CHAPTER 6
CONTRIBUTIONS, CONCLUSIONS AND FUTURE WORK

6.1 Contributions

The development of a new composite material from ceramic additives (Aluminum Oxide, Magnesium Oxide and Nanoclay) separately each with Polyamide 12 (PA2200) has been performed, in order to improve the fire retardant and mechanical properties of the sintered specimen and reduce the cost of the Polyamide 12 through the addition of ceramic additives (Aluminum Oxide, Magnesium Oxide and Nanoclay).

An investigation of the thermal properties of composite material of ceramic additives (Aluminum Oxide, Magnesium Oxide and Nanoclay) separately each and Polyamide 12 of the virgin powder has been carried out with different proportions (0-15wt%) of ceramic additives (Aluminum Oxide, Magnesium Oxide and Nanoclay) filler for controlling SLS parameters and obtaining consistent quality of fabricated SLS specimens.

A method of ‘pressure less casting’ to produce specimens with properties similar to those of SLS parts has been examined with the aim of reducing the amount of time consumed and the large amounts of material used.

A methodology for controlling the proportion of ceramic additives (Aluminum Oxide, Magnesium Oxide and Nanoclay) filler separately each to Polyamide 12 has been projected.

The possibility of using un-sintered powder exposed to high temperature for an extended period in the SLS system has been examined, and the development of a methodology for controlling the amount of virgin powder to be added to use powder has been investigated.

The relationship between mechanical properties and the melt flow index (MFI) indicates that MFI is a proven good indicator of powder fitness and mechanical properties.
Furthermore, an overview of SLS process material is given and a methodology to select material for part fabrication on SLS process based on properties requirement of application for a fluorescent lamp holder product using value engineering technique is developed. The approach shown proved to be good for optimal material selection and fabrication of good quality parts in SLS process.

6.2 Conclusions

Applications of additive manufacturing are growing to new domains. This is mainly true for the Selective Laser Sintering (SLS) process. Consecutively SLS process to be competitive and become a strong candidate for novel applications (i.e. rapid manufacturing); the material used requirements to be improved. This research attempts to bring material optimization and improve SLS fabricated parts quality initially by appropriate material selection of existing material based on properties requirement of applications and thereafter SLS material properties improvements by creating new composite material from ceramic additives (Aluminum Oxide, Magnesium Oxide and Nanoclay) separately each with Polyamide 12, so as to reduce the cost of Polyamide 12, as well as significantly improving the fire retardant and mechanical properties of the sintered specimen by adding ceramic additives (Aluminum Oxide, Magnesium Oxide and Nanoclay).

The thermal properties of the powder plays a vital role in obtaining and setting proper SLS parameters, so that a better understanding of the thermal properties of composite materials of ceramic additives (Aluminum Oxide, Magnesium Oxide and Nanoclay) separately each with Polyamide 12 of the virgin and used (un-sintered) powder is helpful in controlling SLS parameters and obtaining repeatedly same quality in the fabricated SLS specimens. Besides that, the physical properties of unused and used or un-sintered powder is studied to develop
a methodology for controlling the proportion of filler additives to Polyamide 12 and finalizing the amount of virgin powder to be added to the used powder in turn to obtain, consistent, good quality, better mechanical properties and fire retardant property.

From the SEM micrographs, it can also be observed that the powders have an irregular shape and rough surfaces. The powders with a more regular shape and narrower particle size distribution are favourable to distribute powders to form SLS and casting parts with higher accuracy. The average particle size measured through SEM micrographs results agree with the average particle size data below (56-60 microns) and recommended by EOS for processing.

The XRD data h, k, l peak values are perfectly matching for the composite systems and show a strong evidence for composite system formations. In addition, it has been observed that the XRD pattern may not change for the heat treated material which gives evidence of non-alteration of composite materials characteristics with regards to heating of composite materials.

The differential scanning calorimeter (DSC) data analysis suggest that the different proportions (0-15wt%) of ceramic additives (Aluminum Oxide, Magnesium Oxide and Nanoclay) separately each added to the Polyamide 12 do not affect the glass transition temperature (Tg), melting temperature (Tm) and crystallization temperature (Tc), and due to this phenomenon the SLS process part-bed temperature fixed at 176 °C with different proportions of ceramic additives (Aluminum Oxide, Magnesium Oxide and Nanoclay) separately each added to the Polyamide 12. On other hand addition of ceramic filler in Polyamide 12 increases the CI % value of formed composite material and in some cases, it
decreases (see Table 3.2) due to this reason the SLS part bed temperature needed to be set 1-3 °C more from 176 °C for proper sintering and to avoid part curling.

