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Material Properties

Mechanical performance of PEEK produced by additive manufacturing

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ABSTRACT

Recent developments in production methods for polymeric materials have meant that thermoplastics for high temperature mechanical performance can now be selectively laser sintered. This paper describes the performance and the potential applications of EOS PEEK HP3: a high temperature, laser sintered thermoplastic material.

Thermal, tensile, flexural, compressive and fractural tests were conducted to assess the mechanical response of the material. Physical properties, such as porosity and roughness are also presented along with a discussion on the failure mechanisms of the material during testing.

Finally, the significance of this material in the production of prototype parts, the mechanical requirements of the polymer and limitations of its applications are outlined.

1. Introduction

Recent developments in processing methods of polymeric materials have meant that high temperature polymers for structural and mechanical applications can now be selectively laser sintered. High temperature selective laser sintering (HT-SLS) is a method of additive manufacturing used mainly in the aerospace and medical industries [1]. However, the use of this process in the development of mechanical components for dynamic applications is receiving significant interest [2].

Additive manufacturing (AM) allows for a significant improvement in design flexibility; high-complexity bespoke parts can be produced economically, without the need for expensive tooling. There are a number of advantages that SLS has over other polymer AM methods, these include the elimination of the need for support structures when overhangs and thin-walled sections are incorporated into designs, the elimination of binding agents and the large range of potential polymer materials that can be processed via SLS, relative to other AM techniques [3]. Currently, there is a growing number of applications for bespoke components which can withstand high mechanical loads, are biocompatible and can tolerate high-temperature operation. High performance thermoplastics such as polyamide 12 (PA12) have been used in additive manufacturing for several years to produce dense parts with relatively high mechanical strength [4–8]. However, certain material characteristics, such as relatively low melting temperatures and low glass transition temperatures, limit their application. Therefore, there has been an increasing interest in producing high temperature materials for use in high-temperature selective laser sintering.

EOS PEEK HP3 is a material belonging to the group of poly-aryl-ether-ketones (PAEK). This group of polymers has been shown to demonstrate superior performance characteristics compared to other engineering polymers [9,10]. EOS PEEK HP3 semi-crystalline, thermoplastic material was developed by Electro Optical Systems (EOS GmbH., Munich, Germany) and Victrex (Victrex plc., Lancashire, UK) for use on the high-temperature EOSINT P800 machine. The EOSINT P800 high temperature system uses a CO_2 laser that can run at temperatures of 385 °C to build three-dimensional geometry in 0.1 mm layers. This process is capable of laser-sintering high-performance polymers such as polyetherketone (PEK) that otherwise could not be manufactured using conventional laser-sintering systems.

There is very little information available on the properties of EOS PEEK HP3. The majority of the data are based on manufacturer's values, where their significance for a given application is not immediately apparent (EOS GmbH, 2014). Greses and Stoko, and Schmidt et al. outlined the selective laser-sintering (SLS) process for high performance polymers although there was limited analysis of the material properties [12,13]. Beard et al. have attempted to characterise EOS PEEK HP3 components; however, their study was limited to considering only a few practical properties [14].

