Second Magnetization Peak Effect in a Fe(Se,Te) iron based superconductor

A Galluzzi1,2, K Buchkov3, V Tomov3, E Nazarova3, A Leo1,2, G Grimaldi2, A Nigro1,2, S Pace1,2 and M Polichetti1,2

1Department of Physics “E.R. Caianiello”, University of Salerno, via Giovanni Paolo II, 132, Fisciano (SALERNO), I-84084, Italy
2CNR-SPIN Salerno, via Giovanni Paolo II, 132, Fisciano (SALERNO), I-84084, Italy
3Georgy Nadjakov, Institute of Solid State Physics, Bulgarian Academy of Sciences, 72 Tzarigradsko Chaussee Blvd., 1784 Sofia, Bulgaria
E-mail: agalluzzi@unisa.it

Abstract. The iron based superconductor FeSe0.5Te0.5 has been investigated by means of DC magnetic measurements as a function of magnetic field (H). By considering the superconducting m(H) hysteresis loops at different temperatures, the sample shows a strong superconducting signal together with the presence of a peak effect that causes an anomalous increase in the field dependence of the critical current density Jc(H). The presence of the peak effect has been studied by means of the Jc(T) obtained at different magnetic fields starting from the Jc(H) curves. The analysis of the Jc(T) curves shows that the peak effect is due to a crossover from a weak pinning regime to a strong pinning regime.

1. Introduction

The discovery of the iron based superconductors (IBS) in 2008 [1] and in particular the analysis of their fascinating superconducting properties [1–3] gave a boost to the researchers interest for taking into account the possibility of using these materials for applications. Among the IBS, the Fe(Se,Te) is one of the most attractive compound due to its chemical stability, pinning capabilities and rich vortex dynamics. In the framework of the vortex phenomena, one of the most intriguing property is the second magnetization peak effect (named also peak effect) that consists in a non-monotonous behavior of the field dependence of the critical current density Jc(H). This particular Jc(H) trend can be ascribed to several reasons such as matching effect, surface barriers, dynamic effects, different types of phase transition etc. In the years this phenomenon has been widely investigated in Fe(Se,Te) both single crystals and bulk samples [4–6]. The nature of the peak effect phenomenon is very complicated because of the several parameters that can be involved in the birth and the evolution of it such as the material structure, the samples morphology or also pinning energy changes.

In this work we want to study the possible cause of the presence of a peak effect found by means of dc magnetic measurements as a function of the field. At this aim we have performed m(H) measurements at different temperatures and calculated the field dependence of the critical current density Jc(H) that have shown the clear presence of the peak effect. Starting from these curves, we have extracted the temperature dependence of the critical current density Jc(T) considering a large interval of field. By fitting the Jc(T) curves with different pinning models, the cause of the peak effect birth has been determined.

2. Experimental details

We have analyzed a Fe(Se,Te) sample with dimensions 3 x 3 x 0.2 mm3 derivative of the basic FeSe [7]. The sample fabrication details are reported elsewhere [8]. The sample has been characterized using a Quantum Design PPMS-9T equipped with a VSM option. The dc magnetic measurements have been performed as a function of the magnetic field m(H) applying it perpendicular to the sample largest face. To avoid the effect on the sample response due to the residual field inside the
superconducting dc magnet, the entrapped field was zeroed before each measurement [9]. For the m(H) measurements, the sample was first cooled down to the measurement temperature in absence of field (Zero Field Cooling) and thermally stabilized for at least 20 minutes. Then, the field was ramped with a sweep rate of 0.01 T/s to reach +9 T, then back to -9 T, and finally to +9 T again in order to acquire the complete M(H) loop.

