Nano-platinum additives ball milled with hollow carbon spheres for mechanical tensile promotion of 2212- $\text{Pb}_{1+x}(\text{HCNs}/\text{Pt})_x\text{BiSr}_2\text{CaCu}_2\text{O}_8$ superconductor

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Abstract

In the present investigations platinum nano-particles in range of ≤ 20 nm were carefully ball milled with nominal composition of hollow carbon nano-spheres to apply as a softener ductile mechanical tensile promoter for 2212-PBSCCO superconductor. The samples with general formula $\text{Pb}_{1+x}(\text{HCNs}/\text{Pt})_x\text{BiSr}_2\text{CaCu}_2\text{O}_8$ where ($x=0.1, 0.2$ and 0.4 mol) were carefully synthesized via solid state reaction route with a certain thermal treatment cycle involving, annealing step at 865°C for 20 h. The mechanical tensile strength measurements for the sample with $x=0.4$ mol from CNs/Pt achieved maximum mechanical tensile strength value of 45.77 MPa., with promotion ratio $\sim 21.08\%$ in contrast with pure-sample $x=0$ with mechanical tensile of 37.8 MPa. Furthermore, the additions of (HCNs/Pt) does not damage the whole superconductivity on the investigated range ($0 \leq x \leq 0.4$ mol). Results indicated that, the additions of (HCNs/Pt) had a remarkable, suppressing the T_c -values to $T_c\text{-offset} = 62.2$ K for the sample with maximum additive ratio $x=0.4$ mol.

Keywords Hollow Carbon · Mechanical Tensile · XRD · 2212-PBSCCO

1 Introduction

The HTc-pseudo-tetragonal 80–85 K -PBSCCO superconductor of $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_x$, $\text{PbSr Sr}_2\text{CaCu}_2\text{O}_x$ or 2:2:1:2 consists of one Ca atom symmetrically located between the layer sequences Cu–O, Sr–O and Bi–O each layer is parallel to the ab plane [1, 2].

It is well known that, superconducting materials are experimental conditions dependent, as reported by Han-nachi et al. [3] who investigated the effect of the ball-milling process on the flux-pinning mechanisms of bulk YBCO, embedded with nanoparticles of Y-deficient Y-123, and generated by a planetary ball milling. They deduced that, the values of J_c 's and flux pinning mechanisms are affected

sharply by the experimental treatments whether the investigated samples were milled or un-milled. Furthermore, the ball milling processes generate nano-entities which can be induced within synthesized compounds [4]. The Most of previously published investigations reported on the 2223-phase are on Pb-doped compositions [5, 6].

There are a few numbers of researchers reported on the preparation of 2223–from Pb free compositions [7]. BiPb-cuprates as HTc-superconductor exhibited great potential in various electronic and industrial applications. However, weak pinning of flux lines and weak inter-grain links are considered one of most common disadvantages of different phases of BiPb-cuprates [4–6]. In order to promote the flux pinning, numerous routes have been used as adding

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impurities to act as pinning centers [8–12]. Additions of particles such as individual metals or as oxides like TiO_2 , ZrO_2 , Ag_2CO_3 , MgO , Al , Cr , Cd , La , Li and Sm in PbBi -based superconductors have investigated [5–9, 13–18]. Furthermore, doping via strontium and Tb-Nd -co-doping effects were investigated by one of the author themselves [19, 20].

The major disadvantages of all known phases of PbBi -base HTc-superconductors; namely 2212-PBSCCO, 2223-PBSCCO even in 2201-Phase is poor mechanical properties. This reason pushed numerous numbers of researchers to improve and develop mechanical features by using metallic additives as Pb and Ag , especially mechanical tensile strength [21–23].

