The effect of Pr-doping on the transition temperature (Tc) and structural properties of YBa2Cu3O7-δ (YBCO) superconductor have been investigated. The sol-gel method has been employed for the synthesis of Y1-xPrxBa2Cu3O7-δ (YPBCO) samples with the compositions (x=0.0, 0.05, 0.10, 0.20 and 0.30). The broadening in X-ray diffraction (XRD) peaks has been used to calculate the micro-strain by the Williamson-Hall (W-H) plot. The broadening in XRD peaks and micro-strain are found to increase with increase in Pr concentration x which could be representatives for some disorder in Cu-O planes. The resistance-temperature measurements of as prepared YPBCO samples show the monotonic suppression of Tc with increase in Pr concentration from x=0 to x=0.30. The experimental Tc values were in good agreement with theoretical Tc values calculated by the inclusion of disorder effects along with magnetic pair breaking and hole filling effects. It has been suggested that disorder in Cu-O planes might be strain-induced. The disorder effects along with magnetic pair breaking and hole filling effects are responsible for the suppression of Tc in YPBCO system.

The equation (3) also suggested the degradation of Tc due to magnetic pair-breaking mechanism and hole filling effects. The Gill et al.\(^{11}\) reported the variation of Tc (in Kelvin) with x in Y1-xPrxBa2Cu3O7-δ system by the relation

\[
T_c(x) = 97 - 425(0.1 - 0.95x)^2 - 96.5x \quad \ldots \ldots \ldots \ldots (3)
\]

The equation (3) also suggested the degradation of Tc due to magnetic pair-breaking mechanism and hole filling effects. The Gill et al.\(^{11}\) reported the variation of Tc (in Kelvin) with x in Y1-xPrxBa2Cu3O7-δ system by the relation

\[
T_c(x) = 97 - 425(0.1 - 0.95x)^2 - 96.5x - 15.4x^2 \quad \ldots \ldots \ldots \ldots (4)
\]

Where initial quadratic and linear terms have same dependence as given by equation (3) but third square root term is responsible for the disorder in Cu-O planes after doping with Pr.  

In the present work, we synthesized the series samples of Y1-xPrxBa2Cu3O7-δ superconductor with various values of x. The samples were characterized by various techniques and the results are presented in this paper.

**Experimental**

The samples of Y1-xPrxBa2Cu3O7-δ (x=0, x=0.05, x=0.10, x=0.20 and x=0.30) were prepared by using sol-gel method. The appropriate amounts of Y(NO₃)₃, Ba(NO₃)₂, Cu(NO₃)₂ and Pr(NO₃)₃ were mixed in the solution of water and ethyl alcohol. The mixture was stirred at 50-70°C until it became gel. It was dried in oven, then ground and put in the furnace at 500 °C to eliminate moisture and nitrates for 5 h. The material was then reground and calcined in air at 900 °C for about 20 h. It was cooled and pressed in to pellets. Subsequently, the pellets were sintered at 930 °C for 20 hours in the presence of oxygen. The transition temperature Tc of as prepared samples was determined from resistance-temperature measurements by means of standard four probe method. The structure of the samples was characterized using XRD technique. The size and surface morphology of grains were determined from SEM measurements.

**Results and Discussions**

Fig. 1 shows the variation of relative resistance with temperature in Y1-xPrxBa2Cu3O7-δ (x=0, x=0.05, x=0.10, x=0.20 and x=0.30) samples. The transition temperature Tc for various
concentrations of Pr is calculated using fig.1, eq. (2), 3 and 4 are shown in table-1 and found in good agreement with reported values. The variation of experimental $T_c$ with Pr concentration $x$ is shown the fig. 2. The monotonic suppression of $T_c$ with increase in Pr concentration was observed. Further, the various values of transition temperature calculated from equations (2), (3) & (4) along with experimental transition temperature is plotted against Pr concentration $x$ in fig. 3. The transition temperatures calculated from eq. (4) are found in good agreement with experimental $T_c$ values. From fig. 3, this is evident that there is some disorder present in the system.

**Table 1** Comparison between experimental $T_c$ and theoretical $T_c$ calculated from Eq. (2), (3) & (4);

| Pr Conc. (x) | Experimental $T_{c_{onset}}$(K) | Theoretical $T_{c_{onset}}$(K) | Eq. (2) | Eq. (3) | Eq. (4) |
|-------------|---------------------------------|-----------------------------|---------|---------|---------|
| 0.00        | 92                              | 87                          | 97      | 92.75   | 92.75   |
| 0.05        | 86                              | 82                          | 92.18   | 88.12   | 84.68   |
| 0.10        | 79                              | 74                          | 87.35   | 83.87   | 79.00   |
| 0.20        | 71                              | 67                          | 77.70   | 76.07   | 69.18   |
| 0.30        | 62                              | 57                          | 68.05   | 67.96   | 59.52   |

**Fig. 2.** Variation of experimental $T_c$ values in $Y_{1-x}\Pr_xBa_2Cu_3O_7-\delta$ samples for various values of $x$.

**Fig. 3.** Plot of $T_c$ values from experiment and equations (2), (3) & (4) in $Y_{1-x}\Pr_xBa_2Cu_3O_7-\delta$ samples for various values of $x$.

