CHAPTER 7 GENERAL CONCLUSIONS

This dissertation describes a series of experiments in which Al-Si-X powder is consolidated and shaped in the semi-solid state. Hypereutectic Al-Si-X alloys have good wear resistance, high stiffness, and low thermal expansion. They are extensively used for making light-weight wearing parts such as engine pistons, cylinder liners, compressor scrolls and engine blocks. These parts are always fabricated using ingot metallurgy (IM) techniques due to their complex shape. However, segregation and large size of primary Si particles usually present in IM parts and thus degrade mechanical properties and machining ability of these parts. On the other hand, PM techniques lack the ability of net-shape forming of Al-Si-X alloy parts, although they can fabricate the parts with fine and evenly distributed Si particles.

This dissertation presents a novel method, termed as powder thixocasting here, for net-shape forming of hypereutectic Al-Si-X alloys with fine and uniform Si particles. In powder thixocasting, densified powder performs were used as feedstock for thixocasting. Thixocasting is a metal forming process that metals are net-shaped at semi-solid states using a high-pressure die casting machine.

In this dissertation, two prealloyed and gas-atomized Al-Si-X alloy powders with nominal compositions of Al-25Si-2.5Cu-1Mg and Al-20Si-5Fe were investigated. For comparison, a commercialized LM13 alloy and an Al-25Si-2.5Cu-1Mg alloy fabricated using conventional process were also investigated. A thixocasting die with center extrusion gate and a long runner was used to assess the feasibility of this process. This dissertation studied the feasibility of powder thixocasting procedures in net-shape forming of the hypereutectic alloys; besides, strength and wear properties of the thixocast alloys were also investigated and compared with conventional alloys.

Several conclusions can be drawn, as follows:

1. The Al-Si-X powder preforms exhibited very good formability, if they were thixocast at semi-solid states. A hypereutectic demo part, a compressor scroll, and a specimen sample were successfully produced by the novel method, powder thixocasting, to have sound structures as well as fine and evenly distributed primary Si particles.

This indicates powder thixocasting is a feasible method for net-shape forming of the hypereutectic Al-Si-X alloy with integrity and fine microstructures.

2. Both hypereutectic Al-25Si-2.5Cu-1Mg and Al-20Si-5Fe alloys were demonstrated to be able formed into net-shape parts using the novel process, powder thixocasting. However, the former alloy was found to be more suitable for powder thixocasting than the later alloy. This is because the former can stabilize α-Al grains during partial remelting, while the later almost cannot. By elemental addition of 2.5 wt% Cu into the former alloy, α-Al grains could be stabilized to coexist with Si grains and melt in the powders within 525°C to 565°C. At such temperature range, small fraction of melt, for example only about 15 wt% at 560°C, wet the solid α-Al and Si grains, thus the powder compacts could be deformed easily during thixocasting in semi-solid state. However, the α-Al stabilization temperature range for Al-20Si-5Fe alloy was found to be too narrow, about 573°C to 575°C, to be remelt under precise temperature control. Hence, during thixocasting Al-20Si-5Fe alloy exhibited large amount of melt fraction, for example about 80 % at 577°C, resulting in defects of shrinkages and porosities caused by disturbance flow and coarse microstructure caused by Si grain growth after powder thixocasting.

3. In order to success powder thixocasting, several processing parameters should be seriously considered. At first, the powder preforms used for thixocasting should be dense enough to have sufficient strength to be handled and have low porosities to be reheating with an induction coil. To densify the preforms, the powders were found better to be pressed at elevated temperature, or even in semi-solid state. Second, the processing temperature should be suitably controlled within that range in which α-Al grains are stabilized. If not, primary Si grain grow quickly. Third, a special design of die gating system to make powder preforms suffering large plastic deformation during thixocasting is important to obtain favorable strength of the products.

4. Two distinct ranges of Si grain growth were found in semi-solid state of the powders. According to the LSW theory, the activation energies of Si grain growth were calculated to be 174 kJ/mol at temperatures above 565°C and 229 kJ/mol below 565°C. The rate constants of Si grain growth at temperatures above 565°C are around one

order of magnitude than those at temperatures below 565°C. Therefore, heating the powder compacts to the temperature between 540°C and 560°C ensured adequate fluidity of the compacts and prevented the Si grains from coarsening rapidly during thixocasting.

5. Several processing parameters affect the mechanical properties of the consolidated component, including powder particle size, powder consolidating temperature, and the extent of deformation strain during powder thixocast. These influences are strongly dependent on how these parameters offered to eliminate of interfacial oxide layers on the powders, or the consolidation mechanism in powder thixocasting.

6. Consolidation mechanism of powder thixocasting is proposed in this dissertation. Defects of oxide films and inter-granular pores in powder preforms were found to hinder the powder form consolidating. More plastic deformation during thixocasting enhances the probability to break down those defects in powder preforms. However, during thixocasting deformation of the powder preform were mostly accommodated by rotation and sliding of powder particles instead of plastic deformation of powder particles. Therefore, more severe deformation is necessary for powder thixocasting to consolidate the powder than that for conventional powder forging. Besides, using powder particles of larger-sized, 120 μm to 300 μm herein, and quick heating of the preforms, about 200 seconds herein, also found to improve consolidation strength, due to decreasing the surface oxide films.

