STATIC STRENGTH ANALYSIS OF BEAM MELTED PARTS DEPENDENT ON VARIOUS INFLUENCES

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Abstract

For the optimum design and correct use of beam melted parts extensive material comprehension is necessary. For this reason this paper presents static strength analysis of beam melted parts dependent on various influences such as manufacturing position and orientation, exposure strategy and surface quality. It turned out that the anisotropic material properties can be described by the transversal isotropy (2D) since the azimuth angle displays small dependence especially in combination with the rotate scan strategy. In contrast to this the polar angle has the biggest influence at all exposure strategies. Another great influence arises from the surface finish - the better the surface finish the higher the static strength. The exposure strategies in turn have the smallest effect on the static strength.

1. Introduction

Additive manufacturing (AM) technologies allow the production of solid 3D models with high complexity by joining formless material in layers on the basis of digital 3D models. Hereby these technologies make a contribution towards developing individual, innovative and technological products. In many areas of application the beam melting technology emerges as an alternative solution compared to conventional manufacturing methods. This favorable trend of manufacturing metal parts is reinforced by the use of one-component powder materials identical to series materials. This also results in new development and application potentials. [1][2]

Today's advancement of the market requires innovative thoughts and further development of additive manufacturing technologies like beam melting. This neutral term is relatively new and was defined and used in the VDI Guideline 3404 [3] for the first time. Here beam melting is also referred to as Selective Laser Melting (SLM), Laser-Cusing, Direct Metal Laser-Sintering (DMLS) or Electron Beam Melting (EBM). In comparison to conventionally made parts, beam melted parts do not show consistent material properties which lead to limited acceptance in industry and research. However an exact description (proof) of material properties of beam melted parts is very important especially considering these parts being assembled and used as end-products. In order to reduce the risk of mechanical defects in a part, a comprehensive material understanding is essential. A failure of these parts can be avoided in advance by applying appropriate designs and correct manufacturing of the parts. For this reason static strength analysis of beam melted parts made of stainless steel were performed by the Rapid Technology Center (RTC) Duisburg depending on different manufacturing orientations, exposure strategies and surface qualities. Also dynamic strength analyses were investigated at the RTC Duisburg in order to increase the material understanding. The machine for production is the EOSINT M 270 from EOS GmbH.

2. State of the art

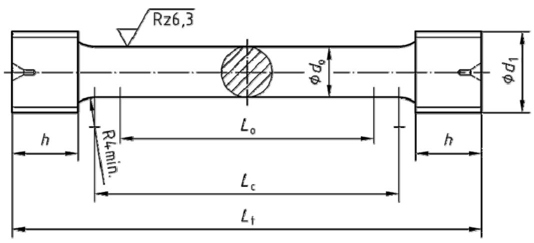
With regard to anisotropic strength characteristics of beam melted parts scientific data were published by Haberland and Meier [4][5] with a stainless steel material (1.4404). They found out that the static strength investigations at a layer thickness of 75 µm resulted in a decrease of the tensile strength of about 68 % and a decrease of the elongation at break of about 84 % at specimens that were manufactured in the horizontal direction compared to those manufactured in the vertical direction. Here the layers of the parts are not firmly bonded to one another. A reduction of the layer thickness to 50 µm resulted in a great reduction of the anisotropic behavior. At these smaller layer thicknesses the tensile strength decreases at 16 % and the elongation at break decreases at 41 % in the same two manufacturing directions. The most extensive studies to anisotropic material properties of beam melted parts were presented in [6] by Rehme and Emmelmann so far. In their paper 145 tensile specimens (material 1.4404) were beam melted twice perpendicular to the surface of a hemisphere. Subsequently all specimens were machined on a lathe and tested on a tensile machine. The results here also show a decrease of the tensile strength at 12.6 %. But here is the maximum at 15° and the minimum at 75° to the xy-plane of the building chamber. In these two orientations the elongation at break is lowered by 63 %. The large standard deviation of the individual values, the strong decrease of the elongation at break and the angles of the extreme values are amazing.

