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MAGNETIC, THERMAL EXPANSION, AND ELECTRICAL RESISTIVITY STUDIES OF FeAlMnC STEELS

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Abstract. Several FeAlMnC alloy samples (Mn: 27.6-29.8 wt%, A: 7.4-9.2 wt%, C: 0.6-1.3 wt%, Fe:Bal.) have been made for magnetic (\(\sigma\)), thermal expansion (\(\Delta \ell/\ell\)), and electrical resistivity (\(\rho\)) studies between 10 and 300 K. Carbon and aluminum contents are found to be important in affecting those measured quantities. Temperature dependences of \(\sigma\), \(\Delta \ell/\ell\), and \(\rho\) are discussed briefly.

1. Introduction

FeAlMnC steels are subjects of growing interests, because of their potential uses. In this paper, we made various measurements such as magnetic, thermal expansion, and electrical resistivity on several FeAlMnC steels at low temperatures (10 K \(\leq T \leq 300\) K). Because of complications of this alloy system, our report does not tend to be exhaustive and quantitative, but rather tends to be qualitative and forms complements to our previous report [1].

It was reported that by adding suitable amounts of carbon (1 wt%) or aluminum (7 wt%) [2, 3], one may stabilize the austenitic phase in FeAlMnC steels. Otherwise, the ferrite phase grows substantially in the original matrix. Also, by thermal aging these steels above 700 K, \(\text{Fe}_3\text{AlC}\) or \(\text{FeAlC}\) may precipitates among various phases [4]. All these structural changes may effectively alter the magnetic, thermal expansion, and electrical resistivity properties of the steels [5-7].

2. Experiments

All the samples (#1-#5, Tab. I) used in the experiments are the same as before [1]. Their thermal treatments have been reported elsewhere [1]. For magnetic and electrical resistivity measurements, we have used the same apparatus working at low temperatures [1]. As to thermal expansion measurements, a Perkin-Elmer TMS-2 system was employed. The dilatometer was calibrated with a pure silver block.

3. Results and discussions

Figure 1 shows the temperature dependence of the magnetic properties of the five steels. Table I also illustrates magnitudes of the magnetic moments \(\sigma\) measured at 20 K and 300 K, and the linear or the non-linear property of \(\sigma (T, H)\). Magnetically speaking, #2 and #3 steels behave similarly, and form a group. Their \(1/\chi\) versus \(T\) plots show that at \(T = 254\) K for #2 steel and at \(T = 269\) K for #3 steel respectively, there exist paramagnetic to antiferromagnetic transitions. For #1 steel, its magnetic properties behave distinctly in that its saturation moment is the highest, and remains ferromagnetic from room temperature to

![Graph showing temperature dependence of magnetic properties.](http://dx.doi.org/10.1051/jphyscol:19888863)

**Table I.** Concentrations, magnetic moment, and electrical resistivity of #1 - #5 FeAlMnC steels.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Fe (wt%)</th>
<th>Mn (wt%)</th>
<th>Al (wt%)</th>
<th>C (wt%)</th>
<th>(\sigma (300\text{ K, 6 kG})) (emu/g)</th>
<th>(\sigma (20\text{ K, 6 kG})) (emu/g)</th>
<th>(\rho (10\text{ K})/\rho_{300})</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Bal</td>
<td>27.6</td>
<td>7.4</td>
<td>0.59</td>
<td>73.8(n)*</td>
<td>90.2(n)</td>
<td>- (d)*</td>
</tr>
<tr>
<td>2</td>
<td>Bal</td>
<td>29.8</td>
<td>7.6</td>
<td>0.94</td>
<td>0.25((\ell))^+</td>
<td>- ((\ell))</td>
<td>1.16(s)*</td>
</tr>
<tr>
<td>3</td>
<td>Bal</td>
<td>29.7</td>
<td>8.7</td>
<td>1.04</td>
<td>1.2 ((\ell))</td>
<td>- ((\ell))</td>
<td>1.08(s)</td>
</tr>
<tr>
<td>4</td>
<td>Bal</td>
<td>29.6</td>
<td>8.4</td>
<td>1.31</td>
<td>17.6(n)</td>
<td>8.4((\ell))</td>
<td>1.03(d)</td>
</tr>
<tr>
<td>5</td>
<td>Bal</td>
<td>29.4</td>
<td>9.2</td>
<td>0.95</td>
<td>14.2(n)</td>
<td>2.6((\ell))</td>
<td>1.04(s)</td>
</tr>
</tbody>
</table>

* (n): non-linear, (\(\ell\)): linear.
+ (d): double-minimum, (s): single-minimum.
For # 4 and # 5 steels, their magnetic characteristics are similar in that they are ferromagnetic at room temperature, however with much lower moments, and $\sigma$ decreases with decreasing temperatures (Fig. 1). Since for this last group of samples, their $\sigma(T,H)$ become linear below around 150 K, we may speculate that the alloys turn into an antiferromagnetic state in the temperature range $10 \, K \leq T \leq 150 \, K$ [8]. Because the phases in the FeAlMnC system is complicated, we only make the following conclusions: (1) for $C \leq 0.6$ wt% or $Al + C \leq 8.0$ wt%, the ferrite phase is the major phase and dominates the magnetic property, (2) for $C = 0.94$ wt% or $Al + C = 8.54$ wt%, the austenitic phase becomes the most favorable phase, (3) for $C \geq 1.31$ wt% or $Al + C \geq 10$ wt%, it is a mixed behaviors emanating from different phases of a mixture system.

Figure 2 shows the normalized electrical resistivity $\rho/\rho_{300}$ plotted varus temperature for # 2 - # 5 steels (data for # 1 steels existed in Ref. [1]). Together with table I, we summarize that: (1) # 2 and # 3 steels are similar. Their $\rho(T)/\rho_{300}$ rise more sharply with decreasing temperatures, and there is only one high temperature minimum $T_{\text{min}}^h \approx 400 \, K$ for these steels, (2) For # 1 and # 4 steels, their $\rho(T)$ rises with lowering temperatures are less, and there are double minima with $T_{\text{min}}^h \approx 400 \, K$ and $T_{\text{min}}^h \approx 40 \, K$. From the above discussions, we may associate the rising characteristics of $\rho(T)$ with the existence of the austenitic phase, although it is still not sure whether it is structurally or magnetically related. However, we also believe the low temperature minimum $T_{\text{min}}^h$ is not related to the austenitic phase.

![Fig. 2](image.png)

Fig. 2. - The temperature dependence of the normalized electrical resistivity $\rho/\rho_{300}$ of # 2 (o), # 3 (o), # 4 (x), and # 5 (\(\Delta\)) steels.

Figure 3 shows the thermal expansion $\Delta l/l$ plot versus temperatures. The problem of $\Delta l/l$ data is that results from successive runs of # 1, 3-5 samples are not repetitive; sometimes $\Delta l/l$ shows a small flat portion, and sometimes it does not. Only $\Delta l/l$ of # 2 steel shows the consistent results as in figure 3. The contraction of $\Delta l/l$ of # 2 steel in the temperature range $223 \, K \leq T \leq 263 \, K$ may be considered as another prominent property of the austenitic phase in the alloy system.

In conclusion, we have performed a series of magnetic, thermal expansion, and electrical resistivity measurements on the FeAlMnC alloys. It is found that the carbon and aluminum concentrations are crucial to their properties. From a practical point of view, # 2 steel would be the best material for cryogenic applications in magnetic fields.

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[8] Zero field cooled data are the same as field cooled data.