7.1: Summary

As against the objectives of the thesis highlighted in Chapter 2, the overall work done can be consolidated under the following categories: (a) Effect of processing temperature and various nano dopants on the properties of bulk MgB$_2$, (b) Optimization of processing parameters and novel preparation techniques for MgB$_2$ wires and (c) Development of MgB$_2$ multifilamentary wires, coils and current leads for technological applications.

The superconducting properties of bulk in situ PIST MgB$_2$ processed at temperatures in the range 750-900 °C were studied. Since the samples heat treated at relatively lower temperatures particularly at 800 °C exhibited best $J_C(H)$ performance, this temperature was chosen for further chemical addition/doping using nano dopants in bulk MgB$_2$ to enhance $J_C$ at higher magnetic fields. Nano SiO$_2$ and typical nano rare earth oxides like Tb$_4$O$_7$ and Ho$_2$O$_3$ were initially tried as nano inclusions for studying their effect on $J_C$ and flux pinning. Later on carbon based dopants such as nano carbon, nano diamond, nano SiC and burned rice husk (BRH) were chosen to enhance $J_C(H)$ property through carbon substitution. Finally, the combined effect of both substitution and inclusions on the enhancement of $J_C$ using typical combinations of above mentioned nano dopants was also analyzed.

In order to convert bulk MgB$_2$ into conductors fit for practical applications, efforts were made to optimize parameters such as sheath material reactivity and processing temperature. The role of the reactivity of commonly used sheath materials such as Cu, Ni, Fe and SS with Mg/B on the phase formation and superconducting properties of MgB$_2$ was studied. The effect of processing temperature on phase formation, microstructure and transport critical current of MgB$_2$ monofilamentary wire samples
processed at temperatures 600-800 °C were studied. Further, an attempt was made to lower the processing temperature of MgB$_2$ wires by the incorporation of nano Cu was quite successful. A novel preparative method was also demonstrated to fabricate Fe sheathed \textit{in situ} MgB$_2$ superconducting tapes with high densities by hot-pressing of electrically self-heated PIT wires.

Subsequently multifilamentary wires with different configurations were developed and the effect of the outer sheath materials like Cu, Fe and Ni on the transport properties of MgB$_2$ multifilamentary wires was studied for a typical 4 filament configuration. The in-field transport $J_C$ of MgB$_2$ multifilamentary wires doped with nano dopants which gave the best results for bulk MgB$_2$ was also studied. Thereafter, MgB$_2$/Fe/Cu/Ni multifilamentary wires with 4, 8 and 16 filament configurations were successfully fabricated. The effect of bending strain on transport properties of these multifilamentary wires was also investigated. The promising results obtained from the studies on multifilamentary wires prompted to develop a prototype MgB$_2$ coil using the wind and react method and a general purpose current lead suitable for practical applications.

\subsection*{7.2: Conclusions}

- The optimization of processing temperature for bulk \textit{in situ} PIST MgB$_2$ showed that 800 °C is the optimum processing temperature since it gives the best $J_C(H)$ performance. The reduced grain size and hence increased grain boundary is the main reason behind the improved flux pinning and $J_C(H)$ for the samples sintered at lower temperatures.

- Addition of nano sized oxides in bulk MgB$_2$ exhibited enhanced $J_C(H)$ behavior for the doped samples as compared to pure MgB$_2$. Among the different additives tried, nano Ho$_2$O$_3$ doped MgB$_2$ gave the maximum flux pinning behavior in the entire field of study. In all samples, the addition induced reacted phases act as strong flux pinners thereby improve the $J_C(H)$ and $H_{irr}$ of the nano oxide added samples.
On comparing the effect of various carbon based dopants in MgB₂, all of them showed competitively enhanced in-field critical current density. In the case of n-SiC and BRH doped samples, both C substitution and the presence of Mg₂Si caused enhanced flux pinning and hence \( J_c(H) \) while for n-C doped one C substitution is solely the reason.

The codoping of n-Ho₂O₃ with n-SiC and BRH exhibits excellent flux pinning performance and \( J_c \) enhancement up to a field of 8 T as compared to pure and their corresponding monodoped samples. The C substitution at B site by carbon dopants and the formation of Mg₂Si and magnetic particles like HoB₄ by Ho₂O₃ as flux pinners are the reasons for the strong improvement of \( J_c(H) \) in these samples.

