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Thermal Expansion of Ni–W, Ni–Cr, and Ni–Cr–W Alloys Between Room Temperature and 800 °C

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Abstract The thermal expansion of Ni–W, Ni–Cr, and Ni–Cr–W alloys has been measured by quartz dilatometry for the 20 °C to 800 °C temperature range. It is found that substitution of nickel by tungsten leads to a considerable decrease of the thermal expansion coefficient (TEC), while chromium has only a small influence on the TEC of the alloy.

Keywords Nickel-based alloys · Textured metal tapes · Thermal expansion

1 Introduction

The development of high-temperature superconducting (HTS) materials for electric current transfer, called coated conductors, has seen rapid progress in recent years. Several approaches have been shown to bring success. One of these approaches is based on the use of biaxially textured tapes of nickel-based alloys, with Ni–5 at% W alloy being

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the most widely used composition. This alloy is ferromagnetic below 335 K, which is not desirable for many ac applications. Some elements, such as W, Mo, and Cr have been shown to reduce the Curie temperature at a rate of about 50 K per atomic% [1]; however, it is a challenging task to obtain biaxial texture in these non-magnetic alloys and to deposit coatings on them without oxidation.

A knowledge of the basic properties of substrate materials is important for technology development. Many of them are already known: mechanical properties [2], ferromagnetic ordering temperature [3,4], and oxidation behavior [5,6]. However, as far as we know, no systematic studies have been yet performed on the thermal expansion coefficient (TEC) of these prospective alloys. The values of the TEC are quite important for understanding of processes, which may take place on heating or cooling of the wire. The thermophysical stability is especially important, since the preparation of coatings and operation of HTS wire cover a large span of temperatures between above 1000 K and below 77 K, so any little difference in TECs of the metal base and layers may result in appreciable strain. In our study we have performed measurements of the TECs for nickel alloys with W and Cr and a ternary Ni–Cr–W alloy.

2 Experimental

All the alloys studied were single phase and possessed cubic fcc structure according to X-ray diffraction (XRD). We have studied alloys with similar or very close compositions to those that are used for production of biaxially textured tapes for HTS deposition. Alloy ingots have been prepared by inductive vacuum melting as described elsewhere [7]. The compositions studied are reported in Table 1.

Table 1 Alloy compositions ([Ni] = rest) and TEC values found (TEC = aT(°C) + b)

[Cr] (at%)	[W] (at%)	a (10^{-9} °C^{-2})	b (10^{-5} °C^{-1})
0.0	0.0	7.35	1.29
0.0	1.1	6.60	1.24
0.0	1.7	7.02	1.17
0.0	1.8	8.60	1.11
0.0	5.0	7.76	1.05
2.3	0.0	6.76	1.28
5.6	0.0	8.33	1.21
13.6	0.0	11.71	1.10
14.8	0.0	11.73	1.08
16.5	0.0	11.85	1.04
22.0	0.0	12.51	1.01
7.7	3.5	8.79	1.10
9.1	1.8	10.93	1.06
9.2	2.4	10.00	1.06
9.4	2.3	9.85	1.09

A quartz dilatometer constructed in our lab has been used to measure the thermal expansion. To measure the elongation of the sample, a linear optical raster encoder LIR-14 with a resolution of 1 μm was used (made by SK BIS Company, Russia). The temperature was controlled by a Type K thermocouple placed near the sample. A programmable temperature controller was used to control the temperature of the sample. Typically, the sample was heated from room temperature to 800 °C at a rate of 10 °C · min^{-1}, then held at 800 °C for 5 min, and cooled to 200 °C at the same rate. The procedure was performed twice or more, to ensure that the results were reproducible. The dimensions of the samples were typically $2 \times 2 \times 10\,\mathrm{mm}^3$. In our calculations we accepted that the TEC changes linearly with temperature (that means, elongation has a quadratic temperature dependence). According to literature data for nickel [8], such a linear approximation works well for the temperature range used. In our study we have neglected the effect of ferromagnetic ordering on the TEC, since the measurement system did not allow us to measure this relatively small effect with the necessary accuracy. For the one ternary alloy we have performed the measurement of thermal expansion repetitively 10 times. The standard deviation of these measurements amounted to ∼2 % of the measured value. Therefore, the measurement error of results presented in this paper is about 4 % of the TEC value.

