Development of Residual Stresses Induced by Deep Rolling at an Additive Structure

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Abstract

This paper shows the residual stress distributions over the depth of a dice out of 1.2344 produced as an additive structure. Because of the layer structure (obtained by SLM) it gives two interesting directions (along with the layer and perpendicular to the layer) to be investigated concerning residual stresses. Next a deep rolling process was done. Deep rolling gives different residual stress distribution. Perpendicular to the rolling track higher compressive residual stress is induced in comparison along the track. Combined with the layer structure of the dice, four different combinations are obtained that are investigated concerning residual stresses.

Keywords: residual stress, deep rolling, additive structure.

Introduction

Additive manufactured structures are very interesting for one-piece manufacturing. The wish is to use them in dynamic applications. Compared with conventional components, the durability is not very high. An increase could be done by mechanical surface treatment like shot peening and deep rolling. The characteristic of the compressive residual stresses plays an important role in the fatigue strength. Deep rolling is one common method to induce high compressive residual stresses with a deep penetration [3]. The layer structure of an additive manufactured component gives different compressive residual stress profiles after shot peening [4,5]. Resulting of this fact, an important question is, how are the compressive residual stress profile by deep rolling in dependence of the layer orientation.

Experimental Methods

Specimen

For this experiment, a specimen with the shape of a dice was printed with the SLM (Selective Laser Melting) method. The edge length is 30 mm, and the layer thickness is 30 µm. The material is H13 (1.2344) with a hardness of 52 HRC.

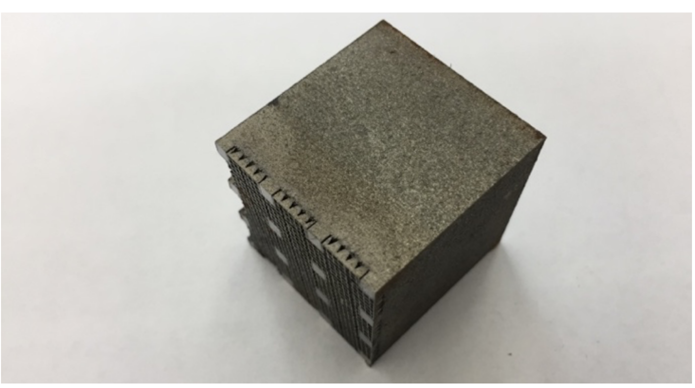

Figure 1: The specimen

Residual Stress Determination
The residual stress was determined via X-ray diffraction. The used equipment was a Strainflex MSF-2M from Rigaku. The tube had a Cr-anode with CrK_α radiation and a current of 10 mA. The detector was a photomultiplier with a slit aperture on the tube and detection side. The exposed area was 6 mm * 8 mm. The measurement errors are +/- 30 MPa or 7% (the higher one). To get the full residual stress profile into the depth, the material was removed electrolytically by an area of 8 mm diameter.

Deep Rolling
The specimen was deep rolled with the tool HG 6 from Ecoroll (see: https://www.ecoroll.de/produkte/hydrostatische-werkzeuge.html). This hydrostatic tool has a ball of 6 mm in diameter. The specimen was rolled in a meander shape with a spacing ΔX of the tracks ΔX =150 µm, and the pressure p was p = 400 bar.

