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Finish machining of laser beam melted parts

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Abstract

The finish machining process of parts manufactured by laser beam melting is of high concern due to the lack of surface accuracy. Therefore, the focus of the work lies on the influence of the build-up direction of the parts and their effect on the finish machining process. The investigated process is drilling with a drill diameter of 6.8 mm and a drilling depth of 30 mm using lubrication. The investigations contain the materials stainless steel (1.4404), titanium (Ti6Al4V) and nickel-base alloy (IN718). Due to the difficulties of machining of nickel-base alloys a cemented carbide drill with a special nitride based coating is utilized for IN718. For the material Ti6Al4V and 1.4404 a cemented carbide drill with a TiAlN coating is chosen. During the experiments the feed rate was varied in the range of 0.1 mm/rev and 0.2 mm/rev. Additionally, the selection of the cutting speed varies for the different materials. For 1.4404 cutting speeds between 60 m/min and 100 m/min were chosen, for IN718 and Ti6Al4V more moderate cutting speeds between 25 m/min and 55 m/min were selected. The results provide the base for processing strategies. Therefore, the specimens are solely laser beam melted without post-processing like heat treatment. During the experiments the drilling forces and the resulting roughnesses are evaluated.

Post processing, Drilling, Laser beam melting

1. Additive manufacturing and finish machining process

In comparison to machining Additive Manufacturing (AM) is rather young of age. AM offers new possibilities in the field of engineering for example integration of functions in parts or lightweight design. Therefore, the interest in research for design limitations or positioning advices in the build envelope, which have to be considered while designing parts are of high interest to minimize the amount of rejects [1].

Holes can be already implemented in the design of a part which shall be manufactured by AM. For holes orientated perpendicular to the build-up orientation of the part a drop shape cross section of the holes is needed to avoid support structure [2]. Even if the holes can be orientated parallel to the build-up orientation of the part the lack of accuracy remains. Therefore, it is advantageous to drill the holes in solid material. The drilling process guarantees a more precise result and assures an assembly possibility at low tolerance level.

Rysava et. al. [3] analysed the quality of holes (1.6 mm diameter) concerning the perpendicularity and constancy of diameter to find the best drilling parameters to achieve these objectives. The experiments were done under dry conditions for additive manufactured Ti6Al4V dental pins. They identified a cutting speed of 60 m/min and a feed per tooth of 10 μm. The build-up orientation of the parts is not mentioned in the paper. Altogether, the machining process of laser beam melted parts is not investigated in detail.

This paper focuses on the drilling process using lubrication of additive manufactured parts by laser beam melting and their influence of the build-up direction. Therefore, three materials were chosen for the specimens: stainless steel (1.4404 or 316L), titanium (Ti6Al4V) and nickel-base alloy (IN718). First, the thrust force by drilling perpendicular and parallel to the layers is evaluated. Additionally, the drilling result by analysing the arithmetic mean deviation of the profile Ra and the average surface roughness Rz is rated.

2. Experimental procedure

2.1. AM process

For the manufacturing of the specimens laser beam melting was utilised. The process parameters for the materials are listed in Tab. 1. The scanning strategy was a chessboard pattern. The subsequent drilling experiments were carried out with as built specimens.

Table 1 Process parameters of LBM-Process

Material	**Layer thickness [µm]**	**Laser intensity [W]**	**Scan velocity [mm/s]**	**Hatch distance [mm]**
Ti6Al4V	50	275	775	0.12
IN718	50	275	760	0.12
1.4404	50	275	700	0.12

The dendritic microstructure and intermetallic phases of Ti6Al4V and IN718 due to the high cooling rates are already part of publications, respectively [4, 5, 6]. Stainless steel was investigated to add a steel grade to the material portfolio. Titanium and nickel-base alloys are used in special fields like biomedical area or for high-temperature applications. In comparison steel has a broader dissemination. Wang et. al. [7] investigated the microstructure of 316L manufactured by laser beam melting.

