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TEMPERATURE BEHAVIOUR OF THE PERMEABILITY OF SOME COMMERCIAL NiFe ALLOYS

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Abstract. – Using a modified Kersten’s model of the permeability to introduce the main parameters: the magnetocrystalline anisotropy, the magnetostriction and a magnetostatic term, we derive a general relation which gives the thermal variation of the permeability. This model is compared with measurements of the permeability versus temperature on different commercial NiFe alloys.

Most commercial NiFe alloys show a low magnetocrystalline anisotropy and thus exhibit large permeabilities. They are mainly used in electronic and security devices where they usually operate near room temperature but can experience temperature variations in usage. Thermal variation of the permeability and its control is thus of importance for these materials.

Temperature is also a means of modifying the alloy electromagnetic parameters and can help us to have a new insight in the behaviour of the permeability. We first give a semi-empirical expression of the permeability including most of the pertinent parameters, then we derive the temperature variation of the permeability and finally we show experimental results of its thermal behaviour in some limited cases of commercial interest.

1. Alloys with low anisotropies

There is no good relation which gives the permeability of an alloy in terms of its electromagnetic parameters. When we deal with alloys with low anisotropies where the Bloch walls move almost reversibly and lead to very high permeability, Kersten’s model is often the most accurate. However in its original form, it expresses the permeability only versus the magnetocrystalline anisotropy [1] whereas most experimental results show the importance of other terms.

In order to take account of most experimental results, we suggest to use a semi-empirical expression including different terms of energy, the magnitude of which is about the same as the magnetocrystalline anisotropy in NiFe alloys.

Modifying the Kersten’s relation, we tentatively write the d.c. permeability

\[ \mu_{dc} \approx \frac{AJ}{\sqrt{b + K_1 + K_u + 3/2 \lambda \sigma}} \]  

(1)

where \( J \) is the saturation magnetisation, \( K_1 \) and \( K_u \) respectively the magnetocrystalline and the induced anisotropy, \( \lambda \sigma \) the magnetoelastic energy and \( b \) a magnetostatic term which is supposed to represent all the regions where \( \text{div} \ J \neq 0 \) (grain boundaries, inclusions, etc.). The importance of the term \( b \), often neglected, is shown for example by the 20-80 Permalloys where \( K_u = \lambda \sigma = 0 \) and no experimental evidence of an infinite permeability is observed when \( K_1 \) is set to zero either by heat treatment or by temperature variation [2]. All the terms in (1) are supposed to behave as scalars and \( A \) is a constant.

Usually the strip thickness is chosen to minimize the eddy currents at the usage frequency; therefore, their importance on the thermal variation of the permeability is small and can be ignored. Differentiating (1), we get

\[ \frac{1}{\mu} \frac{\partial \mu}{\partial T} \approx \frac{1}{J} \frac{\partial J}{\partial T} - \frac{1}{2(b + K_1 + K_u + 3/2 \lambda \sigma)} \times \]

\[ \left( \frac{\partial b}{\partial T} + \frac{\partial K_1}{\partial T} + \frac{\partial K_u}{\partial T} + \frac{3 \partial (\lambda \sigma)}{2 \partial T} \right). \]  

(2)

This relation explains, at least qualitatively, most of the commercial NiFe thermal behaviour near room temperature.

2. Thermal variation of the permeability: experimental results

2.1 30-70 NiFe ALLOY. – This alloy, used mainly as a magnetic shunt in order to stabilize magnets in measuring devices, shows the unusual example of an alloy used near its Curie temperature. Usually \( K_1, K_u \) and \( \lambda \) are slowly vanishing to zero near the Curie temperature and this leads to a negligible value of the second term in (2) compared to the first. As \( \frac{\partial J}{\partial T} < 0 \), the permeability decreases with temperature before the Curie temperature as experimentally observed (Fig. 1).

![Fig. 1. – NiFe 30-70 D.C. permeability versus measurement temperature.](image-url)
2.2 50-50 NiFe ALLOY. - Most commercial magnetic alloys show a fairly high Curie temperature in order to keep their magnetisation as high as possible at room temperature. This leads in ferromagnetic materials to a low temperature variation of the magnetisation near room temperature \( \frac{\partial J}{\partial T} \sim 0 \). Consequently, the thermal stability of these materials is reduced to the second term in (2).

As a first example of this behaviour, we examine the 50-50 NiFe alloy, the Curie point of which is about 500 °C and hence the term \( b \) assumed constant versus measurement temperature. As \( \frac{\partial K_1}{\partial T} \simeq -4 \text{ J} \cdot \text{m}^{-3} \cdot \text{K}^{-1} \) remains roughly constant [4] near room temperature as well as \( \lambda \), we expect a steady increase of the permeability versus temperature. Figure 2 shows this behaviour.

![Figure 2](image2)

Fig. 2. - NiFe 50-50 D.C. permeability versus measurement temperature for different anneals.

We may notice on this figure the increase of \( \mu \) and \( \frac{\partial \mu}{\partial T} \) for different heat treatments which shows the importance of the term \( b \). The smaller the term \( b \) is, as a consequence of the grain growth and alloy purification at high temperature, the larger the permeability and \( \frac{\partial \mu}{\partial T} \).

2.3 80-20 Ni-Fe ALLOY. - It shows the highest permeability among the commercial magnetic alloys. This is due mainly to vanishingly low values of \( K_1 \), \( K_u \) and \( \lambda \) [2]. However only \( J \), \( K_u \), and \( \lambda \) show a low temperature dependence near room temperature. \( K_1 \) unlike exhibits large temperature variations [4]. In this alloy, equation (2) is then reduced to:

\[
\frac{1}{\mu} \frac{\partial \mu}{\partial T} = -\frac{1}{2(b + K_1)} \frac{\partial K_1}{\partial T} \tag{3}
\]

which stresses most of the behaviour observed on these materials [2]:

- the lower the magnetocrystalline anisotropy, the higher the permeability and the worst the temperature stability;
- lowering the baking temperature increases the magnetocrystalline anisotropy and stabilizes the temperature variation of the permeability but reduces its value. Until now, we have only discussed the permeability behaviour; however, most of the magnetic parameters are modified by the temperature as well: the squareness ratio [2], the coercive force (Fig. 3b)... Therefore, as far as temperature is the only parameter involved, a relationship may exist between them. For example, if we assume the coercive force to be proportional to an anisotropy field,

\[
H_c \simeq \frac{b + K_1}{J}.
\]

Differentiating and combining with (3), we obtain

\[
\frac{1}{\mu} \frac{\partial \mu}{\partial T} \simeq -\frac{1}{2} \frac{1}{H_c} \frac{\partial H_c}{\partial T}
\]

which leads to

\[
\mu(T) \simeq \frac{C}{\sqrt{H_c(T)}}. \tag{5}
\]

This relation is in good agreement with the experimental results even when both \( \mu(T) \) and \( H_c(T) \) do not show a simple behaviour (Fig. 3).

![Figure 3](image3)

Fig. 3. - D.C. permeability (a), coercive force (b) versus measurement temperature, and D.C. permeability versus coercive force (c) for a FeNi 20-80 annealed for the best permeability.

Conclusion

The experimental results on the thermal variation of the permeability of various commercial NiFe alloys are in good agreement with the predictions of the modified Kersten’s model and show the importance on the permeability of other terms beside the magnetocrystalline anisotropy.

This semi-empirical model explains fairly well most of the commercial NiFe alloys thermal behaviour including those which have not been presented here. It has been valuable to forecast the behaviour of recently developed materials.