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ASPECTS OF PASSIVE MAGNETIC LEVITATION BASED ON HIGH-T_c SUPERCONDUCTING YBCO THIN FILMS

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Abstract - Passive magnetic levitation systems reported in the past were mostly confined to bulk superconducting materials. Here we present fundamental studies on magnetic levitation employing cylindrical permanent magnets floating above high-T_c superconducting YBCO thin films (thickness about 0.3 μm). Experiments included free floating rotating magnets as well as well-established flexible beam methods. By means of the latter, we investigated levitation and drag force hysteresis as well as magnetic stiffness properties of the superconductor-magnet arrangement. In the case of vertical motion of the magnet, characteristic high symmetry of repulsive (approaching) and attractive (withdrawing) branches of the pronounced force-displacement hysteresis could be detected. Achievable force levels were low as expected but sufficient for levitation of permanent magnets. With regard to magnetic stiffness, thin films proved to show stiffness-force ratios about one order of magnitude higher than bulk materials.

Phenomenological models support the measurements. Regarding the magnetic hysteresis of the superconductor, the Irie-Yamafuji model was used for solving the equation of force balance in cylindrical coordinates allowing for a macroscopic description of the superconductor magnetization. This procedure provided good agreement with experimental levitation force and stiffness data during vertical motion. For the case of (lateral) drag force basic qualitative characteristics could be recovered, too. It is shown, that models based on simple asymmetric magnetization of the superconductor describe well asymptotic transition of drag forces after the change of the magnet motion direction. Virgin curves (starting from equilibrium, i.e. symmetric magnetization) are approximated by a linear approach already reported in literature, only.

This paper shows that basic properties of superconducting thin films allow for their application to magnetic levitation or - without need of levitation forces, e.g. microgravity - magnetic damping devices.

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1. INTRODUCTION

Magnetic levitation and suspension experiments and studies based on either permanent magnets floating above bulk high-T_c superconducting materials or superconducting samples being suspended below magnets, have been reported widely in the past (for a review see [1]). Several basic properties of these arrangements are understood quite well, thus enabling a wide range of possible industrial applications of this new class of materials.

While many efforts are made to further increase important specifications of bulk superconductor-magnet properties, such as maximum force level, long term stability, achievable r.p.m., etc., to our knowledge, no levitation experiments have been reported employing superconducting thin films instead of bulk materials. In this paper we present fundamental studies of such arrangements. These offer new possibilities for applications and devices such as microturbine rotors, micromotors and microgyros, and damping devices in e.g. microgravity environment.

Section 2 gives a short overview of basic properties of superconductor-magnet arrangements. We report on experiments applying typical representatives of bulk materials including sintered as well as melt-quenched samples, describe their characteristic properties and compare the results with those from thin films. In Section 3 we introduce a model of the thin film - permanent magnet interaction which allows for an interpretation of the experimental data. Highly hysteretic force-displacement relations in the case of vertical as well as horizontal magnet motion are explained in terms of a critical-state hysteretic magnetization model of the superconductor. Section 4 deals with force-creep phenomena, which were observed to considerably impair the usable force range. However force-creep is not included in the model presented here.