Joo et al. [21] investigated the effect of silver additions on the mechanical and superconducting properties of sintered bulk $\text{YBa}_2\text{Cu}_3\text{O}_8$ (YBCO), $\text{Bi}_2\text{Sr}_{1.7}\text{CaCu}_2\text{O}_8$ (BSCCO-2212) and they reported that addition of 30 vol.% Ag to 2212 and 2223 increased strength from 58 to 107 and 41 to 90 MPa, respectively. Akio et al. [22] have been studied the effect of Pb addition on superconductivity of $(\text{BiPbx})_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_y$, $(\text{Bi}_{1-x}\text{Pbx})_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_y$ and $(\text{Bi}_{1-x}\text{Pbx})_2\text{Sr}_2\text{Ca}_2\text{Cu}_{3.6}\text{O}_y$. They indicated that melting point decreases monotonically from ~ 880 to ~ 860 °C as x increases from 0 to 0.45 and the fraction of HTc-phase decreased. On the other hand Sekkina and Elsabay [23] investigated promotion of mechanical tensile of highly Pb -content HTc-BPSCCO superconductors regardless its negative effects on superconductive phase by rich Ca_2PbO_4 impurity phase.

The present work is aiming to introduce platinum embedded on hollow carbon nano-spheres as a new soft-ductile material anticipating by its success, as mechanical tensile promoter regardless superconductive features are parallel enhanced or not.

2 Experimental

2.1 Materials processing

1 g of well characterized hollow carbon spheres (HCS) supplied from industrial metallurgy center-(EGYPT) with meso-pore diameter average $\sim (28 \text{ nm})$ and 1 gm of platinum metal nano-particles powders with average particle size of $\sim 20 \text{ nm}$ were ball Milled according to the route giving the nominal purity of each powder (Sigma-Aldrich) in 1:1 wt% ratio. The 2 gm mixture of (HCNs + Pt) was loaded in stainless steel grinding container.

The powder was ball milled in argon atmosphere by a (Retsch PM100 planetary mill for 12 h at 200 rpm). The ball milling process was stopped each 3hrs to collect inner powders to decrease the waste ratio as possible. Increasing

of temperature as result of milling process will be limited and has no effective impact on the HCNs specially, the mailing process was switched off each 10 min to observe and collect any residual powders.

The pure 2212-PBSCCO and different hollow carbon nano-spheres-platinum (HCNs/Pt) added samples with general formula $\text{Pb}_{1+x}(\text{HCNs/Pt})_x\text{BiSr}_2\text{Ca}_1\text{Cu}_2\text{O}_8$ where ($x = 0.1, 0.2$ and 0.4 mol) were carefully synthesized via solid state reaction route. The nominal molar ratios of pure PbCO_3 , Bi_2O_3 , CaCO_3 and CuO all are (Sigma Aldrich of 99% purity) were carefully weighted and mixed in mechanical agate for 2 h. Then (HCNs/Pt) additives were added and mixed by ball milling for 1 h.

The products were initially dried in oven at 210 °C for two hours and then transferred to the muffle furnace. The thermal treatment process was performed at 830 °C under nitrogen atmosphere for 12 h then reground and pressed into pellets (thickness 0.2 cm and diameter 1.2 cm) under 5 Ton/cm². Sintering process carried out under nitrogen stream at 865 °C for 20 h in closed Ni- auto-cleave. The samples were slowly cooled down (20 °C/hr) till 550 °C and annealed there for 1 h under nitrogen stream.

2.2 Materials characterization

The X-ray diffraction (XRD) measurements were carried out at room temperature on the fine ground samples using Cu-K_α radiation source, Ni-filter and a computerized STOE diffractometer /Germany with two theta step scan technique. Scanning Electron Microscopy (SEM) measurements were carried out at different sectors in the prepared samples by using a computerized SEM camera with elemental analyzer unit (PHILIPS-XL 30 ESEM /USA).

High-resolution Atomic Force microscopy (AFM) is used for testing morphological features of HCNs/Pt applying two different mode 1st is STM atomic resolution mode and 2nd is non-contact tapping mode, (Veeco-di Innova Model-2009-AFM-USA). AFM is also applied for high-Tech detection of grain/particle size by using computerized-analyzer unit (USA).