2.2. Drilling

The drilling experiments were performed on the 5-axis machining centre MAG NBH630. The spindle has a maximum rotational speed of 10,000 RPM and the coolant supply has a

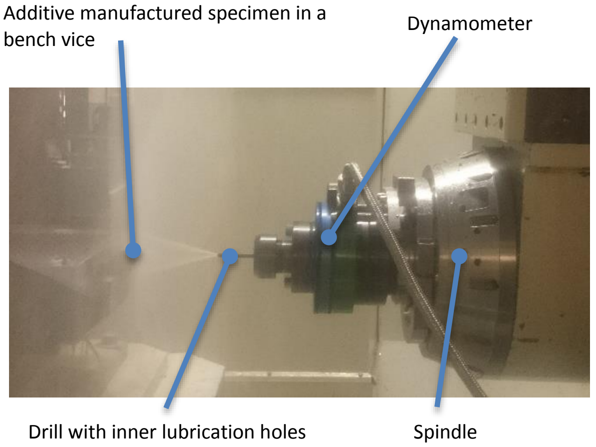

Figure 1. Experimental Setup

pressure of 40 bar. The experimental setup for the investigations is shown in Fig. 1.

The drill diameter was 6.8 mm with a drilling depth of 30 mm using lubrication in the form of emulsion. Due to the high thermomechanical loads while machining nickel-base alloys [8] a cemented carbide drill with a special nitride based coating (RT 100 HF from Gühring oHG) was utilized for IN718. For the material Ti6Al4V and 1.4404 a cemented carbide drill with a TiAlN nanoA coating (RT 100 VA from Gühring oHG) was chosen.

In addition to the material the drilling parameters, cutting speed and feed rate, were varied as listed in Tab. 2. Using these values a full factorial experimental design was chosen, resulting in 27 examined parameter combinations. Each experiment was repeated five times. The maximum and minimum value of those five measurements were rejected. Therefore, three results were considered for the evaluation.

Table 2 Drilling parameters for the experiments

Material	Cutting speed [m/min]	Feed rate [mm/rev]
Ti6Al4V	35	0.10
Ti6Al4V	45	0.15
Ti6Al4V	55	0.20
IN718	25	0.10
IN718	35	0.15
IN718	45	0.20
1.4404	60	0.10
1.4404	80	0.15
1.4404	100	0.20

In Fig. 2 the orientation between the layered specimen and the drill is shown to assure clarity and precision of the chosen designation. The build-up orientation of the layered specimen is indicated by z-direction.

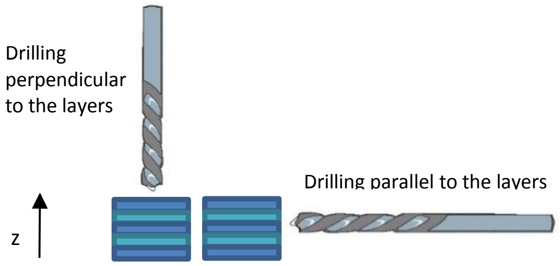

Figure 2. Pictogram of orientation between drill and layered specimen

In Fig. 3 an exemplary graph of the measured drilling process is shown and the relevant time areas for the evaluation is marked. For the evaluation the unfiltered values were taken into account.

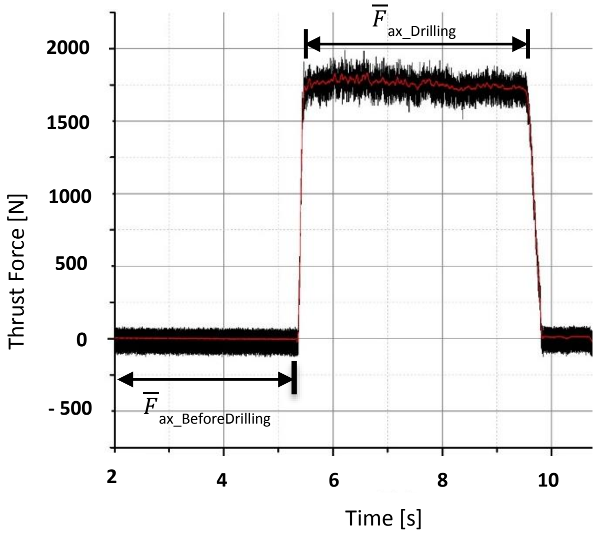

Figure 3. Depiction of the evaluation of the thrust force during the drilling process parallel to the build-up orientation of the specimen (IN718: cutting speed of 45 m/min and feed rate of 0.2 mm/rev)

2.3. Analysis methods

During the drilling experiments the thrust force was measured with a rotating 4-components dynamometer of type 9124B by Kistler Instrumente AG. The sampling rate was set to 20 kHz. Therefore, the maximum parameter set of feed rate 0.2 mm/rev and cutting speed 100 m/min results in 64 measurement-points for the thrust force during drilling through one 50 µm thick layer of the material. This allows analysing the single layers. However, the noise of the signal exceeds the difference between the layers, hence the transition of the layers cannot be resolved.