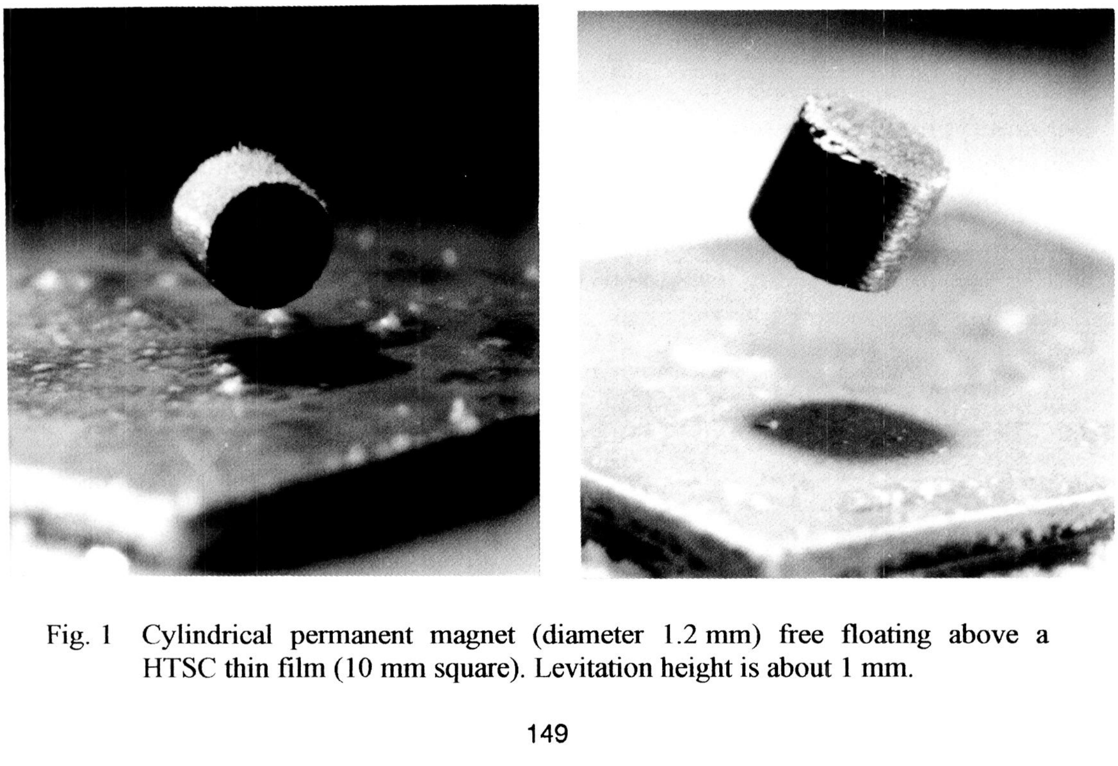

Fig. 1 Cylindrical permanent magnet (diameter 1.2 mm) free floating above a HTSC thin film (10 mm square). Levitation height is about 1 mm.

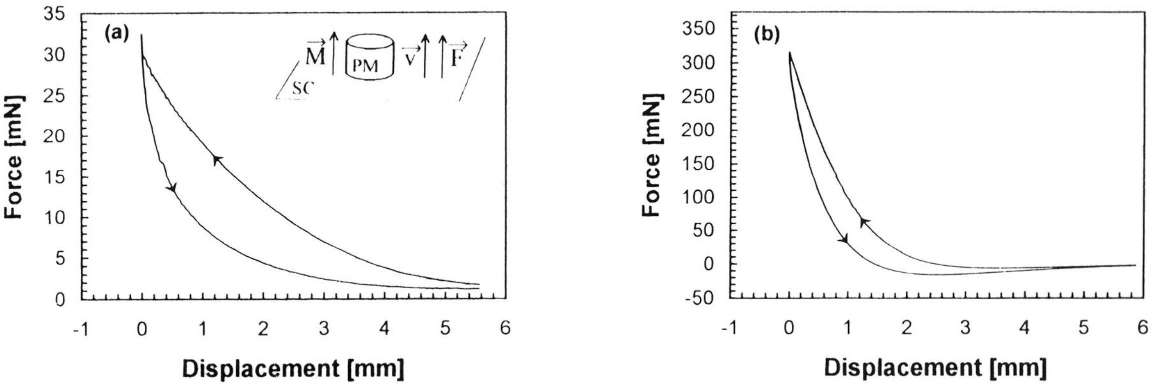

Fig. 2 Typical vertical force vs. magnet height relation for a bulk superconductor (PM ... permanent magnet, SC ... superconductor, **M** ... magnetization, **v** ... magnet velocity, **F** ... vertical force): (a) sintered, (b) melt-quenched sample.

2. SUMMARY OF EXPERIMENTAL DATA AND RESULTS

The free floating permanent magnet

Figure 1 shows a cylindrical permanent magnet free floating above a superconducting YBCO thin film. Although similar pictures from bulk samples are highly familiar to a wide public since 1987 and reported in many journals, it is pointed out, that the experiment shown in Fig. 1 is based on a thin film, the thickness of which is about 0.3 μm, thus at least 4 up to 5 orders of magnitude below that of bulk material. (In fact, the picture primarily shows the glass carrier of the film!) On the other hand, typical values of thin film critical current densities J_c are in the range of 10^6 - 10^7A/cm^2 in comparison to 10^3 - 10^4A/cm^2 in bulk superconductors. The magnet could be placed manually in any arbitrary position within the range of levitation height and resembled a similar behavior as what is known from bulk material and was described by Brandt as "embedded in an invisible heap of sand" [2].

