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Investigation into mechanical and microstructural properties of polypropylene manufactured by selective laser sintering in comparison with injection molding counterparts

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A B S T R A C T

This work evaluated the processibility of a low-isotacticity polypropylene (PP) powder by selective laser sintering (SLS), and systematically analyzed and compared the melting and crystallization characteristics, crystalline structure, tensile properties and thermo-mechanical properties of the PP specimens fabricated by SLS and injection molding (IM). The results show that the PP powder has a nearly spherical shape, smooth surfaces, appropriate particle sizes, a wide sintering window and a low degree of crystallinity, consequently indicating good SLS processibility. In SLS, the molten PP continues to maintain at a high part bed temperature until the whole manufacturing process finished, thus demonstrating a low cooling rate. This gives rise to a high degree of crystallinity, formation of γ phase and coarse microstructure. On the contrary, in IM, the fully molten PP is rapidly cooled down to room temperature after injection, and thus show a higher cooling rate and rapid crystallization, leading to a lower degree of crystallinity, absence of γ phase and finer microstructure. Owing to these differences in crystallization characteristics and crystalline structure mentioned above, the SLS PP parts exhibit higher tensile strengths, tensile moduli and storage moduli, but lower elongation at break, toughness and glass transition temperatures, compared with the IM counterparts.

1. Introduction

Addictive Manufacturing (AM) is a collection of technologies capable of building net-shape components directly from three-dimensional CAD models in an additive mode [1,2]. Selective laser sintering (SLS) is a powder bed fuse process of AM technology, which applies laser beam as a heat source to selectively soften or melt powdered materials layer-by-layer to make three-dimensional objects [3,4].

The main advantage of SLS in comparison with other AM technologies is that it can process an extensive scope of materials including polymers, metals, ceramics and composites. In these SLS materials, polymers are most widely used and also show a broad application prospect, due to the diversity of their species and performance and application of various modification technologies [5]. The polymers used in SLS are primarily thermoplastics, which can be classified into two categories, i.e. semi-crystalline and amorphous polymers. Generally, the SLS green parts of amorphous polymers such as polycarbonate [6] and polystyrene [7] are porous and weak due to their inferior sintering rates in the SLS process [5,8], and have been used as investment casting patterns after infiltrated with wax. On the contrary, semi-crystalline polymers exhibit higher sintering rates owing to their relatively low melt viscosities during the SLS process, consequently achieving near fully dense SLS parts with high mechanical properties [8]. Therefore, semi-crystalline polymers can be applied for SLS to directly manufacture plastic functional components.

Nowadays, some kinds of semi-crystalline polymers have been employed for SLS. Polyamides (PA) including PA11 and PA12, and their composites are the most commonly investigated materials in SLS [9–12], and have been commercialized by some companies such as 3D Systems (US) and EOS (Germany) making up more than 95% of the current SLS materials market [5]. This can be attributed to their good laser sintering processibility including wide sintering windows, low degrees of crystallinity and high sintering rates, as well as relatively high densities and mechanical properties of SLS parts. Besides PA, the semi-crystalline polyethylene, i.e. high density polyethylene (HDPE) [13,14] and ultra-high molecular polyethylene

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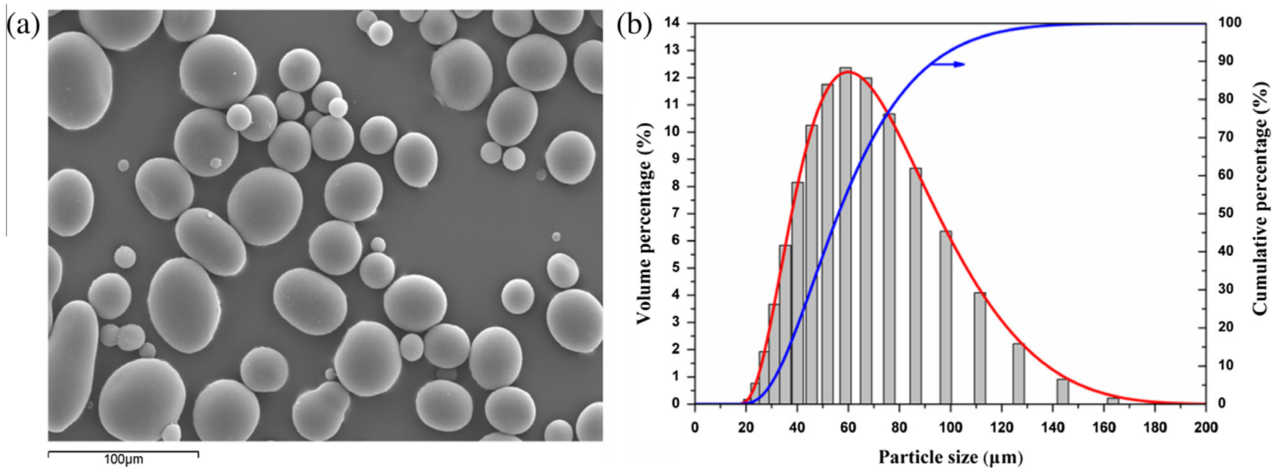

Fig. 1. (a) SEM morphology and (b) particle size distribution of the PP powder.

