# Hausdorff analysis of magnetic flux front penetration into NbTi and the pinning structure transformation as a result of mechano-thermal effect

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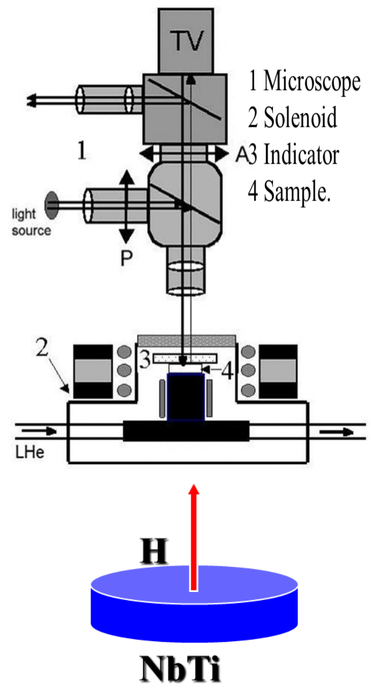
**Abstract** The Hausdorff dimension has experienced application in the characterization and comparison of highly rough structures. It is famous that the concept of Hausdorff dimension is applied as well to magnetic flux front (induction of the magnetic field) analysis in superconductors [1,2]. In this report, MO registration of the magnetic flux penetration was used in the NbTi superconductor for visualization of the mechano-thermal effect on the pinning structure as key element of high critical current density. The flux pinning centers in the NbTi alloy are produced by the thermo-mechanical cycling consisting of a series of material drawing and heat treatments [3]. Disc shape sample was cut from a rod of NbTi after extrusion. The structure of the boundary between the Meissner and critical states was studied during external magnetic field penetration into alloy a) after the extrusion and b) after the heat treatment stages. Based on the analysis of the correlation function S(k), it was found that: the fractal Housdorff dimension of flux front amounts to about 1.5; the fractal dimension increases a) with increasing external magnetic field and b) in fixed external magnetic field with increasing level of induction. The heat treatment stage leads to significant changes of fractal Housdorff dimension of flux front and the value of critical current density. The obtained values of roughness exponent α lie in the range of 0.435–0.480. A system with a roughness value $\alpha<0.5$ is described by a model of dynamic stochastic disorder [4], which is characteristic of the fractal nature of the structure of the magnetic flux front in a superconductor [1]. Other features of magnetic field penetration into SC were discusses.

## Experimental set-up and sample




Magneto-optical method provides a measure of the normal component of the induction $B_z$. An indicator was used to image the dynamics of magnetic induction pattern at the surface of disc at temperatures 4.5 – 7K. One side of the disk was polished to a mirror to reflect the incident polarized light. The magnetic flux penetration into the 0.1 mm thick superconducting NbTi 50 at % disc with diameter 12 mm at remagnetization in the magnetic field up to 600 G was studied. The magnetic field was applied perpendicular to the surface of disc. A MO-technique allowed observations of the flux dynamics and registration of the field maps. From these maps, we obtained profiles of the constant flux density and analyzed their width, length, correlation functions, and power spectra.

## Results of an experiment to study the dynamics of the magnetic flux front

### SC after the extrusion

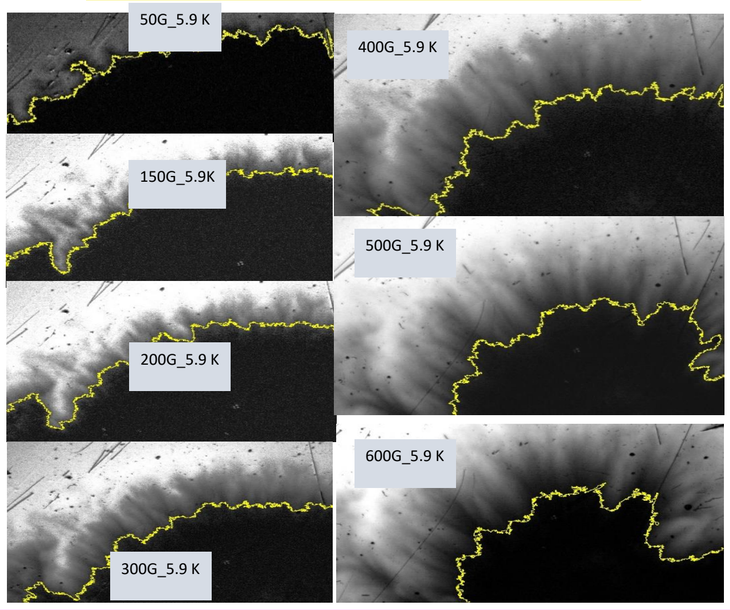



**Fig 1**. Position of the flux front at different values of the external magnetic field in the NbTi disk at $T$ = 5.9 K after hydroextrusion.