The resulting arithmetical mean deviation of the profile Ra and the average surface roughness Rz of the holes was measured by a MarSurf XR20 perthometer with a diamond tip. The parameters chosen for the roughness measurement, Ra and Rz, are the measuring distance of 5.6 mm, the measuring speed of 0.5 mm/s, the measuring interval of 0.5 µm and the filter type Gauss. The expanded uncertainty *U* of the perthometer is lower than 3%. Each hole was measured four times in machining direction at various positions of the circumference.

3. Results

3.1. Thrust Force

To investigate the influence of the build-up orientation of the specimens the thrust force during the drilling process was taken into account. The results of the evaluation are shown in Fig. 4 for the different feed rates. Generally, the standard deviation was insignificant for the measured thrust forces. Therefore, to guarantee the clarity the standard deviation was omitted.

Furthermore, the thrust force is increasing for an increasing feed rate, which was expected. In comparison to IN718 and Ti6Al4V, the thrust force of 1.4404 increases significantly about 60 N between a feed rate of 0.1 mm/rev and 0.2 mm/rev.

The drilling perpendicular to the layers of IN718 evokes either the same thrust forces than the machining parallel to the layers or the thrust forces lie below the value of drilling parallel to the layers.

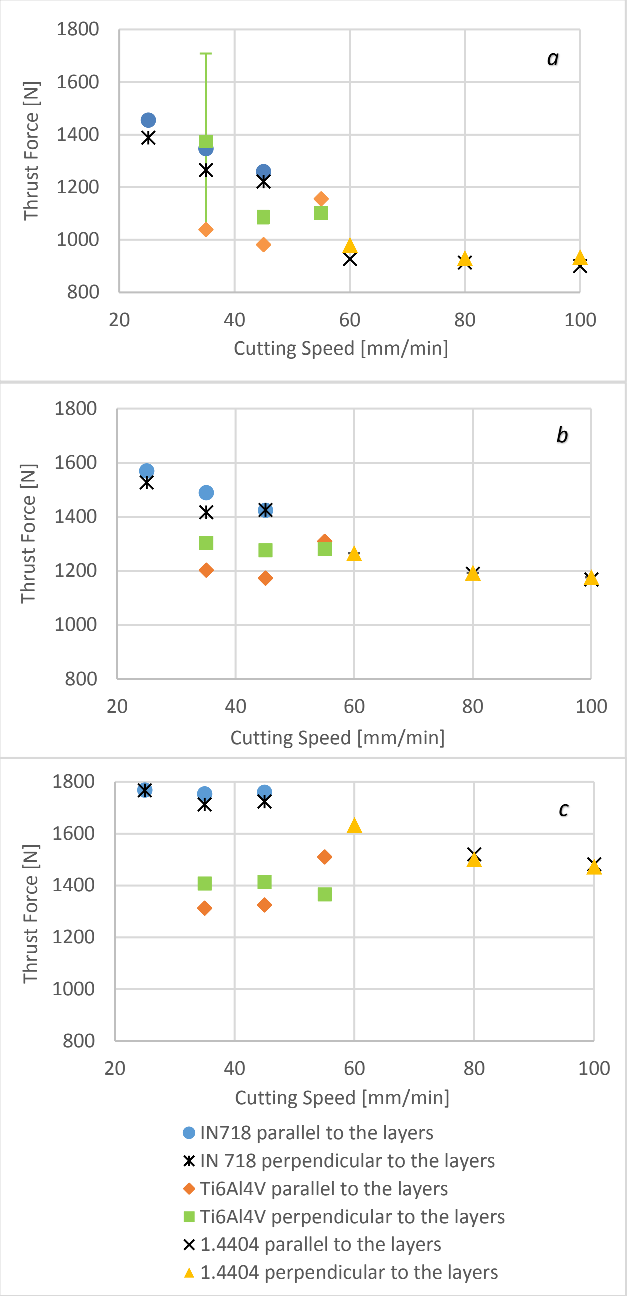

Figure 4. Thrust Force during the drilling process for various feed rates a) 0.1 mm/rev, b) 0.15 mm/rev and c) 0.2 mm/rev

