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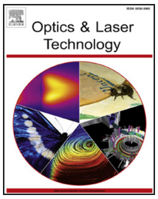

Adjustment of isotropic part properties in laser sintering based on adapted double laser exposure strategies

Andreas Wegner*, Gerd Witt

University of Duisburg-Essen Chair for Manufacturing Technology Lotharstrasse 1, 47057 Duisburg, Germany

HIGHLIGHTS

- Anisotropy is a big issue in laser sintering.
- For mechanically loaded components in particular, insufficient layer-to-layer bonding has so far been a major obstacle.
- Double laser exposure strategies are seldom used due to an increase in processing time.
- Isotropic part properties can be achieved, when double laser exposure strategies are used.
- Elongation at break in z-direction increases to values over 20%.

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ABSTRACT

Laser sintering of polymers gets more and more importance for small series production. However, laser sintered parts have often an explicit anisotropy of mechanical properties. Due to the layer-wise production, parts show no homogenous morphological structure as known from injection molded parts. Voids appear within the part and are concentrated in the area between two consecutive layers, resulting in reduced bonding. Therefore, mechanical properties and in particular the elongation at break show significantly lower values in the direction of build compared to the properties within the build plane. Sometimes, these effects are an obstacle in the usage of laser sintering for series production of parts.

The aim of the experiments was to investigate to what extent an improvement of the layer-to-layer bonding and thus of the characteristic values in the building direction can be achieved by alternative exposure strategies. For this purpose, the influence of adaptive double laser exposure strategies on layer-to-layer bonding and anisotropy was investigated. The influence of different parameter settings for the first and second exposure was investigated. In a further step it was examined to what extent the influence of disturbances on the process, such as the inhomogeneous temperature distribution or cycle time variations can be reduced by applying the developed double laser exposure strategies. For this purpose, a comparison was made between an optimized double laser exposure parameter set and the standard parameter set.

1. Introduction and state of the art

Increasing competition, decreasing product life cycles, the wish for customized products and a shortage of resources cause the need for innovative production techniques for small series production [1]. Going beyond the stage of Rapid Prototyping on to Rapid Manufacturing (RM), Additive Manufacturing (AM) offers possibilities for small series production of customized products and an increased freedom of design, due to the lack of tools [2]. The laser sintering of plastic parts is one of the few AM-processes which have at the moment the capability to be used for Rapid Manufacturing [3].

In general laser sintered parts have an explicit anisotropy of mechanical properties. Due to the layer-wise production, parts show no homogenous morphological structure as known from injection molded parts. Voids appear within the part and are concentrated in the area between the layers resulting in reduced bonding. Therefore, mechanical properties show significantly lower values in the building direction compared to the properties within the build plane. These effects are sometimes an obstacle in the usage of laser sintering for series production of parts. The reason for that results from the workflow of Additive Manufacturing. Other manufacturing techniques, like injection molding (IM), also show anisotropic mechanical properties. The

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[*] Corresponding author.
E-mail address: andreas.wegner@uni-due.de (A. Wegner).

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anisotropy in IM results from an orientation of polymer molecules while filling the cavity of the injection molding die. In contrast to AM, the intended direction of loading within parts is also considered when designing the molding die. However, in AM the design of parts and the production of parts take often place in different companies due to the point that the AM market is dominated by service providers. This requires a detailed flow of information. Additionally, there is a lack of design rules in AM like information on the degree of anisotropy or the optimal part orientation. The actual ISO/ASTM DIS 52911-2 "Additive manufacturing - Technical design guideline for powder bed fusion - Part 2: Laser-based powder bed fusion of polymers" gives a first overview in that field. However, the intended direction oftentimes does not fit the optimal part orientation in laser sintering. The loading direction should be oriented within the xy-plane. However, effects like part distortion, stair stepping, optimal utilization of the build envelope or even the shape and dimension of parts may force the manufacturer to choose another part orientation, which is optimized on process conditions. Thus, the manufactured parts may not fit the requirements and could cause part failure when being in use. Isotropic part properties are a possible solution to avoid these problems in AM of parts. On the one hand, the part's orientation during the build can be chosen independently from the loading direction, resulting in an optimized utilization of build space, while on the other hand, in general, a process limitation of laser sintering is dissolved at the same time.

Technical literature contains several papers with analyses and advancements of the laser sintering process. As a result, and due to the permanent advances in materials and machine development, this AM technique has reached a high technical level, creating the possibility for RM in some applications.