The cryogenic AC-susceptibility of the prepared materials was undertaken as a function of temperature recorded in the cryogenic temperature zone down to 30 K using liquid helium refrigerator equipped with a superconducting quantum interference device (SQUID) magnetometer. The field was kept at $H = 4 \text{ Oe}$ throughout the measurement. The measured magnetic moment (emu) was divided by the weight of the sample to yield mass magnetization, M (emu/g) which was plotted as a function of temperature.

The mechanical tensile measurements were carried out on the samples which cut from the bulk by certain dimensions $6 \times 4 \times 4 \text{ mm}^3$, to make as possible the longitudinal loading direction of the specimens parallel to the

a- or *b*-direction and perpendicular to the *c*-direction of the bulk. Tensile tests were carried out at room temperature 295 K and details of loading was described by Tomita and Murakami [24], the displacement speed of the actuator of testing machine was adjusted in between 0.10 and 0.18 mm/min. and observation of fracture morphology of the samples was carried out using digital camera.

3 Results and discussion

3.1 Structural properties

Figure 1 exhibits X-ray powder diffraction patterns of the pure 2212-PBSCCO ($\text{BiPbSr}_2\text{CaCu}_2\text{O}_8$) and different hollow carbon nano-spheres-Pt (HCNs/Pt) added samples with general formula $\text{Pb}_{1+x}(\text{HCNs/Pt})_x\text{BiSr}_2\text{Ca}_1\text{Cu}_2\text{O}_8$ where ($x=0.1, 0.2$ and 0.4 mol) respectively.

Analysis of the corresponding 2θ values and the *d* spacing distances (Å) were carried out by means of STOE computerized program, and indicated that, all samples including the parent one are mainly belong to a single the tetragonal phase 2212-BPSCCO as major crystalline phase besides with minority contributions from common secondary phases impurities as 2201 and calcium plumbates ($\text{Ca/Sr}_2\text{PO}_4$) in minor as clearly appears in the patterns of samples with $x=0.1$, 0.2 and 0.4 mol (Fig. 1). Volume fractions of different

superconducting phases were estimated by means of a rietveld refinements accompanied with supportive (Fullprof-software package). PXRD-profiles patterns measured for pure and different HCNs/Pt added samples were used to evaluate the volume fractions of each present phase. The major phase which gave highest figure of merits was 2212-phase by ratio of $\sim 82\%$ volume fraction, then minor phases were 2201 by ratio of $\sim 13\%$ and finally calcium plumbates phase $\sim 5\%$.

The unit cell dimensions were calculated by using the most intense X-ray reflection peaks and found to be $a=b=3.8132\text{Å}$ and $c=30.7131\text{Å}$ for the pure 2212-BPSCCO phase which is in full agreement with those mentioned in [19, 20, 23].

These results indicated that the investigated range of additives from 0.1 to 0.4 ($0 \leq x \leq 0.4$ mol) are suitable to be located out of main crystalline structure without destructive act.

Microstructural features of pure $\text{BiPbSr}_2\text{CaCu}_2\text{O}_8$ and different hollow carbon nano-spheres-Pt (HCNs/Pt see Fig. 2e) added samples with general formula $\text{Pb}_{1+x}(\text{HCNs/Pt})_x\text{BiSr}_2\text{Ca}_1\text{Cu}_2\text{O}_8$ where ($x=0.1, 0.2$ and 0.4 mol) respectively were carefully investigated by both of AFM and SEM instrumentations Fig. 2a-f.

The analysis of surface of pure-2212-BPSCCO indicated that the sample has regular homogeneous arrayed surface represented by green color topology, with maximum height of $0.23\text{ }\mu\text{m}$ as shown in Fig. 2f upper graph.