For conductor fabrication, the role of the reactivity of sheath material with Mg/B on the phase formation and superconducting properties of MgB₂ was studied. Fe and SS added samples gave higher volume fraction of MgB₂ core and hence better \( J_c(H) \) characteristics which infers that Fe and SS are more suitable sheath materials in MgB₂ wire fabrication.

The effect of processing temperature on phase formation, microstructure and transport critical current of MgB₂ monofilamentary wire samples processed at temperatures 600-800 °C was studied. The sample processed at 650 °C gave the best self-field transport \( J_c \) value of \( 1.19 \times 10^5 \) A/cm² at 7 K. The presence of reasonable amount of unreacted Mg and the reduced grain size are the reasons for enhancing the critical current of the sample processed at 650 °C.

An attempt to lower the processing temperature of MgB₂ wire showed that a substantial reduction in the processing temperature (~ 550 °C) can be achieved using nano Cu as an additive. The transport \( J_c \) of Cu added wire processed at 550 °C is quite comparable with that of Cu-free wire processed at 650 °C.

A simple and easy method for preparation of in situ MgB₂ superconducting tapes with highly densified core has been
demonstrated. A core density of 2.45 g/cm³ and nearly 4-fold increase in critical current are achieved for the best hot-pressed sample.

- Development of multifilamentary wires with different configurations was carried out and the effect of the outer sheath materials like Cu, Fe and Ni on the transport properties of MgB₂ multifilamentary wires was studied for a typical 4 filament configuration. The choice of Ni as outer sheath and Cu filament as stabilizer proved to be the best configuration yielding higher transport current.

- The influence of typical nano dopants on the in-field transport Jₐ of multifilamentary MgB₂/Fe/Cu/Ni wires was examined. Both substitution of C at the B site and flux pinning due to the reacted phases like Mg₂Si and HoB₄ contribute to the strong enhancement of Jₐ, significantly higher than the monodoped ones as observed in their respective bulk samples.

- MgB₂/Fe/Cu/Ni multifilamentary wires with 4, 8 and 16 filament configurations were successfully fabricated. The transport Jₐ of 4, 8 and 16 filamentary MgB₂ multiwires was almost comparable at self-field and 4.2 K which indicates that filamentation of multiwires into 4, 8 and 16 filament geometry has negligible impact on the transport properties of MgB₂ wires.

- The effect of bending strain on the transport properties of multifilamentary wires was also investigated. It was observed that almost constant transport Jₐ was obtained in 4, 8 and 16 filamentary MgB₂ multiwires heat treated after bending even up to a diameter of 5 cm.

- A prototype MgB₂ coil having an OD of 6.5 cm and length ~165 cm was developed using the wind and react approach. An overall homogenous Jₐ ~ 10⁵ A/cm² was achieved in the coil at 4.2 K.

- A general purpose conduction cooling type current lead based on MgB₂/Fe/Cu/Ni with a rating of 1000 A at 20-37 K has been successfully developed.
7.3: **Scope for future work**

The present thesis focused on the optimization of processing parameters and enhancement of in-field critical current density in bulk MgB$_2$ through doping. The results obtained in bulk MgB$_2$ were successfully used for the development of good quality mono/multifilamentary wires, coils and current leads with an application point of view. Though much effort has been taken to bring out the potential of MgB$_2$ for technological applications, there are still certain areas both in bulk and conductor development which need further attention.

The issues to be addressed regarding the bulk MgB$_2$ are:
- To enhance self-field $J_C$ of bulk MgB$_2$ by improving the core density using different preparation techniques.
- Fine tuning of the C and SiO$_2$ in rice husk by suitable heat treatment to optimize the ratio of C to SiO$_2$.
- To explore further on natural and economic alternatives like BRH for expensive C based nano dopants.

While considering conductor development focus must be given on:
- Finding more dopants like Cu for reducing the processing temperature of MgB$_2$.
- Studying the influence of self-heating and hot-pressing on the doped variants of MgB$_2$.
- Improving the fill factor of superconducting core in multifilamentary MgB$_2$ wires without affecting its stability.
- Making appropriate modifications in the MgB$_2$ superconducting coil demonstrated so as to make it suitable for superconducting magnet applications such as in MRI.
- Scaling up of the current rating of the MgB$_2$ based current lead without compromising its thermal stability.