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Reviewed Paper

Understanding hatch-dependent part properties in SLS

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Abstract

Selective laser sintering of polymers (SLS) is on the verge from pure prototyping to producing individualized complex parts for series application. As the parts are generated layer-wise and the influence of process-parameters as well as part orientations are well-known, the aim of the paper is to point out the influence of the layer-wise manufacturing in dependence of the hatching strategy on the resulting part properties as these are constant process-steps. Therefore, tensile bars with different number of layers but constant layer-thickness were produced using different hatching strategies and investigated depending density, surface roughness and mechanical properties. The results showed a strong increase of the mechanical properties, ductile breaking behavior and part density as well as decreasing surface roughness with higher layer numbers as well as the hatching strategies. Therefore, the results point out significant interaction between constant process steps and resulting part properties.

Key Words: selective laser sintering, hatching, mechanical behavior, Polyamide 12

Introduction

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Additive manufacturing techniques like selective laser sintering (sls) of polymers have changed from a pure prototyping techniques to manufacturing small lot sizes or individualized products. Their fields of application range from architectural models, functional prototypes in the automotive and aerospace industry, to individualized applications in series production in form of handling systems [1]. The sls process therefore has developed as a manufacturing technique to produce prototypes or small lot sizes with good mechanical properties. Nevertheless, the resulting parts possess specific characteristics like anisotropical mechanical behavior, a porosity between 3-5 % and a high surface roughness due to the pressureless and layer-wise manufacturing of the parts [2, 3]. Many investigations exist concerning the resulting part properties and the influence of different process parameters but no knowledge exists about the layer-wise forming of the part properties in dependency of the hatching strategy. Therefore, the presented results show the influence of successive increased layers with different scanning strategies to point out the influence of the layer-wise building concerning the resulting part properties.

State of the Art

The sls-process of polymers is a powder bed based additive manufacturing technique that consists of three main process steps. In the first step, a blade or a roller distributes the powder across the building chamber. In the next step, the powder is heated just below the melting temperature and a cross-section of the parts is molten by a CO_2-laser. These steps repeat until the whole parts is generated [4]. Influences of the processing parameters like the used temperature [5], the energy-density [6-9] as well as the orientation of the parts during the processing [9] have a well-known influence on the resulting part properties. With an increasing energy density, the mechanical properties of SLS parts increase until a certain maximum. A

further increase negotiates the properties due to material degradation [6]. The increase also reduces the anisotropic behavior, between parts produces along the building platform and dissenting orientations [9]. Besides the used process temperatures [10], the used layer thickness [11] and the part orientations during the processing define the resulting melt pool and scanning length [12] and therefore the interaction between process parameters and part properties. Within these influences, the materiel specific temperature dependent properties like the viscosity [6, 13], surface tension [14] and absorption of the laser radiation have a significant influence of the layer attachment and therefore the resulting part properties [6]. Resulting of the process characteristics, like the high building temperature and slow cooling down, specific part properties in comparison to conventional manufactured parts like injection molding [15] occur. These result in a high degree of crystallinity and a homogenous morphology across the parts [2]. Besides the morphology, the surface structure is mainly influenced by the surrounding powder, which due to the pressureless and tool-less processing acts as a mould. Therefore, a high surface roughness occurs to the attaching of semi molten powder particles as well as the forming of the surrounding powder [16, 17]. SLS-parts typically exhibit a porosity which reduce the cross-sections are orientated mainly along the powder deposition and lead to a higher notch effect and therefore have an influence on the mechanical part properties [17]. The layer-wise manufacturing of the parts mainly influences the part properties and especially the mechanical properties [3]. The part orientation during the processing lead to anisotropic part behavior. An orientation along the building platform leads to higher mechanical properties especially the elongation at break varies significantly [4]. This is also influenced by the used energy density [6]. Besides the process parameters and the part orientation, the used hatching strategy during processing also influences the resulting part behavior [12].
Summing up the state of art, many influences on the process have been investigated like the process parameters in different experimental series. However, the interaction of the layer wise building and hatching strategy on the resulting part properties is unknown. Therefore, the aim of this paper is to investigate the layer wise building of part specimens with different hatching strategies and the continuous forming of the part properties and mechanical behavior.

