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Coexistence of Ferromagnetism and Superconductivity in Rapidly Quenched Ni_2NbSn Heusler Alloy

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We present the study on production and structural, electric and magnetic properties of superconductive Ni_2NbSn Heusler alloy. The sample has been produced by melt-spinning method using tangential speed of copper wheel 20 m/s. Polycrystalline structure has been obtained showing single phase with $B2$ disorder with lattice constant $a = 6.1654$ Å. Resistance measurement shows superconductive behavior with critical temperature close to 5 K. Magnetic measurements also exhibit diamagnetic contribution from superconductive phase. Additionally, the ferromagnetic state has been observed below 20 K, which points to the coexistence of magnetic and superconducting state.

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1. Introduction

Superconductive materials have many great features e.g. levitation or conducting electricity with no resistance. Magnetic superconductors are a special type of superconductors, in which the ferromagnetism and superconductivity can coexist at the same time which leads us to a totally new phenomenon of electromagnetic invisibility [1].

Thanks to the wide range of physical properties e.g. high spin polarization, magnetic ordering, shape memory effect and many more, the Heusler alloys are one of the most interesting groups for technical use. In the last years, even the superconducting Heusler alloys attract attention [2]. One of the few disadvantages of the Heusler alloys is their complicated production process that contains high temperature (> 1100 K) processing for a long time (7–12 days [3–5]). Recently, rapid quenching method has been proved to be very efficient for cheap and easy production of large amount of the Heusler alloys [6].

In the given contribution we have studied the structural and magnetic properties of rapidly quenched Ni_2NbSn alloy. It was shown that Ni_2NbSn is characterized by a critical temperature 5 K. Moreover, it shows transition to ferromagnetic phase below 3 K. The coexistence of the ferromagnetism and superconductivity in rapidly quenched Ni_2NbSn alloy is confirmed by hysteresis loop measurement.

2. Experiment

High-purity metals (Ni = 99.95%, Nb = 99.8%, Sn = 99.99%) were used for the sample preparation. Master alloy with composition of the Heusler alloys (Ni_2NbSn) have been produced using arc melting method in an argon atmosphere. Rapidly quenched ribbon have been produced from master alloy using melt spinning technique in a helium atmosphere. Tangential speed of surface of a copper wheel was set to 20 m/s.

Microstructural study has been performed by scanning electron microscope (SEM) — system TESCAN VEGA 3 XMU equipped with the energy-dispersive X-ray spectroscopy (EDX) to estimate chemical composition. Chemical analysis of the sample surface was performed by the X-ray photoelectron spectroscopy (XPS) from SPECS and analyzing software SpecsLab2 CasaXPS was used. X-ray diffraction (XRD) powder diffraction was used to determine the crystal structure using Cu K_α radiation at room temperature. The temperature dependence of resistance was measured by PPMS from Quantum Design using DC resistivity option under the current of 1 mA. Magnetic properties were studied by MPMS XL-5 from Quantum Design. The temperature dependence of magnetization was measured in the magnetic field with intensity 0.24 Oe and 10 kOe. Hysteresis loops were measured at temperatures of 2, 10, and 20 K.

3. Result and discussion

Microstructural analysis reveals polycrystalline character of the sample. It can be seen in Fig. 1 that the ribbon is 40–50 μm wide and the column shaped crystals grow from the side of the cylinder (left part of the ribbon) with length of 10 μm. As the distance of the crystals from the cylinder increases, the size of crystals increases, too. This is because of decrease of the quenching rate during production. On the right part of Fig. 1 the surface of the ribbon from the side of air is shown, in which crystals with size of the 20 μm and smaller crystals with the size of 2 μm growing between them are present.

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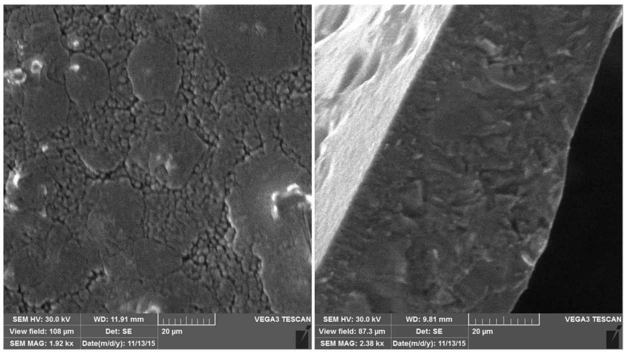

Fig. 1. SEM image of the cross-section of Ni_2NbSn ribbon (left). SEM image of the surface of the Ni_2NbSn ribbon from the air-side (right).

