FABRICATION OF LARGE DOMAIN $YBa_2Cu_3O_x$ FOR MAGNETIC SUSPENSION APPLICATIONS

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ABSTRACT

Large domain $YBa_2Cu_3O_x$ levitators have been fabricated using a seeded melt processing technique. Depending upon the seed, either a single or five domained sample can be obtained. The grain boundaries separating each domains in the five domain levitator are found to be 90 degrees. Similar levitation forces can be observed for single and five domained samples. After thermal cycling, however, a small decrease in the levitation force of the five domain levitator was observed as a function of thermal cycles while nearly no change in force was observed in the single domain levitator. Finally it is shown that both, single and five domain YBCO, behave similarly as a function of sample thickness.

INTRODUCTION

A stable levitation or suspension of a magnet is one of the fascinating properties of a superconductor. Unlike active suspension between magnets, the suspension of a magnet by a superconductor is completely passive. A magnet can be suspended above as well as below a type II superconductor (Fig. 1 & 2). A large number of applications are envisioned utilizing this unique property. These applications include rotary motion bearings, cryopumps, cryocoolers, cryoflowmeters, energy storage devices, contactless transportation, and vibration isolators.(1)

The stable suspension of superconducting materials was first demonstrated by Arkadiev.(2,3) Although the levitation by the superconducting material was studied in

Figure 1. A ring magnet is suspended above a group of large domain levitators.

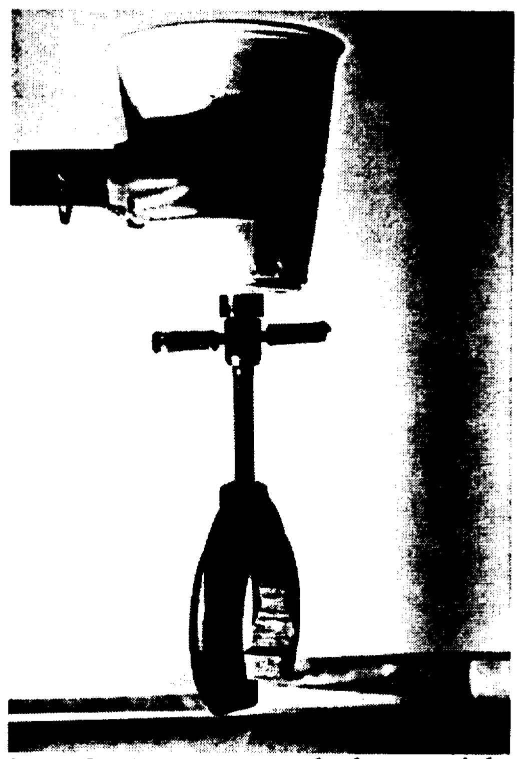

Figure 2. A magnet attached to a weight is suspended below a single large domain levitator (in cup).

1950s and 60s, the necessity of using expensive liquid helium (Temp.= 4.2 K) greatly hindered further development.[4] The discovery of a high T_c superconductor with transition temperatures above liquid nitrogen (77 K) renewed the interest in superconducting levitation.[5] Devices based on the principle of superconducting levitation are now being developed at various laboratories all over the world.[6-10] The levitation force on a magnet due to a superconductor is an integrated paramcter which depends on the characteristics of the magnet as well as the superconductor. These factors include:

1. the distribution and the intensity of the magnetic field.
2. the local critical current density, J_c, of the superconductor, and
3. the characteristic length scale, d, of the induced current loop in the superconductor.

For a given magnet and for superconductors with similar dimensions, the levitation force can be enhanced by increasing J_c and/or d of the superconductor. The critical current density can be improved by introducing defects that can act as flux pinning centers, and d can be increased by increasing the size of the strongly linked regions.

The melt processing technique offers an attractive way to fabricate strongly linked $YBa_2Cu_3O_x$ (YBCO).[11-19] Moreover, defects like Y_2BaCuO_5 inclusions and other structural defects (like dislocations and stacking faults) can be incorporated during processing that can further enhance the current carrying capability in these materials.[17-19] In a typical melt processing method, YBCO is heated above its peritectic point where it melts incongruently into Y_2BaCuO_5 and a Ba- and Cu-rich liquid. The semi-solid melt is cooled slowly to obtain aligned grains of YBCO. The grains are aligned, however, only in small regions called domains. Within the domain the superconductor is mostly strongly linked. The domains are separated by large angle grain boundaries which act as weak links, thereby reducing the current carrying capability in the presence of magnetic fields (Only under some special situations like 90 degree grain boundaries, may the boundary act as strongly linked and be able to carry currents comparable to that within a domain).