3. Experimental Setup

Former strength analyses mostly consider post processed samples to compare the results on the one hand to conventional made parts and on the other hand to fulfill the requirements in accordance with DIN (standards). Another reason for turning the samples is to exclude the influence of the relatively rough beam melted surface (notch effect). However in practice only a few parts are processed to perfection. Most parts are only sandblasted. This may have economic reasons or there is no need for finishing the surface (non visible surfaces) or surface areas are not accessible with tools. To be able to assess these parts with regard to their strength characteristics and to be able to design parts optimally, strength values of the raw and just sandblasted material are also necessary. The performed strength analyses at the RTC Duisburg at the University of Duisburg-Essen can be utilized to describe the phenomenon of the anisotropic material properties of beam melted parts in detail and statistically ensured. All tests have been carried out with the GP1 stainless steel on an EOSINT M 270 machine from EOS GmbH and with layer thicknesses of 20 µm (standard parameters). In addition to the effect of the orientation of the samples also the effects of different exposure strategies and surface conditions are investigated.

Specification of tensile specimens

To ensure economic efficiency in consideration of the high number of tensile specimens, the form B out of DIN 50125, a round specimen with a screw head, a sample diameter of 5 mm and a reference length of 25 mm was chosen for the investigations (see Fig. 1).



d_0	L_0	d_1	*h min.*	L_c	L_t *min.*
5	25	M 8	7	30	50

measurements in mm

Fig. 1: Tensile specimen DIN 50125 - B 5 x 25 [7]

Due to the fact that in addition to the orientation influence also different exposure strategies and surface qualities are investigated the number of different spatial orientations is held as low as possible without limiting the result. On the basis of various preliminary considerations the choice of possible orientations of the tensile specimens on the building platform can be reduced to an octant of the coordinate system and perpendicular to the surface of an eighth spherical. Moreover the angle between most specimens is set to 22.5°. So the following spatial arrangement of the specimens arises (see Fig. 2).

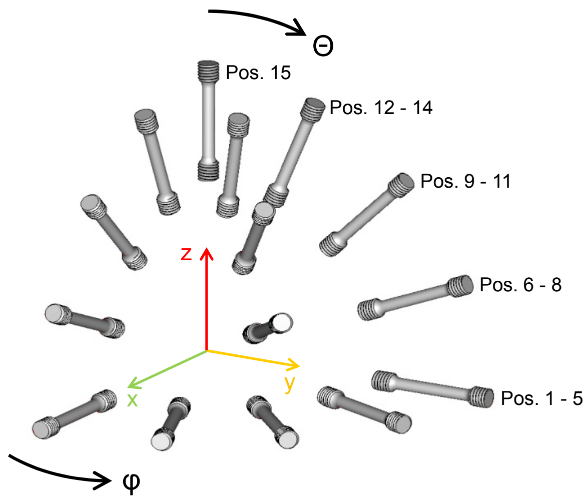


Fig. 2: Spatial arrangement of the tensile specimens per group [8]

Altogether, there are 15 samples with different orientations in each group. In order to check the directional influence of different exposure strategies to the material properties, the above-mentioned group will be manufactured with both strategies – the xy-scan strategy and the rotate scan strategy. The scan vectors of the xy-scan change the direction at 90° from layer to layer and at the rotate scan they change the direction at 67° from layer to layer. For further investigations of the dependence of the surface quality to the manufacturing orientation of the samples on the building platform the tensile specimens are manufactured near-net-shaped and as a solid cylinder. This cylinder is then turned to the desired geometry with a surface quality of Rz = 6.3 µm according to DIN 50125. All four different groups are manufactured three times in different build processes to statistically ensure the results and to make a statement about the process stability. One of these build processes can be seen in Fig. 3.