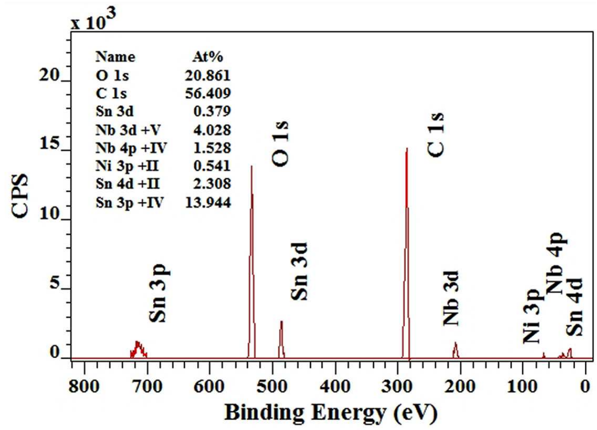

Fig. 2. Energy spectrum of the Ni_2NbSn ribbon measured by XPS.

The EDX analysis was performed on 18 points at the surface of the sample and the average composition is Ni: 52.7 at.% , Nb: 24.8 at.% and Sn: 22.5 at.%, which is quite close to the nominal one.

Six months after the sample was prepared the chemical analysis of the surface was done by XPS. Except the Ni, Nb, and Sn, sample contained oxygen and carbon, too. There was also Ni found in the oxidation state +II most probably as the nickel oxide, Nb in the oxidation state +V as the niobium pentoxide and tin in the oxidation state +II as the tin oxide (Fig. 2).

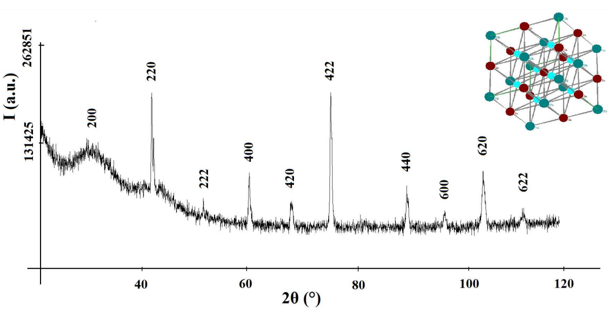

Fig. 3. X-ray diffraction of the Ni_2NbSn ribbon.

X-ray diffraction of the rapidly quenched Ni_2NbSn alloy is shown in Fig. 3. Analysis reveals single phase $L2_1$ characteristic for full Heusler alloys with the lattice parameter $a = 6.1654$ Å. The lattice constant is slightly lower than that observed for bulk materials (6.179 Å [3]). The absence of super lattice reflections (111) and (311) confirms structural disorder between Nb and Sn elements (which is called $B2$ disorder structure) [2,7].

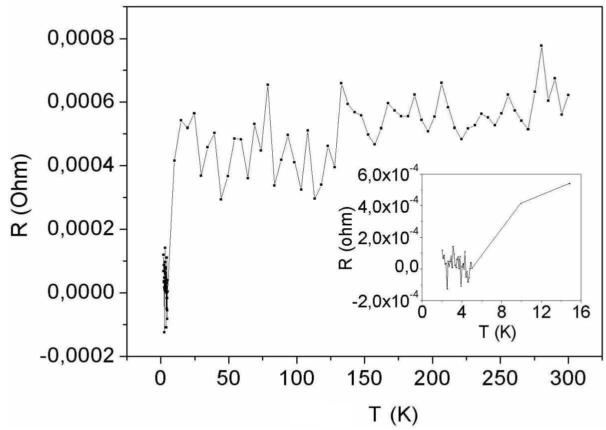

Fig. 4. Temperature dependence of resistance of the Ni_2NbSn ribbon. Inset shows the low temperature detail.