Fig. 1 X-ray diffraction pattern recorded for pure-2212-PBSCCO and different hollow carbon nano-spheres-platinum (HCNs/Pt) added samples

Fig. 2 **a** SEM-micrograph captured for pure 2212-PBSCCO $x=0.0$ mol. **b** SEM-micrograph captured for 2212-PBSCCO with HCNs/Pt $x=0.1$ mol, **c** $x=0.2$ mole and **d** $x=0.4$ mol. **e** SEM-micro-

graph captured for HCNs/Pt additives. **f** 3D-AFM-image for pure and for sample with 2212-PBSCCO $x=0.4$ mol

Table 1 EDX-elemental analysis for pure 2212-PBSCCO-superconductor

Actual Formula	Bi _{0.987} Pb _{0.98} Sr _{1.96} Ca _{0.98} Cu _{0.99} O _{8±δ}					
Element	BiL	PbL	SrK	CaK	CuK	OK
Atomic%	23.28	23.11	19.41	4.43	14.28	15.26

Table 2 EDX-elemental analysis for sample 2212-PBSCCO with additive ratio 0.1 mol

Actual Formula	Bi _{0.988} Pb _{0.994} Sr _{1.98} Ca _{0.98} Cu _{0.99} O _{8±δ}						Pt _{0.96}
Element	BiL	PbL	SrK	CaK	CuK	OK	PtL
Atomic%	23.31	23.23	19.51	4.47	14.19	15.21	2.03

Table 3 EDX-elemental analysis for sample 2212-PBSCCO with additive ratio 0.2 mol

Actual Formula	Bi _{0.991} Pb _{0.994} Sr _{1.98} Ca _{0.98} Cu _{0.99} O _{8±δ}						Pt _{0.192}
Element	BiL	PbL	SrK	CaK	CuK	OK	PtL
Atomic%	23.39	23.24	19.56	4.39	14.27	15.06	4.22

Table 4 EDX-elemental analysis for sample 2212-PBSCCO with additive ratio 0.4 mol

Actual Formula	Bi _{0.994} Pb _{0.995} Sr _{1.97} Ca _{0.98} Cu _{0.98} O _{8±δ}						Pt _{0.389}
Element	BiL	PbL	SrK	CaK	CuK	OK	PtL
Atomic%	23.44	23.27	19.35	4.48	14.23	15.11	8.56

The grain size was estimated from SEM and AFM-grain size analyzer and found to be 1.52 μm.

The micrographs Fig. 2b-d are for smoothed pellets of pure and different (HCNs/Pt) added samples. The EDX analyses as shown in Tables 1, 2, 3 and 4 were examined at different spots on the samples surfaces of pure-2212-PBSCCO and different added samples see Tables 1, 2, 3 and 4. EDX-elemental analysis for pure 2212-PBSCCO gave actual

molar ratios of (Pb_{0.98}Bi_{0.987}Sr_{1.96}Ca_{0.98}Cu_{0.99}O_x) as shown in Table 1 which is fully fitted with calculated value and shows structure quality synthesis. The analyses of EDX-Tables 2, 3 and 4 indicated, by presence of (Pt) with high degree of fitting. These results are confirming that, HCNs/Pt additions were homogeneously distributed. The ratio of HCNs is so difficult to observe at the surface layers and cannot detected accurately via EDX-analysis. These results

are consistent with those reported in [19, 20 and 23] especially, in the point of view grain sizes calculations.

3.2 Superconducting features measurements

Figure 3a shows magnetization temperature curve recorded for pure PBSCCO sample with $T_{c\text{-onset}} \sim 73.2$ and $T_{c\text{-offset}} = 67.11$ K respectively which is fully consistent with literatures as [16, 18, 19 and 23] with typical profile of Meissner's effect ~ 0.0018 emu/g as shown in Fig. 3a.

$T_{c\text{-onset}}$ and $T_{c\text{-offset}}$ were evaluated accurately by curve differentiation method in the inflection points zones as shown in Fig. 3b. It can be seen that the $T_{c\text{-offset}}$ is 67.11 K which is lower than the value expected of 70 K for lead-free 2212-BSCCO. This is due to changes on the ratios of chemical compositions of the main phase 2212-PBSCCO that, reveals to lead-ions can be substituted on the bismuth sites of the tetragonal superconductive phase 2212-PBSCCO. These changes are always accompanied by forming 2201-PBSCCO and calcium plumbates Ca_2PbO_4 as secondary phase [18, 19].