The thrust force shows the same behaviour like IN718 for a cutting speed of 55 m/min while machining Ti6Al4V. The thrust force during drilling parallel to the layers increases significantly for a cutting speed of 55 m/min, whereas for lower cutting speeds the thrust force is almost constant. The influence of wear can be excluded in this case due to a drill change before proceeding with the experiments at this cutting speed. Furthermore, the thrust force is constantly around 100 N higher for drilling perpendicular to the layers. However, in the case of Ti6Al4V the standard deviation by machining with a cutting speed of 35 m/min and a feed rate of 0.1 mm/rev is significantly high. During one drilling operation with these parameters a drill breakage happened. This result indicates an inappropriate parameter combination. Additionally, the standard deviation of the thrust forces calculated for the drilling processes perpendicular to the layers of Ti6Al4V show a higher value of ±24 N compared to the machining operation parallel to the layer orientation of the material with a value of ±6 N.

For stainless steel the influence of the inhomogeneous layered material is only relevant for low cutting speeds where the forces are little higher at machining perpendicular to the layers.

By comparing the thrust forces of IN718 and 1.4404 of drilling parallel to the layers the thrust force behaves opposite. For 1.4404 at the lowest feed rate the thrust force is almost constant and increases for higher feed rates and a cutting speed of 60 m/min. The highest thrust force appears at a feed rate of 0.2 mm/rev and a cutting speed of 60 m/min. For machining IN718 the highest thrust force appears also for a feed rate of 0.2 mm/rev, but the thrust force is almost constant for the three cutting speeds. For the other feed rates a significant decrease of the thrust force by about 200 N is noticed while the cutting speed is increased from 25 m/min to 45 m/min.

In general, the assumption is that during the drilling process parallel to the layers the thrust force is stationary due to the uniform material in machining direction. In addition, it was expected that drilling perpendicular to the layers would result in an oscillating thrust force due to an expected hardened intermediate zone between two successive layers. The reason is the manufacturing process. The laser has to melt the powder of the actual layer and partially the prior layer to connect both layers. Regarding Ti6Al4V, the higher range of standard deviation of machining perpendicular to the layers compared to the drilling process parallel to the layers could be an indication for this assumption.

Due to the fact that the noise of the recorded signal was too high so that the individual layer could not be resolved. Instead the experiments reveal more general information about the occurring thrust force while drilling perpendicular or parallel to the layers. The effect of the build-up direction on the drilling process of IN718 is insignificant. The reason could be that the hardness of the material is already very high, so that a further laser hardening during the manufacturing process cannot be resolved. For machining Ti6Al4V the thrust force depends on the build-up orientation and the drilling parameters significantly. It seems that for lower cutting speeds, 35 m/min and 45 m/min, the perpendicular drilling to the layers induce higher thrust forces compared to the parallel drilling. But for an increased cutting speed the opposite is the case. Regarding the material 1.4404 an influence of the build-up orientation could only found for a cutting speed of 60 m/min and a feed rate of 0.2 mm/rev. Therefore, the perpendicular drilling to the layers show higher a higher thrust force.

3.1. Roughness

Initially, the arithmetic average and the standard deviation of Ra and the average surface roughness Rz of the laser beam manufactured specimens were examined. The results are shown in Tab. 3 and were categorized by lateral surface, indicating the surfaces of the specimen which were surrounded by powder, and deck surface, indicating the last layer (maximum z-direction) of the part, to point out the different conditions. The roughness values are similar to those found in the literature [9, 10].

The results for the holes for Ra are depicted in Fig. 5 and the values of Rz are presented in Fig. 6. For IN718, Ra and Rz decrease for an increasing feed rate and at a cutting speed of 55 m/min the machining of the different layered material is negligible. Ra and Rz of Ti6Al4V show a parabolic function with a minimum at a cutting speed of 45 m/min. The layers of the material is only an issue while drilling with a feed rate of 0.15 mm/rev. The drilling process perpendicular to the layers of the material results in higher Ra as machining parallel to the layers. This correlates to the force behaviour at this parameter set.