Experimental details

Four samples of pulsed laser ablated YBCO thin films on MgO substrate mounted on glass carriers were provided by the School of Applied and Engineering Physics at Cornell University and one by NASA Lewis Research Laboratory, respectively. The sample size was typically 10 mm square and about 0.3 μm thick. For levitation experiments, a reliable setup, tested and described earlier [3], was used with only minor modifications for the thin film experiments. With the exception of the demonstration of the free floating magnet, all experiments were performed with a cylindrical magnet (3.2 mm height and 3.2 mm diameter) mounted on flexible beams with its magnetic and geometric axis perpendicular to the film plane.

Comparison between various bulk materials and thin films

Hysteretic force-displacement relations in passive magnetic levitation systems are caused by irreversible flux motion within the superconductor and are therefore a common feature in such arrangements. With (weak-pinning) sintered superconducting material, the vertical motion hysteresis loop is typically restricted to repulsive values during the

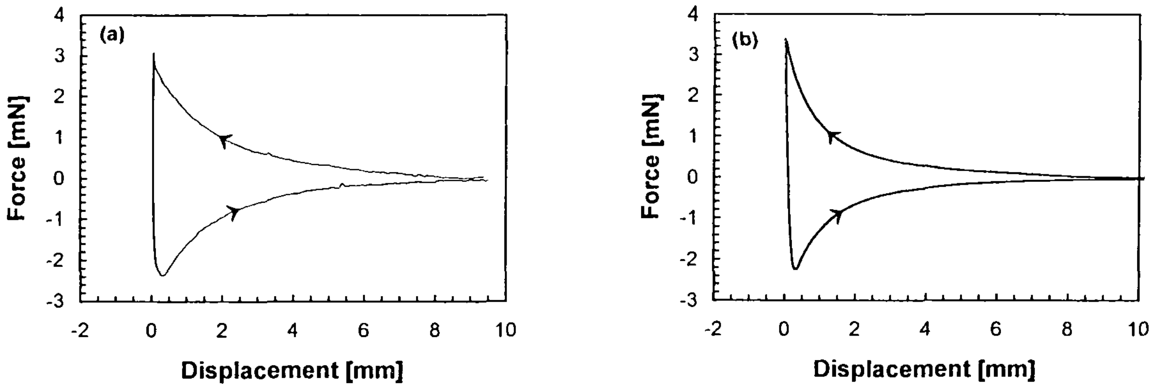

Fig. 3 Vertical force vs. magnet height (= displacement) above thin film sample: (a) measured, (b) calculated.

whole approaching and retreat cycle (Fig. 2a). By introducing modern melt-quenched materials with considerably higher critical current densities, higher force levels can be reached. At the same time, strongly pinned fluxoids cause a transition to attractive forces during the retreat cycle, thus enabling suspension (Fig. 2b). This effect proves to be especially pronounced in the field cooled case. This behavior was predicted on the basis of theoretical considerations [4]. In addition, it was argued, that the amount of the attractive region within the hysteresis depends on the amount of the superconductor volume affected by a sufficiently high magnetic field [5].

The vertical motion hysteresis loop

In the case of the superconducting thin films considered here, the amount of superconducting volume penetrated by a sufficiently high magnetic field is especially high, resulting in pronounced attractive regimes and almost symmetric repulsive and attractive branches of the hysteresis (Fig. 3a). With the 3.2 mm magnet used here, the range of measurable interaction was about 10 mm. Force vs. displacement (i. e. magnet height above thin film) was of exponential type (cf. [1]) with maximum force values of about 4 mN. In contrast to bulk material, the retreat branch exhibited an exponential-type behavior, too. By performing arbitrary back and forth procedures any point within the