In a melt processed YBCO sample the levitation force can be enhanced by increasing the domain size or by developing samples with strongly linked large angle boundaries. One way to increase the domain size is by initiating grain growth by using a seed crystal. In presence of a favorable temperature gradient the seed not only ensures a single nucleation site but also permits controlled orientation of the grains. Using the seeding technique along with a controlled temperature gradient YBCO domains as large as that of the sample size (single domain) can be fabricated. Seeding with a single crystal of MgO, Al_2O_3, $SmBa_2Cu_3O_x$ and $Nd_{1+x}Ba_{2-x}Cu_3O_y$ have been reported by various groups.[20-24] The seed can be added to the coldest point of the sample prior to heating or after an extra melting step. The addition of the seed prior to heating is preferable as it reduces the difficulty of mass production.

In this paper, fabrication of large domain levitators using a $Nd_{1+x}Ba_{2-x}Cu_3O_y$ seed is considered. A five domain or a single domain levitator can be produced based on the type of seed crystal used. The properties of the five domain as well as single domain levitators are also considered.

PREPARATION AND PROPERTIES OF THE SEED CRYSTALS

$Nd_{1+x}Ba_{2-x}Cu_30_y$ crystals are used as seeds in order initiate grain growth in melt processed YBCO. The crystals are prepared by using a self flux method. Specifically, a Barium and Copper rich mixture of Nd_2O_3, $BaCO_3$, and CuO are mixed and heated in Al_2O_3 crucibles above the peritectic point of $NdBa_2Cu_3O_x$. The melt was then slowly cooled and the excess liquid drained after adequate crystal growth. The crystals were then collected and cleaned for seeding.

Two types of seeds were obtained depending upon the amount of flux in the melt. When the amount of flux is low, the crystals obtained have a cubic appearance. These crystals are, however, not single crystals and do have a unique microstructure as shown in Figure 3. The crystal clearly shows five different regions. The central region is surrounded by four differently oriented crystals of the same crystal structure. Transmission electron microscopic studies have revealed that the surrounding crystals are rotated 90 degrees with respect to the central crystal. Furthermore, the surrounding crystals are also rotated by 90 degrees with respect to its adjacent crystal. The flat seeds on the other hand are single crystals. No special microstructure was observed as shown in Figure 4.

Figure 5 shows the X-ray diffraction of the crushed seeds (both cubic and flat) and near phase pure $NdBa_2Cu_3O_x$ produced by calcination in low partial pressure O_2 atmosphere. As evident from the figure, both the cube and the flat seeds have lattice structure similar to that of $NdBa_2Cu_3O_x$ powder.

Energy dispersive x-ray analysis showed an average cation composition of Nd:Ba:Cu of 1.25:1.85:2.4 with about 6 % Al contamination from crucible reactions for flat crystals. A composition of Nd:Ba:Cu of 1.35:1.75:2.8 with about 2 % Al contamination for the center of the cube shaped crystal was found, while the surrounding crystals showed a composition of Nd:Ba:Cu of 1.3:1.7:2.5 with about 6 % Al contamination. These compositional differences, especially those in Al-contamination, can be explained by differences in the initial phase composition and by processing during heat treatment. During the growth of the flat seeds a relatively larger contact between the crucible and its content existed. For the growth of cubic seeds, the contact of the melt with the crucible wall was less, leading to a reduction of contamination of the central crystal. The reason for the stronger contamination of the surrounding crystals may be due to the prolonged

Figure 3. Photomicrograph of a "cubic" seed consisting of a central crystal and four surrounding single crystals.