Fast Fourier transformation of flux profile data yielded the spectral function $S(k)$ of the surface. It has a power dependence on $k$ (Fig 2), similar to the results [1, 2]. The roughness exponent α can be obtained from the tilt of dependence log$S(k)$ vs log$(k)$. The Housdorff dimension of the rough surface, D, was defined using the obtained value $\alpha$.

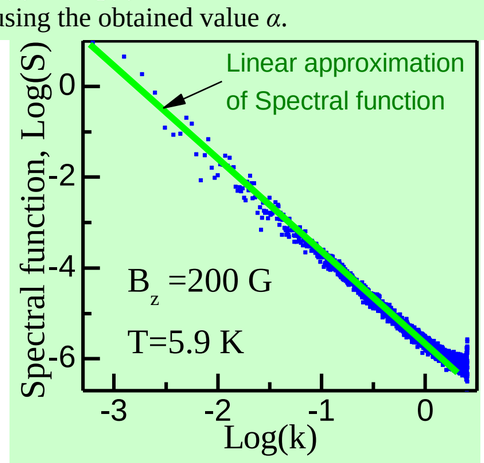



**Fig 2.** Spectral function, from which roughness parameter α and Housdorff dimension D = 2-α were found .

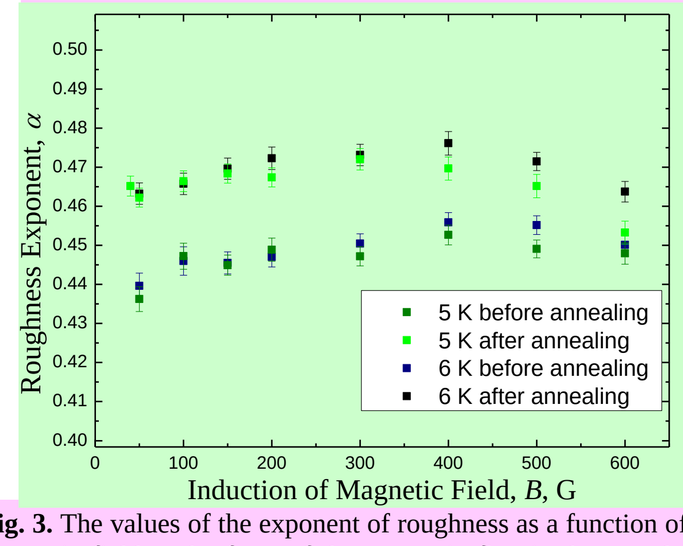
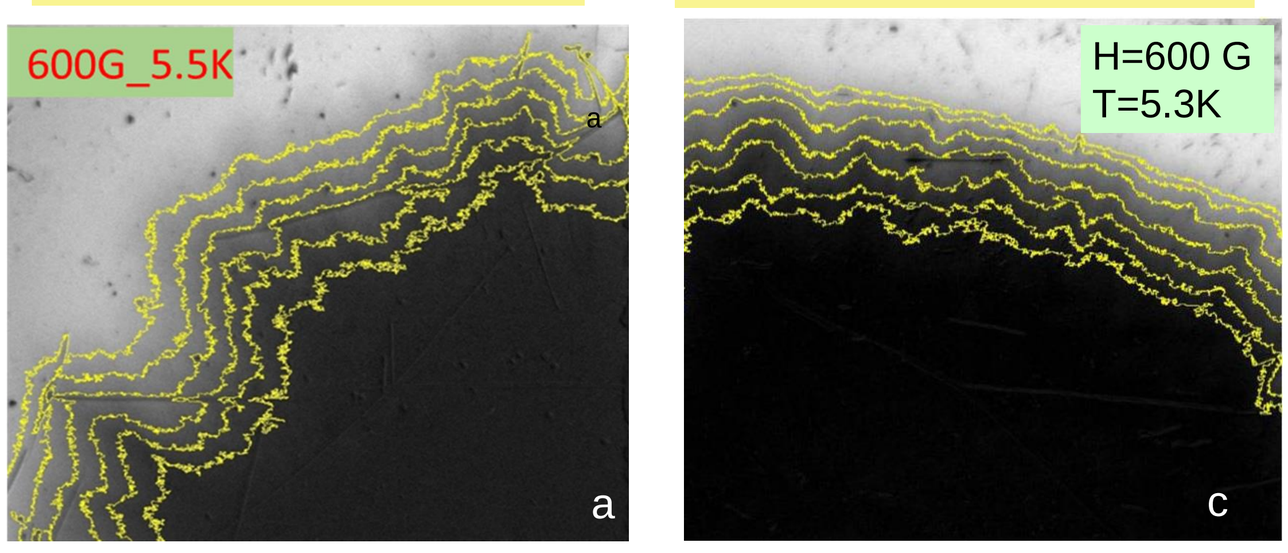