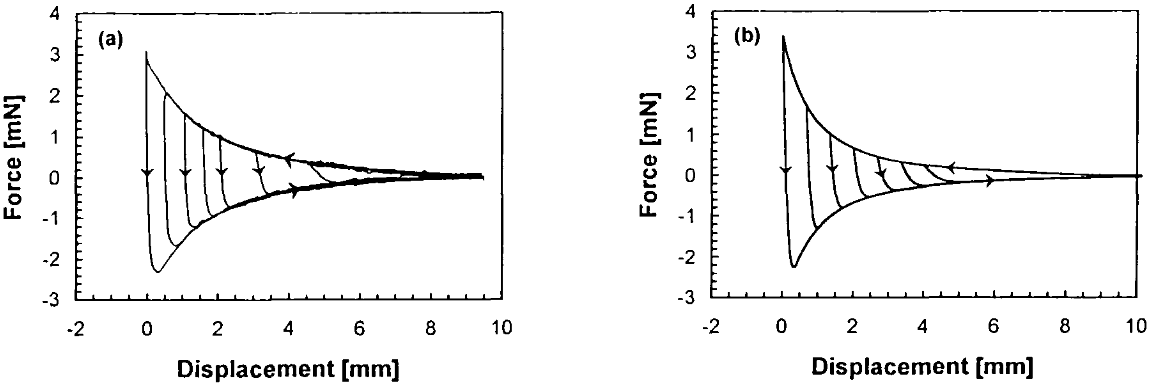

Fig. 4 Set of force-displacement hysteresis loops for a thin film: (a) measured, (b) calculated.

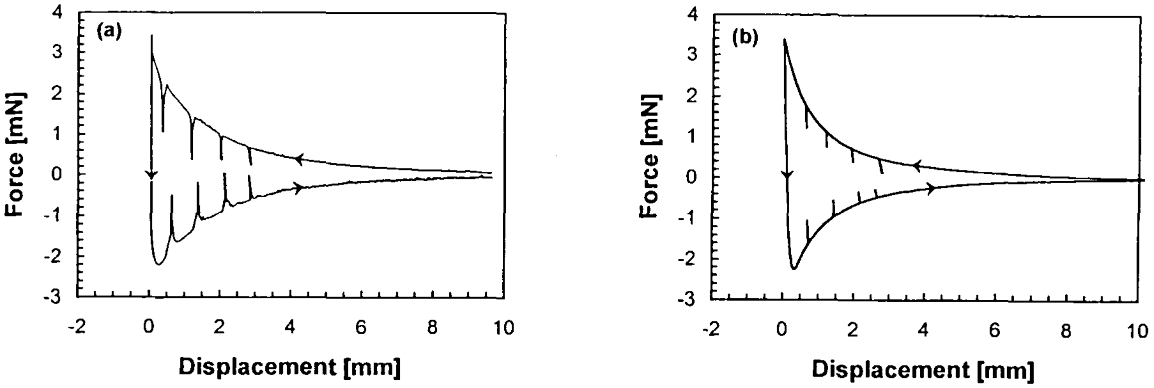

Fig. 5 Set of minor loops for stiffness evaluation: (a) measured, (b) calculated.

hysteresis loop received by a monotonic cycle can be reached. A set of hysteresis loops is shown in Fig. 4a. Here, the reversal point was increased step by step from the film surface. Regarding minor loops, large amplitude reversals were of irreversible hysteretic behavior, while reversible loops of considerably small amplitudes (less than 80 μm, depending on the respective force level) were used for stiffness evaluation (Fig. 5a).

The lateral motion hysteresis loop

For the lateral motion of the magnet, a behavior was found very similar to that known from bulk material. A rather steep linear increase of the drag force opposing the magnet motion direction is followed by a saturating force value. Once the saturation is reached in one direction, rather symmetric branches result from magnet cycling over a sufficient large distance in the mm range. Local reversals of the magnet motion direction yield reversible (or weak hysteretic in the case of high amplitudes, respectively) minor loops, appropriate for stiffness evaluation of the arrangement (Fig. 6, the above mentioned initial curve is not shown in the experimental result, Fig. 6a).