Experimental Setup

The presented investigations were performed using a Polyamide 12 (PA12) of the type PA 2200 (EOS GmbH, Krailing German) using a refreshing rate of 50 % (ratio of new and used powder). The powder exhibits a melting temperature of 185 °C and a crystallization temperature of 150 °C. The mixture was fabricated using a mixer MP-20 (Somakon UG, Lünen Germany) with a rotation speed of 200 min^{-1} for 30 min. Afterwards the viscosity number (Vn) of the powder was determined according to DIN EN ISO 307 [18] and exhibited a Vn of 63 ml/g.
Specimens according to DIN EN ISO 572 [19] of the type 1A with a length of 170 mm were used. The specimens were produced with different number of layers and therefore changing the resulting part thickness. A layer thickness was set to 100 µm and specimens were produced with 1, 2, 3, 4, 5, 10, 15, 20, 25, 30, 35 and 40 layers for every hatching strategy. The specimens were orientated along the powder deposition in the used Formiga P110 (EOS GmbH, Krailing Germany). The keep the thermal history of every building job constant three building jobs were performed, one for every scan strategy. The building chamber was heated to 167°C, with a scanning-speed of 2500 mm/s, a laser power of 21 W and a hatch-distance of 0.25 mm. The layer thickness was set to 100 µm. For the processing three different hatching strategies were used during processing. Two unidirectional strategies (x and y) where every layer was hatched in a constant direction as shown in figure 1and an alternating which changes the direction between x and y for every layer.

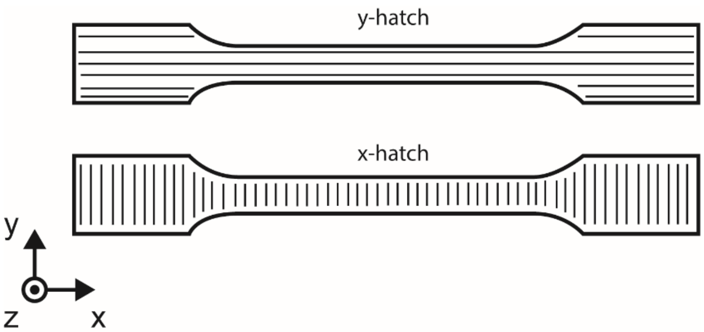


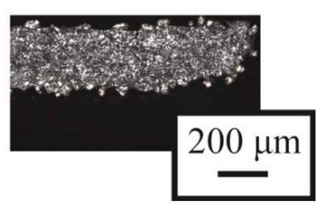
figure 1: scanning strategies during the specimens production with SLS

The cross-sections of the specimens were determined using thin-cuts across the middle of the sections. The surface roughness was measured tactile using a stylus instrument of the type Waveline 20 (Jenoptik, Jena Germany) with a stylus tip of 2 µm an a attaching force of 0,8 mN. The roughness was measured in 3 parallel lines in the middle of the test specimens along the longest axes for the surface on top and on the bottom of the specimens. The measuring length was 15 mm and the Rz was determined according to DIN EN ISO 4287 [20].
For determine the mechanical properties the specimens were conditioned in a humid state until reaching weight-constant. The mechanical testing followed DIN EN ISO 527 [19] with a testing speed for the young's modulus of 1 mm/min and 50 mm/min for the elongation at break and the tensile strength. The modulus was determined using a tensile testing machine of the type 5948 (Instron, Darmstadt Germany) and the elongation at break as well as the tensile strength a Type 1484 (Zwick Roell, Ulm Germany). The stress conditions of the specimens and transversal contraction were measured using a video extensometer (Limess, Krefeld Germany), which was correlated with the crosshead travel of the tensile testing machine.