The melt flow index (MFI) test proposes that the addition of ceramic additives (Aluminum Oxide, Magnesium Oxide and Nanoclay) into Polyamide 12 affects the MFI of the composites. As the proportion of ceramic additives (Aluminum Oxide, Magnesium Oxide and Nanoclay) increases, so does the viscosity of the composite, due to a decrease in melted Polyamide 12. Furthermore, the gap between the ceramic additive (Aluminum Oxide, Magnesium Oxide and Nanoclay) particles becomes narrower due to this reason the extruded material becomes more viscous. This is an indication of a decrease in the MFI and it finally differs the surface finish quality of fabricated SLS parts. Thus, a suitable proportion of additives filler of ceramic (Aluminum Oxide, Magnesium Oxide and Nanoclay) separately each to Polyamide 12 to be established. During the SLS part fabrication, the large amount (80% to 90%) of powder remain un-sintered and could be reused depending upon powder material properties. However, the properties of un-sintered powder deteriorate through an introduction to high temperatures, just below the melting point of the composite material for an extended period during SLS parts building and cool-down stage. The temperature and heating time to which the un-sintered powder are exposed are the major parameters which cause the powder ageing and deterioration of material properties.

The MFI test proposes that the temperature on which the un-sintered composite powder was exposed, and the time duration of exposure influences the MFI of the composite. The MFI of the composite material decreases by 17-35 g/10min with powder usage and this attributed to the increased molecular weight, which leads to increased viscosity and then decreasing MFI.
The composite powder without exposure to temperature has the lower viscosity and highest MFI, while the powder exposed to the maximum temperatures over the greatest period has the utmost viscosity and lowest MFI. The MFI of the samples tested for continuous and cyclic heating is less significant than the temperature and heating time of the SLS process on material deterioration.

The DSC data analysis of materials suggests that the temperature and heating time at which the un-sintered powder is exposed affect the glass transition temperature (Tg), melting temperature (Tm) and crystallisation temperature (Tc) and due to this reason changes are made in the part-bed temperature with different grades of powder. The Tm of the composite materials increases by 0.5-1 ºC with every construct or cycle until it reaches 4ºC at the highest time of exposure of the powder (100 hours) to the SLS part bed temperature. The process parameters in the SLS process are mostly dependent on the properties of powder material used, so changing the process parameters as the ageing powder changes can give balanced and good quality fabricated SLS parts.

The results obtained from the mechanical properties and MFI tests recommend that there is a relationship between results obtained from the MFI and tensile and compressive strength measures. As the powder degrades due to exposure to higher temperatures for an extended period during the SLS process, the tensile and compressive strength deteriorates. Therefore, the amount of virgin powder to be added to achieve the target melt index has varied from 20% to 50%. The MFI has proved to be a good indicator of powder fitness and mechanical properties.

From the above cast parts properties result, it has been found that the mechanical properties (i.e. tensile strength, tensile modulus, flexural strength, flexural modulus, compressive...
strength and impact strength) of composite materials increases while mechanical property (elongation at break (%)) of material decreases with addition of fillers in PA2200. Further, it has been concluded that by the addition of Aluminium Oxide and Magnesium Oxide improved mechanical properties of casted PA2200 parts/specimens and it is optimal at 10wt% for most of the cases. In the case of Nanoclay filler the optimal property mainly tensile modulus becomes better by the addition of lower proportion (less than 5wt %) of Nanoclay in PA2200 material. The improvement made in fire retardant property of the composite (V0 grade) is achieved at more than 10wt% addition of Aluminium Oxide Magnesium Oxide separately in the PA2200 while in the case of Nanoclay filler addition in PA2200 gives V1 grade maximum at 15wt%. So it has been finalised that the proportion of 10wt% in case of Aluminium Oxide Magnesium Oxide separately in the PA2200 and 5wt% for Nanoclay is selected for further experiments using SLS process.

A comparison was applied between the mechanical properties of measured values of actual parts produced by casting, SLS EOSINT P395, and data-sheet values supplied by EOS for pure Polyamide 12, in order to ensure that SLS system (EOSINT P395) was capable of producing consistent parts. Compared with the data-sheet, results confirmed that the SLS system (EOSINT P395) used in this research was reliable to produce parts with consistent mechanical properties.