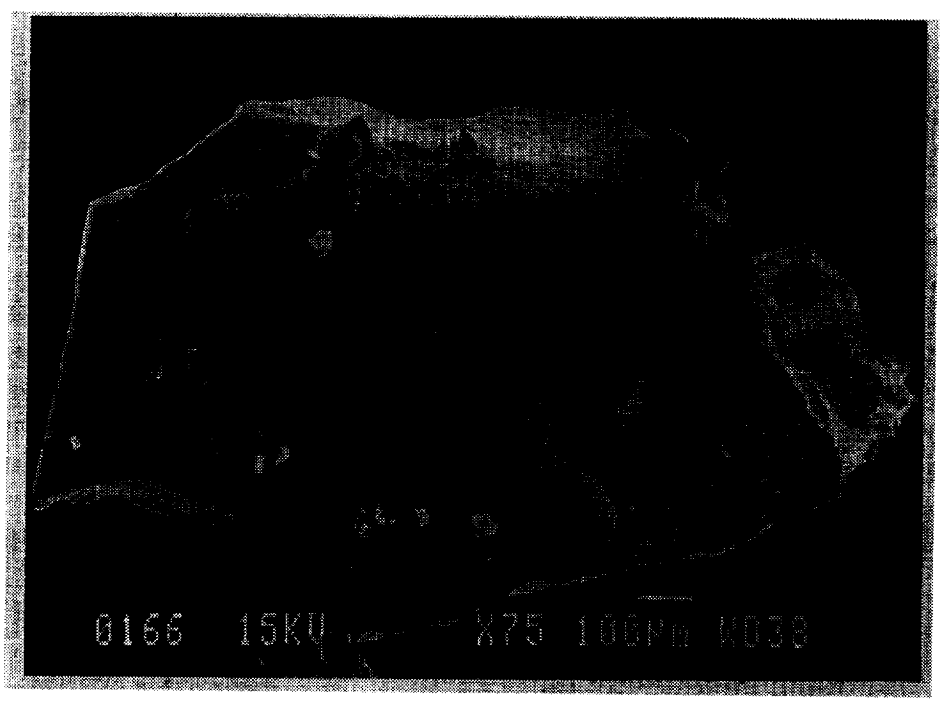

Figure 4. SEM photo of a flat, single crystal seed.

processing at the elevated temperatures. This in turn may account for the increased Al dissolution and diffusion through the content of the crucible.

A crystal can only work as a seed to initiate grain growth in melt processed YBCO, if the seed has a melting point higher than that of YBCO. Figure 6 shows the DTA of crushed flat and cube crystals. As evident from the figure, the crystal melts at about 1120 ^{o}C, which is considerably higher than the melting point of YBCO (~ 1010 ^{o}C). Interestingly, near phase pure $NdBa_2Cu_3O_x$ prepared by calcination in low partial pressure O_2 atmosphere melts at about 1070 ^{o}C. This difference in the melting point may be related with the surface energy of the faceted structure of the seeds. The higher melting point of both the cube and flat seeds thus open the possibility of using them as seeds for melt processing $NdBa_2Cu_3O_x$ itself.

FABRICATION AND PROPERTIES OF THE LEVITATORS

A top seeding method is used to melt process YBCO levitators. As mentioned earlier both cubic and flat shaped crystal were used for seeding. The details of the method have been reported previously.[24,25] Figure 7 shows some of the melt -processed YBCO levitators. Samples seeded with cubes as well as flat crystals showed similar appearance. However, a difference in the structure was obvious after polishing. A five domain structure was observed when the levitator was seeded with a cube seed (Fig. 8). Seeding with flat seeds, however, resulted in a single domain sample (Fig. 9). The melt processed YBCO levitators are therefore observed to replicate the feature of the seed used to initiate grain growth.

Transmission electron microscopy has been used to study the grain boundaries developed between two domains in a five domain levitator. Two kinds of grain boundaries were observed as shown in Figures 10 & 11. The first kind of grain boundary was observed between two domains that are rotated 90 degrees about a common [100/010] axis with both [001] axes lying in the plane of the paper. The boundary plane is always very sharp, free of secondary phases and shows macroscopical facetting. The boundary plane varies macroscopically from a symmetrical configuration - predominantly in the upper part of the pellet - to configurations where the grain boundary lies perpendicular to the [001] direction of one of the domains. The grain boundary is often inclined and meandering in the third dimension (into the paper plane) as well. The second kind of grain boundary is observed between two domains that are rotated 90 degrees about a common [100/010] axis with one [001]-axis normal to the plane of the paper and one [001]-axis contained within the plane of the paper. This type of grain boundary has been reported to support a high critical current density in thin film superconductors.