Table 3 Ra, Rz and the standard deviation of the specimen surface

Material	Ra [µm]	s [µm]	Rz [µm]	s [µm]
Ti6Al4V (lateral surface)	8.46	±0.67	45.41	±3.50
IN718 (lateral surface)	2.93	±0.19	14.63	±0.47
1.4404 (lateral surface))	5.28	±0.41	26.5	±2.63
Ti6Al4V (deck surface)	5.53	±1.64	31.81	±7.27
IN718 (deck surface)	3.99	±1.51	19.23	±6.07
1.4404 (deck surface)	6,11	±1,41	30,24	±6,36

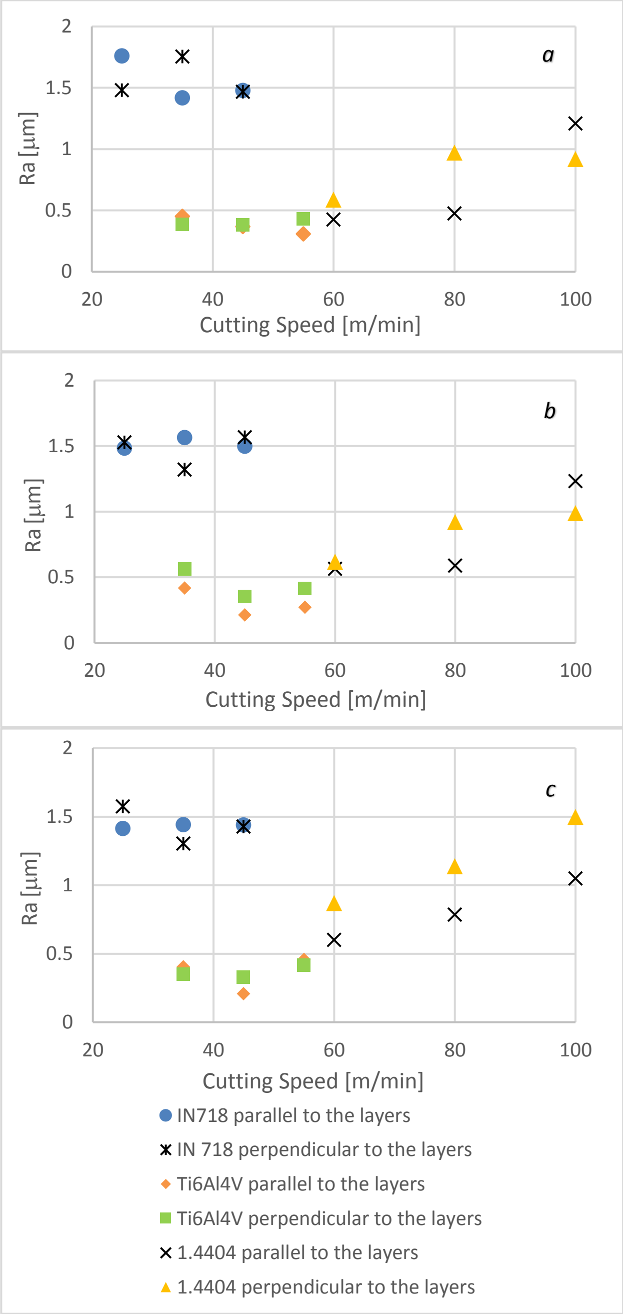

Figure 6. Ra in µm of the holes for various feed rates a) 0.1 mm/rev, b) 0.15 mm/rev and c) 0.2 mm/rev

For 1.4404, the layers of the material to the machining direction is of significance while the thrust forces show no significant influence. At lower cutting speeds the holes drilled perpendicular to the material layers show a higher average roughness Ra and absolute roughness Rz. An exception appears at a cutting speed of 100 m/min and a feed rate of 0.2 mm/rev. Ra increases also for the drilling perpendicular to the layers while Rz of the parallel machined specimen is higher than that of the perpendicular machined one.

It was expected that the roughnesses Ra and Rz are lower at drilling parallel to the material layers because of the expected homogeneity of the layer. In general, the results confirm this assumption. For IN718 such a difference cannot be identified.