Figure 4 displays magnetization/temperature curves recorded for pure $\text{BiPbSr}_2\text{CaCu}_2\text{O}_8$ and different hollow carbon nano-spheres-Pt (HCNs/Pt) added samples with general formula $\text{Pb}_{1+x}(\text{HCNs/Pt})_x\text{BiSr}_2\text{Ca}_1\text{Cu}_2\text{O}_8$ where ($x = 0.1, 0.2$ and 0.4 mol) respectively.

The recorded $T_{c\text{-offset}}$ s were found 67.11, 64.3, 63.6 and 62.2 K corresponding to samples with $x = 0.0, 0.1, 0.2, 0.4$ mol of HCNS/Pt additions respectively.

Figure 5, it can be seen that the additions of hollow carbon nano-spheres-Pt (HCNs/Pt) have remarkable suppressing effects on the $T_{c\text{-}}$ values recording $T_{c\text{-offset}} = 62.2$ K

Fig. 3 Magnetization curve recorded for pure PBSCCO sample

Fig. 4 Magnetization/Temperature curves recorded for pure 2212-PBSCCO and variant HCNS/Pt added samples.

Fig. 5 $T_{c\text{-offset}}$ versus amount of HCNS/Pt additives

is for samples with maximum additive ratio $x = 0.4$ mol instead of $T_{c\text{-offset}} = 67.11$ K for pure 2212-BPSCCO.

This depression in the values of $T_{c\text{-offset}}$ s is attributable to that hollow carbon nano-spheres-Pt additives scattered super-current flow and their random incorporating in the solid solution during sample synthesis interrupted the super-current flow of 2212- superconductive phase and hence $T_{c\text{-offset}}$ s decreased [4, 13]. This behavior of depression on the values of $T_{c\text{-}}$ values offsets are in full agreement with Akio et al. [22] who have investigated the effect of lead additions on the superconductivity and mechanical features of 2223-BPSCCO superconductor. They reported that the volume fraction of the high- T_c phase decreases as x amount of added lead increase due to added lead ions act a catalytic effect to form the Ca_2PbO_4 secondary phase.

3.3 Mechanical performance

Mechanical features were investigated by stress/strain testing machine in which applied stress is longitudinally loading direction of the specimens parallel to *a*- or *b*-direction and perpendicular to the *c*-direction of the bulk material. The strain values were correlated with applied stress until fracture points as clear in Figs. 6, 7 the mechanical tensile strength values were measured as function of hollow carbon nano-spheres-Pt (HCNs/Pt) additives and found to be 37.8, 40.3, 42.33 and 45.77 MPa. are for $x = 0.0, 0.1, 0.2$ and 0.4 mol respectively.

The maximum applied stress as clear in Fig. 6 was 45.77 at $x = 0.4$ mol while it was 42.33 MPa. at $x = 0.2$ mole this means mechanical tensile strength was improved by ratio $\sim 21.08\%$ with respect to pure-sample $x = 0$ with mechanical tensile of 37.8 MPa.

Figure 7 indicated that there is good correlation between HCNs/Pt additives ratios and mechanical tensile strength of PBSCCO-2212-sample, meanwhile this correlation is not achieved parallel in the superconductivity features as mentioned before due to at $x = 0.4$ mol from HCNs/Pt impurity phases are maximum and as results reduction on T_c -offsets was present (i.e. mechanical tensile features promoted at expense of superconducting properties).