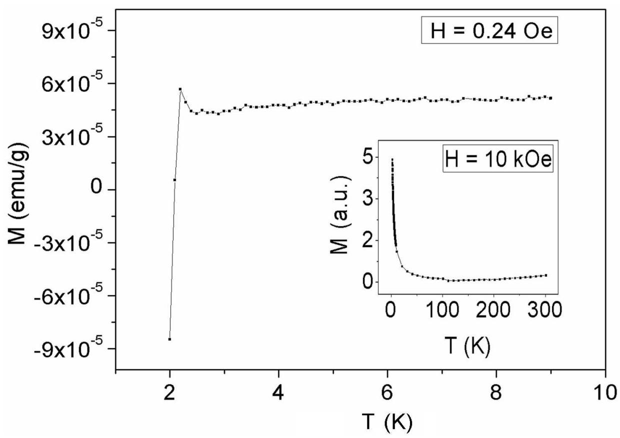

Fig. 5. Temperature dependence of the magnetization measured at low field ($H = 0.24$ Oe) of the Ni_2NbSn ribbon. Inset shows the temperature dependence of magnetization measured at the field $H = 10$ kOe.

Although the temperature dependence of resistivity (Fig. 4) is not perfect (most probably due to the quality of contacts on oxidized surface), it clearly shows the drop of resistance at 5 K down to zero, which is characteristic for superconductive materials. Another characteristic of superconductivity is clear from the temperature dependence of magnetization measured at low field (0.24 Oe — see Fig. 5). Magnetization starts to increase with the decrease of temperature below 3 K and then suddenly drops down to negative values. The critical temperature is estimated to be 2.1 K, which is lower than that determined from resistivity measurement.

Increase of magnetization with the temperature decrease could be a result of magnetic ordering transition. It is confirmed by hysteresis loop measurement (Fig. 6) that the sample shows ferromagnetic behavior with the coercivity 165 Oe at 2 K. The coercivity decreases with temperature down to 110 Oe at 20 K. This behavior confirms that with the decrease of temperature, the ferromagnetic behavior of the sample is getting stronger.

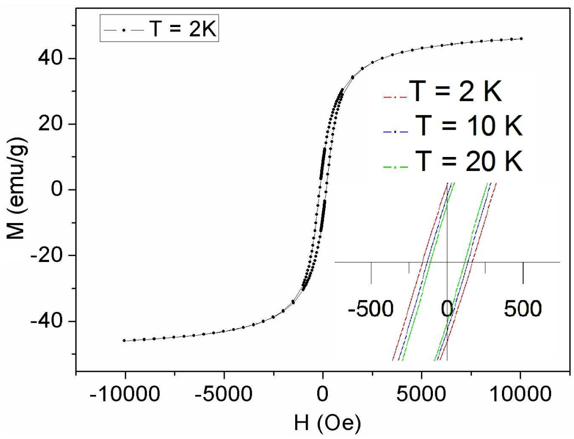

Fig. 6. Hysteresis loop of the Ni_2NbSn ribbon at temperature 2 K. Inset shows the low field zoom for hysteresis loops measured at 2, 10, and 20 K.

One possible explanation for such behavior can be offered in terms of different lattice constant of rapidly-quenched and bulk Ni_2NbSn alloys [4]. The interatomic distance affects strongly electrical as well as magnetic properties. However, more experiments must be done to reveal the origin of coexistence of ferromagnetism and superconductivity.

4. Conclusions

In the given contribution, we have studied the production and structural, electric and magnetic characterization of rapidly quenched Ni_2NbSn Heusler alloys. It is shown that rapid quenching produces the polycrystalline structure with oriented crystal growth direction. Rapidly quenched ribbons are characterized by single *B*2 phase with Nb–Sn disorder. Samples are characterized by superconducting state with the critical temperature 5 K. Magnetization measurements confirms mutual coexistence of superconductive and ferromagnetic phases below 2 K. The origin of this coexistence is still not understood although it could be attributed to the different lattice constant of rapidly quenched and bulk Ni_2NbSn Heusler alloy.

Acknowledgments

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