7. The ultimate tensile strength (UTS) values of powder-thixocast Al-25Si-2.5Cu-1Mg alloys are 225 MPa and 304 MPa in as-thixocast and T6-treated states, respectively, which are close to those thixocast using feedstock made by spray forming followed by extrusion. In addition, the tensile fractographs of the powder-thixocast alloys show coexisting small dimples and cleavages of silicon particles. Furthermore, no decohesion of powder particles in tensile fracture surface were found, indicating an evidence of eliminating detrimental oxide interfaces after powder thixocasting. The above results indicate that powder particles have been effectively consolidated after powder thixocasting.

8. Powder-thixocast samples have finer Si particle size and better strength than the

samples fabricated by conventional routes. However, the strength values of powder-thixocast samples are far lower than those of powder forging alloys, about 400 to 500 MPa. The reason of lower strength as compared with powder forging is not only because the tendency of aggregation and coarsening of Si grains in the former case but also because that there are additional strain hardening effect in the latter case.

9. Powder-thixocast Al-25Si-2.5Cu-1Mg alloy showed greater wear resistance than that of the conventional alloys, owing to its finer Si particles and higher hardness. However, powder-thixocast Al-20Si-5Fe alloy shows lower wear resistance at low loads than that of the conventional alloys despite of its fine microstructure, owing to its low hardness.

10. The plots of the wear rate of the powder thixocast alloy varied with the load could be divided into three regions. The wear rate increased about linearly with the load below 67N (region I); it then slowly decreased as the load increased from 67N to 97N (region II). It finally slowly increased to seizure (region III). The transition from wear region I to region II is attributable to the formation of the mechanical mixed layer (MML) generated by plastic deformation of a heavy loaded worn surface. The transition from wear region II to region III is probably governed by the delamination of MML under more severe load conditions.

11. The MMLs formed at high loads herein contain plenty of Si, Fe and Al_2O_3 phases embedded in an α-Al matrix. The formation of the MMLs was accompanied by a large plastic deformation of the material that is adjacent to the sliding surface. The formation of stable mechanical mixing layers (MMLs) on sliding surfaces is responsible for the superior wear performance of the powder thixocast alloy. In contrast, the formation of MMLs was found to have less beneficial effect on the conventional Al-Si-Cu-Mg alloys. This difference is attributable to the fact that the delamination rate of MMLs in the conventional alloys is higher than that in the powder thixocast alloy, because subsurface cracks tend to be generated from the sites of the fractured large Si particles or the soft matrix of the conventional eutectic Al-Si-Cu-Mg alloys.

CHAPTER 8 FUTURE WORKS

This dissertation presents a novel process that combines SSMF and PM techniques and is introduced as powder thixocasting, to net-shape forming of hypereutectic Al-Si-X alloys. The dissertation demonstrated that the new process is feasible to produce hypereutectic Al-Si-X alloys with fine size of primarily Si particles and high wear resistance; whereas these alloys made by conventional IM routes is difficult to have the fine microstructure and the superior wear resistance.

In future, fabrication issues in powder thixocasting can be further improved, thus can decrease fabrication costs and increase material properties. SSMF is a process in that metals are processed in their semi-solid states. One of the key technologies of SSMF is how to prepare “non-dendritic” or “thixotropic” slurries. However, this issue can be ignored in powder thixocasting, since powder materials normally have the near “non-dendritic” structures that are suitable for thixocasting. On the other hand, the main issues for powder thixocasting must include how to effectively consolidate the powder and how to prevent microstructure coarsening. This dissertation provides some solutions about the two issues in fabricating hypereutectic Al-Si-X alloys during powder thixocasting. For example, the powder compacts could be deformed severely during thixocasting by adequate mold gating design. The severe plastic deformation of the powder-compacts during thixocasting could effectively eliminate the detrimental interfacial oxides, yielding thixocast specimens with favorable strength characteristics. However, much further improving can be further studied, including the ingate system of mould, selection of powders, and alloying of different elements in Al-Si-X or using other materials etc.

The other future works that associated with this dissertation is about the wearing mechanism. This dissertation has already found that the powder-thixocast Al-Si-X alloys have a special wear rate decrease with load when the applied load is high. Although this result was attributed to the MMLs found in this study, it is still interesting that whether the oxides in MMLs came from powder surface oxides or formation during sliding, and how about the formation and delaminating rate of the

MMLs, so that explain why the conventional hypereutectic Al-Si-X alloys can not benefit from the MMLs in wear performance.

Finally, it is considered that powder thixocasting may be applied to many kinds of traditional PM process in future, so that net-shape forming ability in conventional PM routes can be effectively improved. In future, materials that are difficultly produced using IM routes can be alternatively made by powder thixocasting. Powder thixocasting may be applied in fabricating not only aluminum alloys, but also other materials, for instance, ceramic reinforce metal matrix composites such as $Al_2O_{3(p)}$/Al, $SiC_{(p)}$/Al, high-alloyed aluminum such as Al-Fe-V-Si [132,133], in-situ reaction composite such as TiO_2/Al [134]…etc. The above alloys are usually fabricated by PM routes, however, as mentioned above PM still cannot easily achieve net-shape forming of several engineering parts, such as engine pistons, because the powder compacts in the solid state exhibit limited formability. Powder thixocasting solve the issue of net-shape forming in PM routes, including liquid phase sintering [135]; besides, all the alloys mentioned above contains the reinforcement particles that substantially coarsen slowly at elevated temperature, such as ceramic particle or Fe, V contained intermetallic dispersions. Therefore, they are suitable for powder thixocasting due to the stability of reinforcements in these alloys during semi-solid processing.