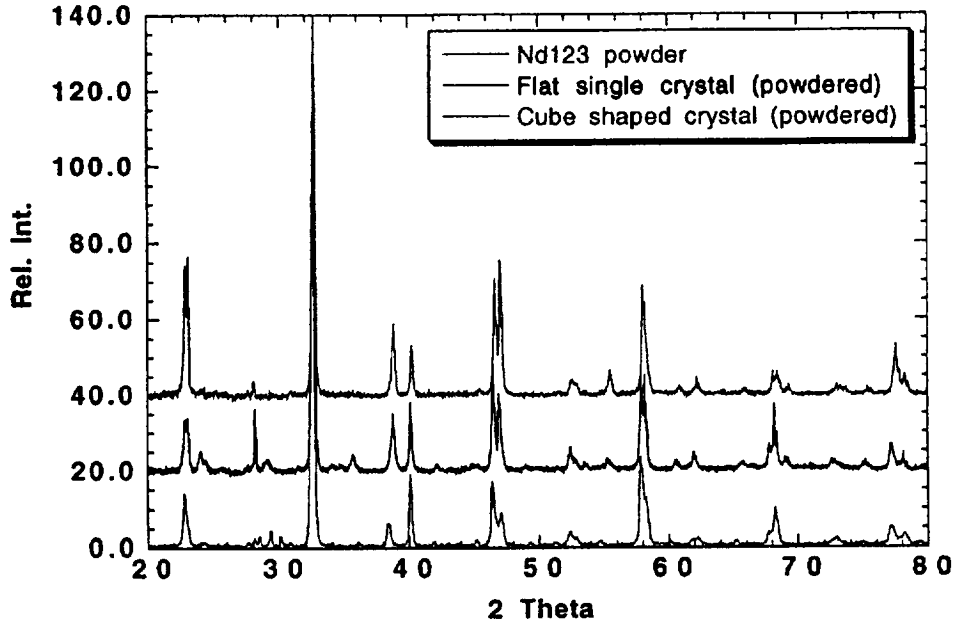

Figure 5. X-ray diffraction of $NdBa_2Cu_3O_x$ powder, crushed single crystals, and crushed cubed crystals. (in order from top to bottom)

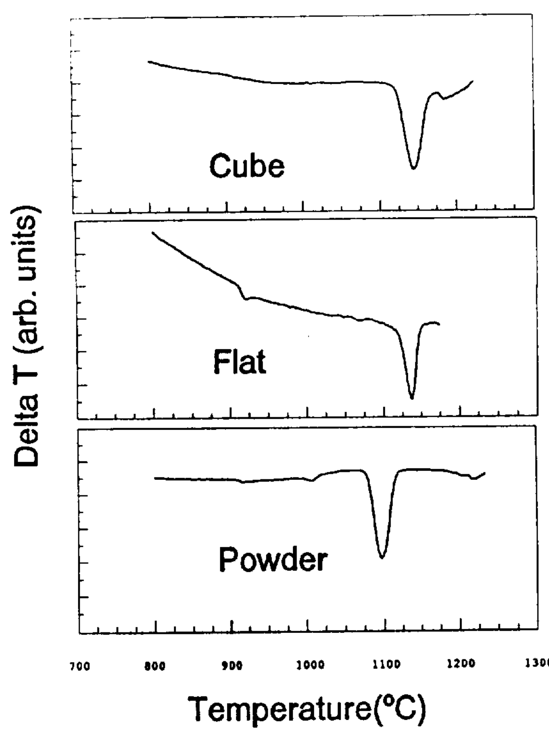

Figure 6. Differential thermal analysis of cubed crystals, flat single crystals, and Nd123 powder.

