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What triggers a microcrack in printed engineering parts produced by selective laser sintering on the first place?

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ABSTRACT

The proximity of un-melted particles within Selective Laser Sintered (SLS) printed engineering parts made of Nylon-12 is found as a major triggering effect for cracking and ultimately failure. The numerical investigation, by means of the eXtended Finite Element Method (XFEM), was performed over samples with different arrangements of un-melted particles obtained experimentally. The onset and propagation of microcracks was simulated. This included inherently how the degree of particle melt (DPM) in SLS parts affects and controls both crack initiation and propagation. The results evidenced that a microcrack started invariably between the two closest un-melted particles in all numerical tests performed considering different arrangements of un-melted particles.

1. Introduction

Since the invention of the technology in the 1980s, the additive manufacturing (AM) industry has progressed a significant distance, going from what was originally an expensive prototyping technique to becoming what can be regarded as a process able to produce end-use parts that can rival the material properties of traditional methods, if the limitations of the technology are properly understood [1]. AM manufacturing processes distinguish themselves from other methods by building parts from CAD (Computer-Aided Design) files separated into layers. These layers are bonded together within the machines in order to produce the parts, differing from the usual subtractive techniques. It is notorious that the material properties of additively manufactured parts vary significantly due to the often inhomogeneous nature of the build parameters used. In addition, the presence of un-melted particles due to incomplete melting introduces instabilities. This means that parts used in a true engineering setting can often fail unexpectedly, often through fracture, and therefore a wider understanding of the performance of printed parts is needed not only with regards to mechanical testing, but also fatigue and fracture behaviour. This can be done experimentally, but often on a microscopic scale where individual particles play a significant role simulation methods can have significant advantages. There are a number of works presenting finite element analyses on laser sintering products, see e.g. [2,3,4,5], however, this is the first time that XFEM [6] is applied to failure analyses of SLS specimens resulting in new findings on the mechanical behaviour of nylon-12. The main source of failure is attributed to geometric discontinuity or stress concentration. This form of discontinuity usually takes the form of a sharp change of geometry, opening, hole, notch, crack, etc. [7]. Modelling and analysis of these discontinuities is meaningful, as it will build on the understanding of their behaviour within Selective Laser Sintered (SLS) parts and will contribute to their enhanced life and performance. The effect to which un-melted particles influence the onset and direction of the propagation of microcracks in SLS printed engineering parts is presented in this study. How the degree of particle melt (DPM) in SLS parts affects and controls both crack initiation and propagation is one of the aims of this study. This paper is structured as follows. Firstly, a brief background on additive manufacturing, laser sintering process and properties of Nylon-12 is provided. Secondly, tests and results conducted by using the eXtended Finite Element Method (XFEM) in Nylon-12 samples with different arrangements and degrees of particle melt are presented. Finally, discussion of results and concluding remarks are provided.

1.1. Additive manufacture and laser sintering process

Before the arrival of additive manufacturing, methods of manufacturing were classified as either being 'forming' processes or 'subtractive' processes, where material was either deformed or removed respectively to shape the final part. Additive manufacturing has provided a new third group where material is instead added, usually in layers, to build up a part [8]. Since the 1980s, when additive manufacture was invented,

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the industry has been growing and expanding, with new machines, processes and methods being developed every month. Selective Laser Sintering (SLS) [9,10,11] is a process which involves starting with an initial powder bed and then generating complex parts by Selective melting the cross section of a part layer by layer. The input of thermal energy via a laser beam provides the means by which the power both melts and consolidates together. The process has become well established over time as the parts it produces have improved regarding their higher mechanical properties, and reliability between build jobs. The most widely known advantage is that the machine builds directly from a CAD file, so the complexity of the part can be far higher compared to conventional techniques, meaning parts are limited by the process rather than design freedom; this opened the door for many new uses of the technology. Limitations on SLS process include that the final surface finish of the parts is generally poor, where a high amount of post processing is usually required to achieve end-use parts. Thermal variations and build temperatures in the build volume can also cause significant warping and curling of parts, in tandem with incomplete melting introducing un-melted particles, both of which alter the part strength. Although the reliability of the build part properties has improved significantly allowing many more applications, they still pose issues for the technology. In the SLS process, mechanical properties of the produced part are not solely influenced by the base material itself, but also by the process parameters. It is important to breakdown the SLS process and analyse the different parameters which will affect the end properties of the part. Some of the parameters will have a more marked effect on the end mechanical properties than others, and also parameters affect one-another, so the result is a complicated network of interlinking factors. It is outside of the scope of this study consider them all, so in this case, three of the more significant parameters are highlighted next: temperature, degree of particle melt and anisotropy.