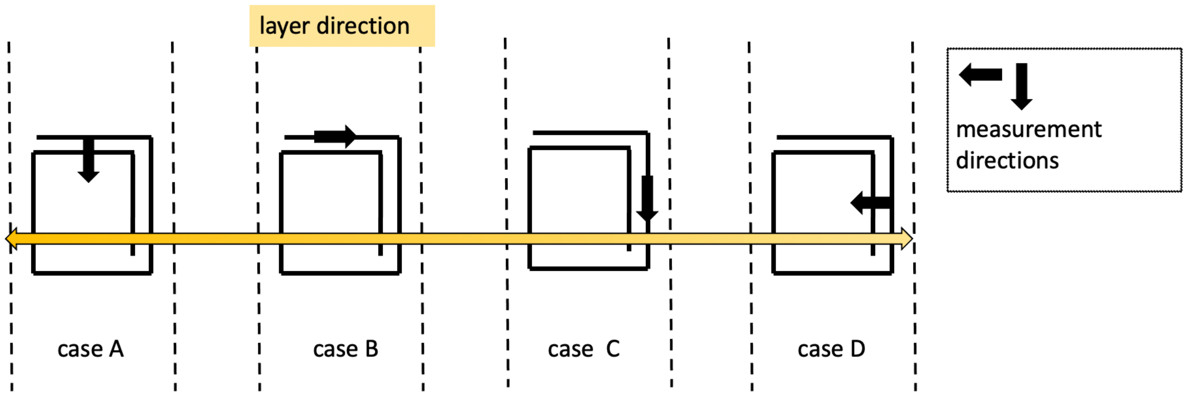

Figure 2: The four different cases between deep rolling and layer structure

Deep rolling induces fundamental different residual stresses along and perpendicular to the rolling track, which means there are four cases:

Table 1: Explanation of the different cases (**≣** = parallel**,** ⊥ = perpendicular)

case	**rolling track ↔ layer directions**	**measuring direction ↔ trolling track**
A	≣	⊥
B	≣	≣
C	⊥	≣
D	⊥	⊥

These four cases were examined concerning residual stress distribution in dependence of the depth.

Experimental Results

At first, the residual stress profiles for the non-deep-rolled side of the dice are shown what the initial state is (fig. 3 a). Additionally, the full width of half maximum (FWHM) is given as a relative the number of dislocations (fig. 3b). If there are dislocations, the spacing of the atomic layers differs a lot which causes a widening of the reflected beam.
There are different residual stress distributions. All residual stresses are tensile stresses, but perpendicular to the layers, they are very high in opposite to the moderate tensile residual stresses along with the layers. The FWHM is very high, which means lots of dislocation.

