CHAPTER V
CONCLUSION AND FUTURE RESEARCH

5.1 Conclusions

This thesis work showed that low-temperature liquid phase sintering (LPS) in vacuum requires no extensive post-sintering processing, and thus is a facile technique for mass production of LTP-MnBi with good magnetic properties. Powder of LTP-MnBi with coercivity of about 5 kOe at room temperature has been achieved by a single-step low-temperature LPS. The highest $(BH)_{max}$ of 5.5 MGOe was obtained for the MnBi powder sintered at 325 °C.

The complex nature of the liquid phase sintering processes for synthesizing LTP-MnBi was explained. The diffusion mechanism plays an important role in the formation of LTP-MnBi during low-temperature LPS in vacuum. At sintering temperatures higher than the melting point, Bi powder was melted into liquid before migrating over the surface of the Mn particles, and along the cracks within the Mn particles. LTP-MnBi layers were formed when Bi diffuses into the bulk Mn particles from their exterior surfaces and from interior surfaces of cracks within the particles.

The diffusion coefficient was deduced from the measured diffusion length obtained by using EDS line scans of the cross-sectional MnBi particles. At temperatures between 275 and 375 °C, the diffusion coefficient was found to follow the Arrhenius equation with the pre-exponential factor of 5.33×10^{-10} cm^2/s and activation energy of 0.45 eV. This equation provides the information to estimate the thickness of LTP-MnBi layers sintered at any temperature between 275 and 375 °C for a given sintering duration. Therefore, proper parameters of the starting materials and optimum conditions for the sintering process could be chosen to achieve the best performance sintered LTP-MnBi. The optimum sintering temperature shall not exceed 340 °C to obtain high performance LTP-MnBi with no HTP-MnBi.

At room temperature, sintered LTP-MnBi exhibits interesting changes that the magnetic performance improved with aging. The coercivity and energy product were found to increase with aging (or storing time). At room temperature, LTP-MnBi is rather stable. However, LTP-MnBi is easily decomposed at 150 °C in air atmosphere. The decomposition was caused mainly by oxidation, yielding Mn oxides and Bi. Therefore, the prevention to expose to air must be taken into account seriously to utilize this material at elevated temperatures. Capsulated or thin film coating maybe a solution to this problem.

5.2 Future works

Low-temperature sintering in vacuum is quite a promising method for mass production of LTP-MnBi magnetic materials. However, there is a stringent condition that high content LTP-MnBi shall be obtained from the sintered products. Since diffusion is the main process limiting the formation of LTP-MnBi, especially at low temperatures limited by the maximum sintering temperature avoiding the formation of HTP-MnBi. Thus, there are two possible approaches for enhancing the LTP-MnBi content i.e., increasing sintering time and reducing the initial Mn particle size. The former may not be favorable since it is both time and energy consuming. The latter is very attractive to explore. Reducing the starting Mn powder particles to be about or less than 1 μm will greatly decrease require sintering time to transform a whole Mn particle to be LTP-MnBi. Ball-milling may not be applicable for reducing the Mn particle prior to sintering. Atomizing technique might be the technique for mass production of Mn powder with particle size of about or less than 1 μm. Not only the increase in LTP-MnBi content, but also the increase in the value of coercivity will benefit from the small particle size.

The formation of LTP-MnBi layers on exterior surface of the Mn particles and on the interior surfaces on the cracks inside the Mn particle resulting complex LTP-MnBi materials. It is interesting to investigate the magnetic domains in this material system. The LTP-MnBi layers are in fact the MnBi sheets with irregular feature due to the complex nature of the cracks. Magnetic force microscope (MFM) shall be employed for this kind of investigation.

Thermal stability and decomposition of LTP-MnBi shall be explored more in-depth. Study of thermal stability of the LTP-MnBi at different elevated temperatures shall be carried to identify the maximum working temperature. Capsulating and thin film coating shall also be investigated to seek for solutions for protecting the LTP-MnBi in hazardous ambient.

Last but not least, development of permanent magnets using shall also be investigated. This might also include the utilization of LTP-MnBi as a hard phase magnetic materials for composited permanent magnets.