All the measurements have been performed in air. Oxidation of alloys has been observed; however, it had a negligible effect on the measurements. Indeed, the oxide layer thickness hardly exceeds a few micrometers under our experimental conditions [5,6]. Even if the absolute difference in TECs of oxide and metal is as large as $10^{-5}\,\mathrm{K}^{-1}$, the error of the $\Delta L/L_0$ determination does not exceed 0.1 % of its value.

High-temperature X-ray diffraction was performed on the Ni–9.2 at% Cr–2.4 at% W ternary alloy, using a Rigaku D/MAX 2500 diffractometer with a high-temperature attachment. Measurements were performed in vacuum (10^{-2} mbar), and sample oxidation did not have any impact on alloy lattice parameters.

3 Results and Discussion

The observed nickel TEC averaged over the 20 °C to 800 °C temperature interval is close to that from the literature: $15.8 \times 10^{-6}\,{}^{\circ}\mathrm{C}^{-1}$(our study), $16.3 \times 10^{-6}\,{}^{\circ}\mathrm{C}^{-1}$ (as calculated from experimental data of [8]).

The typical elongation curve and TEC of pure nickel and the most widely used nickel–tungsten alloy, Ni–5 at% W, are given in Fig. 1. It can be seen that substitution of nickel by tungsten leads to a noticeable decrease of the thermal expansion. To the best of our knowledge, there is only one report on the TEC of Ni–W alloys, and it gives values for room temperature [9]. The authors have calculated lattice parameters, bulk moduli, the TEC, and the mixing energy of Ni–W alloys using Harris functional LMTO–CPA calculations. Additionally, two experimental points are given in their article. Our data for room temperature are compared in Fig. 2 to their results. Our measurements systematically differ from those of [9] giving somewhat lower values of the TEC. The reason for this difference is unclear. However, the decreasing trend of the TEC is evident in both cases. The TEC of Ni–W alloys decreases on substitution also at higher temperatures (Fig. 3a).

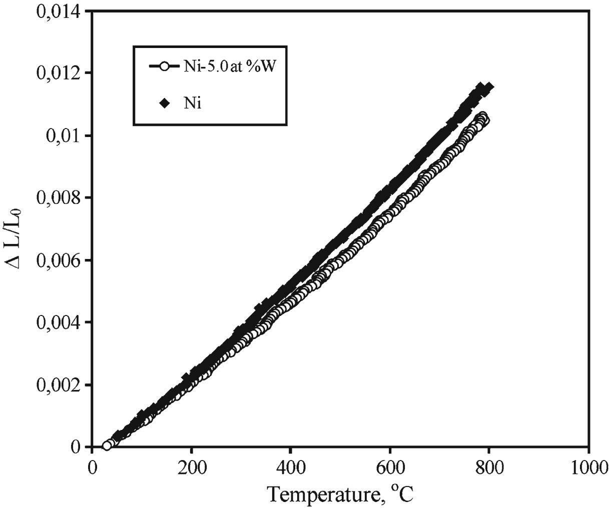

Fig. 1 Temperature dependence of normalized elongation of nickel and Ni–5 at% W alloy

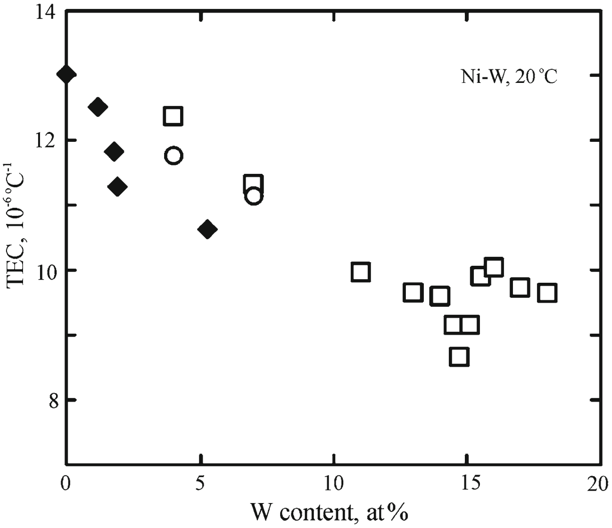

Fig. 2 Room temperature TECs for Ni–W alloys: ◆ present study, □ calculated data from [9], ○ experimental data from [9]

In contrast, an increase of the chromium content leads to a decrease of the TEC at low temperature and an increase of the TEC value at high temperature. It results in a relatively constant average TEC (20 °C to 800 °C) value of Ni–Cr alloys. This behavior, in comparison with the data for Ni–W alloys is presented in Fig. 3. The weak dependence on chromium content observed for Ni–Cr TECs is in accordance with data reported in the literature [10]. Judging by the atomic concentration, tungsten produces a much stronger effect on the TEC than chromium.