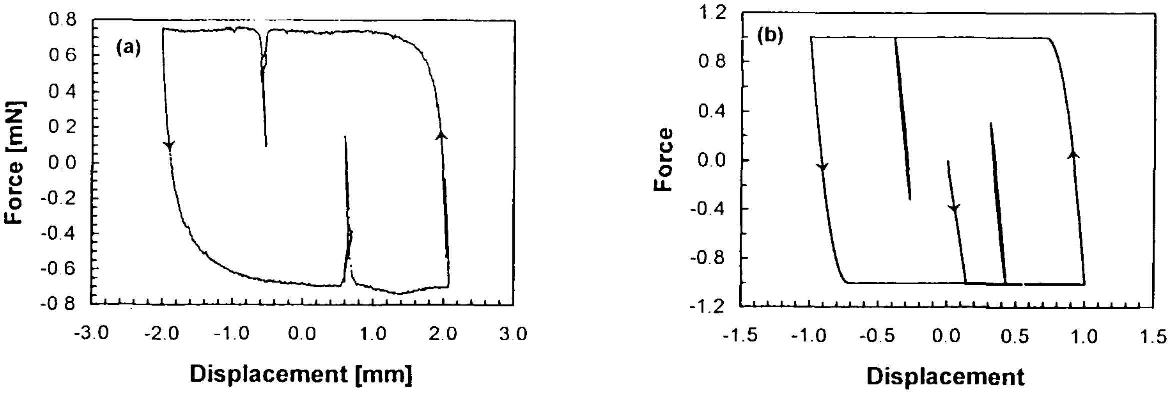

Fig. 6 Lateral force vs. lateral magnet displacement above thin film: (a) measured, (b) model, normalized to maximum force and displacement, respectively.

Vertical and lateral magnetic stiffness

By evaluating the reversible minor loops, thin films were found to have superior stiffness properties than bulk materials. This is especially true for the vertical motion case, where thin films approached an order of magnitude higher values than sintered and melt-quenched bulk samples. This is considered as another consequence of high critical current densities in thin films. In the lateral motion case the effect was not as pronounced but still clearly seen (cf. Fig. 8).

3. MODELING OF THE HYSTERESIS LOOPS

Considerable effort in modeling magnetic levitation forces have been reported (for a review see e. g. [1]). This includes analytical methods to solve the field problem. Here, certain simplifications, such as the image method, cover type I superconductors only. But even more sophisticated methods such as those applied by Z. J. Yang et al. [6] do not take into consideration hysteretic effects. However, keeping in mind that the pronounced magnetic hysteresis of the superconducting material is one of the basic features (maybe the most important one) necessary for self-stabilizing passive magnetic levitation or suspension systems, respectively, we tried to setup a model which is mainly based on the magnetic hysteresis of the superconductor.

Here we follow arguments outlined in the work of Irie and Yamafuji [7] and discussed in more detail in [8]. Solving the balance of force equation (based on the confrontation of Lorentz force and pinning force) formulated for fluxoids yields locally varying flux density and magnetization distributions. By averaging out the sample volume, we get expressions for the superconductor's bulk magnetization [8]. A typical result is shown in Fig. 7 for cycling in an unipolar field including minor loops. (It is realized, that the Bean model, Fig. 7a, is included as a special case of the more general Irie-Yamafuji model, Fig. 7b). With this, the force calculation is performed under the

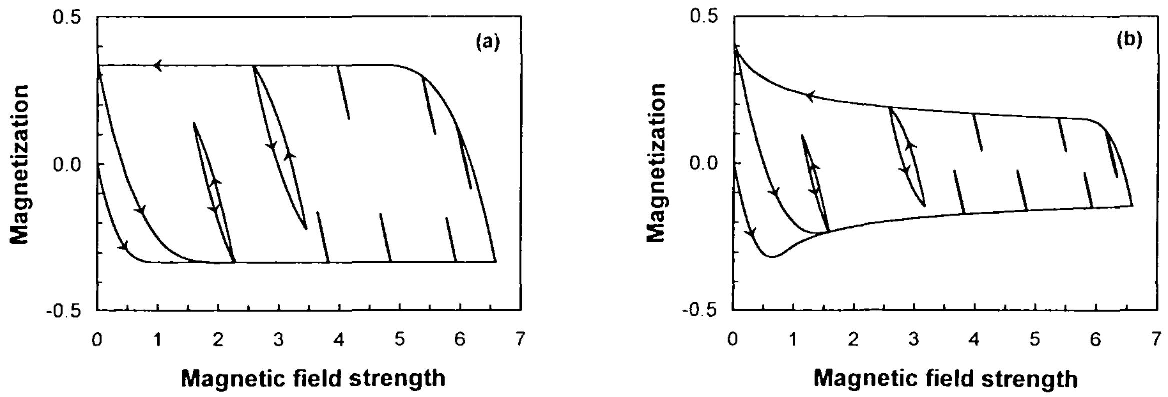

Fig. 7 Calculated magnetic hysteresis of a strong pinning type II superconductor (normalized to penetration field, see [8]): (a) Bean model, (b) Irie-Yamafuji model.