Results:

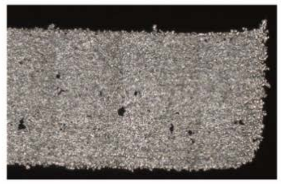
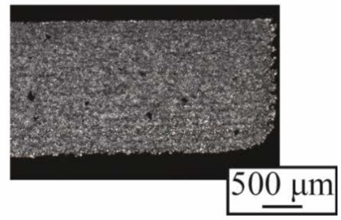
Concerning the presented investigations, the morphological structure and forming of the different number of layers were investigated by microscopic investigation of thin-cuts across the cross-section of the parts. As shown in table 1 the forming of specimens with 2 layers develop nearly flat specimens which show a slight round outer edge which may occur from melting of the powder during the processing and therefore an resulting volume contraction. Nearly no pores can be seen in the cross-sections of the specimens. In the outer surfaces of the adhering powder particles can be seen which results from adhering of powder particles to the molten cross-sections during the processing.

table 1: morphological structure of specimens build of 2 layers with different hatching strategies

X	y	xy
		

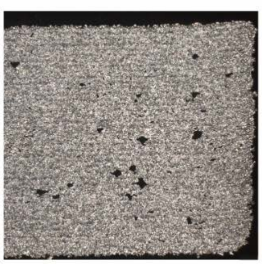
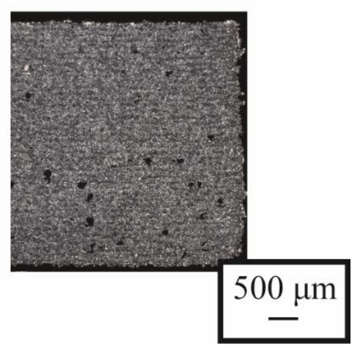
With increasing layers the morphological structures of the specimens slightly change. As the first layers have developed a round edge the increasing layers form a sharper structure on the outside with an increasing cross-section. On the outer surface differences in the surfaces on the side of the specimens occur. It seems that the xy-scanning strategy develops a higher roughness on the side surface as well as the x-strategy. In comparison, the y-strategy leads to a smoother side surface as the scanning strategies are orientated along the specimens and therefore 90° orientated to the shown cross-sections. All the specimens combine an increase of the porosity within the cross-section of the specimens.

table 2: morphological structure of specimens build of 20 layers with different hatching strategies

X	y	xy
		

A further increase of the layers lead to sharp outer surfaces independent from the hatching strategy but differences in the form of the cross-sections occur. The y- and x-hatching orientation show in comparison to the xy-orientation a rounded form of the specimens, which lead to higher edges and lower center of the specimens, where in comparison the xy-orientation, leads to nearly an equal height of the upper surface and the edges on the side. All the cross-sections show in comparison to the smaller number of layers a further increase of the melting of the attached powder and therefore lead to smoother surfaces.

table 3: morphological structure of specimens build of 40 layers with different hatching strategies

x	y	xy
		

As the morphological investigation of the cross-sections showed differences in the surface structure (figure 2), the roughness of the parts on the bottom and the top surface was investigated. In general, the evaluation of the Rz exhibited slight differences comparing the top and the bottom surface of the specimens. The roughness on the bottom surface is slightly higher especially for the increasing number of layers. Comparing the hatching strategies, differences in the surface structures occur with increasing number of layers and lead to smaller Rz values for the alternating hatching strategies.

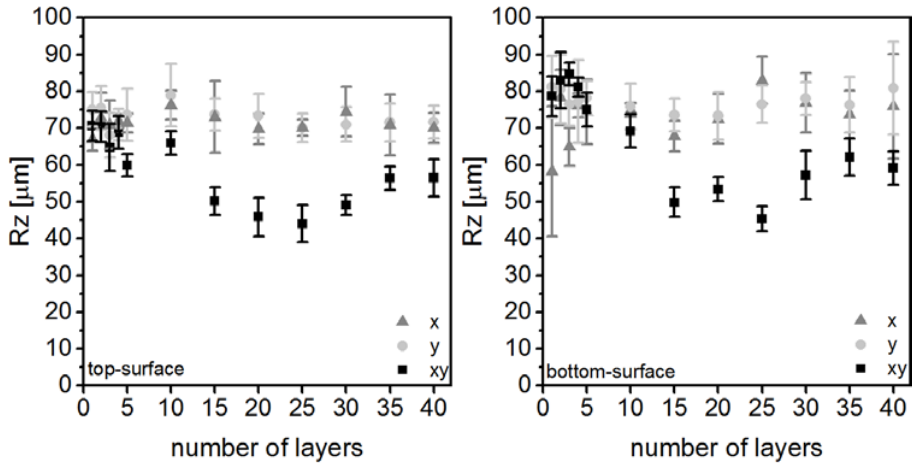


figure 2: surface roughness for the specimens produced with different hatching-strategies in dependency of the number of layers