The present results confirmed that HCNs/Pt additives promote mechanical tensile strength by dual factors, 1st is increasing ductility of 2212-PBSCCO texture via incorporating of hollow carbon and platinum-ions since both of them acts as softer materials resist fracture deformation resulted from applied stress on the sample during mechanical tensile strength measurements

Fig. 6 Stress–Strain curves versus PBSCCO with different additives ratios of HCNs/Pt

Fig. 7 Maximum applied stress at fracture points versus variant HCNs/Pt additives ratios

and 2nd factor is metallic softening effects of platinum ions on the surface's and that diffused in hollow carbon nano-spheres molecule as shown in Fig. 8 enhance and reinforce micro-structural weakness centers defects resulted from meso-porous nature texture of HCNs and 2212-PBSCCO-superconductor.

It is well known that as many researchers reported, on the impact of metallic additions as softer materials for instance silver, Aluminum, magnesium or lead [4, 8, 10 and 23] can promote mechanical features specially in the point of view their fracture resistance against applied stresses [10, 23], but others like Salazar et al. [25] had the same trend as present studies. They investigated the mechanical properties of 2223 and BSCCO 2223/Ag composites processed by hot-pressing and they indicated that, the flexure strength of the composites showed the balance

HCNS-with Pt-on Surfaces and Embedded Platinum

Fig. 8 Molecule of Hollow Carbon Sphere Loaded/Embedded with Platinum Ions

between the benefits due to the presence of metallic-Ag ions, and the harmful impact of higher porosity and reduced texture.

4 Conclusions

The present work was successfully introduced HCNs/Pt as new mechanical tensile strength promoter by its acting as a soft-ductile matrix that resist deformation at fracture points and mend micro-structural weakness defect centers resulted from porous 2212-BPSCCO ceramic material. Sample with $x = 0.4$ mol of HCNs/Pt achieved maximum mechanical tensile strength value of 45.77 MPa., with promotion ratio $\sim 21.08\%$ in contrast with pure-sample $x = 0$ with mechanical tensile of 37,8 Mpa. Furthermore, additions of hollow carbon nano-spheres-Pt (HCNs/Pt) does not damage superconductivity on the investigated range, since T_c - values remarkably decreased and recorded T_c -offset = 62.2 K was for samples with maximum additive ratio $x = 0.4$ mol instead of T_c -offset = 67.11 K for pure 2212-BPSCCO.

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Declarations

Conflict of interest The authors declare that, there are no any kind of conflict of interests regarding this manuscript.