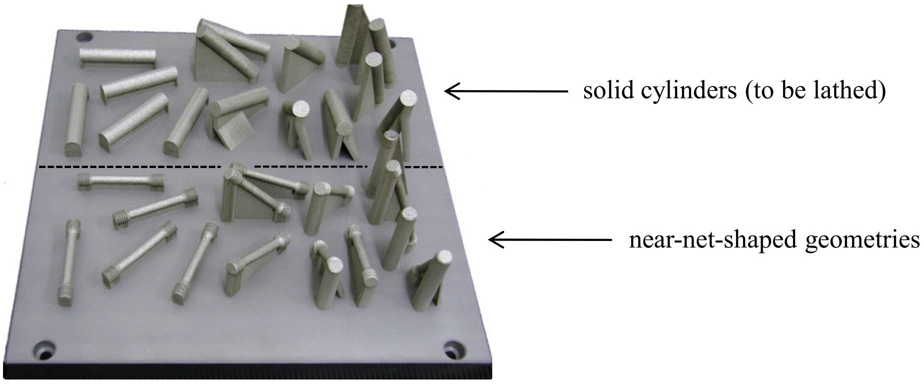


Fig. 3: Building platform with two groups of tensile specimens

4. Results and Discussion

The evaluation of the results of the different groups that differ from each other by the surface quality and the exposure strategy is made depending on the polar angle θ and the azimuth angle φ. When investigating the dependence on the polar angle θ all samples of each group mentioned above are considered. In contrast to this the dependence on the azimuth angle φ is investigated on samples oriented at φ = 0°-90° and at θ = 67,5°-90°. Here the limitation of the polar angle θ results from the minor influence of the cross section areas (exposure surface) of the samples at lower values for the polar angle θ (see Fig. 4).

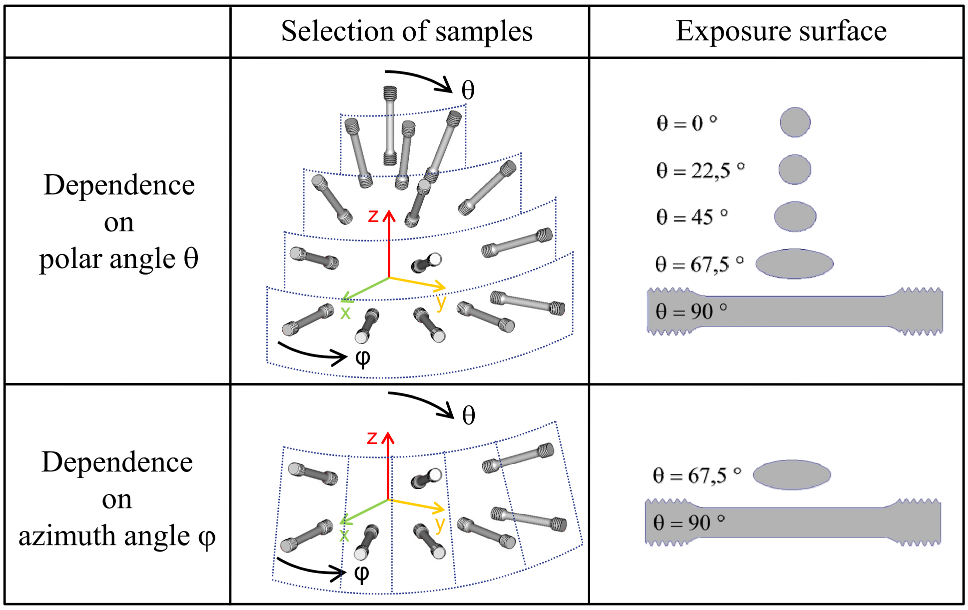


Fig. 4: Dependence on polar and azimuth angle [8]

Tensile strength in dependence on the polar angle θ

The tensile strength shows a very strong directional dependence on the polar angle θ (see Fig. 5). As expected, the tensile strengths of all samples in the respective groups have the biggest values at polar angles of 90° (parallel to the xy-plane). These values decrease with decreasing polar angles up to a minimum at θ = 0°. On average the tensile strength values of all samples at θ = 0° (877 N/mm²) are about 8 % lower compared to those at θ = 90° (954 N/mm²).

