_{12}\text{Si}_{16} \)

The specimen 6 030 was polished to study a possible effect of the surface roughness. With a pressure of 20 Pa and a diamond polish-grain of 1 μm, the polishing times were: \( P_1 = 20 \text{ min}, \ P_2 = 40 \text{ min} \) and \( P_3 = 60 \text{ min} \). The label UP means the unpolished case.

4. Results.

The damping parameter is obtained from the Landau and Lifshitz relation considering the demagnetizing field of a specimen having a disc shape [5].
$K$ is the flattening factor given by:

$$K = \frac{\Delta \mu_M^v}{r_0^2 |\Delta \mu_M' - \Delta \mu_M^v|} \quad [4].$$

$\Delta \mu_M^v$, $\Delta \mu_M'$ and $\Delta \mu_m'$ are given by the following relations [1], (see Fig. 2):

$$\Delta \mu' = \frac{\varepsilon''(1 - r_0^2)}{4} \Delta \phi$$

$$\Delta \mu'' = \frac{\varepsilon'' r_0^2 (1 - r_0^2)}{4} \frac{\Delta r}{r}$$

Where $\varepsilon''$ is the imaginary part of the complex relative permittivity [1, 4].

![Fig. 2. — Shape of $\Delta \mu'$ and $\Delta \mu''$ from FMR reflection measurements.](image)

We give the data depending on the position of the ribbon axis with respect to the microwave field $\mathbf{h}$:

- the ribbon axis is perpendicular to $\mathbf{h}$: indicated by $\perp$ in the tables;
- the ribbon axis is parallel to $\mathbf{h}$: indicated by $\parallel$ in the tables.

The values of the magnetic fields are given in Oersteds: $H(A/m) = 79.5 \ H(Oe)$.

5. Discussion.

First of all, let us notice that the linewidth $\Delta H$ and the amplitudes of the peaks (see Figs. 3 and 4 and Tabs. I and II) show the very disordered nature of the alloys investigated, allowing us to be sure of the amorphous state of these materials [6, 7].

Considering the data of $\Delta \mu_M^v$, we can see that the anisotropy of the alloys is enhanced at $T = 77 \ K$. For example, with the specimen 6 025 Z, BS : ($\Delta \mu_M^{v,\parallel} - \Delta \mu_M^{v,\perp}$)$_{298 \ K}$ = 26 and ($\Delta \mu_M^{v,\parallel} - \Delta \mu_M^{v,\perp}$)$_{77 \ K}$ = 37. This observation is confirmed on other studies on iron-based amorphous materials [4].

We notice, with few exceptions, a high homogeneity of the data when the temperature $T$ drops from 296 $K$ to $77 \ K$: increase of $\Delta H$, $\Delta \mu_M^v$, $g$ and $\lambda$, decrease of $H_0$, $K$ and $T_2$. Both surfaces present the same trends. These trends pores, cracks or surface pits which affect significantly the observed properties [8]. As we can see in the tables III and IV, a polishing time of 20 min permits to eliminate these singularities.
Fig. 3. — The observed FMR reflection at \( T = 398 \, \text{K} \) and \( 77 \, \text{K} \) of \( \text{Co}_{70}(\text{FeMo})_2\text{Mn}(\text{BSi})_{21} \), \( 6 \, 030 \, \text{UP} \), BS, axis \( \perp \, \text{h} \).

Fig. 4. — The observed FMR reflection at \( T = 298 \, \text{K} \) and \( 77 \, \text{K} \) of \( \text{Co}_{66}\text{Fe}_4\text{Mo}_2\text{B}_{12}\text{Si}_{16} \), \( 6 \, 025 \, \text{Z} \), MS, axis//\( \text{h} \).

Table I. — \( \text{Co}_{70}(\text{FeMo})_2\text{Mn}(\text{BSi})_{23} \), \( 6 \, 030 \, \text{UP} \).

