Development of the paramagnetic RABiTS tapes for coated conductors

A E Vorobieva, I M Abdyukhanov, D N Rakov, V V Samusevich, A V Nikolaev, A V Borisov, Yu N Belotelova, V A Drobyshhev, M M Potapenko, L M Kryukova, M V Polikarpova, V V Guriev, A K Shikov and S V Shavkin

1 Bochvar Institute of Inorganic Materials (JSC VNIINM), 123098, Rogova 5a, Moscow, Russia
2 National Research Center «Kurchatov Institute», 123182, Kurchatov sq.1, Moscow, Russia

E-mail: vniinmbochvar@yandex.ru

Abstract. RABiTS production process was developed for tapes from Ni-W alloys with W content in the range of 4-10.5 at.%. Tapes' composition, structure and magnetic properties were investigated. High purity Ni-W ingots were smelted and tapes with thickness of 0.06-0.09 mm and various total accumulated deformations in the range of 90-99.2% were fabricated. Texture quality dependence on accumulated deformation in the tapes with W various content was studied. X-ray analysis data including pole figures show that high quality cube texture can be formed in the tapes with W content up to 9 at.% inclusive, but not formed in the tapes with 10.5 at.%. According Curie temperature values and saturation magnetization measurements of alloys with W content more than 8 at.% are paramagnetic at liquid nitrogen temperature. Summarizing it can be stated that RABiTS tapes with 8-9 at.% W content have optimal combination of structure and magnetic properties for using in coated conductors.

1. Introduction
Substrate materials are the key element of the HTSC-2G coated conductors. There are two types of substrate materials: textured RABiTS Ni-W tapes and non-textured tapes based on Hastelloy alloys or stainless steel. The main requirement for the RABiTS tapes is the presence of the sharp biaxial cube texture [1]. Usually for the fabrication of such tapes the alloys on the base of Ni-W systems are used. These alloys have the FCC crystallographic structure and enable to form the desired sharp biaxial cube texture with {100} direction perpendicular to the tape's surface. Such texture is formed as a result of the appropriate thermomechanical treatment in the process of thin tape formation which consist of cold rolling with large amount of total accumulated deformations (usually 95% and more) and subsequent annealing in vacuum or in reduction atmosphere in the temperature range of 1050-1250 °C [2].

Applications of HTSC-2G in different superconducting devices, which work in alternating current mode, demand the minimization of electromagnetic hysteresis losses values which depend on the magnetic properties of the substrate material at working temperature (77 K and lower) and are the function of the value of mass magnetization (Msat) of the chosen alloy. Nickel is a ferromagnetic metal with Curie temperature 631 K. The doping of Ni with W leads to decrease of the Curie temperature and Msat value [2]. Curie temperature of these alloys diminishes lower than 77 K with the increase of

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.
Published under licence by IOP Publishing Ltd
W content up to 8 at.% [3]. But the drawback of high W content is related with the enhanced difficulty to form the sharp texture, especially with increase of W content more that 5 at.%. Recently it was shown that the cube texture forming is also possible in the Ni-W alloys with W content up to 9 at.% but with much difficulties at tapes fabrication and the part of cube texture orientation in {100} direction was only 97-98.5% [4].

In the previous work [5] we have reported about possibility of the forming sharp cube texture in Ni-W tapes with W content up to 7.7 at.% (20.7 wt.%). Msat values at 77 K and at 4.2 K were as small as 7 and 10 emu/g correspondently, that is by factor of 9 and of 6 lower than of pure Ni. Although such Msat value decrease is favorable for using such alloy as HTSC-2G substrate but nevertheless the Curie temperature of this alloy was 97 K and so it remains ferromagnetic at all possible working temperatures of HTSC. So the main objective of present work was to increase the W content in alloy up to 10.5 at.% and to elaborate paramagnetic Ni-W tapes in combination with sharp cube texture.

In our previous work 100% cube texture in tapes with W content in the range of 5 – 7.7 at.% was obtained by thermomechanical treatment that consisted of tapes rolling with 99% of total accumulated deformation and subsequent texturing vacuum annealing at 1150 °C [5]. The texture quality of various alloys at lower amounts of accumulated deformation wasn’t investigated. In the present work we have investigated the effect of W content in the range of 4 – 10.5 at.% and total accumulated deformation during cold rolling in the range of 90 – 99.2% on texture quality of Ni-W tapes.

2. Experimental part
At Ni-W alloys preparation we proceeded from the assumption that the most part of metal impurities have negative effect on the texture quality and so for ingots melting only high purity Ni and W were used. Also we avoided any doping elements (e.g. Zr, Y, Al) which are usually added for improvement of the homogeneity of the ingot.

The set of 5 ingots with the weight of ~ 7 kg each has been fabricated with the following W contents: 4.8, 6.0, 7.7, 9.0 and 10.5 at.% (13.6, 16.6, 20.7, 23.5, 27.0 wt.% correspondently). After appropriate thermomechanical treatment tapes with the thickness of 60 – 90 µm were obtained. The total accumulated deformation of these tapes before the texturing annealing was varied from 90 up to 99.2% with 0.5 – 1.0% interval.

According to the metallographic investigations after cold rolling all samples had similar homogeneous structure. Grains which were formed at earlier stages of thermomechanical treatment were completely eliminated.

Mechanical properties of tapes with various W content differed from each other. For example figure 1 shows the dependence of microhardness as a function of total accumulated deformation for alloys with various W content. The microhardness of the alloy with 4.8 at.% W at final stage of the cold rolling was only 370 Hv, whereas for alloys with 7.7 and 9.0 at.% its value exceeds 500 Hv.