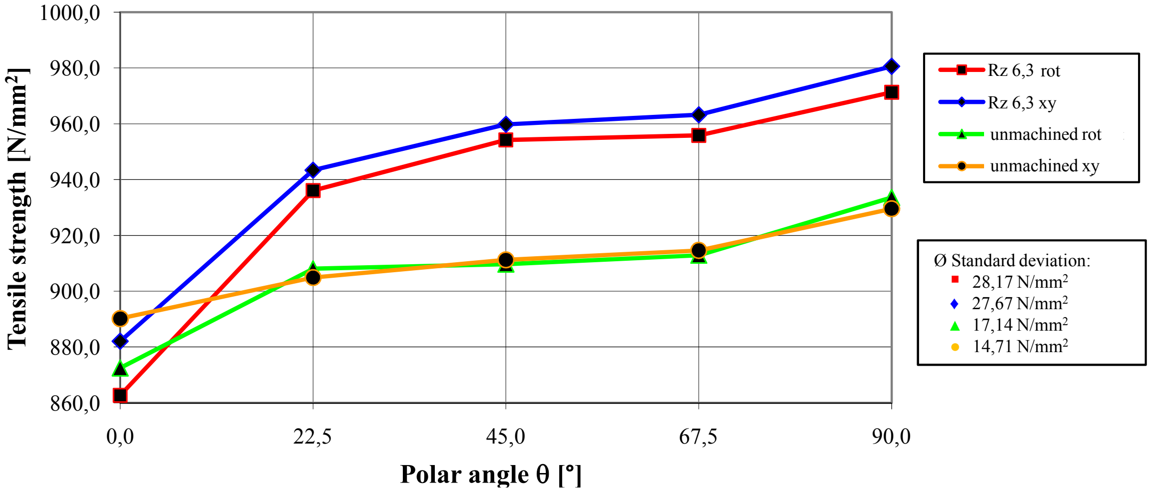


Fig. 5: Tensile strength in dependence on the polar angle θ [8]

Furthermore the tensile strengths of the lathed samples with a good surface quality are about 5 % higher than the unmachined. There is only one exception at the vertical manufactured samples at the polar angle of 0°. Here the values of the unmachined samples at both exposure strategies are about 1% higher compared to the values of the processed samples. Nevertheless the standard deviations of the tensile strength values are higher. It can also be seen that the strength values of both scan strategies at the machined samples (red and blue line) only decrease about 4 % between θ = 90°-22.5° but about 6.5 % in the last segment. A similar but flatter trend can be seen at the unmachined samples with the rotate scan strategy. The values of the xy-scan are in average 1.1 % higher compared to those of the rotate scan at the machined samples. No trend with regard to the scan strategy can be seen at the unmachined samples.

Tensile strength in dependence on the azimuth angle φ

The tensile strength as a function of the azimuth angle φ does not show such a strong dependence compared to the polar angle θ (see Fig. 6). An even smaller dependence can be seen at the rotate scan strategy. The strength values of both exposure strategies only differ by a maximum of 2 % from each other at the same surface quality. The biggest variation of the tensile strength in dependence on the azimuth angle in a group can be seen at the post-processed specimens with the xy-scan strategy. Here the maximum difference of the values is 4.6 %. The progression of the strength values is more homogenous for both surface qualities at the rotate scan strategy. Here the strength values of the machined samples with a good surface quality are about 4-5 % higher compared to those that are unmachined. Especially at the unmachined specimens but also at the machined specimens and the rotate scan strategy you can see small local maxima of the tensile strengths at azimuth angles of 22.5° and 67.5°.