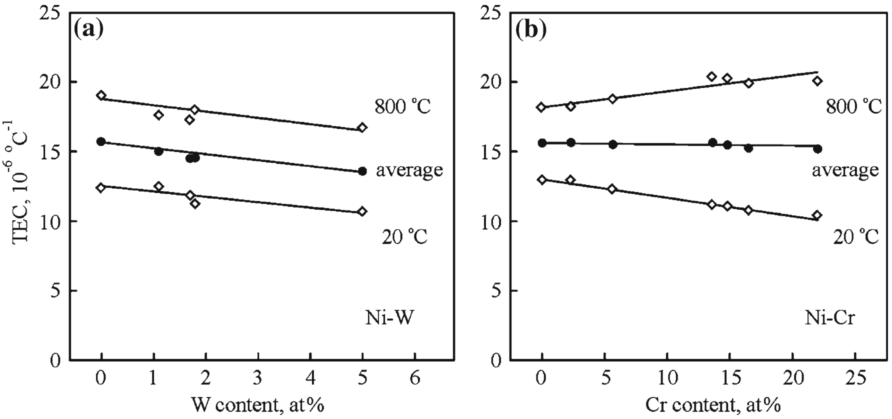

Fig. 3 TECs for Ni–W and Ni–Cr binary alloys at 20 °C, 800 °C, and average values

TEC values have also been measured for several ternary Ni–Cr–W alloys. They are summarized in Table 1. The TEC of the Ni–9.2 at% Cr–2.4 at% W ternary alloy determined from high-temperature XRD corresponds with our dilatometry result rather well: $14.1 \times 10^{-6}\,°\mathrm{C}^{-1}$ (high-T XRD), $14.8 \times 10^{-6}\,°\mathrm{C}^{-1}$ (dilatometry).

Using the data collected by dilatometry of alloys studied, we derived a simple empirical formula to calculate the average TEC (20 °C to 800 °C) value for binary and ternary alloys:

$$\mathrm{TEC}\ (20\,°\mathrm{C}\ \mathrm{to}\ 800\,°\mathrm{C})10^{-6}\,°\mathrm{C}^{-1} = 15.63 - 0.416[\mathrm{W}] - 0.0097[\mathrm{Cr}] \qquad (1)$$

The comparison of experimentally measured and calculated values is given in Fig. 4. It is evident from this presentation, that the TEC (20 °C to 800 °C) value of any fcc Ni–Cr, Ni–W, or Ni–Cr–W alloy can be calculated with an uncertainty of better than 5 % of the experimental value, which is comparable to our measurement error. We also added to the graph the TEC values reported for typical buffer layer materials and for YBCO. The unit cell symmetry of YBCO changes from orthorhombic to tetragonal on heating, and the change of the TEC is not uniform (in fact, it is even negative for the *b* lattice parameter in a narrow temperature range). Therefore, for the calculation of the TEC from the data of [14], we took into consideration the average $(a + b)/2$ values of YBCO.

It can be seen that the thermal expansion of YBCO is close to that of Ni–Cr and Ni–W alloys with a minor tungsten content. The TEC of the conventional Ni–5 at% W alloy differs from that of YBCO significantly, while it corresponds rather well to the TEC of MgO. In contrast, the TEC values of $\mathrm{CeO_2}$ and YSZ are considerably lower than those of the alloys studied.

