Spin Wave Dispersion Relation and Damping in Sendust Alloy in 8 to 295 K Temperature Range

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Abstract. Previous neutron scattering experiments on single crystal of Sendust alloy (73.5 at. % Fe, 17 at. % Al, and 9.5 at. % of Si) revealed extremely high spin wave damping at room temperature. The aim of present studies was to test if the spin wave damping originates from lattice disorder or comes from mutual spin waves interactions or other excitations that would be temperature dependent. The spin wave dispersion relation and damping were studied in temperature range from 8 to 295 K. No regular changes of both spin wave damping and stiffness constant (which characterises dispersion relation) with temperature were found. Thus, within this temperature range, spin waves interactions with dynamical excitations of all kinds must be negligible, and their damping is most likely produced by lattice disorder alone. It is of interest to note that the inelastic background intensity below the spin wave peaks increases with temperature and for energy transfers higher than 30 meV this increase is larger than that of spin-wave peak intensity.

1. Introduction
Sendust is a ternary alloy of Fe, Si, and Al (85 wt. % Fe, 5 wt. % Al, and 10 wt. % of Si). It has no crystalline anisotropy and its magnetostriction is negligible. Sendust structure is of the DO₃ type, same as for Fe₃Si and Fe₃Al alloys, and constitutes of four sublattices with basis atomic sites A(0,0,0), B(1/4,1/4,1/4), C(1/2,1/2,1/2), and D(3/4,3/4,3/4) [1, 2]. In the stoichiometric alloy (like Fe₃Si or Fe₃Al) A, B and C positions are occupied mainly by Fe atoms, while Si and Al atoms occupy D positions. In Fe-deficient alloys appropriate parts of Si and Al atoms occupy iron positions [3]. Atom in position B is surrounded by 8 equivalent nearest neighbours (NN) of the A and C type. The surrounding of symmetry equivalent A and C sites consists of 4 NN of the B type and 4 NN of the D type [1].

Previous neutron scattering measurements on the same sample of Sendust alloy at room temperature revealed extraordinarily high spin wave damping [1, 2]. To find the origin of the damping, the temperature dependence of spin wave dispersion relation and damping at 8 to 295 K were studied by means of inelastic neutron scattering. The results do not show the changes of stiffness constant and damping expected for cubic ferromagnetic metals on the assumption that spin waves interact with each other and with electrons only [4]. The measurements reveal surprisingly high increase of q-independent neutron scattering with temperature.

2. The sample and experimental technique
The sample used in the experiment was a single crystal of Sendust (73.5 at. % Fe, 17 at. % Al, and 9.5 at. % Si), produced by Bridgman method, which was already investigated by other authors [1, 2]. Its composition is nearly stoichiometric, thus mainly Fe atoms occupy A, B, and C positions. Si or Al...
atoms probably occupy D positions randomly. It follows from the stoichiometry that 6 at. % of Al/Si atoms must enter iron positions. Sample dimensions are $20 \times 15 \times 27 \text{mm}^3$, the latter being parallel to [110] crystallographic direction. Curie temperature of the sample is $794\pm1 \text{K}$ [2].

The experiments were carried out with the neutron triple axis spectrometer H6 in the Institute of Atomic Energy, Świerk, Poland. The monochromator and the analyzer were made of pyrolytic graphite. Inelastic neutron scattering (INS) was investigated for three crystallographic directions: [100], [110] and [111], close to (111) and (022) reciprocal lattice points. The spin waves studies were carried out in the temperature range from 8 to 295 K (well below the Curie temperature), and energy transfers ranged from 8 to 40 meV. To obtain better resolution the energies of scattered neutrons were fixed to 14.8 meV and 20.5 meV ($\lambda = 2.35 \text{Å}$ and $\lambda = 2 \text{Å}$) for energy transfers below and above 20 meV, respectively. The range of investigated energy transfers did not contain values for which $k_i \approx 2k_f$ so no filter was used. The number of neutrons emerging from reactor core was monitored and determined the duration of the intensity measurement at every point of measured distribution.

3. Results and data analysis

Scattered neutron intensities were measured for fixed neutron energy transfers and varying scattering vectors. Figure 1 shows examples of the intensity distributions for chosen temperature values.