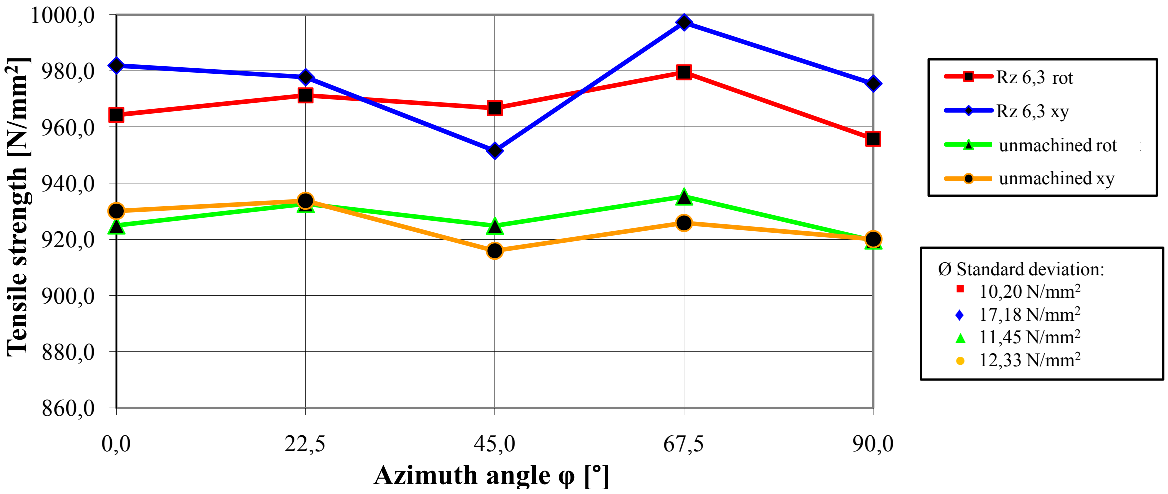


Fig. 6: Tensile strength in dependence on the azimuth angle φ [8]

<u>Elongation at break in dependence on the polar angle θ</u>

An even bigger dependence on the polar angle θ can be seen at the following graphs in Fig. 7 for the values of the elongation at break.

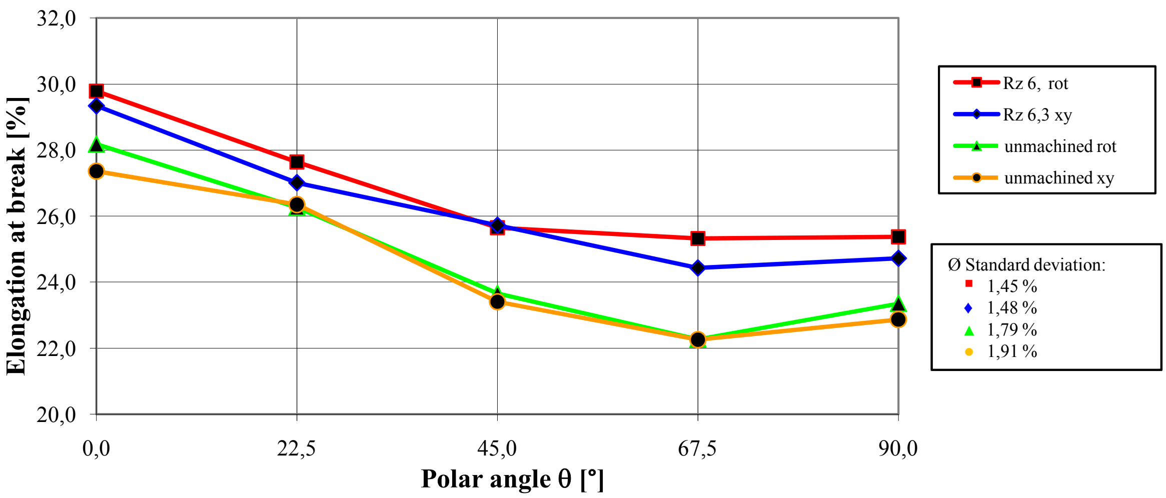


Fig. 7: Elongation at break in dependence on the polar angle θ [8]

All in all the values of the elongation at break are decreasing with increasing polar angles in every group. The elongation at break of the machined samples drops about 15.3 % from average 29.6 % at θ = 0° to about 25 % at θ = 90 %. The values of the unmachined specimens are lowered by an average of 16.8 % in the same directions. In addition these values are 5-12 % below the values of the machined samples. All graphs in Fig. 7 have a local minimum at polar angles of 67.5° which is even more obvious at the unmachined samples. But also here the standard deviations of the groups are higher than the variation of the graphs. There is no clear development in a certain direction when looking at the different exposure strategies.