3. Results and discussion

In order to study the transport and pinning properties of the sample, measurements of magnetic moment (m) as a function of magnetic field (H) have been performed at different temperatures as reported in Figure 1 in the case of positive fields. Looking the m(H) curves, it can be noted a strong superconducting signal accompanied by the presence of a second magnetization peak effect (or only peak effect) that causes a non-monotonous behavior of the curves. A shift of the second peak in the m(H) curves is evident and in particular its position moves to lower fields as the temperature increases. A symmetric behavior is obtained for negative values of magnetic field. It was not possible to individuate the peak effect for T > 10 K, probably due to the competition between the small superconducting signal and a non-zero magnetic signal near Tc originating from magnetic impurities present in our sample.

Figure 1. Field dependence of magnetic moment for different temperatures. The non-monotonous behavior of the curves is well visible.

In order to analyze the peak effect, the field and temperature dependencies of the critical current density $J_c(H,T)$ have been considered. In particular, from the m(H) curves of Figure 1, the critical current densities $J_c(H)$ have been obtained at different temperatures by means of the Bean critical state model[10,11]

$$J_c = \frac{20\Delta M}{a \left(1 - \frac{a}{3b}\right)}$$

where $\Delta M = M_{dn} - M_{up}$ are the magnetization measured with decreasing and increasing applied field, respectively, and a and b are the lengths (in cm) characterizing the cross section of the sample perpendicular to the applied field (H\(|c\)). The unit of $\Delta M$ is in electromagnetic unit per centimeter cubic and the calculated $J_c$ is in Ampere per square centimeter. The obtained $J_c(H)$ curves are reported in Figure 2 for different temperatures. In particular, the $J_c(H)$ curves have been reported in a log-log scale that allows to observe the low dependence of $J_c$ as a function of the magnetic field that is a clue of the strength of the pinning inside the material. In addition, the peak effect characterized by an anomalous increase of the $J_c$ as a function of the field is well visible. By carrying out isofield cuts of $J_c$ for certain fixed fields from the $J_c(H)$ curves at different temperatures, the $J_c(T)$ dependencies have been extracted in order to obtain information about the pinning regime acting in the sample. At this aim, the $J_c(T)$ data have been analyzed and fitted with several pinning models reported in the literature. In particular, the
first two fits were performed considering the $\delta l$ pinning and the $\delta T_c$ pinning [12]. The first one is due to the spatial variation in the charge carrier mean free path while the second one is due to randomly distributed spatial variation in $T_c$. According to the theoretical approach proposed by Griessen [13], the $\delta l$ pinning is described by the equation $J_c(t) = J_c(0)(1 - \delta l^2)\sqrt{(1 + \delta l^2)}$ while the $\delta T_c$ pinning is described by $J_c(t) = J_c(0)(1 - \delta T_c^2)\sqrt{(1 + \delta T_c^2)}$, where $J_c(0)$ is the value of $J_c$ at $T = 0$ K and $t = T/T_c$. These equations have been used to fit the $J_c(T)$ curve for a low field value, exactly $H = 0.5$ T. As shown in the main panel of Figure 3, it is clear that neither the $\delta l$ pinning (red solid line) nor the $\delta T_c$ pinning (green dashed line) fit the data.

**Figure 2.** Magnetic field dependence of the critical current density $J_c$ reported in log-log scale at different temperatures extracted from the M(H) curves of Figure 1.