After investigating the cross-section, the mechanical properties of the specimens the mechanical properties were examined. In figure 3 the elongation at break is shown with different number of layers and in dependency of the hatching-strategy. It can be seen that independent from the hatching strategy the elongation increases with a higher number of layers but differences occur resulting from the hatching-strategies. The xy-hatching strategy leads to higher elongation at break from the beginning. The main differences in the resulting elongation occur at layer numbers of 10 and higher were an increase of nearly 50% in the elongation can be seen from x or y-hatching in comparison to xy-hatching. Independent from the hatching strategy the elongation reaches it's maximum after 15-20 layers and is therefore nearly constant in the differences between the hatching strategies. Comparing x and y hatching nearly no differences in the elongation at break occur neither for small number of layers or higher numbers.

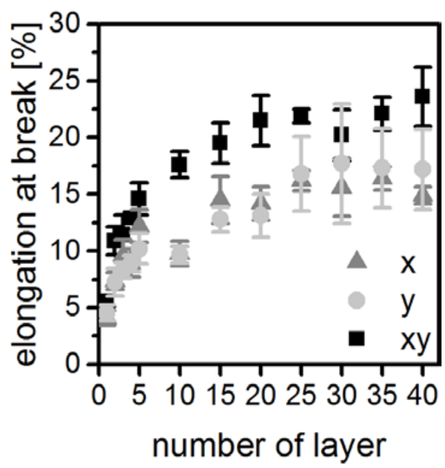


figure 3: elongation at break for the specimens produced with different hatching-strategies in dependency of the number of layers

Besides the elongation at break, differences in the young's modulus are exhibited in figure 4. Like the elongation, the young's modulus shows an increase until up to 5 layers. Between 10 and 30 layers differences in young's modulus in dependency of the hatching strategy occur. The alternating hatching leads to the highest young's modulus whereas the x and y strategy develops a smaller modulus and show nearly the equal modulus for 30 up to 40 layers as the alternating hatching.

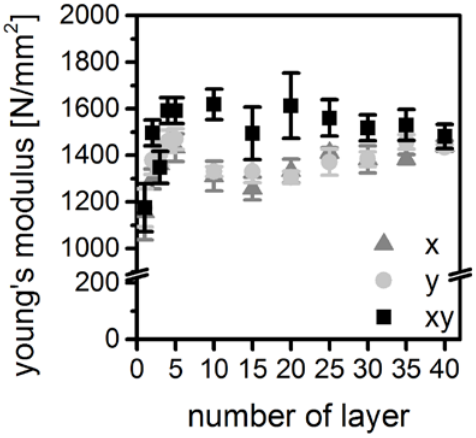


figure 4: young’s modulus for the specimens produced with different hatching-strategies in dependency of the number of layers

Concerning the tensile strength the independent from the hatch orientation the tensile strength increases up to a layer number of 15 -20 layer. Between the x and y hatching orientation, no difference occurs in the resulting strength. The alternate hatched specimens showed an earlier increase of the tensile strength beginning at a layer number of 5 up to 15-20 layer. A further increase showed no differences between unidirectional hatching and alternate hatching occurs.

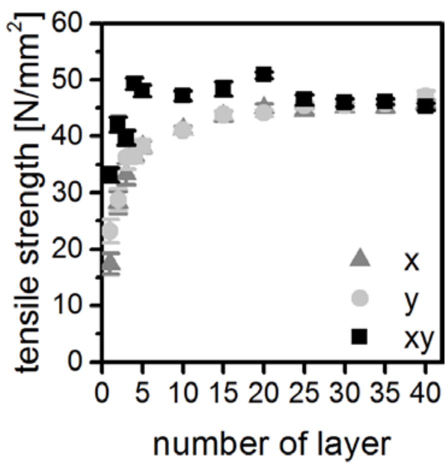


figure 5: tensile strength for the specimens produced with different hatching-strategies in dependency of the number of layers