Elongation at break in dependence on the azimuth angle φ

In Fig. 8 the values of the elongation at break are shown in relation to the azimuth angle φ.

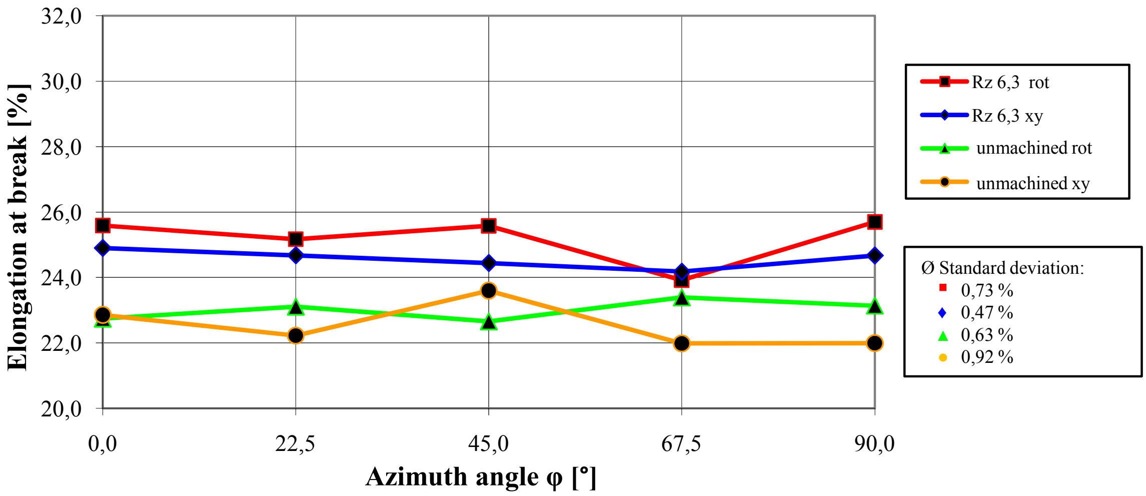


Fig. 8: Elongation at break in dependence on the azimuth angle φ [8]

When looking at the graphs in Fig. 8 no significant dependence on the orientation can be recognized. But it can be seen that the values of the elongation at break of the machined samples are about 10 % higher than the unmachined. The fluctuation of the values for the xy-scan strategy and the machined samples are smaller than those of the rotate scan strategy. However this ratio reverses for the unmachined specimens.

5. Conclusion

The different material properties here result from the layered structure of the beam melting process compared to conventional manufacturing processes. This is also the reason for the great influence of the polar angle to the tensile strength and the elongation at break. The building layers of the specimens with $\theta = 90°$ are parallel to the loading direction and with $\theta = 0°$ they are perpendicular to it. In addition the dependence on the polar angle can be explained by the increasing number of layers with decreasing polar angles. So the horizontal oriented tensile specimens at $\theta = 90°$ consist of 400 layers whereas the vertical oriented specimens at $\theta = 0°$ consist of 2500 layers. Due to the higher number of layers the chances of an incorrect feeding process of the powder or an incorrect melting process with the laser increases. Nevertheless the tensile strength only varies about 8 %. The variation of the azimuth angle φ has no important influence on the results. That means more homogenous values of the tensile test can be achieved by the rotate scan strategy. This is due to the fact that the exposure directions are rotating at 67° from layer to layer. So every 180th layer has the same exposure direction. Furthermore the strength values increase with better surface qualities. This is due to the notch effect. Since the material properties only change slightly at a rotation around the z-axis the description of the beam melted material properties can be reduced from a 3D anisotropy to a 2D anisotropy (transversal isotropy). That also simplifies the implementation of the material properties for FEM analysis.

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