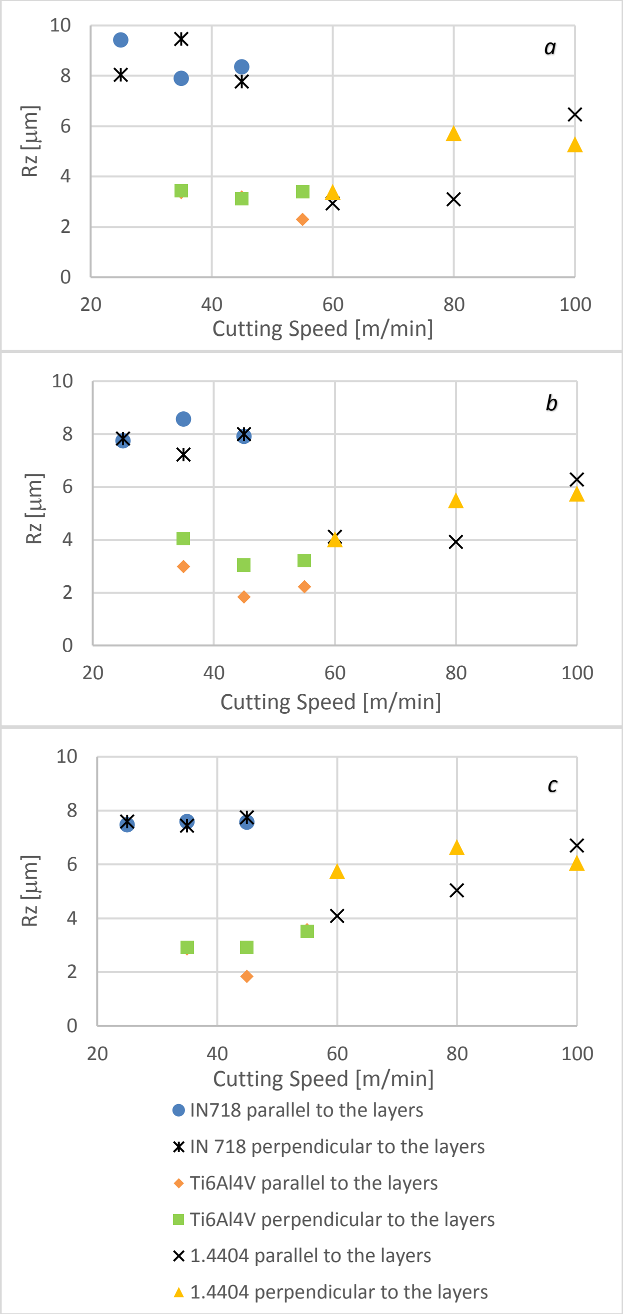

Figure 7. Rz in µm of the holes for various feed rates a) 0.1 mm/rev, b) 0.15 mm/rev and c) 0.2 mm/rev

5. Conclusion

The additive manufactured parts request a finishing process like drilling due to the lack of accuracy after laser beam melting when high demands on holes is preferred. To understand the influence of different process parameters on thrust forces during drilling and the roughness of the drilled holes while drilling, machining experiments parallel and perpendicular to additive manufactured parts were performed. The materials IN718, Ti6Al4V and 316L (1.4404) were focused during this analyses and were manufactured by laser beam melting. Additionally, the selection of the cutting speed was dependent on the material. For 1.4404 cutting speeds between 60 m/min and 100 m/min were chosen, for IN718 and Ti6Al4V more moderate cutting speeds between 25 m/min and 55 m/min were selected while the same feed rates (0.1 mm/rev, 0.15 mm/rev and 0.2 mm/rev) were used for all materials.

For IN718 the evaluation of the thrust force reveals that during machining perpendicular to the layers of the material the thrust forces are equal or slightly lower than for drilling parallel to the layers. Furthermore, there is no identifiable correlation of roughness and the layers of the material.

A relevance of the layers of 1.4404 occurs only for a cutting speed of 60 m/min and increases with increasing feed rate. The drilling process perpendicular to the layers of the specimens indicate higher thrust forces than the drilling parallel to the layers. To achieve a high surface quality by machining 1.4404 the lowest investigated cutting speed of 60 m/min is recommended and a feed rate of 0.1 mm/rev to further reduce the thrust force during the drilling process.

During the evaluation Ti6Al4V emphasises as a special material. For cutting speeds of 35 m/min and 45 m/min the drilling parallel to the layers is constantly 100 N lower than the drilling perpendicular to the layers of the specimen. But for a cutting speed of 55 m/min the opposite appears. This phenomenon needs further analysis and can currently not be explained.

Further experiments with wrought or conventional manufactured IN718, Ti6Al4V and stainless steel have to be done to compare and contextualize the results.

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