Various materials and indeed, any material that can be triturated, may be used in the SLS process. Still, with continuous development and the rise of new powder and composite materials for use in SLS process, limitations could arise, caused by the time-consuming character of the SLS process itself when testing new materials (machine set-up, preheating, building, cool-down and cleaning the machine properly). Also, there is the difficulty of the
enormous amount of the material required to make parts using SLS. The casting method is thus used herein research to simulate the fire retardant property and mechanical properties of SLS parts while reducing the amount of time and a massive amount of material involved when testing new materials. It was found that the casting method was suitable for predicting the fire retardant property and mechanical properties of SLS specimens in the same material, as the data of mechanical properties for both methods do not vary more.

The research is mainly focused on primarily proper selection of existing available SLS materials based on properties requirement of application and based on material physical properties setting of optimal parameter to optimize the materials for SLS process which leads to good functionality at minimum cost, consequently product have higher value and secondly improved fire retardant property and mechanical properties of the new composite materials and specimens made from that materials, but it should be obvious that the new materials will be cheaper than pure Polyamide 12, as ceramic additives (Aluminum Oxide, Magnesium Oxide and Nanoclay) are much less expensive than Polyamide 12 (see Appendix for a brief analysis of the cost of different materials) to further improve value of existing material.

During the fabrication of specimens using Aluminum Oxide and Magnesium Oxide additives 10wt% in PA2200 in SLS process, the part building process is terminated due to curling phenomenon. For addressing the curling phenomenon, extensive research experiments need to be carried out by changing part bed temperature 1 ºC every time till parts are not satisfactorily fabricated. But due to minimum access of available SLS system, the addressing of curling by setting different part bed temperature is still remaining and is to be addressed in future.
6.3 Future work

One possible future research direction is the study of a phenomenon termed “curling”, which occurs due to temperature differences in different regions of the fabricated part, leading to uneven shrinkage. Shrinkage causes the surfaces of the part to display a curved profile when they are supposed to be flat.

In the SLS process, the sintered parts also exhibit varying degrees of inherent porosity, due to the nature of layer-by-layer construction. Through the sintering process, bonds between the particles occur. Therefore, blocking tortuous and interconnected pore channels leads to the development of isolated porosity. This is usually an undesired trait, as the part integrity decreases with increased porosity. The porosity phenomena could generate further work to investigate, eliminate or reduce the porosity in sintered components.

Finally, another possible further investigation course is the study of the effect of proportions of ceramic additives (Aluminum Oxide, Magnesium Oxide and Nanoclay) separately each to Polyamide 12 and SLS processing parameters on the surface quality of sintered components. The most important factors considered to be an influence on the surface roughness are layer thickness (powder thickness of each layer in the part-cylinder) which leads to “stair-stepping”, laser power, laser beam speed, laser beam offset, beam diameter, scan spacing and part bed temperature. Furthermore, GPC analysis will be done for molecular weight prediction and decide the suitable amount of refreshing material for developed composite material exposed in different temperature and extended period of time. Besides, the work needs to be done in future to make this process more viable, related with SLS process stability and parameter: (a) In order to “Right first time” processing, develop methodologies for setting optimal process parameter, (b) Develop, lasers having improved efficiency and
control, also tools for improved temperature management during processing is needed, (c) Improve process control thereby surface finish of processed parts so as to increase material processability, quality as well as performance, (d) Expand multi-material manufacturing for SLS technology, (e) To make improvements to SLS systems that will allow production components to be produced with required properties, thus analyze stability of the SLS process; related with material: (a) Develop new materials for SLS process such as, high performance metal alloys, ultra-high temperature ceramic composites, biomaterials, superconductors and new magnetic materials, metal-organic frameworks, new nano-particulate, also nano-fibre materials, (b) To allow for more user friendly, a catalogue of materials performance information for particular applications, materials and processes, develop databases, (c) For comparison and sharing, develop an “online” portal of AM materials information, (d) Develop a database which will allow to select the appropriate material, process and machine anchored in the weightage criteria set for considered attributes; Finally, related with cost: (a) Develop databases which characterize the properties of the materials and cost in terms to achieve unit properties. This system will be useful in finding out the cost to attain certain properties range and vice-versa increased processing rate/output, (b) For designing of assembly/subassembly/parts and systematically remove the parts which are not adding any value within product to build it simple and cost effective without impairing the functionality, use VE technique principles (c) Use VE technique for reduction in equipment and material costs through developing or suggesting the low-cost alternative for similar functionality, (d) Use VE technique to improve utilization of material by selecting suitable material.