Within the mechanical testing a poisson’s ratio occurs as the elongation along the mechanical load is higher than perpendicular. The ratio therefore can be seen as hint for the elongation at break and therefore the formation of a yield strength. In figure 6 is the poisson’s ratio for parts produced of 5, 10, 20 and 40 layers. The comparison exhibits a slight difference between the poisson’s ratio occurring from the hatching strategy. It shows that the xy alternative hatching leads to the smallest poisson’s ratio independent from the number of layers. In general, an increase of the poisson’s ratio with an increasing number of layers can be seen. In comparison the hatching strategy between x and y hatching show nearly no difference in the resulting poisson’s ratio. The increasing ratio therefore may lead to a higher deformation in the zone of the highest mechanical stress. As higher layers lead to more elastic deformation behavior of the parts.

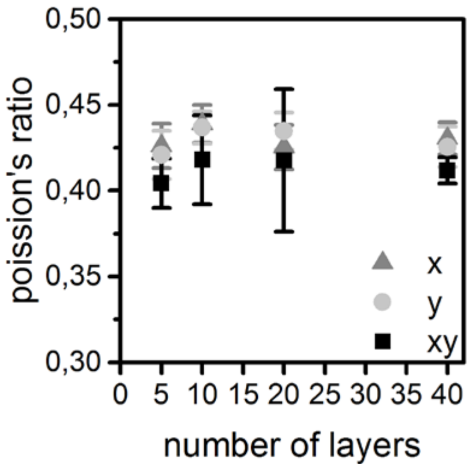


figure 6: poisson's ratio for the specimens produced with different hatching-strategies in dependency of the number of layers

As the elongation at break and the poisson's ratio showed differences resulting from the hatching strategy the force at elongation is shown in figure 7. The comparison of the elongation behavior differences of the hatching strategies occur. It seems that the x-hatching which is perpendicular to the force application and has the shortest hatching lengths and therefore the longest hatching time per layer develop the lowest elongation. The elongation can be increased by using the y-hatching and leads to the highest elongation for the xy-hatching. Comparing the elongation in dependency of the layer number, it can be seen that with a higher numbers of layers the elongation and the formation of a yield strength increase for the different hatching orientations. Combining the elongation and the poisson's ratio the deformation is further increased with the xy-hatching strategy and therefore higher elongation occur. It can be seen independent from the hatching strategies that the resulting force at the yield strength are nearly equal for all hatching strategies.

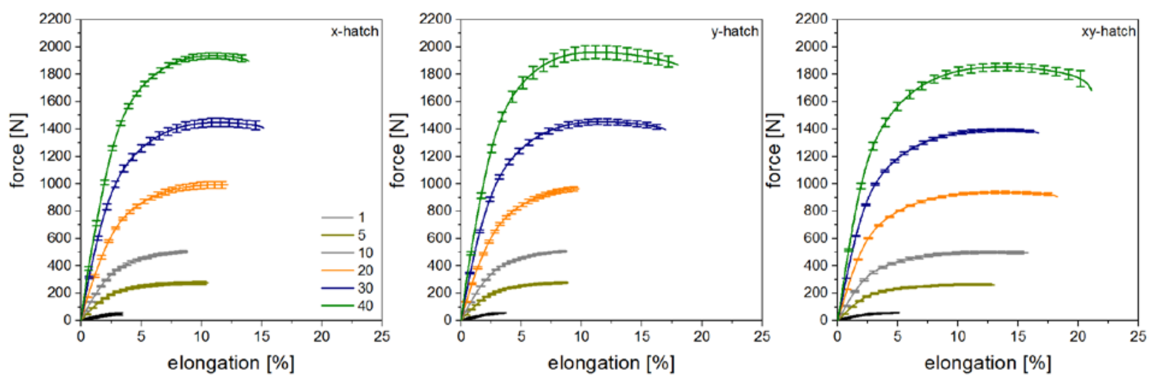
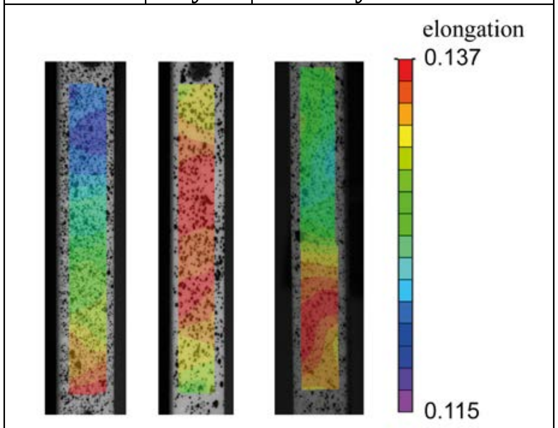