The correlation between process parameters and mechanical properties of laser sintered parts was the subject of several analyses in the past and is described in several publications [4–13]. Most of these studies investigate the influence of energy input or individual process parameters on the processing of polyamide 12 in the laser sintering process with the aim of optimizing the properties or pointing out the process limits for good processing. In [11,14], Jain states a minimal energy density of 0.1 J/mm^3. Below this point no sintering occurs. Additionally, he defined a maximum energy density of 0.48 J/mm^3 where polymer degradation starts. Zarringhalam found in [15], that part crystallinity can be correlated with the elongation at break. An increase of energy input by higher energy density or multiple laser exposures, as well as greater cooling rates after the build, reduce the crystallinity of the part, resulting in a higher elongation at break. However, using multiple laser exposures leads to lower values for tensile strength and young's modulus. Additionally, he demonstrated that a low energy input is not sufficient to fully melt the powder material resulting in a two phase material, showing unmelted particle cores and melted regions. A study by Wegner in [10] shows the relationship between crystallinity and elongation at break in laser-sintering.

Beyond the analyses which describe correlations between process parameters and part properties, several publications demonstrate the anisotropic character of laser sintered parts. Fig. 1 compares the results of various studies on the anisotropy of laser-sintered PA 12 components as a function of the volume energy Density, as far as this can be determined [4,6–8,16–23]. For this purely qualitative comparison, powder qualities used or differences in sample conditioning are not taken into account. The evaluation of the studies shows that especially for the tensile strength and the elongation at break an anisotropy of the tensile properties occurs, while the deviations between build plane and building direction for the Young's modulus are always under 5% and thus an almost isotropic behaviour is present here [22]. In contrast, the average deviation for tensile strength 14.1% and for elongation at break even 29.1%. In most cases, the characteristic value within the build plane is higher than in the building direction, which is due to the problems encountered with layer bonding. A significant difference from this behaviour was found in the Caulfield study, in which significantly higher elongations at break in the building direction were determined over a large energy density range [7]. No explanation can be found from Caulfield's own comments or from other publications, as similar behaviour has not been observed in any other study. Since there is no comprehensible explanation for these results, the values are considered as outliers for further evaluations. If the deviations and characteristic values are evaluated as a function of the volume energy density, it is shown that for the tensile strength from an energy input of 0.25 J/mm^3 in most studies high values in the range of approximately 50 MPa are achieved for both orientations. At the same time, the deviation between the orientations in this area is usually under 10%. Especially the investigations of Gibson [6] and Sauer [8,22] show a very pronounced anisotropy of over 60% for tensile strength, which differs strongly from the other studies. Both used for their tests a DTM Sinterstation 2000, which is the first commercial laser-sintering system still known for a very strong fogging of the laser window. The resulting reduction in laser power, especially during long processes, could provide an explanation for the different behavior. Such effects still represent a significant problem with laser power reductions of up to 10% in today's systems, as studies by Fulcher in [24] show.

Compared to strength, there are significantly higher deviations between the orientations for elongation at break, Fig. 1. From an energy density of 0.33 J/mm^3, the anisotropy is reduced to values between 2.6 and 25%. Nevertheless, deviations of up to 50% also occur in the area of high energy densities. Thus, the energy density alone does not seem to be decisive for a low anisotropy. At the same time, the increase in anisotropy for the highest energy density indicates an influence by decomposition effects, especially since the energy density value is significantly above the degradation limit determined by Jain [25] and Vasquez [26]. In addition, even for high energy densities, the comparison shows clear differences between the individual elongation at break values. Due to the dependence on the quality of the layer connection, the elongation at break in the build-up direction in particular represents a variable that reacts particularly strongly to process influences and thus an important quality parameter for the laser-sintering process.

The main reason for the poor layer-to-layer bonding is the fusion of the interlayer area. The author's own investigations in [10] and studies by Dupin [27,28] and Zarringhalam [15] show that accumulations of pores and unmelted particle cores can be found, especially at low energy densities in the interlayer area. As the investigations show, these lead to a poor layer-to-layer bonding. If the energy input is increased, these porous interlayers no longer occur [10,27,28], although unmelted particle cores [15] can still be found, which is still associated with low elongations at break in the building direction [10]. At even higher energy inputs, all particles melt completely and form a homogeneous morphology with few pores and an optimal layer-to-layer connection [10,15,27,28]. If the energy input is too high, on the other hand, the porosity of the components increases again due to decomposition effects, which is reflected in round pores [10]. However, this is not initially connected with an reduction of the layer-to-layer bonding. Furthermore, the temperature balance in the interlayer area is decisive for a good layer-to-layer bonding. If the temperatures of the melted area before powder application are above the material melting point, the applied powder layer can be partially melted from below by heat conduction, which reduces the layer thickness to be melted by the laser. This was summarized by Wegner as the theory on the continuation of the melting processes in laser-sintering in [10]. At the same time, higher temperatures in the interlayer area of PA12 materials with unregulated end-groups such as the EOS PA2200 can cause increased post-condensation and thus a bonding of molecular chains beyond the layer boundary, as described in [29].

Studies by Kaddar [5], Zarringhalam [15], Grießbach [30,31] or Usher [32] also prove that anisotropy can be reduced by adjusting the process parameters and especially by double or multiple exposures.