After that, a model assuming the Ginzburg-Landau temperature dependencies for the thermodynamical critical magnetic field [14] has been tried to fit the data using the equation $J_c(t) = J_c(0)(1 - \delta l^2)\sqrt{(1 + \delta l^2)}$ where $J_c(0)$ is the value of $J_c$ at $T = 0$ K and $t = T/T_c$. The blue dotted line of Figure 3 shows that also in this case the fit is not satisfactory. Another fit was performed considering a model that takes into account the existence of giant flux creep [15] and using the equation $J_c(t) = J_c(0)(1 - \delta T_c^2)\sqrt{(1 + \delta T_c^2)}$ where $J_c(0)$ is the value of $J_c$ at $T = 0$ K and $t = T/T_c$. The cyan dashed-dotted line associated to the giant flux creep does not reproduce the data. Finally, by following the approach of Polat et al [16], we have considered equations that predict the presence of weak or strong pinning centers inside the sample. For what concerns the weak pinning, the equation describing the critical current in presence of this type of pinning centers, in particular considering lattice defects associated to point-like disorder or to in-plane dislocations inside the sample[12,16], is $J_c^{\text{weak}}(T) = J_c^{\text{weak}}(0) e^{-T/T_0}$ where $J_c^{\text{weak}}(0)$ is the value of $J_c$ at $T = 0$ K, and $T_0$ is the characteristic pinning energy of weak (typically point-like) pinning defects. For what regards the strong pinning, the equation describing the critical current in presence of this type of pinning centers, in particular considering defects generated by correlated disorder such as twin boundaries, columnar pins or defects[16–18], is $J_c^{\text{str}}(T) = J_c^{\text{str}}(0) e^{-3(T/T^*)^2}$ where $J_c^{\text{str}}(0)$ is the value of $J_c$ at $T = 0$ K, and $T^*$ is the vortex pinning energy of strong pinning centers. Fitting the data of Figure 3 with the strong pinning expression (purple short dashed line), it can be noted that the fit is better than the other pinning models used so far but it presents big deviations from the data at certain temperatures. On the other hand, using the weak pinning expression (see inset of Figure 3), the fit describes very well the data. This has been verified for all the magnetic fields minor than 1 Tesla. So, in this low field region (H ranging from 0.1 T to 0.9 T ) the best fit was obtained by using the equation describing the critical current in presence of weak pinning centers.

Now we want to analyze the $J_c(T)$ curves behavior considering a high magnetic field value, for example $H = 7$ Tesla, in order to understand if the pinning regime acting in the sample is still characterized by the weak pinning centers. Following the previous approach, it is worth to underline that $\delta l$ pinning and the $\delta T_c$ pinning are effective only in the single vortex pinning regime, i.e. in low-
field and zero-field regions [19,20]. For this reason they have been excluded in the analysis of the curves at high fields.

In Figure 4 it is evident that the Ginzburg-Landau (blue dotted line) together with the weak (magenta dashed line) pinning model are the worst models for describing the data at 7 T. In addition, the giant flux creep model (cyan dashed-dotted line) characterizes well the data at 7 T but it predicts an increase of the \( J_c \) values at high temperatures that is not observed in our case and for this reason it has to be discarded. In the inset of Figure 4, it is shown the fit of the data at 7 T with the strong pinning model (purple short dashed line) and it is clear that the fit in this case is good and describes very well the experimental data. This has been verified for all the magnetic fields \( H > 3 \) T. So, in the high field region (\( H \) ranging from 3 T to 8.5 T) the best fit was obtained by using the equation describing the critical current in presence of strong pinning centers. At this point it is reasonable to think that in the intermediate region \( 1 \) T \( \leq H < 3 \) T the \( J_c(T) \) can be described by a combination of the weak and the strong pinning contributions (fit not reported), expressed through the equation [16] \( J_c(T) = J_{c,\text{weak}}(T) e^{-T/T_0} + J_{c,\text{str}}(T) e^{-3(T/T^*)^2} \) where \( J_{c,\text{weak}}(T), J_{c,\text{str}}(T), T_0 \) and \( T^* \) are the same parameters seen previously for weak and strong expressions.

---

**Figure 3.** Temperature dependence of \( J_c \) at \( H = 0.5 \) Tesla fitted with \( \delta l \) (red solid line), \( \delta T_c \) (green dashed line), Ginzburg-Landau (blue dotted line), giant flux creep (cyan dashed-dotted line) and strong (purple short dashed line) pinning model. Inset: \( J_c(T) \) at \( H = 0.5 \) Tesla fitted with weak pinning model (magenta dashed line).