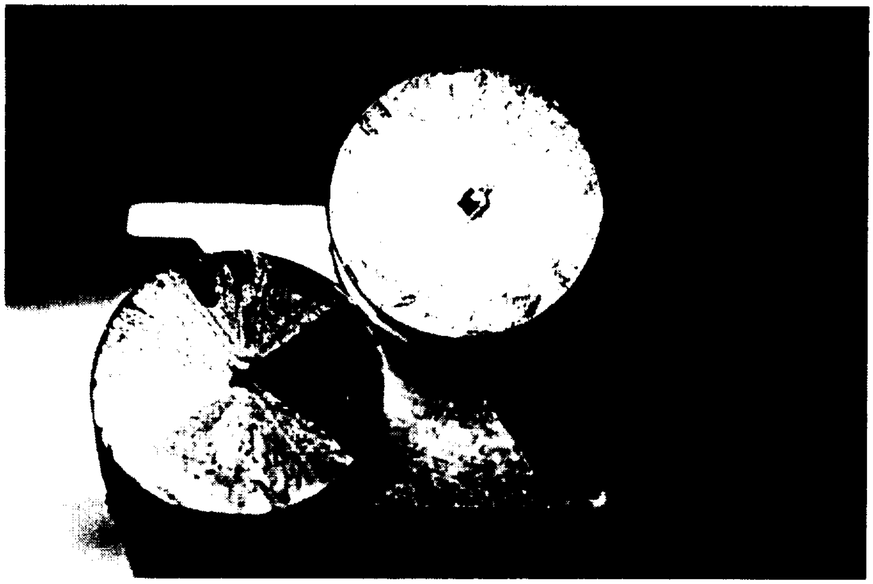

Figure 7. Photo of two melt-processed YBCO levitators.

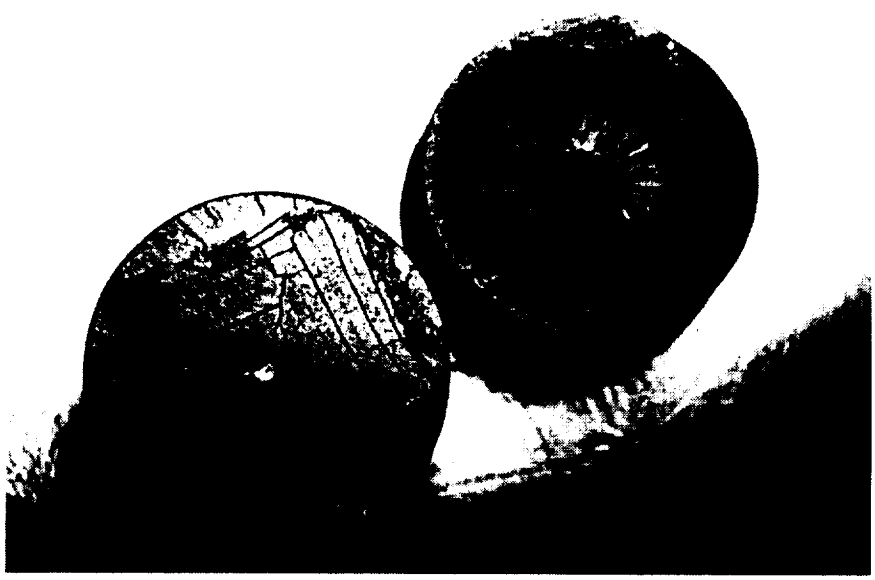

Figure 8. Photo of two polished, five domain levitators processed using cube seeds.

Figure 9. Photo of a single domain levitator processed using flat seeds.

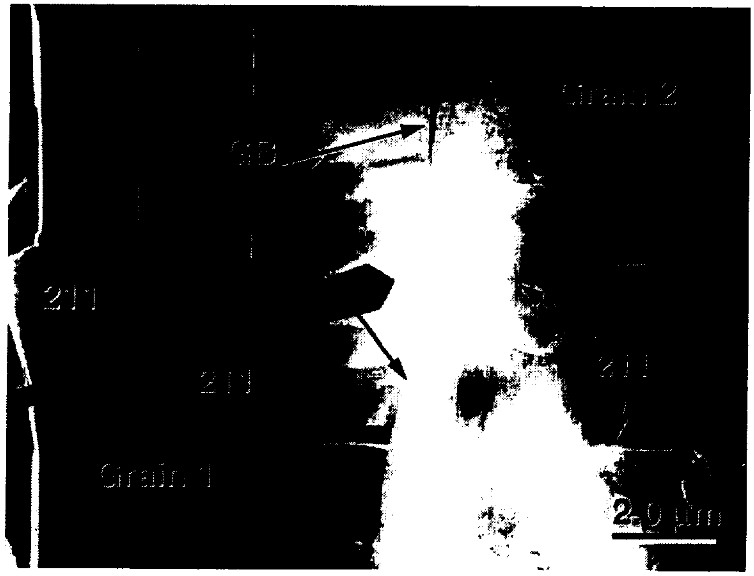

Figure 10. Transmission electron micrograph of two domains with both [001] axes lying in the plane of the paper.