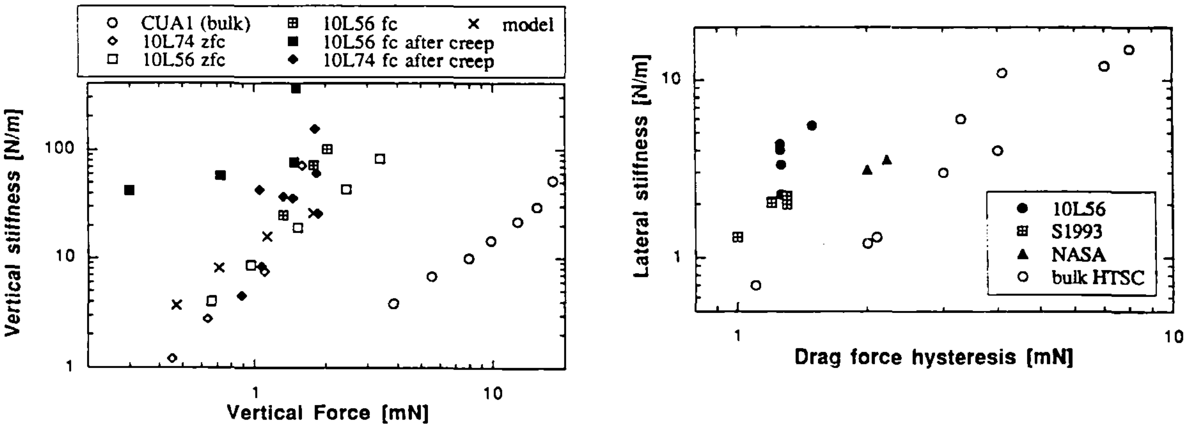

Fig. 8 Magnetic stiffness vs. force for sintered bulk and various thin film samples: (a) vertical, (b) lateral motion.

assumption of a dipole-like magnetic field. Figs. 3b - 5b show respective results of the calculation, simulating similar conditions as in the experiments (Figs. 3a - 5a). Calculated stiffness values taken from minor loops in Fig. 6a proved to be in reasonable accordance to measured results (Fig. 8).

For the case of lateral magnet motion, the modeling process is based on an assumed asymmetric magnetization of the superconductor only. The averaging process over the locally varying magnetization is restricted to each of the two halves, one facing the magnets motion direction and the other averting it. An obvious shortcut is the neglect of the actual field distribution. In spite of the ad-hoc nature of this model, some basic qualitative features can be reproduced in the simulation (Fig. 6).

4. FORCE-CREEP PHENOMENA

In contrast to bulk material, the levitation with thin film specimens showed

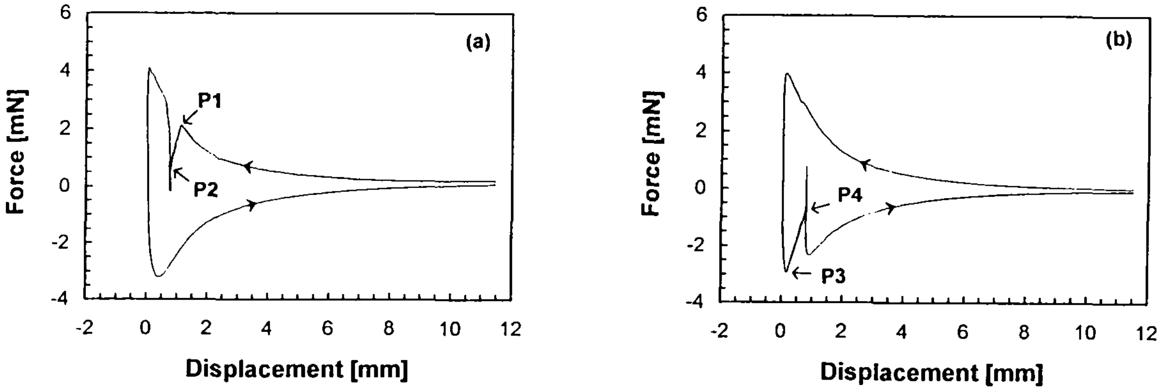

Fig. 9 Force creep during 650 s in maximum force-displacement hysteresis loop in (a) approaching (P1->P2) and (b) retreat (P3->P4) branch.