When the coated conductor technology is developed, it should be kept in mind that the larger the TEC difference is, the larger are stresses that appear on heating or cooling. If the oxide is deposited on metal at a relatively high temperature—which is often the case—it is put under compressive strain on cooling. Even though the compressive strain does not favor the formation of cracks, the stresses generated may relax,

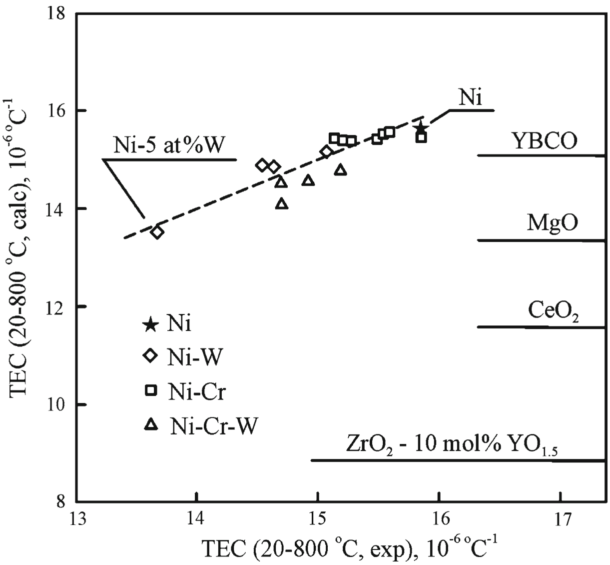

Fig. 4 Calculated values of TEC versus experimental values. Dashed line represents an exact correlation between experiment and calculation. Literature data for YSZ [11], CeO_2 [12], MgO [13], and YBCO [14] are given for comparison

causing the spallation of the layer [15]. When the oxide layer is grown at a relatively low temperature, the cracks in the oxide layer can appear on subsequent heating [16].

4 Conclusions

Thermal expansion coefficients of several Ni–W, Ni–Cr, and Ni–Cr–W alloys with cubic fcc structure were measured in a temperature range of 20 °C to 800 °C. It was found that tungsten significantly reduces the TEC value of nickel-based alloys at a rate of approximately 0.416 $°C^{-1}$ per atomic percent of W. In contrast, chromium was shown to have negligible effect on the average 20 °C to 800 °C TEC value, even though it has an influence on TECs at 20 °C and 800 °C.

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References

1. P.P. Bhattacharjee, R.K. Ray, A. Upadhyaya, J. Mater. Sci. **42**, 1984 (2007)
2. C.C. Clickner, J.W. Ekin, N. Cheggour, C.L.H. Thieme, Y. Qiao, Y.Y. Xie, A. Goyal, Cryogenics **46**, 432 (2006)
3. B. De Boer, J. Eickmeyer, N. Reger, L.G.R. Fernandez, J. Richter, B. Holzapfel, L. Schultz, W. Prusseit, P. Berberich, Acta Mater. **49**, 1421 (2001)
4. J.H. Claassen, C.L.H. Thieme, Supercond. Sci. Technol. **21**, 105003 (2008)
5. S. Espevik, R.A. Rapp, P.L. Daniel, J.P. Hirth, Oxid. Met. **14**, 85 (1980)

6. A. Tuissi, E. Villa, M. Zamboni, J.E. Evetts, R.I. Tomov, Physica C **372–376**, 759 (2002)
7. D.P. Rodionov, I.V. Gervasyeva, Y.V. Khlebnikova, V.A. Kazantsev, in *Proceedings of the 15th International Conference on Textures of Materials*, Pittsburgh, PA, June, 2008, Ceram. Trans. **201**, 11 (2008)
8. T.G. Kollie, Phys. Rev. B **16**, 4872 (1977)
9. S.I. Simak, A.V. Ruban, Y.H. Vekilov, Solid State Commun. **87**, 393 (1993)
10. A.S. Pavlovich, V. Suresh Babu, M. Seehra, J. Phys.: Cond. Matter **8**, 3139 (1996)
11. H. Hayashi, T. Saitou, N. Maruyama, H. Inaba, K. Kawamura, M. Mori, Solid State Ionics **176**, 613 (2005)
12. H. Hayashi, M. Kanoh, C.J. Quan, H. Inaba, S. Wang, M. Dokiy, H. Tagawa, Solid State Ionics **132**, 227 (2000)
13. L.S. Dubrovinsky, S.K. Saxena, Phys. Chem. Miner. **24**, 547 (1997)
14. J. Mizusaki, H. Tagawa, K. Hayakawa, K. Hirano, J. Am. Ceram. Soc. **78**, 1781 (1995)
15. M. Parans Paranthaman, T. Aytug, H.Y. Zhai, L. Heatherly, A. Goyal, D.K. Christen, Supercond. Sci. Technol. **18**, 223 (2005)
16. M.M. Nagl, W.T. Evans, J. Mater. Sci. **28**, 6247 (1993)