Figure 11. Transmission electron micrograph of two domains with one [001]-axis normal to the plane of the paper and one [001]-axis contained within the plane of the paper.

The levitation forces of a single domain and five domain levitator are plotted in Figure 12. As can be seen from the figure, similar levitation forces were observed for both samples. This result suggests that the 90 degree grain boundaries in the five domain levitator may be acting as strongly linked boundaries. Recent transport measurements across the these boundaries further confirms our results.[26]

In order to further investigate the properties of these two types of levitators (five domain and single domain) the levitation forces as a function of thermal cycling were studied. The levitators were cooled to liquid nitrogen temperature and then heated rapidly by using a copper block as a heat source. Figure 13 shows the zero distance levitation force of a five domain and a single domain levitator as a function of thermal cycling. As can be seen from the figure, only a small decrease (~10 %) in the levitation force of the five domain levitator was observed after 60 thermal cycles. Nearly no change was observed for the single domain sample. The result can be explained by considering the anisotropic nature of the thermal expansion in YBCO. This anistropy may lead to the development of microcracks during thermal cycling in a five domain levitator thereby reducing the levitation force.

Figure 14 shows the levitation force as a function of sample thickness for a five domain and a single domain levitator. In both cases the samples are sliced from the bottom. As evident from the figure, a small decrease in the levitation force is observed for both levitators with decreasing thickness. The force however drops rapidly once the thickness is reduced beyond 0.5 cm. The single domain levitators also show different behavior depending upon the position of the cut. The forces decrease much more rapidly when the levitator is cut from the top in comparison to that of the levitator cut from the bottom. This result shows the deleterious effect of the reaction from the crucible.

CONCLUSIONS

Large domain $YBa_2Cu_3O_x$ levitators have been fabricated using a seeded melt processing technique. Two types of seed crystals were prepared by a self flux method. The levitator was found to replicate the type of seed used to initiate grain growth. Based on the seed type, the levitators were either single domained or five domained. The levitation force for the single as well as five domain levitators were found to be similar. The grain boundaries separating two domains in the five domain levitator were found to be 90 degrees. Only a small change in the levitation force was observed as a function of thermal cycling in a five domain levitator. Nearly no change in the force was observed for the single domain levitator. The result can be explained by the anisotropic nature of the thermal expansion in YBCO. Finally, both single domain and five domain YBCO showed similar behavior as a function of thickness.

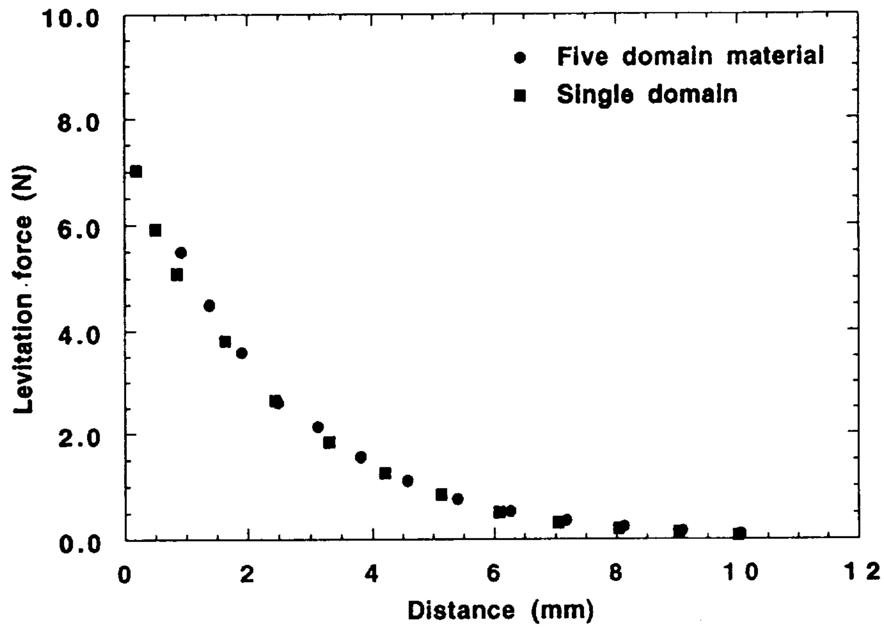

Figure 12. Levitaion force as a function of distance is plottted for a single and five domain levitator.