figure 7: force-elongation of different layer number and hatching strategies

Correlating the elongation at break (figure 3) and the formation of a yield strength (figure 7) the deformation behavior of the specimens with 40 layers are shown in table 4 by the elongation along the specimen's length at yield strength. In general, the deformation zone increases with a higher number of layers independent form the hatching strategy, which correlates with the increasing elongation at break and the forming of a yield strength. Comparing the different hatching strategies, differences occur depending the deformation zone. As can be seen the y-orientation in comparison to the x-orientation leads to a bigger deformation zone. With 40 layers all specimens showed a lager deformation zone and lead to the broadest deformation for the xy-hatching strategy which therefore leads to the highest elongation at break and the formation of the broadest yield strength.

table 4: load distribution in direction of the force application across the specimens in dependency of the hatching strategy at yield strength

X	y	Xy



Discussion

As the results show, differences in the mechanical behavior occur depending on the layer-wise building and the used hatching strategy. By using unidirectional hatching strategies in comparison to an alternating hatching strategy differences occur in the scanning times and therefore may influence the temperature in the molten cross-sections during the processing of the specimens. All of the used hatching strategies showed round edges of the cross-sections at low number of layers which may result from the free volume contraction of the powder and the area between the powder during the melting process. The forming of sharper side surfaces and more detailed edged on the top edges with an increasing number of layers may result from the layer wise processing by which with increasing layers to uneven surface can be filled by fresh powder until an even surface occurs. With higher layer numbers the first layers may also cool down due to the deposition of fresh powder over time and therefore no further geometrical deviation occur and the layers are added flat. The analyzation of the surface roughness showed a decrease for the roughness with increasing layers and also a higher roughness for the bottom surface and the lowest roughness for the specimens produced by alternating hatching. The higher roughness of the bottom results from the attaching of the powder to the molten cross-sections and the fast cooling of the first layers. Within the specimens with a higher number of layers the top surface has a reduced roughness due to semi molten particles because of a higher temperature in the melt. By characterizing the mechanical properties of the specimens, the main differences in the behavior occurred in the elongation at break and the development of the yield strength. The increase with higher number of layers mainly result from a decrease of the ratio between the influence of the rough surface and the resulting notch effect to the cross-section of the parts. As the alternating hatching strategy showed the highest elongation at break and an earlier forming of yield strength and longer plateau, this may result from a more homogenous melting of the specimens in comparison to the unidirectional hatching strategies which lead to higher elongation at breaks for hatching along the introduction of the mechanical strength in comparison to the x-hatching. Due to this behavior a more ductile deformation behavior of the alternating hatched specimens occur and therefore also the poisson’s ratio is decreased which leads to higher yield strengths as the mechanical load can be exhausted by the deformation of the specimens over the hole cross-sections as the load distributions exhibited.

Summary and Outlook

As parts produced by selective laser sintering show a strong dependency of the layer-wise manufacturing and a resulting anisotropy. The presented investigations therefore showed the influence of the two constant processing steps the hatching and the layer-wise building on the resulting specimen properties. Therefore, parts were produced with different number of layers but a constant layer-thickness using two unidirectional and an alternating hatching strategy. The resulted part properties showed a dependency of the surface roughness of the hatching strategy whereby alternating hatching lead to the smoothest surface and an increase in the part thickness. In addition, the forming of the parts shown in microscopy exhibited that the alternating hatching leads to a more accurate forming of the defined cross-sections. The resulting mechanical properties showed a strong dependency of the number of layers and therefore an increase in the specimen thickness as well as on the hatching strategy. The alternating hatching strategy led to nearly equal tensile strength and young's modulus but resulted in a higher elongation at break as well as a higher yield strength and lower poisson's ratio in comparison to the unidirectional hatching strategies.

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