The effect of temperature on pinning mechanisms in HTS composites

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Abstract. Pinning mechanism in samples of second generation tapes (2G) of high-temperature superconductors (HTS) was studied. The critical current and the pinning force were calculated from the magnetization curves measured in the temperature range of $4.2 - 77$ K in magnetic fields up to 14 Tesla using vibration sample magnetometer. To determine the pinning mechanism the dependences of pinning force on magnetic field were constructed according to the Dew-Hughes model and Kramer's rule. The obtained dependences revealed a significant influence of the temperature on effectiveness of different types of pinning. At low temperatures the 2G HTS tapes of different manufacturers demonstrated an equal efficiency of the pinning centers but with temperature increase the differences in pinning mechanisms as well as in properties and effectiveness of the pinning centers become obvious. The influence of the pinning mechanism on the energy losses in HTS tapes was shown.

1. Introduction
Modern 2G HTS tapes produced by a number of commercial manufacturers such as American Superconductors, SuperPower, SuNaM. et al. have different transport properties, especially under applying magnetic fields $H$. Differences in values of the critical current $J_c$ and in $J_c(H)$ dependences are associated with different types of artificial pinning centers in the tapes [1, 2]. Determination of pinning type (volume, surface, point) in the tapes and analysis of pinning evolution with temperature are still actual problems studied in this paper.

2. Materials and methods
Industrial tapes with artificial pinning centers manufactured by AMSC (magnetic substrate), SuperPower (non-magnetic substrate) and tape without artificial pinning centers manufactured by SuNam were selected for study. Magnetization measurements were carried out at the International Laboratory of High Magnetic Fields and Low Temperatures in Wroclaw by use of the vibration sample magnetometer. The temperature and magnetic field varied in the ranges $T = 4.2 - 100$ K and $H = 0 - 14$ T. The field was applied perpendicular to the tape plane. The dependences of the critical current on external magnetic field were calculated from magnetization curves using Bean model.

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3. Results and discussion
The examples of the magnetization curves measured for AMSC tape in the temperature range from 4.2 K to 77 K are shown on Figure 1. As seen, width of the curves decreases as temperature increases indicating a decrease the critical current with temperature. According to the Bean model the hysteresis width is proportional to the critical current of a sample. Field dependences of the critical current densities obtained from the magnetization curves using the Bean model are presented in Figure 2.

![Figure 1](image1.png)  
**Figure 1.** Magnetization curves from $T = 4.2$ K to 77 K for AMSC sample of 4x4x0.1 mm size.

![Figure 2](image2.png)  
**Figure 2.** Field dependence of the critical current density for AMSC sample at a wide temperature range.

The pinning force was calculated as product of the critical current density and magnetic field values. Analysis of pinning mechanism was carried out in the frame of Dew - Hughes model for the normalized pinning force \[ F_p \sim F_{po} \times b^n \times (1 - b)^m \]  
(1)  
where $b = \frac{H}{H^*}$, $F_{po}$ - the maximal pinning force, $H^*$ is the magnetic field at which the critical current density is equal to zero. Combination on $n$ and $m$ parameters depends on the pinning mechanism. It refers to a surface pinning if $n = 0.5$ and $m = 2$, to a point pinning when $n = 1$ and $m = 2$, and to a volume pinning for $n = 0$ and $m = 2$.

A scalable field $H_k$ proportional to $H^*$ is commonly used instead of $H^*$. The former can be easily found from so-called Kramer’s plots representing a function $j_{c0.5} \times H^{0.25}$ vs $H$ [4]. These Kramer plots are in general linear with field. To find a magnetic field at which the critical current is equal to zero, the obtained dependences were approximated by linear functions (Fig. 3). For each sample the pinning force was normalized by its maximal value.

Obtained field dependences of the pinning force (Fig. 4(a)) showed that the surface pinning dominates at low temperatures 4,2 - 20 K in all investigated samples. At low temperatures all samples demonstrated high critical currents, but as temperature increases an efficiency of the surface pinning centers is reduced and difference in pinning mechanisms comes into effect (Fig. 4(b)). It was found that from low to high temperatures the pinning type in AMSC and SUNAM tapes changes respectively from surface to volume and from surface to point. At the same time, temperature does not affect the
pining type of the SP tapes. This can be explained by the different magnetic properties of substrates and properties of pinning centers [5, 6].

![Graph](image)

**Figure 3.** Sample of Kramer’s plot for $T = 65$ K.

Analysis of the field dependences of the pinning force revealed a significant influence of temperature on the effectiveness of the different types of pinning in the tapes. At low temperatures the efficiency of the pinning centers in all samples is approximately the same, but at high temperatures there is the obvious difference in both efficiency of the centers and pinning mechanisms.

Field dependence of the energy losses at different temperatures was also researched. Losses were determined by calculating of the hysteresis loop area. To compare field dependences of the losses for different tapes, they were normalized to maximal value of the losses calculated for each sample. Obtained curves are presented in Figure 5. Field dependences of the normalized losses coinciding at low temperatures (Fig. 5 (a)) gradually diverge each other with temperature increase and at 77 K the difference is most pronounced (Fig. 5 (b)).

![Graph](image)

**Figure 4.** Dependences of normalized pinning force $F/F_{p \text{max}}$ on scaled magnetic field $B / B_{p \text{fmax}}$ at 4,2 K (a) and at 77 K (b). The lines correspond to: solid – surface pinning, dashed – point pinning, dotted – volume pinning.
Study of the losses has also indicated that low-temperature efficiency of the pinning centers is approximately the same in all samples, but it differently changes with temperature in different tapes.

Figure 5. Dependences of normalized losses on magnetic field in HTS tapes at 4.2 K (a) and 77 K (b).

4. Conclusions
Obtained results demonstrated a significant influence of temperature on pinning in tapes with different landscapes of the pinning centers. The surface pinning dominates in all investigated samples at low temperatures and the efficiency of the pinning centers is approximately the same. At high temperatures the obvious differences in magnetic properties of the samples is caused by change of dominated pinning mechanism which becomes the volume pinning in AMSC tapes and the point pinning in SUNAM tapes. The type of pinning in SP tapes does not changed by temperature.

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