**Fig. 3.** The values of the exponent of roughness as a function of the external magnetic field at the front of the magnetic flux in the samples before and after heat treatment at two temperatures (5K and 6K). The correspondence of the graphs is indicated in the inset in the figure.

### SC after the extrusion

### SC after heat treatment



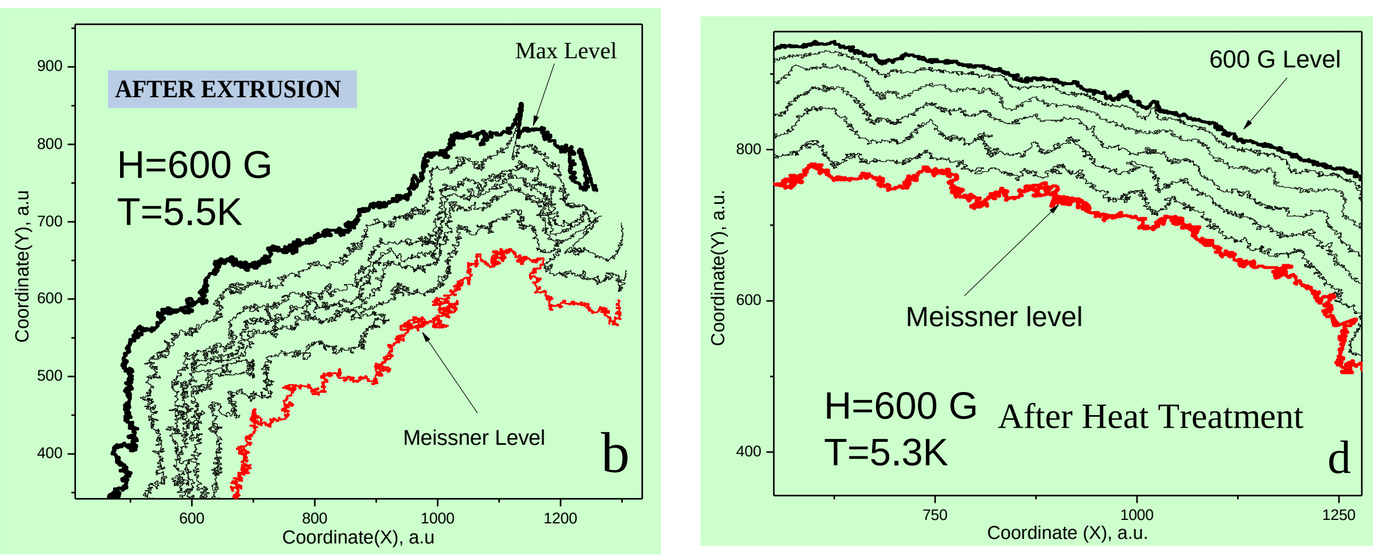




**Fig. 4.** Magneto-optical images of flux penetration in magnetic field $H$ = 600 G in NbTi-disk and the profiles of induction at different $B_z$ levels; a, b – after extrusion, c, d – after heat treatment

## Conclusion

- Magneto-optical studies of vortex dynamics in magnetic field penetration into NbTi disk revealed strongly rough boundary between Meissner state and the front of magnetic flux. Roughness of boundary is defined by the stochastic jumping of vortex bundles and the pinning structure.
- Based on the analysis of the correlation function of boundary roughness in extruded SC, it was found that the fractal dimension of Housdorff amounts to ≈ 1.5, which is close to the result in niobium [1].
- Analysis of the above data shows that (at least in the indicated temperature range) temperature has weakly effect on the roughness index. With increasing temperature, it slightly increases, both before and after heat treatment. Heat treatment has a more significant effect; as a result of heat treatment, the roughness index increases. Annealing leads to a significant increase in the critical current, which indicates a change in the pinning structure. We suppose that a change in the roughness index is also associated with a change in the pinning structure.

References

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