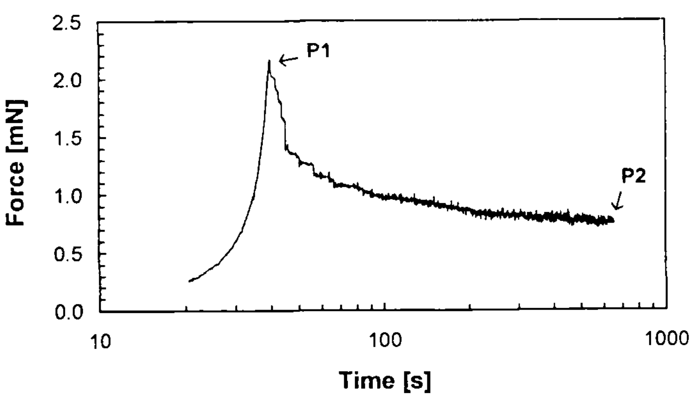

Fig. 10 Force vs. time during creep-phase shown in Fig. 9a.

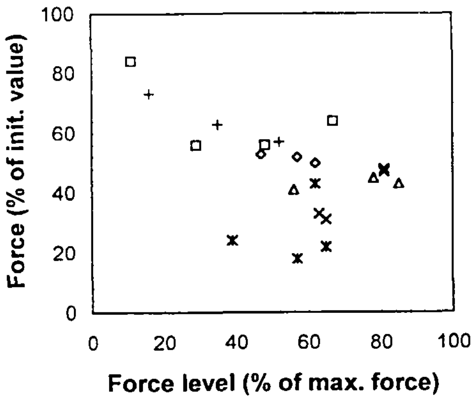

Fig. 11 Percent of remaining force (after creep) vs. initial force level for various film samples.

considerable force-relaxation with time, the amount of which significantly reduced the practical usable force range. As a typical result, Fig. 9 shows the force history after stopping the magnet at a point P1. The linear relation of simultaneously decreasing force and magnet height reflects the beam characteristics and is therefore found to be rather independent of the force level (as long as the force-deflection relation of the beam is linear). A force reduction by about 65% during 650 s lead to a rather stable force level P2 thereafter. By inspection of the course of time of the force (Fig. 10) a strikingly pronounced rather steep initial creep phase followed by several discontinuities and jumps can be observed. As preliminary experiments indicated, such jumps could be produced by external sources such as slightly tapping on the experimental setup. However, although utmost care was taken during the experiments (including the use of a low-stiffness, high-mass table) we could not completely avoid the occurrence of such jumps. They are, therefore, considered to be possibly characteristic for the creep process in the thin films. Fig. 11 shows data concerning the amount of force-creep related to the respective force. From that, a moderate scattering of the amount of creep can be seen.

Improvements of thin film materials such as implementing additional pinning centers may be able to reduce force creep. However possible applications are still to be expected in the low-mass range or where gravity is low e.g., in microgravity environment and magnetic damping is required.

5. CONCLUSIONS

The following conclusions can be drawn from this work:

(a) High-Tc superconducting YBCO thin films can successfully be used for magnetic levitation. This includes free floating cylindrical magnets as well as samples fixed to elastic beams for precise deflection measurements.

(b) Highly symmetric force-displacement hysteresis loops with respect to (repulsive) approaching and (attractive) retreat curves, the latter giving rise to suspension systems, are found to be characteristic for thin film-magnet arrangements described here.

(c) Application of the critical state Irie-Yamafuji-model provides reasonably good simulation data for the force-displacement behavior. Further improvement can be expected from the application of appropriate oblate spherical geometry instead of simple cylindrical one used here.

(d) Simulation of lateral drag force hysteresis, based on asymmetric macroscopic magnetization of the superconductor, exhibits basic features observed experimentally. However more refined models will be necessary for detailed studies including quantitative predictions of achievable force values.

(e) With the thin film samples used in this study, a pronounced force-creep effect was observable, thus considerably reducing the usable force range. Uncertainties arise from a distinct scattering of the amount of creep. However stiffness properties were not affected by the creep phenomenon. Material processing techniques may be possible to minimize this creep effect.

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