**Fig. 4.** XRD patterns of $Y_{1-x}\Pr_xBa_2Cu_3O_7-\delta$ samples for various values of $x$.

**TABLE 2** Lattice parameters for various values of $x$ in $Y_{1-x}\Pr_xBa_2Cu_3O_7-\delta$ samples;

| Pr Conc. (x) | a(Å) | b(Å) | c(Å) | Unit cell volume (Å$^3$) |
|-------------|------|------|------|-------------------------|
| 0.00        | 3.822| 3.885| 11.645| 172.91                  |
| 0.05        | 3.827| 3.876| 11.654| 172.87                  |
| 0.10        | 3.826| 3.885| 11.679| 173.60                  |
| 0.20        | 3.830| 3.898| 11.686| 174.46                  |
| 0.30        | 3.830| 3.893| 11.705| 174.52                  |
Fig. 5. The variation unit cell volume in $Y_{1-x}Pr_xBa_2Cu_3O_7-\delta$ samples for various values of $x$. Inset: variation of lattice parameters $a$, $b$ and $c$ with $x$.

Fig. 6 shows the variation of the full-width half maximum (FWHM) of the (005) peak in YBPCO system and, confirms that the FWHM monotonically increases with Pr concentration $x$. From the results, it can be said that Pr-doping influences the structure of entire unit cell. The FWHM of XRD peaks can be expressed as linear sum of FWHM of size, strain and Instrumental.$^{17}$

$$\beta = \beta_{size} + \beta_{strain} + \beta_{instrumental}$$  \hspace{1cm} (5)

Here, in order to find the strain broadening each XRD peak fitted with Lorentzian profile. The micro-strain, $\varepsilon$ and the average grain size, $D$ can be calculated from Williamson-Hall (W-H) plot for the X-ray diffraction peak broadenings.$^{18}$

$$\beta \cos \theta = 4 \varepsilon \sin \theta + \lambda / D$$ \hspace{1cm} (6)

Where $\lambda$ is wavelength of incident X-rays. In fig. 7, plotted against and linearly fitted to find micro-strain $\varepsilon$. The micro-strain $\varepsilon$ increases with increase in Pr concentration $x$ as shown the fig. 8. Further, fig. 9 shows that transition temperature $T_c$ of YBPCO system decreases monotonically with increase in micro-strain $\varepsilon$. The variation of $T_c$ with micro-strain $\varepsilon$ has not been reported elsewhere and, suggested that micro-strain $\varepsilon$ is a good variable to define the suppression of $T_c$ along with magnetic pair-breaking and hole filling effects. A closer correlation can be found between micro-strain $\varepsilon$ and transition temperature $T_c$ compared with the correlation between the disorder present in Cu-O planes and transition temperature $T_c$.

Fig. 6. The variation of FWHM for (005) peak in $Y_{1-x}Pr_xBa_2Cu_3O_7-\delta$ samples for various values of $x$.

Fig. 7. Plot of $\beta$ versus $\theta$ of $Y_{1-x}Pr_xBa_2Cu_3O_7-\delta$ samples for various values of $x$.

Fig. 8. Plot of microstrain ($\varepsilon$) versus Pr concentration $x$.

Fig. 9. Plot of transition temperature $T_c$ versus microstrain $\varepsilon$ (%).

From these results, it can be said that the disorder in Cu-O planes might be strain-induced. Fig. 10 shows the SEM of $Y_{1-x}Pr_xBa_2Cu_3O_7-\delta$ samples with (a) $x=0$, (b) $x=0.05$, (c) $x=0.10$, (d) $x=0.20$ and (e) $x=0.30$. The average size of the grains calculated from SEM images ranges from 4 to 15 $\mu$m. The EDAX
analysis of grains in $Y_{x}Pr_{1-x}Ba_{2}Cu_{3}O_{7-\delta}$ samples for the range $0 \leq x \leq 0.30$ revealed that the various elements were present in the appropriate proportion.

Conclusions:
The effects of Pr-doping on the superconducting transition temperature $T_c$ and XRD patterns of YBCO samples have been investigated. The monotonic suppression of $T_c$ was observed with increase in Pr-doping. The broadening in XRD peaks was found to increase with increase in Pr-doping and, has been used to calculate the micro-strain $\varepsilon$. We have observed an increase of $\varepsilon$ and a decrease of $T_c$ with increase in Pr-doping. Our experimental $T_c$ values were in good agreement with theoretical $T_c$ values calculated from equation (4) which includes the disorder term along with the magnetic-pair breaking and hole filling terms. Probably, the theoretically predicted disorder in Cu-O planes was strain-induced. The more experimental studies will be required to correlate the micro-strain and disorder effects in YPBCO system. The present work emphasizes on the strain-induced disorder effect, along with the other effects, to explain the suppression of $T_c$ in Pr-doped YBCO superconductor.

Fig. 10. SEM of $Y_{1-x}Pr_xBa_{2}Cu_{3}O_{7-\delta}$ samples; (a) $x=0.0$, (b) $x=0.05$, (c) $x=0.10$, (d) $x=0.20$ and (e) $x=0.30$.  

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