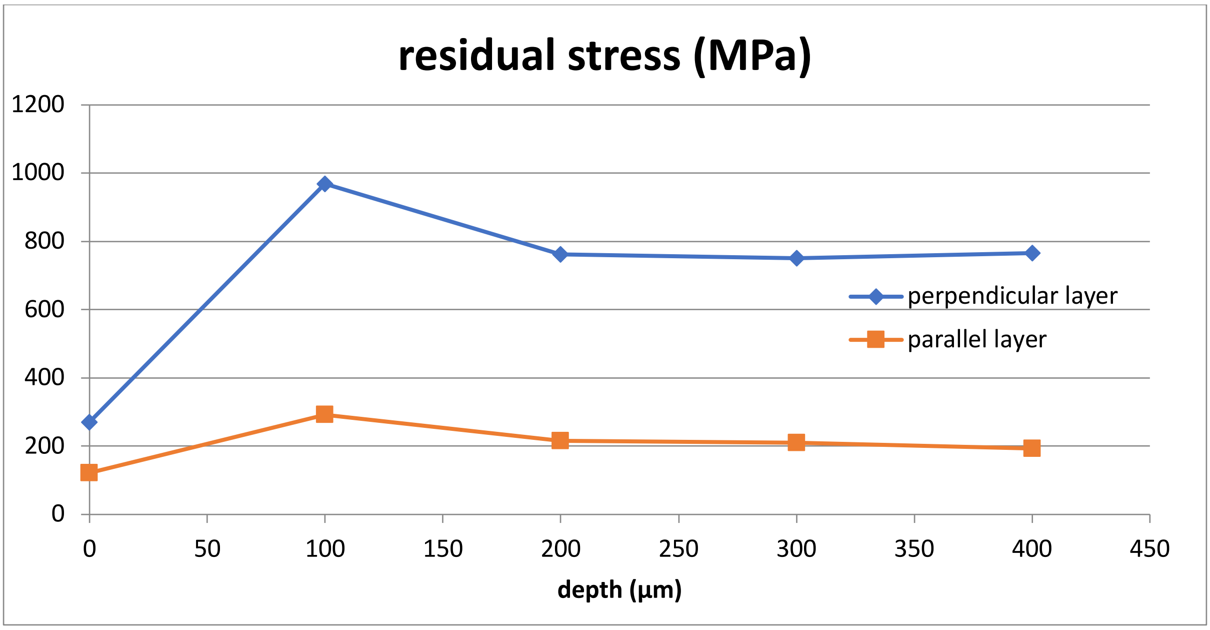

Figure 3a: Residual stress profile in the untreated state

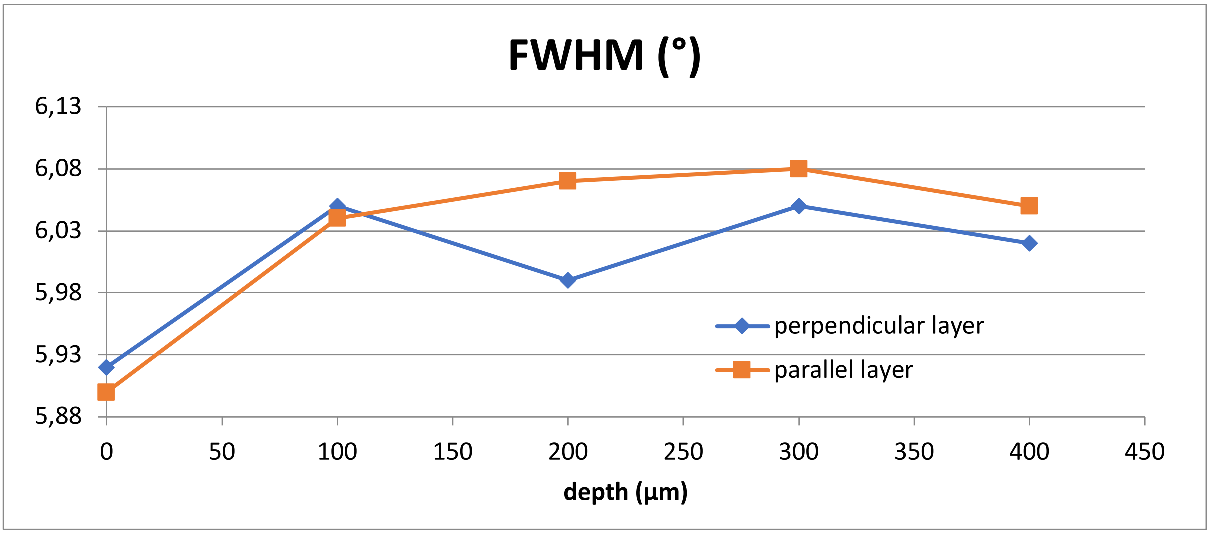

Figure 3b: Development of the FWHM over the depth.

Interesting is, to compare cases A and D respectively cases B and C. At cases A and D, the residual stresses are determined perpendicular to the rolling track. For deep rolling in this direction, higher compressive residual stresses are expected. Cases B and D are both along the track, and the expected compressive residual stresses are significantly lower. In this case, the profile looks like induced by Hertzian pressure. Perpendicular, the compressive residual stresses are decreasing continuously with the depth [6, 7].
Figure 4 shows the comparison of case A and case D in the residual stresses and the FWHM.