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References

- Larbalestier D (1996) Superconductor flux pinning and grain boundary control. *Science* 274(5288):736–737
- Weinstein R, Sawh P, Gandini A, Mayes B, Parks D (2007) Is it really possible to increase J_c by reducing the pinning potential. *Supercond Sci Technol* 20(9):S167–S173
- Hannachi E, Hamrita A, Slimani Y, Ben Salem M K, Zouaoui M, Ben Salem M, F. Ben Azzouz F, (2015) Effect of the Ball-Milling Technique on the Transport Current Density of Polycrystalline Superconductor YBa₂Cu₃O_y-Pinning Mechanism. *J Supercond Nov Magn* 28:493–498
- Slimani Y, Hannachi E, BenAzzouz F, BenSalem M (2018) Impact of planetary ball milling parameters on the microstructure and pinning properties of polycrystalline superconductor Y₃Ba₅Cu₈O_y. *Cryogenics* 92:5–12
- Hamid NA, Abd-Shukor R (2000) Effects of TiO₂ addition on the superconducting properties of system. *J Mater Sci* 35(9):2325–2329
- Abbasi H, Taghipour J, Sedghi H (2010) Superconducting and transport properties of (Bi–Pb)–Sr–Ca–Cu–O with Cr₂O₃ additions. *J Alloys Compd* 494(1–2):305–308
- Annabi M, Chirgui AM, Ben Azzouz F, Zouaoui M, Ben Salem M (2004) Addition of nanometer Al₂O₃ during the final processing of superconductors. *Physica C* 405(1):25–33
- Abbasi H, Taghipour J, Sedghi H (2009) The effect of MgCO₃ additions on the Superconducting properties of Bi₂223 superconductors. *J Alloys Compd* 482(1):552–555
- Jia ZY, Tang H, Yang ZQ, Xing YT, Wang YZ, Qiao GW (2000) Effects of nano-ZrO₂ particles on the superconductivity of Pb-doped BSCCO. *Physica C (Amsterdam, Neth)* 337(1):130–132
- Gul IH, Amin F, Abbasi AZ, Anis Rehman M, Maqsood A (2006) Effect of Ag₂CO₃ addition on the morphology and physical properties of Bi-based (2223) high- T_c superconductors. *Physica C (Amsterdam, Neth)* 449(2):139–147
- Ghahfarokhi SE, Shoushtari MZ (2010) Structural and physical properties of Cd-doped Bi_{1.6}Pb_{0.4}Sr₂Ca₂Cu₃O_y superconductor. *Phys B* 405(22):4643–4649
- Sekkina MM, Jansen M, Eldally HA, Elsabawy KM (2007) Effect of the Zr₄+Oxide additives on raman spectra and superconducting properties of 2212-BPSCCO. *Mater Sci J* 3(1):1–7
- Albiss BA, Obaidat I, Gharaibeh MM, Ghamlouche H, S. M. Obeidat S M, (2010) Impact of addition of magnetic nanoparticles on vortex pinning and microstructure properties of BiSrCaCuO superconductor. *Solid State Commun* 150(33–34):1542–1547
- Ozeri HS, Ghazanfari N, Ozkan H, Kilic A (2007) Enhancement in the high- T_c phase of BSCCO superconductors by Nb addition. *Supercond Sci Technol* 20(6):522–528
- Mihalache V, Aldica G, Popa S, Lifei F, Miu D (2004) Effect of Li₂CO₂ addition on the Bi_{1.7}Pb_{0.4}Sr_{1.5}Ca_{2.5}Cu_{3.6}O_x superconducting system. *Mater Lett* 58(24):3040–3044
- Biju A, Vinod K, Aloysius RP, Syamaprasad U (2007) Improved superconducting properties by La addition in (Bi, Pb)-2212 bulk superconductor. *J Alloys Compd* 431(1–2):49–55
- Aloysius RP, Guruswamy P, Syamaprasad U (2005) Enhanced critical current density in (Bi, Pb)-2223 superconductor by Nd addition in low percentages. *Physica C* 426–431:556–562
- Prabitha VG, Biju A, Kumar RG, Sarun P, Aloysius RP, Syamaprasad U (2005) Effect of Sm addition on (Bi, Pb)-2212 superconductor. *Physica C* 433(1–2):28–36
- Sekkina MM, Eldaly H, Elsabawy KM (2002) Sr-doping for promoted high- T_c BPSCCO superconductors. *Physica C* 377:254–259
- Sekkina MM, Eldaly H, Elsabawy KM (2004) Terbium-neodymium co-doping in Bi sites on the BPSCCO bismuth cuprate superconductors. *Supercond. Sci Technol* 17:93–97
- Joo J, Singh J, Warzynski T, Grow A, Poeppel RB (1994) Role of silver addition on mechanical and superconducting properties of high- T_c superconductors. *Appl Supercond* 2(6):401–410
- Akio O, Akihiro K, Yoshinobu S, Kentaro O (1988) The effect of Pb addition on superconductivity in Bi-Sr-Ca-Cu-O. *Jap J Applied Physics* 27(12):44–53
- Sekkina MM, Elsabawy KM (2003) Mechanical tensile promotion and superconducting properties of highly Pb-content HTc-BPSCCO superconductors. *Mater Sci Eng B* 103:71–76

24. Tomita M, Murakami M (2000) Improvement of the mechanical properties of bulk superconductors with resin impregnation. *Supercond Sci Technol* 13(6):722–724
25. Salazar J, Pastor Y, Lorca J (2003) Strength and fracture toughness of hot-pressed bulk $\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_x$ and $\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_x/\text{Ag}$ at 77 and 300 K. *Phys C* 385(3):404–414

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