**Figure 4.** Temperature dependence of \( J_c \) at \( H = 7 \) Tesla fitted with Ginzburg-Landau (blue dotted line), giant flux creep (cyan dashed-dotted line) and weak (magenta dashed line) pinning model. Inset: \( J_c(T) \) at \( H = 7 \) Tesla fitted with strong pinning model (purple short dashed line).
Figure 5. $J_c(T = 0 \text{ K})$ versus $H$. The crossover among different pinning regimes, which determines the beginning of the peak effect phenomenon, is visible.

From the fittings by weak, strong and weak+strong equations it is possible to obtain the values for the parameters $J_c^{\text{weak}}(0)$, $J_c^{\text{str}}(0)$ and $J_c^{\text{weak}}(0) + J_c^{\text{str}}(0)$, respectively, i.e. the zero-temperature critical current densities $J_c(0)$ as a function of the magnetic field. These values are plotted in a log-log scale in Figure 5. It is clear that the critical current density has a non-monotonous behavior also at $T = 0 \text{ K}$ and in particular its value starts to increase when the weak pinning centers are ineffective and the contribution to the pinning is given only by the strong pinning centers. On the basis of the reported results we can claim that the crossover between weak and strong pinning regimes determines the birth of the peak effect phenomenon of the sample. A summary of the pinning models used for fitting the $J_c(T)$ data in low and high field region is reported in Table I.

| Pinning model  | Low field region (H < 1 T) Data fitted? | High field region (H > 3 T) Data fitted? |
|----------------|----------------------------------------|----------------------------------------|
| $\delta l$     | No                                     | Not possible                           |
| $\delta T_c$   | No                                     | Not possible                           |
| Ginzburg-Landau| No                                     | No                                     |
| Giant flux creep| Yes                                    | No                                     |
| Weak           | Yes                                    | No                                     |
| Strong         | No                                     | Yes                                    |

4. Conclusions

By means of DC magnetic measurements as a function of magnetic field (H) we have analyzed the magnetic behavior of a FeSe$_{0.5}$Te$_{0.5}$ sample. In particular, performing m(H) measurements at different temperatures we have observed wide superconducting hysteresis loops accompanied by the presence of a peak effect. This phenomenon is visible in the anomalous increase of the field dependence of the critical current density $J_c(H)$ extracted from the m(H) loops at different temperatures. From these curves, by performing isofield cuts of $J_c$ at fixed fields, the $J_c(T)$ curves have been acquired. Fitting the $J_c(T)$ dependencies with several pinning models at different magnetic fields ranging from 0.1 T up to 8.5 T, the information about the pinning regime acting in the sample have been obtained. In particular, it has been found that the sample undergoes a pinning crossover from a weak pinning regime acting until $H > 1 \text{ T}$, to a strong pinning regime when $H > 3 \text{ T}$. Observing the $J_c(T = 0 \text{ K})$ values as a function of field, obtained from the $J_c(T)$ fits, it is evident that the origin of the peak effect can be ascribed to this weak/strong pinning crossover.
References

[1] Kamihara Y, Watanabe T, Hirano M and Hosono H 2008 Iron-based layered superconductor La[(1-x)FeAs + xFeSe] with Tc = 26 K. J. Am. Chem. Soc. 130 3296–7

[2] Leo A, Braccini V, Bellingeri E, Ferdeghini C, Galluzzo A, Polichetti M, Nigro A, Pace S and Grimaldi G 2018 Anisotropy Effects on the Quenching Current of Fe(Se,Te) Thin Films IEEE Trans. Appl. Supercond. 28 1–4

[3] Grimaldi G, Leo A, Nigro A, Pace S, Braccini V, Bellingeri E and Ferdeghini C 2018 Angular dependence of vortex instability in a layered superconductor: the case study of Fe(Se,Te) material Sci. Rep. 8 4150

[4] Miu D, Noji T, Adachi T, Koike Y and Miu L 2012 On the nature of the second magnetization peak in FeSe1–δ xTex single crystals Supercond. Sci. Technol. 25 115009