- Feed/Part Bed Temperatures: The temperature at which the powder feed and part bed is held at influences the end properties significantly.
  The main objective of maintaining part bed temperature is to reduce or eliminate the part distortion during the SLS of nylon-12. Temperatures which are too high can lead to premature melting. Temperatures which are too low can lead to significant deformation and curling of the final parts. Generally, the lower the temperature the lower the density and therefore mechanical properties [12]. The Part Bed Temperature, T_b is the temperature at which the powder is held within the central part cylinder or bed, in which the part is built. This temperature is usually reached via a *preheat* where the T_b value is obtained before any of the laser parts move. The Powder Feed Temperature T_f is the temperature at which the powder in the powder supply is held before it is dispensed across the powder bed. The rheology of the powder as it is applied is strongly affected by this value. In an ideal scenario, the temperature of the powder is as close to the melting temperature as possible without the powder prematurely consolidating or thermally degrading. This reduces the thermal gradient and expansion due to laser heating resulting in parts with lower roughness and better properties [13]. When establishing the simulations, it is assumed that any parts are built under this ideal condition.
- Degree of particle melt (DPM): The degree of particle melt (DPM) conveys the idea that during the sintering process many particles within a SLS printed part may not have achieved the fully melted state, and, hence, have un-melted cores. These regions arise where insufficient energy has been input to the powder in order to fully melt the particles. The amount of energy input to the material will determine the proportion of the powder which is fully melted, so defining a universal energy density based on the machine parameters is necessary. This has been known as the Andrew Number in Eq. (1) [14] which defines energy density as follows:

$$\text{Andrew Number} = \text{Energy Density} = \frac{\text{Fill Laser Power}}{\text{Scan speed} \times \text{Scan Spacing}}. \quad (1)$$

1. Fill laser power determines to what degree the laser will heat the powder (measured in W), where it will melt and flow allowing coalescence to occur.

$$\text{Fill laser power} = P = \frac{BS \times \rho \times D_b \times C \times \left[(T_m - T_b) + L_f\right]}{1-R} \quad (2)$$

where BS is the laser beam speed, D_b denotes diameter of the laser beam, C is the specific heat, T_m denotes the powder melting temperature, T_b is the part bed temperature, L_f is the latent melting heat, and R is the reflectivity.

2. Scan speed determines the speed at which the laser travels, influencing the fill laser power and building time.
3. Scan Spacing refers to how close together each scanned path is, and should not exceed the diameter of the beam itself.

The higher the energy density, the higher the chance the larger particles in the powder will melt, which decreases the chance of un-melted particles. It was concluded by [15] that the varying energy input into the SLS process directly affects the completeness of melting within the part. If a Differential Scanning Calorimetry (DSC) test is performed on an SLS part, two distinct melt peaks are observed which relate to the presence of the both un-melted and crystallised regions around un-melted particles. The relationship between these two proportions is what is used to define the DPM which strongly affects the mechanical properties and thus usefulness of a part.

From the DSC scan a percentage crystallinity can be calculated based on the relation between the two peaks and the temperature at which they occurred. This represents the ratio between the un-melted cores and melted/re-crystallised material. Based on the research by [16], the crystallinity of a fully melted part and powder itself was found to be 25% and 47% respectively. Further to this, from the DSC data the Melted and Crystallised Material (MCM) crystallinity can be calculated along with the core crystallinity defined as being $[1 - \%MCM]$, the DPM can be calculated using Eq. (3). Having calculated the DPM of the part, it is then possible to perform a study to relate the DPM to the overall mechanical properties. By investigating how the tensile strength is affected by the energy input (and therefore DPM) the behaviour trends can be observed [17]. There is an optimal point of DPM with regards to the value of tensile strength. As the DPM increases, the number of un-melted cores decreases, where the material goes from being a 'double phase' structure with both melted and un-melted Nylon-12 to a 'single phase' structure where the material is fully melted. During this increase in DPM the tensile strength also increases, but beyond the optimal DPM, the tensile strength then drops. This sudden tipping point is not easily explained but shows that once melting is complete the trends become different, meaning that the structure can be treated as a new material. From these trends, it is clear that the degree of DPM and therefore number and structure of un-melted particles plays a crucial role in determining part strength. When establishing the simulation conditions, the DPM is certainly the most crucial factor, where DPM directly determines the number of un-melted particles and thus fracture behaviour.

$$\text{DPM}\ (\%\ \text{MCM}) = \frac{\text{Total Crystallinity} - \text{Core Crystallinity}}{\text{MCM Crystallinity} - \text{Core Crystallinity}} \quad (3)$$

- Part Orientation and Anisotropy: A factor which is almost exclusive to additive manufacture is the dependence of the part properties on the