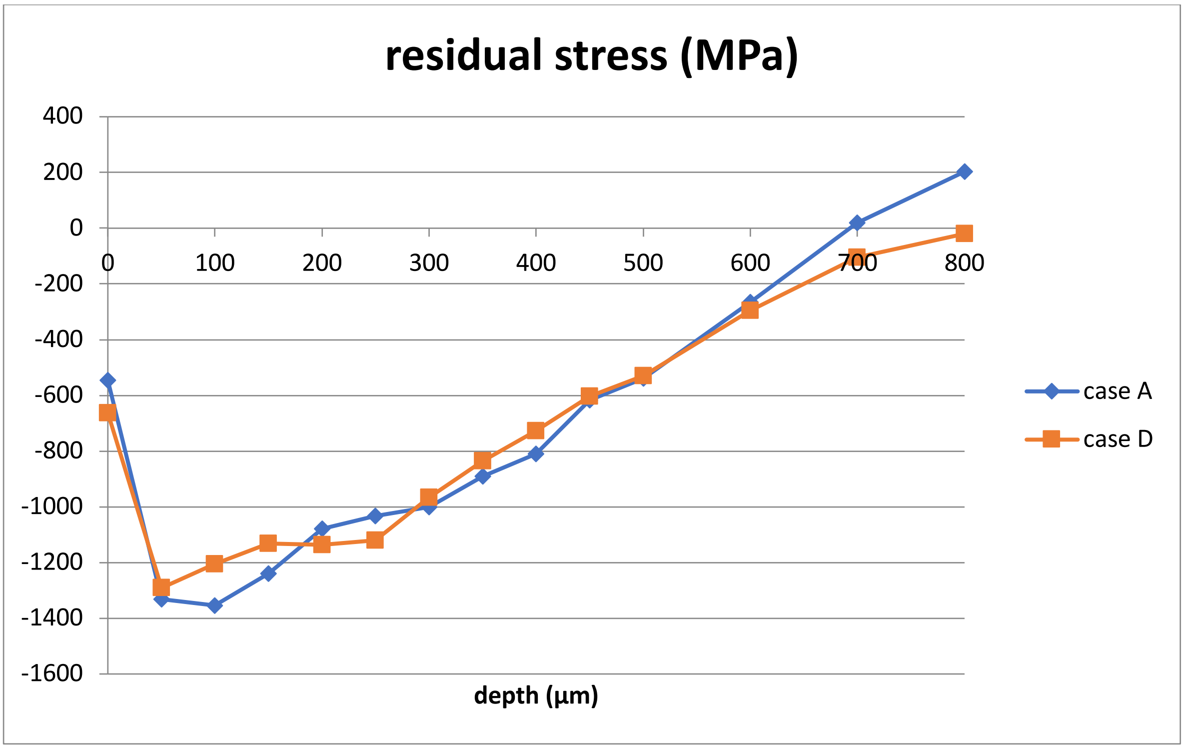

Figure 4a: Residual stress distribution of the cases A and D

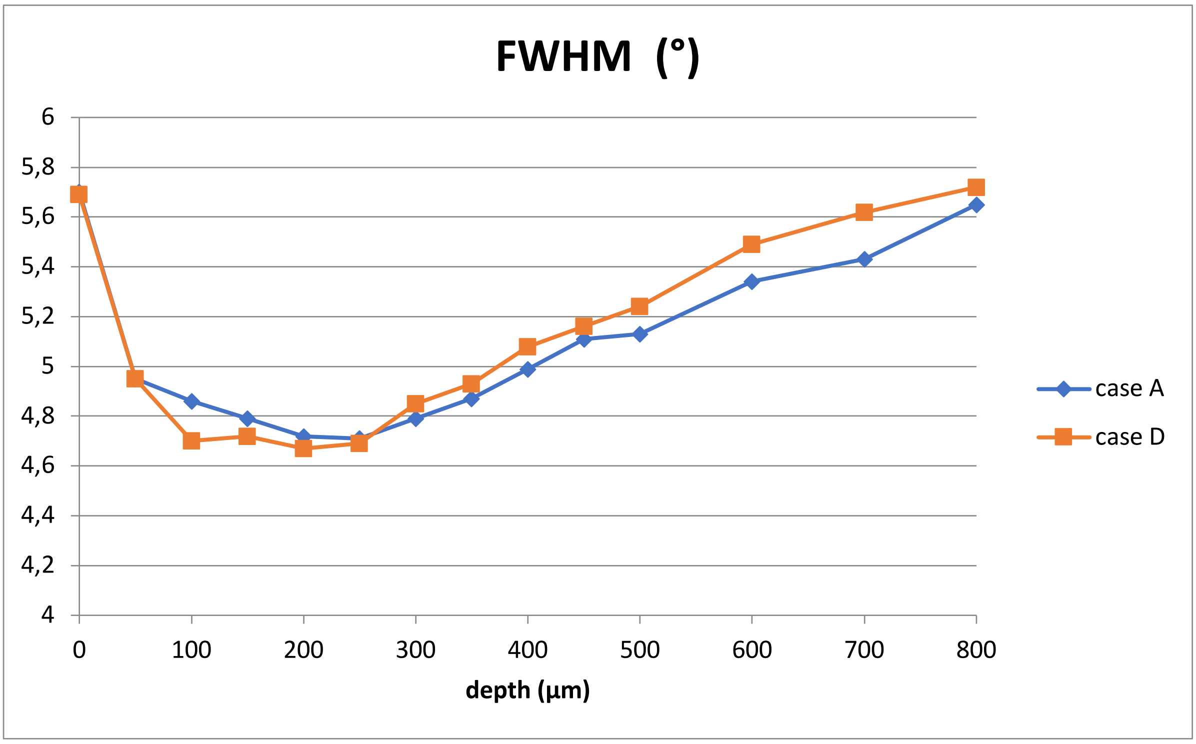

Figure 4b: Development of the FWHM over the depth for cases A and D

The residual stress profile and FWHM for cases B and C are shown in figure 5. The typical residual stress distribution induced by Hertzian pressure is achieved, and the compressive residual stresses are lower compared with the compressive residual stresses perpendicular to the rolling track.