Table 1
Summary of the processing parameters for the SLS experiments.

Processing parameters	
Laser power (p)	8.25–16.5 W (intervals of 2.75 W)
Laser scan speed (v)	1500–3000 mm/s (intervals of 500 mm/s)
Laser scan spacing (s)	0.2 mm
Layer thickness (h)	0.15 mm
Powder bed temperature (T_b)	105 °C

(UHMPE) [15], have been investigated on the feasibility of SLS processing. Recently, poly (ether-ether-ketone) (PEEK) with superior mechanical properties and thermal and chemical resistance and its composites were applied and studied for SLS [16–19], and EOS is also providing a commercial PEEK powder for its SLS equipment [20]. At present, the types of semi-crystalline polymers suitable for SLS are, however, critically limited. The narrow range of semi-crystalline polymers provides limited material properties, which are no longer sufficient to meet the high demands for a growing number and variety of functional components, and thus greatly restrict the development of SLS technology. Therefore, it will be of particular interest to investigate new semi-crystalline polymers for SLS with the aim to increase material varieties and thus extend the application fields of SLS technology.

Polypropylene (PP) is an important semi-crystalline thermoplastics, and has an increasing numbers of applications in automotive, electronic instruments, textile industry, etc. because of its good mechanical performance and chemical stability, and low density and cost [21]. Although PP for SLS is on the verge of entering the market [5], only few published investigations have been done on its SLS process and part properties. Fiedler et al. [22] evaluated the properties of PP being essential for the SLS processibility, and proposed strategies for materials modification of commercially available PP for adapting to SLS. But, SLS experiments and evaluation on part properties have not been carried out in their work. Drummer et al. [23] compared the melting and crystallization behaviors of PA12, PEEK, PP, HDPE and polyoxymethylene, and presented a method for the qualification of new materials for SLS.

It has been proven that there are a number of advantages of the SLS process over the conventional injection molding (IM) including short cycle time from design to manufacturing, high degrees of geometrical freedom and product customization and the inexpensive manufacture of small batch products [24]. However, to compete with IM, SLS should offer sufficient mechanical properties for its parts, at least comparable to those of IM, to meet the in-service loading and functional requirements. Consequently, it is quite necessary to make a comparison in mechanical properties of parts made by SLS and IM. Attempts have been made to compare the mechanical properties of PA parts fabricated by SLS and IM. Van Hooreweder et al. [24] found that the fatigue properties of the unnotched SLS PA-12 specimens are equal to those of unnotched IM specimens, whereas the notched SLS PA-12 specimens show more brittle failure and increased fatigue resistance. Athreya et al. [25] demonstrated that the flexural modulus, tensile modulus and strength of the PA-12 system made by SLS is 25%, 35% and ~10% higher than those of the PA-12 system made by IM, respectively. But, to the best of the authors' knowledge, very little published work has been done to systematically investigate the differences in the mechanical and microstructural properties of PP parts made by SLS and IM.

As mentioned above, currently, most of the knowledge available on the SLS process of semi-crystalline thermoplastics is based only on the processing of PA [5]. The strong requirements to develop new semi-crystalline polymers for SLS and further extend application fields of SLS exist. Therefore, this work investigated the processibility of a new semi-crystalline low-isotacticity PP powder by SLS, and systematically analyzed and compared the melting and crystallization characteristics, crystalline structure, thermo-mechanical properties, and mechanical properties of the PP specimens fabricated by SLS and IM using the same PP powder.

2. Experimentation

2.1. Materials

The PP powder used in this study was purchased from Trial Corporation, Japan. According to the specification, the as-received PP powder has the bulk density of 0.85 g/cm^3. The SEM image of the PP powder in Fig. 1(a) shows a nearly spherical morphology and smooth surfaces, which indicate an excellent flowability during powder feeding and are beneficial to part accuracy. The laser particle size analysis shown in Fig. 1(b) reveals that the powder has an average particle size of 68 μm and particle size range of 40–80 μm is found to be dominant, which are regarded as appropriate particle sizes for SLS process [26].

2.2. Selective laser sintering process

The SLS experiments were conducted on the HRPS-IV SLS system (Huazhong University of Science and Technology, China),