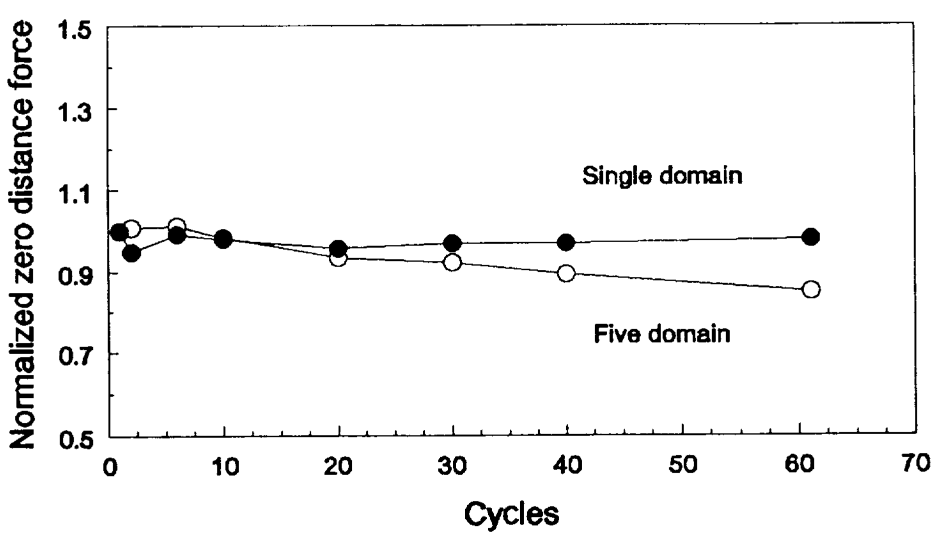

Figure 13. Zero distance levitation force as a function of thermal cycling is plotted for a single and five domain levitator.

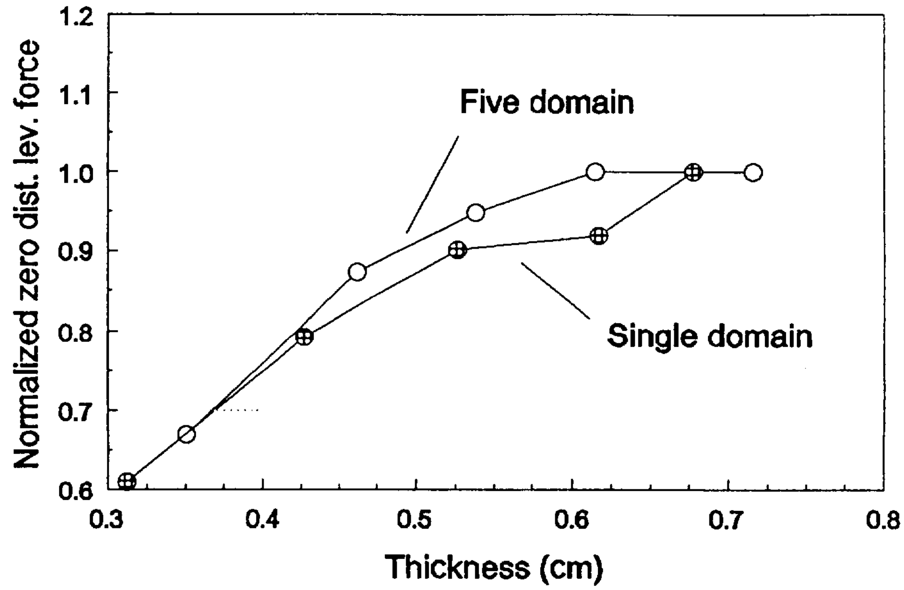

Figure 14. Levitation force as a function of thickness is plotted for a single and five domain levitator

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