![Figure 1. Examples of the neutron scattering intensity distributions at several temperatures in the vicinity of (111) reciprocal lattice point in [100] direction and 8 meV (a) and 12 meV (b) energy transfer, and in the vicinity of (022) reciprocal lattice point in [022] direction and 30 meV energy transfer (c). Solid lines are fits for 8 K and 295 K.](image)

Figure 1. Examples of the neutron scattering intensity distributions at several temperatures in the vicinity of (111) reciprocal lattice point in [100] direction and 8 meV (a) and 12 meV (b) energy transfer, and in the vicinity of (022) reciprocal lattice point in [022] direction and 30 meV energy transfer (c). Solid lines are fits for 8 K and 295 K.

Apparently, not only the intensity of spin wave peak increases with temperature but one also detects an increase of the $q$-independent intensity, $B$ (see equation (1)), especially for energy transfers above 30 meV. For the 8 meV energy transfer in the range from 8 to 295 K this increase is three-fold slower than that for neutron scattering on spin waves at the distribution maximum. For 12 meV energy the increase of the background and that of spin scattering are roughly proportional to each other. For 30 meV it is $\sim1.5$-fold faster than that of spin wave scattering. The increase of $B$ with temperature indicates that it likely comes from the incoherent scattering.

Every distribution was fitted with the convolution of spectrometer resolution function $R(Q, \omega, Q', \omega')$ and neutron scattering cross-section, with a simultaneous background ($B$) adjustment.

$$I = I_0 \int dQ' d\omega' R(Q, \omega, Q', \omega') \frac{d^2\sigma(Q', \omega')}{d\Omega d\omega} + B$$  \hspace{1cm} (1)
where $I$ is scattered neutrons intensity and $I_0$ is the intensity of incoming neutrons. Neutron scattering cross-section on damped spin waves was assumed in the form \[4\]

$$
\frac{d^2 \sigma}{d\Omega d\omega} \propto \frac{k_f}{k_i} f^2(Q)(n_B(\omega)+1) \left[ \frac{\hbar \Gamma_q}{(\hbar \omega - \hbar \omega_q)^2 + [\hbar \Gamma_q]^2} - \frac{\hbar \Gamma_q}{(\hbar \omega + \hbar \omega_q)^2 + [\hbar \Gamma_q]^2} \right]
$$

where $\hbar \Gamma_q$ is the energy broadening of a spin wave of energy $\hbar \omega_q$.

Since Sendust is a ferromagnet with negligible anisotropy, if any, the dispersion relation was assumed in the form

$$
\omega^2 D q^2 = \hbar (3)
$$

The general $q$ dependence characterizing energy broadening $\hbar \Gamma_q$ was fitted with [4, 5]

$$
\hbar \Gamma_q = A q^n
$$

According to previous results [2]: $n_1 = 2.83$ (for the [111] direction) and $n_2 = 1.95$ (for the [110] direction). In our fittings $n$ was taken to be equal to 2 or 3.

Parameters $D$, $A_2$, and $A_3$ determined for several distributions are listed in table 1 (a) - (f).

| Table 1. Fitted stiffness constants $D$, damping parameters $A_2$ and $A_3$, and energy broadenings for neutron inelastic scattering intensity distributions at chosen temperatures. The displayed results concern scans in the vicinity of (111) reciprocal lattice point in [100] direction for energy transfers 8 meV (a, b) and 12 meV (c, d) energy transfer, and in the vicinity of (022) reciprocal lattice point in [022] direction for the energy transfer of 30 meV (e, f). |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (a) Spin wave energy 8 meV (111) [100] | (b) Spin wave energy 8 meV (111) [100] | (c) Spin wave energy 12 meV (111) [100] | (d) Spin wave energy 12 meV (111) [100] | (e) Spin wave energy 30 meV (022) [022] | (f) Spin wave energy 30 meV (022) [022] |
| $T$ [K] | $\chi^2$ | $\chi^2$ | $\chi^2$ | $\chi^2$ | $\chi^2$ | $\chi^2$ | $\chi^2$ | $\chi^2$ | $\chi^2$ | $\chi^2$ | $\chi^2$ | $\chi^2$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 8 | 1.6 | 158±4 | 15±10 | 0.77±0.48 | 8 | 1.6 | 161±4 | 80±41 | 0.88±0.45 | 8 | 1.4 | 159±2 | 29±6 | 2.22±0.44 |
| 100 | 1.4 | 163±2 | 13±5 | 0.65±0.23 | 100 | 1.3 | 165±2 | 62±21 | 0.67±0.22 | 100 | 0.9 | 169±2 | 16±4 | 1.11±0.25 |
| 295 | 4.6 | 160±2 | 22±5 | 1.08±0.26 | 295 | 4.0 | 163±2 | 103±23 | 1.12±0.25 | 295 | 3.0 | 170±3 | 28±7 | 1.95±0.52 |
| 3 | 1.4 | 137±3 | 30±7 | 6.5±1.7 | 3 | 1.3 | 139±3 | 67±17 | 6.7±1.8 | 3 | 1.3 | 139±3 | 88±15 | 8.8±1.5 |
| 100 | 1.5 | 127±4 | 66±12 | 15.6±2.9 | 100 | 1.4 | 125±12 | 146±31 | 17.2±4.4 | 100 | 1.1 | 139±4 | 99±17 | 10±2 |
| 125 | 1.1 | 138±3 | 42±7 | 9.2±1.4 | 125 | 1.1 | 139±4 | 99±17 | 10±2 |
| 175 | 1.4 | 138±3 | 38±6 | 8.3±1.3 | 175 | 1.3 | 139±3 | 88±15 | 8.8±1.5 |
| 295 | 1.0 | 147±3 | 49±8 | 9.9±1.7 | 295 | 1.1 | 147±6 | 127±24 | 11.8±2.4 |
The values of \( D \) and \( h\Gamma_q \) obtained for both \( n = 2 \) and \( n = 3 \) assumptions do not differ within standard deviations for individual distributions. Both exponents, \( n \), turned out to describe the spin wave linewidths equally for \( |q| < 0.45 \). For \( |q| > 0.45 \), however, the \( q \) dependence is apparently stronger.