[5] Galluzzo A, Buchkov K, Tomov V, Nazarova E, Leo A, Grimaldi G, Nigro A, Pace S and Polichetti M 2018 Evidence of pinning crossover and the role of twin boundaries in the peak effect in FeSeTe iron based superconductor Supercond. Sci. Technol. 31 015014

[6] Bonura M, Giannini E, Viennois R and Senatore C 2012 Temperature and time scaling of the peak-effect vortex configuration in FeTe0.7Se0.3 Phys. Rev. B 85 134532

[7] Fiamozzi Zignani C, Corato V, Leo A, De Marzi G, Mancini A, Takano Y, Yamashita A, Polichetti M, Galluzzo A, Rufoloni A, Grimaldi G and Pace S 2016 Fabrication and Characterization of Sintered Iron-Chalcogenide Superconductors IEEE Trans. Appl. Supercond. 26 1–5

[8] Galluzzo A, Buchkov K, Tomov V, Nazarova E, Kovacheva D, Leo A, Grimaldi G, Pace S and Polichetti M 2018 Mixed state properties of iron based Fe(Se,Te) superconductor fabricated by Bridgman and by self-flux methods J. Appl. Phys. 123 233904

[9] Galluzzo A, Mancusi D, Cirillo C, Attanasio C, Pace S and Polichetti M 2018 Determination of the Transition Temperature of a Weak Ferromagnetic Thin Film by Means of an Evolution of the Method Based on the Arrott Plots J. Supercond. Nov. Magn. 31 1127–32

[10] Bean C P 1962 Magnetization of hard superconductors Phys. Rev. Lett. 8 250–3

[11] Bean C P 1964 Magnetization of High-Field Superconductors Rev. Mod. Phys. 36 31–9

[12] Blatter G, Feigel’man M V., Geshkenbein V B, Larkin A I and Vinokur V M 1994 Vortices in high-temperature superconductors Rev. Mod. Phys. 66 1125–388

[13] Griessen R, Wen Hai-hu, van Dalen A J J, Dam B, Rector J and Schnack H G 1994 Evidence for mean free path fluctuation induced pinning in YBa2Cu3O7 and YBa2Cu4O8 films Phys. Rev. Lett. 72 1910–3

[14] Di Gioacchino D, Celani F, Tripodi P, Testa A M and Pace S 1999 Nonuniversal temperature dependencies of the low-frequency ac magnetic susceptibility in high-Tc superconductors Phys. Rev. B 59 11539–50

[15] Yeshurun Y and Malozemoff a. P 1988 Giant flux creep and irreversibility in an Y-Ba-Cu-O crystal: An alternative to the superconducting-glass model Phys. Rev. Lett. 60 2202–5

[16] Polat A, Sinclair J W, Zuev Y L, Thompson J R, Christen D K, Cook S W, Kumar D, Chen Y and Selvamanickam V 2011 Thickness dependence of magnetic relaxation and E-J characteristics in superconducting (Gd-Y)-Ba-Cu-O films with strong vortex pinning Phys. Rev. B Condens. Matter Mater. Phys. 84 024519

[17] Nelson D R and Vinokur V M 1993 Boson localization and correlated pinning of superconducting vortex arrays Phys. Rev. B 48 13060–97

[18] Hwa T, Le Doussal P, Nelson D R and Vinokur V M 1993 Flux pinning and forced vortex entanglement by splayed columnar defects Phys. Rev. Lett. 71 3545–8

[19] Ghorbani S R, Wang X L, Hossain M S A, Dou S X and Lee S-I 2010 Coexistence of the δl and δTc flux pinning mechanisms in nano-Si-doped MgB2 Supercond. Sci. Technol. 23 025019

[20] Lei H, Wang K, Hu R, Ryu H, Abeykoon M, Bozin E S and Petrovic C 2012 Iron chalcogenide superconductors at high magnetic fields Sci. Technol. Adv. Mater. 13 054305