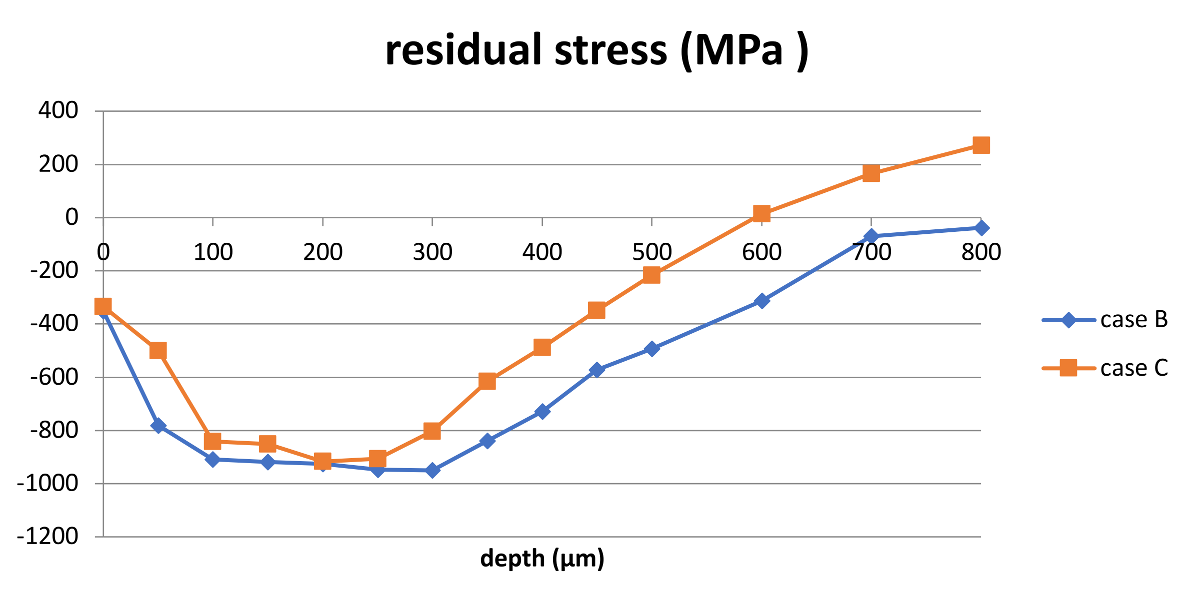

Figure 5a: Residual stress distribution of the cases B and C

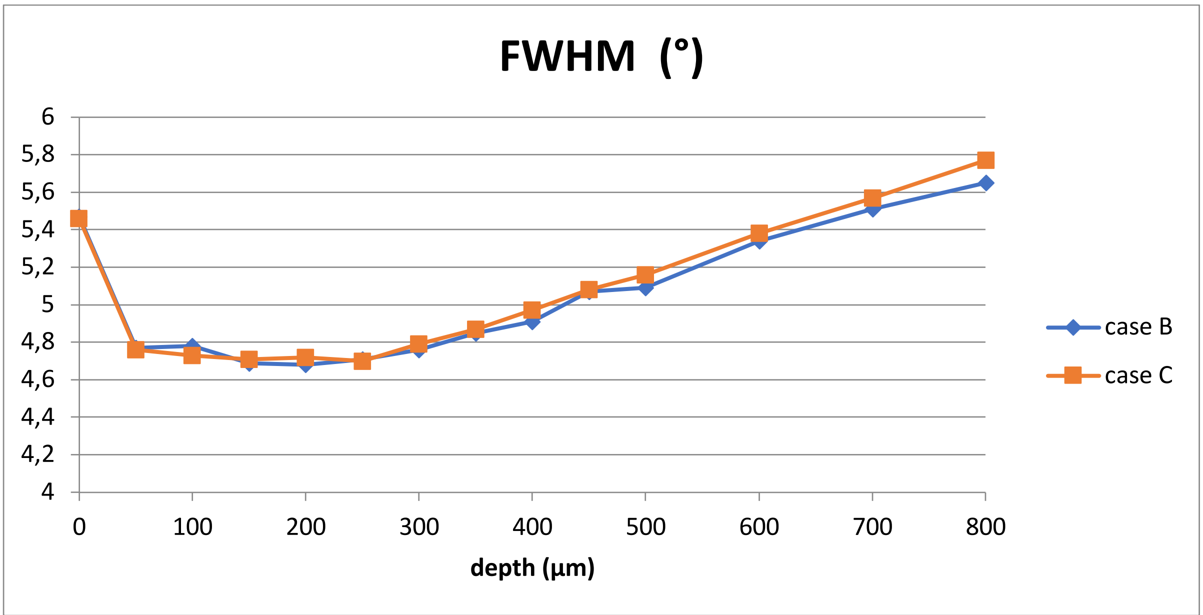

Figure 5 b: Development of the FWHM over the depth for cases B and C

The interpretation of the result will follow now.

Discussion and Conclusion

The different tensile stresses are strongly dependent on the layer orientation at the untreated surface. After deep rolling, this splitting of the profiles is totally gone for the induced compressive residual stresses perpendicular to the rolling direction (cases A and D). The behavior of the residual stresses is as expected surface values [6,7]. Here, surface effects cause the lower values of the compressive residual stress. No dependence on the layer orientation can be seen. The distribution of the FWHM shows that the number of dislocations has been decreased like also at shot peening. [8] At the maximum of the compressive residual

stress, the dislocations are moving to the grain borders, and the scattering of the X-ray beam is less.
Looking at the residual distributions that are along the track, show the distributions obtained by Hertzian pressure and the maximum of the compressive residual stress is lower compared to the stresses perpendicular to the track. The splitting of the profiles started around 300 µm in depth. Is the track along with the layer, a higher penetration depth of the compressive residual stresses can be observed. The FWHM distribution is nearly the same as perpendicular to the track.
The conclusion is that the induced residual stresses by deep rolling are dependent on the layer orientation. For a deep rolled component, it is important to take this fact into account to improve the fatigue strength in an optimal way.