The spin wave dispersion relation and energy broadening were calculated for fitted \( D \) and \( A_2 \) parameters. The results are illustrated in figure 2.

![Figure 2](image_url)

**Figure 2.** The spin wave energy and broadening as a function of wave vector at three temperatures. The solid line represents the dispersion relation of the form \( \hbar \omega = Dq^2 \), dashed and dotted lines represent the energy broadening fit \( \hbar\Gamma_q = A_2q^2 \) and \( \hbar\Gamma_q = A_3q^3 \) respectively, fitted to the spectra measured at 8 K. We do not mark the results measured along separate directions of measurements as no anisotropy was observed.

4. Discussion and conclusions

The number of spin waves propagating in the lattice ruled by the Bose statistics increases when the temperature is increasing. The greater number of spin waves should result in greater number of their interactions with each other, with other types of excitations in the lattice, and interactions with electrons. This is why the damping should increase with temperature. The various types of interactions of spin waves may affect not only the spin wave damping but also dispersion relation - stiffness constant is expected to decrease with temperature [4, 5].

To see the reason for previously observed high spin-wave damping, the temperature dependences of dispersion relation and spin wave damping in single crystal of Sendust were measured. The measurements were performed in temperature range 8 to 295 K for various neutron energy transfers.

The determined spin wave stiffness constant and damping parameter do not show any regular changes with temperature. The lack of temperature dependence of damping as represented by the spin wave peak widths indicates that spin wave energy broadening probably is produced neither by their mutual interactions nor by their interactions with other types of thermal excitations. The source of extraordinarily large energy broadening must be tracked to other features of the material. The broadening may be induced by some disorder within the crystal arising e.g. from the randomness of
the occupation of D positions by Si and Al atoms. Also the slight deviation from stoichiometry of the alloy (73.5 at. % Fe instead of 75%) may be an additional source of the lattice disorder. Apparently different metallic radii of aluminum and silicon can result in local stretching and contraction of the lattice. Different local Fe surroundings and distances may induce local changes in exchange integrals producing broadening of dispersion relation or affect spin wave propagation in the lattice, producing their damping.

We have observed that inelastic background intensity below the spin wave peaks increases with temperature and for energy transfers higher than 30 meV this increase is larger than that of spin-wave peak intensity. The elucidation of this effect as well as that of the rapid increase of damping at larger quasi-momentum needs further work.

References
[1] Parzych G, Jankowska-Kisielińska J and Dobrzyński L 2010 Acta Phys. Polonica A 117 578
[2] Dobrzyński L, Wiśniewski A, Uemura Y J, Shapiro S M and Wicksted J P 1988 Phys. Rev. B 37 7175
[3] Suwalski S, Schneeweiss O, Zemčík T and Tucholski Z 1979 Physica Status Solidi (a) 53 K195
[4] Marshall W and Lovesey S W 1971 Theory of Thermal Neutron Scattering. The Use of Neutrons for the Investigation of Condensed Matter (Oxford, Oxford University Press) pp 261-290
[5] Singh A and Tešanović Z 1989 Phys. Rev. B 39 7284