<table>
<thead>
<tr>
<th>( 6030 , \text{UP} )</th>
<th>( H_0 ) (Oe)</th>
<th>( \Delta \text{H} ) (Oe)</th>
<th>( K )</th>
<th>( \Delta \mu_{\text{M}} )</th>
<th>( T_2 ) (10^{-10}s)</th>
<th>( \varepsilon )</th>
</tr>
</thead>
<tbody>
<tr>
<td>BS 298 K, ( \perp )</td>
<td>1087</td>
<td>443</td>
<td>1.00</td>
<td>279</td>
<td>1.54</td>
<td>2.05</td>
</tr>
<tr>
<td>BS 77 K, ( \perp )</td>
<td>981</td>
<td>477</td>
<td>0.88</td>
<td>366</td>
<td>1.31</td>
<td>2.16</td>
</tr>
<tr>
<td>BS 298 K, //</td>
<td>1074</td>
<td>430</td>
<td>1.01</td>
<td>290</td>
<td>1.38</td>
<td>2.06</td>
</tr>
<tr>
<td>BS 77 K, //</td>
<td>994</td>
<td>516</td>
<td>0.88</td>
<td>392</td>
<td>1.23</td>
<td>2.15</td>
</tr>
<tr>
<td>MS 298 K, ( \perp )</td>
<td>1113</td>
<td>516</td>
<td>0.99</td>
<td>291</td>
<td>1.36</td>
<td>2.02</td>
</tr>
<tr>
<td>MS 77 K, ( \perp )</td>
<td>1067</td>
<td>490</td>
<td>0.92</td>
<td>311</td>
<td>1.31</td>
<td>2.13</td>
</tr>
<tr>
<td>MS 298 K, //</td>
<td>1127</td>
<td>602</td>
<td>1.02</td>
<td>243</td>
<td>1.18</td>
<td>2.01</td>
</tr>
<tr>
<td>MS 77 K, //</td>
<td>1021</td>
<td>582</td>
<td>0.84</td>
<td>279</td>
<td>1.11</td>
<td>2.12</td>
</tr>
</tbody>
</table>

Table II. — \( \text{Co}_{66}\text{Fe}_4\text{Mo}_2\text{B}_{12}\text{Si}_{16} \), \( 6 \, 025 \, \text{Z} \).

<table>
<thead>
<tr>
<th>( 6025 , \text{Z} )</th>
<th>( H_0 ) (Oe)</th>
<th>( \Delta \text{H} ) (Oe)</th>
<th>( K )</th>
<th>( \Delta \mu_{\text{M}} )</th>
<th>( T_2 ) (10^{-10}s)</th>
<th>( \varepsilon )</th>
</tr>
</thead>
<tbody>
<tr>
<td>BS 298 K, ( \perp )</td>
<td>1350</td>
<td>387</td>
<td>1.09</td>
<td>163</td>
<td>1.40</td>
<td>2.11</td>
</tr>
<tr>
<td>BS 77 K, ( \perp )</td>
<td>1219</td>
<td>404</td>
<td>1.04</td>
<td>179</td>
<td>1.24</td>
<td>2.24</td>
</tr>
<tr>
<td>BS 298 K, //</td>
<td>1364</td>
<td>354</td>
<td>1.07</td>
<td>189</td>
<td>1.88</td>
<td>2.10</td>
</tr>
<tr>
<td>BS 77 K, //</td>
<td>1219</td>
<td>377</td>
<td>1.00</td>
<td>216</td>
<td>1.67</td>
<td>2.24</td>
</tr>
<tr>
<td>MS 298 K, ( \perp )</td>
<td>1351</td>
<td>427</td>
<td>1.12</td>
<td>218</td>
<td>2.12</td>
<td>2.11</td>
</tr>
<tr>
<td>MS 77 K, ( \perp )</td>
<td>1219</td>
<td>437</td>
<td>1.13</td>
<td>236</td>
<td>2.06</td>
<td>2.24</td>
</tr>
<tr>
<td>MS 298 K, //</td>
<td>1364</td>
<td>569</td>
<td>1.25</td>
<td>232</td>
<td>1.99</td>
<td>2.10</td>
</tr>
<tr>
<td>MS 77 K, //</td>
<td>1219</td>
<td>589</td>
<td>1.22</td>
<td>274</td>
<td>1.89</td>
<td>2.24</td>
</tr>
</tbody>
</table>

We can see from the data (Tabs. III, IV and V), that the variations of the polished specimens are smaller when the temperature drops. More precisely, the relative variations of the samples P2 and P3 are on the whole 10\% smaller than those of the UP and P1 ones. These 10\% are an estimation of the influence of the imperfections within the surface layer. Since this difference of 10\% occurs only with the samples P2 and P3, we can say that 20 min is not enough to eliminate correctly these imperfections, a polishing time of 40 min is necessary.
The decrease of the resonance field \( H_0 \) (which is more important with the sample 6 025 Z, see Tab. III) shows an easier magnetization of the material and confirms a better aligning of the spins at 77 K as well as a stronger spin-orbit coupling [9]. Since this decrease comes with a diminishing of \( T_2 \) as well as an increase of \( \Delta \) and \( \Delta \mu_{\mu}^\prime \) (see Tab. V), the samples present at 77 K a stronger magnetic absorption (i.e. a more important spatial dispersion of the magnetization) due to a stronger skin effect.