References

[1] D. H. Wohlfahrt, *Einfluß von Mittelspannung und Eigenspannung auf die Dauerfestigkeit*, VDI-Berichte 661: Dauerfestigkeit und Zeitfestigkeit, VDI-Verlag, Düsseldorf, 1988, p 99

[2] M. Habschied, B. de Graff, A. Klumpp, V. Schulz, F*ertigung und Eigenspannungen,* Journal of Heat Treatment Materials, Vol. 70 (2005) 3, p 119

[3] I. Altenberger, *Deep rolling – the past, the present and the future*, in V. Schulze, A. Nikulari: Shot Peening and other Mechanical Surface Treatments, IITT-International, Noisy-le-Grand, 2005, pp 144-155

[4] E. Müller, *Die Ausbildung von Eigenspannungen durch Kugelstrahlen bei einer additiven Struktur*, in H.-J. Christ (ed.), Werkstoffe und Bauteile auf dem Prüfstand, Inventum GmbH, Sankt Augustin, 2019, pp 57-62

[5] E. Müller, *Eigenspannungsverteilungen durch Kugelstrahlen in einer additiv gefertigten austenitischen Struktur*, in S. Brockmann, U. Krupp: Werkstoffe und Bauteile auf dem Prüfstand, Stahlinstitut VDEh, Düsseldorf, 2021, pp 343-346

[6] E. Müller, *Comparison of the Residual Stresses Induced by Shot (Stress) Peening and Rolling in Spring Steel*, in L. Wagner (ed.): Shot Peening, Wiley-VCH-Verlag, Weinheim 2003, pp 441 – 446,

[7] E. Müller, *Evolution of the residual stresses by stress rolling*, in V. Schulze u. A. Nikul-Lari (ed.): Shot Peening and other Mechanical Surface Treatments, IITT-International, Noisy-le-Grand, 2005, pp 436 – 441

[8] E. Müller: *Die Ausbildung von Eigenspannungen nach der Additiven Fertigung und nach dem Kugelstrahlen eines ferritischen Stahls*, in M. Eiber, R. A. Richard (ed.): Additiv gefertigte Bauteile und Strukturen, Bericht 406, DVM, Berlin, 2021, pp. 31-45, https://doi.org/10.48447/ADD-2021-BB