After texture annealing (1150 °C, 15 min) the texture quality was studied by X-ray analysis. It was carried out at CoKα-irradiation by 3 steps. At the first stage the general survey was made in the 2θ angles range from 30 up to 120 degrees and integrated intensity ratio between the main Ni line (002) and secondary ones (111), (220) and (113) were determined. At the second stage, for samples in which integrated intensity of the secondary lines were less than 1% of the intensity of the main Ni line (002) the full width at half maximum
of Ni (002) peak were determined. These measurements were carried out in two directions $\bar{1}$ along and across the direction of cold rolling. And at the third stage for complete texture characterization pole figures were created for some selected samples.

The magnetic properties in relation with the concentration of W in Ni-W alloys were investigated by the measurements of the Curie temperatures on the tape samples by the method of magnet shielding at the frequency of 1000 Hz in temperature range 330 $\pm$ 4.2 K.

3. Results and discussion

X-ray investigations have shown that the tapes with W content 4.8 at.% have the best structure. Only Ni (002) peaks were presented at diffractogram. For samples with total accumulated deformation from 92% up to 99.2% the full width at half maximum along and across the direction of cold rolling was 4.4 $\bar{1}$ 4.8 and 7.3 $\bar{1}$ 7.6 degrees accordingly. Only in samples with 90 and 91% deformation the full width at half maximum increased up to 9.6 degree and so they had somewhat worse texture. Hence the best texture quality in tapes Ni-4.8 at.% W can be obtained only in the case of cold rolling with total accumulated deformation no less than 92%.

Contrary to this required texture wasn’t obtained in any sample with W content 10.5%. At all diffractogram the Ni (002), (113), (220) and (111) peaks were presented. Intensity of the last 3 peaks decreased with the increasing of total accumulated deformation value but even at 99% deformation they haven’t disappeared. The integrated intensity ratio of (002) and (113) lines was no more than 9:1.

The sharp cube texture was achieved in tapes of 3 others compositions. The texture quality depends on W content in tape and on total accumulation deformation value during cold rolling. For Ni-6.0 at.% W tapes after deformations 93 $\bar{1}$ 99% only Ni (002) lines were presented at diffractogram. At lower deformations traces of Ni (113) and (220) peaks were also presented. The minimum widening of the texture maximum with the full width at half maximum values less than 5 and 8 degrees in two perpendicular directions was obtained only after no less than 96% deformation.

The conditions of obtaining reasonable texture in tapes Ni-7.7 at.% W were more strict. Quality texture was achieved only after deformation 98 $\bar{1}$ 99%. Pole figures confirmed that in tapes with W content 4.8 $\bar{1}$ 7.7 at.% the part of cube texture exceeds 99%.

The most difficult was the texture formation in tapes with W content 9.0 at.% W. Although the integrated intensities of Ni (113), (220) and (111) secondary peaks decreased greatly with increase of total accumulation deformation value but nevertheless even at 99.2% deformation the trace of (113) (the main among secondary peaks) was presented at the diffractogram. The integrated intensity ratio of (002) and (113) intensities was 400:1 (figure 2). Such high ratio was only in the case of deformations no less than 99.2%. At lower deformations secondary peaks were more noticeable. For example at 97.5% deformation the ratio of (002) and (113) was only 100:3. The full width at half maximum in two perpendicular directions in samples with 99% deformation was 4.5 and 7.5 degrees (figure 3) which is not worse than that in tapes with W content 4.8 at.%.

Figure 2. X-ray diffractogram of the Ni - 9.0 at.% W tape, 99.2% total accumulates deformation (CoK$_\alpha$ irradiation)

Figure 3. Tilt curves for Ni (002) line along (left) and across (right) direction of cold rolling. The full width at half maximum is shown by arrows. The sample Ni-9.0 at.%W, 99% total accumulated deformation
According to the pole figure (figure 4), the portion of cube texture \{100\} orientation in this sample was more than 97%. It is somewhat worse than that in tapes with lower W content but available for HTSC-2G production.

Thus it can be stated that desired texture was achieved in tapes with W content up to 9.0 at.% inclusive. The texture quality depends on total accumulation deformation. The tapes with higher W content demands more deformation to obtain desired quality. The border conditions for achieving available texture are shown on figure 5.

Previously we have reported [5] that Curie temperature linearly decreased with increase W content and drop from 300 K for alloy Ni-5.5 at.% W down to 97 K for alloy with 7.7 at.% W. Present work measurements confirmed these data and also had shown that tapes with 9.0 at.% W are paramagnetic in whole investigated temperature range.

4. Conclusion
In Ni-W tapes biaxial cube texture quality dependence on W content and total accumulated deformation value at cold rolling was investigated. It was shown that acceptable texture can be formed in tapes with W content up to 9.0 at.%. At the same time tapes with such high W content are paramagnetic.

Summarizing it could be stated that tapes Ni-9 at.% W are favorable for the HTSC-2 coated conductors to be used in ac applications.

5. References
[1] Goyal A, Norton D P, Budai J D et al. 1996 Appl. Phys. Lett. 69(12) 1795
[2] Specht E D, Goyal A, Lee D F et al. 1998 Supercond. Sci. Technol. 11 945
[3] Sakamoto H, Nagasu Y, Ohashi Y, Nakasaki R, Mimura M, Nakai A 2007 Physica C 463 600–603
[4] Rupich M W, Xiaoping Li, Sathyamurthy S et al. 2013. IEEE Transactions on Applied Superconductivity, vol: 23, issue: 3, part: 3. Article# 6601205
[5] Pantsyrny V I, Vorobieva A E, Abdyukhanov I M et al. 2012 Proc. of ICMC-2012 Conf. (Fukuoka, Japan, 14-19 May 2012) pp.895-898