The question is to know whether we are in presence of normal or anormal skin effect. The data show an increase of \( \Delta H \) and \( \Delta g \) at 77 K (Tab. IV and Fig. 3): the interaction between the conduction electrons and those responsible of the ferromagnetism are more important and the basic contribution to this phenomenon is made by the spin-current interaction. This interaction leads to a change of the total spin quantum number (i.e. \( \Delta S = \pm 1 \), in \( h/2\pi \) units). This change is only linked with the normal skin effect and the number of conduction electrons taking part in

\[
\begin{array}{c|cccccc}
\text{increase of } \Delta H (\text{Oe}) & 6030 \text{ UP} & 6030 \text{ P1} & 6030 \text{ P2} & 6030 \text{ P3} & 6025 \text{ Z} \\
\hline
\text{BS, } & 34 & 61 & 40 & 40 & 17 \\
\text{BS, } & 86 & 32 & 40 & 10 & 23 \\
\text{MS, } & -26 & 20 & 5 & 12 & 10 \\
\text{MS, } & -20 & 20 & 0 & 0 & 20 \\
\end{array}
\]

\[
\begin{array}{c|cccccc}
\text{increase of } \Delta \mu_{\mu}^\prime (\text{g}) & 6030 \text{ UP} & 6030 \text{ P1} & 6030 \text{ P2} & 6030 \text{ P3} & 6025 \text{ Z} \\
\hline
\text{BS, } & 87 & 70 & 59 & 52 & 42 \\
\text{BS, } & 102 & 71 & 49 & 45 & 18 \\
\text{MS, } & 20 & 50 & 38 & 27 & 27 \\
\text{MS, } & 35 & 30 & 33 & 32 & 16 \\
\end{array}
\]

\[
\begin{array}{c|cccc}
\Delta g & 0.14 & + & + & + \\
0.11 & + & + & + & + \\
0.09 & + & + & + & + \\
\hline
\text{UP, P1, P2, P3, 6025 Z} & & & & \\
\end{array}
\]

Fig. 5. — Variations of \( g \) vs. type of materials when \( T \) drops from 298 K to 77 K.

Table III. — Decrease of \( H_0 \) when \( T \) drops from 298 K to 77 K.

Table IV. — Increase of \( \Delta H \) when \( T \) drops from 298 K to 77 K.

Table V. — Increase of \( \Delta \mu_{\mu}^\prime \) when \( T \) drops from 298 K to 77 K.
the phenomenon. Thus the anomalous skin effect, leading to a decrease of $\Delta H$ and $\Delta g$ and linked with $\Delta S = 0$ type, does not play a dominant part in FMR above 77 K: in spite of a lower resistivity of these materials at 77 K [10], their conductivity is still not high enough (unlike their corresponding crystalline ones), to notice any anomalous skin effect.

We can assume that the line broadening passes through a maximum as the temperature drops below 77 K: from that maximum, the anomalous skin effect becomes dominant with respect to the normal skin effect.

Moreover the raising of $\Delta g$ is more important with the specimen 6 025 Z: the spin-electron relaxation is more noticeable with this sample than with the 6 025 one and the variation of its mean free path is greater. Another studies on iron-based amorphous materials [4] confirm these observations.

6. Conclusion.

Our investigations allowed us to determine the microwave magnetic properties of amorphous magnetic conductors. The measurements enable to quantify the influence of the surface imperfections. This influence disappears after a polishing times of 40 min.

Our work permitted us to point out that the anisotropy of the amorphous alloys is enhanced at 77 K.

Moreover, we showed that no anomalous skin effect appears at 77 K and that the alloys 6 025 Z presents greater variations: it may come from a higher concentrarion of iron.

References