This paper outlines the physical and mechanical properties of EOS

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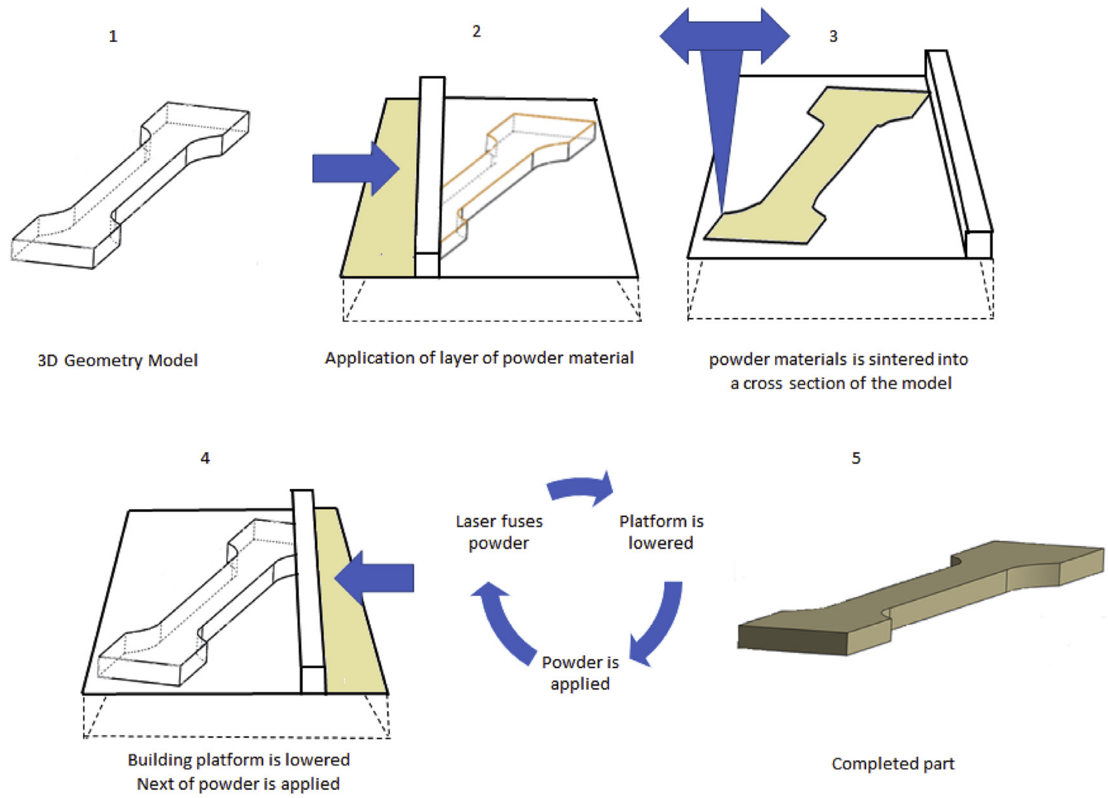

Fig. 1. A schematic of the HT-SLS process used to produce the PEEK samples.

PEEK HP3. Characterisation of the tensile, flexural, compressive, fracture and thermal properties was performed, together with specific physical material properties such as porosity and roughness. This highlights the potential of EOS PEEK HP3 as a material for high performance applications.

2. Test methodology

Test samples were manufactured by 3D Systems Corporation (Langhorne, PA, USA), using an EOSINT P800 (EOS Electro Optical Systems, 2011a) high-temperature laser-sintering system. EOS PEEK HP3 powder, specifically designed for the EOSINT P800 additive manufacturing system, was used to produce the parts. This is shown schematically in Fig. 1.

Sample geometries were produced in the x-y plane and were based on the corresponding International Standard Organisation (ISO) standard (described for each test below). This allowed the mechanical properties of the samples to be evaluated against existing data for high performance polymers. However, it should be noted that the mechanical tests performed are based on standards for polymers processed by injection moulding as, currently, no standard for the mechanical testing of HT-SLS materials exists. Therefore, as roughness was a result of the manufacturing process, samples were tested 'as-produced', i.e. neither polished nor machined to fit roughness tolerances suggested in the ISO standards.

2.1. Physical properties

A JEOL 6060 Scanning Electron Microscope (SEM) was used to observe the surface characteristics of the HT-SLS material. The sample was gold-coated. The topography of the surface was measured using an Alicona G5 InfiniteFocus (Alicona, Raaba, Austria) using 10 × magnification.

A mercury porosimetry was used to examine sub-surface pores in the material. The mercury porosimetry analysis used the intrusion of mercury into a porous structure under controlled pressures to determine sample properties such as pore size distributions, total pore volume, median pore diameter and sample densities (bulk and skeletal). In this study, a Micrometrics AutoPore IV was used allowing theoretical pore diameters from 6 nm to 360 μm to be detected. Mercury intrusion into the sample was analysed using the Washburn equation (Equation (1)) in order to determine the pore diameter distribution, assuming cylindrical pore geometry [15]:

$$D = -\frac{4\cdot\gamma}{P}\cdot cos\theta \tag{1}$$

where D is pore diameter, P is the applied pressure, γ is the surface tension of mercury at 20 °C, which was assumed to be 0.485 N/m, and θ is the contact angle between the mercury and the solid, which was assumed to be 130° [15].

2.2. Mechanical properties

The tensile, flexural, fractural and compressive responses of EOS PEEK HP3 were investigated following the appropriate ISO guidelines for polymeric materials.

2.2.1. Tensile testing

(EN ISO 527-1:2012 and EN ISO 527-2:2012).

In this test, five tensile tests were run following ISO 527-2/1A/1; this corresponds to an extension rate of 1 mm min^{-1} and a strain rate of approximately 1%/min assuming uniform deformation. The specimen dimensions were determined according to EN ISO 527-2:2012 Plastics - Determination of tensile properties.

2.2.2. Flexural testing

BS EN ISO 178:2010 describes a three-point-bending method for determining the flexural strength and flexural modulus rigid and semi-rigid plastics. In this test, five samples were tested at a strain rate of